SMALL-SCALE AND ARTISANAL FISHERIES: INSIGHTS AND APPROACHES FOR IMPROVED GOVERNANCE AND MANAGEMENT IN A GLOBALIZED CONTEXT

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SMALL-SCALE AND ARTISANAL FISHERIES: INSIGHTS AND APPROACHES FOR IMPROVED GOVERNANCE AND MANAGEMENT IN A GLOBALIZED CONTEXT

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Editorial: Small-Scale and Artisanal Fisheries: Insights and Approaches for Improved Governance and Management in a Globalized Context

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Editorial on the Research Topic

Small-Scale and Artisanal Fisheries: Insights and Approaches for Improved Governance and Management in a Globalized Context

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INTRODUCTION

Small-scale fisheries (SSFs) make important but often poorly quantified contributions to national and regional economies, to local food security and nutrition of millions of people. As such they provide an important lever for achieving the UN Sustainable Development Goals, particularly in rural areas. The dynamics that drive SSFs and their observed social, economic and environmental outcomes tend to be a complex mix of endogenous factors, such as over-fishing and conflict over resources, and external pressures such as climate change and international demand for seafood.

As a generalization, small-scale and artisanal fishers suffer from poorly defined rights to marine resources, which can negatively affect conservation incentives. They are often (but not always) among the poorest and most marginalized parts of society and are generally poorly represented in national and international policy fora. However, poorly defined access rights are only part of a complex puzzle of diverse fishing practices and often weak governance structures to regulate them. As shown by Smith and Basurto, many countries display weak political will to engage comprehensively with SSFs. Weak community institutions and sparse data availability often further undermine the capacity for assessment and management. Past failures to address these issues have had significant social consequences and have affected livelihoods, increased vulnerability to poverty, and meant less availability of fish protein per capita. New and improved ways of understanding, analyzing and governing and SSFs are therefore still in demand, in order to allow SSFs to become the lever for sustainable contribution the SDGs it ought to be.

A growing number of studies have shown the importance of broadening policy and academic inquiry to include the entire value chain, as many drivers of exploitation are channeled through and influenced by market structures and market actors (Brewer et al., 2009; Crona et al., 2010, 2016; Cinner et al., 2016; Purcell et al., 2017; Drury O'Neill et al., 2019). Sustaining marine resources and fisheries livelihoods therefore demands consideration of the interactions between ecosystems, small-scale fishing, and the domestic and international seafood markets. Institutional contexts of SSFs also play an important role in resource sustainability, yet successful fisheries governance remains a challenge. In this Research Topic we therefore bring together a broad selection of papers that, in different ways, shed new light on these challenges and how to address them.

RECOGNIZING THAT SSFS ARE EMBEDDED WITHIN GLOBAL MARKETS

One set of papers in this Research Topic heeds the call to explore new approaches, concepts, and methods including the under-examined market connections between small-scale fisheries and global markets, ecosystem-based management and diagnosing and monitoring fisheries. Several of the papers highlight the complexity of SSF value chains—which in fact are better portrayed as networks than chains (Drury O'Neill et al.; Smith and Basurto). These papers point to the importance of describing the relations of fishers and intermediary traders to better understand and predict the behavior of market actors, and thus both social and ecological outcomes.

Stoll et al. show that a similar complexity exists even at the scale of trading nations. Their analysis of lobster trade highlights how the existence of a diverse set of intermediary trading nations for lobster is creating a false sense of trade diversification among lobster producers, which in turn masks increased dependencies on a reduced number of end-markets, particularly in Asia. Using the lobster trade as a case, they outline a method for making explicit the vulnerabilities that face many SSF participating in global markets, and which stem in part from "teleconnectivity" among local SSF created through seafood trade routes.

DIAGNOSIS AND MANAGEMENT OF SMALL-SCALE FISHERIES

A multitude of new approaches and tools are emerging for diagnosing and monitoring SSFs and associated value chains. Some build on existing concepts and ideas, while others are the result of cross-pollination and the introduction and deployment of experimental and modeling approaches from other disciplines, for the benefit of improved SSF governance.

Lindkvist et al. review agent-based modeling (ABM) in fisheries and show how it has been used as a research tool for understanding cooperation and over-harvesting, as a decision-support tool, or as a participatory tool. While ABM is a resource-intense endeavor, the simple structural design of agent-based models allows stakeholders, experts, and scientists across disciplines and sectors to reconcile different knowledge bases, assumptions, and goals. As such, ABM can aid the development and testing of new policies and management strategies.

Drury O'Neill et al. show how behavioral economic experiments can be used to test hypotheses about causality within fisheries markets that are hard to examine from purely empirical enquiry. Behavioral economic experiments have not been widely used to understand SSFs. Such tools might uncover gaps in our understanding of human behavior in fisheries, and can be used to test whether "conventional truths" of fishers' responses might need to be challenged in order to achieve truly sustainable governance strategies.

Just like agent-based models and economic experiments, behavioral science is a field not extensively linked to fisheries research. Yet behavioral science can contribute to improved understanding and management of SSFs. In this regard, Battista et al. trace the drivers of illegal fishing and review how behavioral science can inform interventions to combat this prevalent phenomenon. Once the norms and beliefs of fishers are understood, actions can be taken to correct beliefs (e.g., perceived illegitimacy of regulations) and address drivers of illegal fishing.

The multi-species, multi-gear, and data-poor nature of SSF makes implementation of traditional single-species management approaches (e.g., catch quotas) challenging and insufficient. Herrón et al. therefore propose indicators (taxonomic, sized-based, functional, conservation) to be used in evaluations of multi-gear and multi-species SSFs in tropical coastal areas. These can help to understand ecological impacts of different fishing gears and contribute to ecosystem-based fisheries management. The multispecies and multi-gear nature of SSFs also make their diagnoses and management difficult. Purcell et al. assess geographic and gendered variation in catches and gear use in a tropical multispecies SSF. Their novel graphical techniques for visualizing such trends across a fishery can inform the planning of regulatory measures and fishery development initiatives.

Local ecological knowledge (LEK) is broadly considered the body of knowledge built up by a group of people through generations of living in close contact with nature. Berkström et al. assess fishers' LEK on connectivity between multiple habitats within a tropical seascape, differences in LEK among fisher groups, and the coherence between LEK and conventional scientific knowledge (CSK). The study highlights benefits of LEK as complementary information in the management of SSFs.

Finally, trophic models of the Ecopath with Ecosim (EwE) type and Local Ecological Knowledge (LEK), have been widely applied for fisheries assessment and management. However, no specific methodologies describe how (LEK) from local fishers can be incorporated in the models. Sánchez-Jiménez et al. aims to do this and present a systematic integration of LEK with EwE modeled output. They demonstrates how integrating knowledge systems can enhance understanding of the state and changes in ecosystems, helping to improve fisheries management. EwE models can also contribute in communication between managers and fishers, promoting discussion and engagement.

NEW APPROACHES AND PARADIGMS FOR SSF GOVERNANCE

A couple of papers in this special issue also explore key challenges and new approaches in the governance of SSFs. Co-management has long been advocated, yet is still not a dominant paradigm within SSF governance. As such, it is still finding new places of adoption and new ways of being used. Tilley et al. examine the adoption of community-based resource management (CBRM) in Timor-Leste and show the effectiveness of co-management in engaging communities in resource management. However, their analysis also shows the risk of a monolithic, narrow interpretation of CBRM (in fact, no-take zones) becoming the norm. They highlight a need for guiding principles to ensure a diverse contextualized implementation of management strategies, as well as legitimate community engagement.

de la Torre-Castro highlights that inclusion of both genders in the management process is needed and better inclusion of women in fisheries management can foster new solutions. Achieving the SDGs goals of gender equality while also ensuring conservation of life below water requires management approaches that consciously and explicitly consider gender and diversity of actors (de la Torre-Castro; Biswas, 2017). In a similar vein Cohen et al. elaborate on the importance of conceptualizing a just space for SSFs in the blue economy. Their proposed "just space" explicitly accounts for the voices, interests, and human rights of both women and men who service, fish and trade from SSFs. Accordingly, a balance must be struck between artisanal livelihoods, industrial-scale fishing and conservation of fishery resources through the consideration of both ecological and social objectives.

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All authors contributed to the ideas and writing of this Editorial.

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Seafood Trade Routes for Lobster Obscure Teleconnected Vulnerabilities

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Reliance on international seafood markets leaves small-scale fishers and fishing economies vulnerable to distant disturbances that can negatively affect market prices and trigger social, economic, and environmental crises at local levels. This paper examines the role of seafood trade routes and re-exports in masking such market linkages. We employ a network approach to map the global trade routes of lobster (*Homarus* spp.) from small-scale producers in North America to terminal markets and evaluate the extent to which intermediary nations act to obscure producer-market relationships. In taking this approach, we provide a method for systematically measuring "teleconnectivity" created through seafood trade routes, and thus making explicit vulnerabilities to small-scale fisheries from this teleconnectivity. Our empirical analysis shows that the perceived trade diversification of lobster producers is masking increased dependencies on a reduced number of end-markets, particularly in Asia. These results suggest, paradoxically, that the apparent diversification of trade partnerships may actually amplify, rather than reduce, the vulnerabilities of small-scale fishers associated with international trade by making risk harder to identify and anticipate. We discuss our results in the context of local fisheries and global seafood trade and describe key impediments to being able to monitor market dependencies and exposure to potential vulnerabilities.

Keywords: seafood trade, teleconnectivity, globalization, lobster, China, vulnerability

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INTRODUCTION

The world is witnessing unprecedented levels of global trade of natural resources as a result of increasingly liberal trade policies (OECD, 2003; Melchior, 2006; Campling, 2016) and advancements in technology and logistical capacity (Anderson et al., 2010). Tveterås et al. (2012) report that an estimated 78% of worldwide seafood supply is now influenced by global trade competition and 36% is directly traded across international borders at a value of US$148 billion. This represents a 515% increase in the trade of fisheries products for human consumption by value from 1976 to 2014 (FAO, 2016).

Increased seafood trade has been argued to produce a suite of benefits to nations, including wealth production, employment opportunities, and food security (Thorpe, 2005; Toufique and Belton, 2014; Asche et al., 2015). However, these gains are often unevenly distributed across regions and sectors and tend to disadvantage developing nations in the global south (Béné et al., 2010a,b; FAO, 2012; Prell et al., 2017). Trade also plays a paradoxical role by simultaneously making systems both more and less connected. In fisheries, for example, decreased connectivity is exemplified by the way trade decouples marine ecosystems and the often small-scale harvesters that depend on them, from consumers through geographic, socioeconomic, and cultural separation (Cheung and Chang, 2011; Fabinyi and Liu, 2016). Crona et al. (2015a) argue that this decoupling weakens the feedback loop between harvesters and consumers, making it difficult for consumers to track the ecological impacts of their purchasing decisions and respond accordingly. This dynamic is further compounded by widespread seafood mislabeling (Jacquet and Pauly, 2008) and gray and illegal trade activities, which have been estimated at 11 to 26 million tons per year (Agnew et al., 2009).

Increased connectivity on the other hand is simultaneously witnessed through new interdependencies between previously disassociated places and processes created by international trade. These emergent linkages expose small-scale fishers in geographically distinct regions to seemingly unrelated threats and disturbances, making them susceptible to what Liu et al. (2013) and Adger et al. (2009) have described as "teleconnected" surprises and vulnerabilities. "Teleconnected" refers to the idea that phenomena occurring far away are correlated through a global process, such as trade. Examples of teleconnected surprises caused by trade in small-scale fisheries are widespread. Severe flooding in southern China in 1998, for instance, caused a sudden drop in the price of bêche-de-mer (sea cucumber) in the Philippines because Chinese consumers were preoccupied with clean-up efforts and temporarily reduced consumption of luxury food products (Akamine, 2005). Another case is the ban imposed by the European Union on tilapia from Lake Victoria in the late 1990s, which resulted in severe socioeconomic hardship for lakeside communities and displaced trade from the European Union to Israel (Abila, 2003; Geheb et al., 2008). Similarly, elevated levels of heavy metals were detected in shipments of spiny dogfish from the United States that were bound for the European Union, where standards for heavy metals and PCBs are more stringent. The discovery caused the market to come to a sudden halt, adding additional strain on an already depressed fishing sector (Stoll et al., 2015).

These experiences have catalyzed interest in alternative and local seafood distribution systems (Bolton et al., 2016), but the pace of trade has not waned. More than 200 nations currently participate in international seafood trade (FAO, 2016) and the average number of trade partners per country has risen by 65% since 1994, increasing from 25.3 in 1994 to 41.7 in 2012 (Gephart and Pace, 2015).

Diversification among trade partners theoretically offsets the risk of exposure to distant threats and reduces vulnerabilities by decreasing the dependency that any one producer-nation and its small-scale producers has on a particular market (importer). However, in today's hyper-connected world, many new trade partnerships are not necessarily correlated with an increased number of markets, but rather an increase in the number of intermediaries acting as waypoints between producer-nations and terminal markets. Product is exported to these intermediaries and then re-exported again. A number of interwoven socioeconomic and political factors related to the location and cost of processing, tariffs, and illegal and gray trade practices drives this phenomenon (Jacquet and Pauly, 2008; Agnew et al., 2009; Collins and Sun, 2010; Prell et al., 2017). This makes it increasingly difficult to discern the true reliance that producers have on particular markets, and therefore obscures looming vulnerabilities of local fisheries to distant market dynamics.

Given the rising potential for teleconnected surprises created by increasing trade, efforts to assess teleconnectivity and measure the masking of market dependencies created by indirect seafood trade routes is important. Elucidating these relationships will not reduce exposure to trade related vulnerabilities *per se* but can reduce the potential for surprise otherwise imminent if unnoticed or misrepresented trade teleconnections are not acknowledged. This logic is consistent with standard risk management approaches employed in numerous sectors including those associated with public health, engineering, and project management. Such approaches provide estimates of hazards and the probability and magnitude of threat, yet in the fisheries sector trade related risks are poorly understood.

This paper provides a method for systematically assessing the teleconnectivity created through seafood trade routes using network analysis. We show how the methodology can be employed by using the case of lobster (*Homarus* spp.) and analyzing trade routes for it through time, as well as evaluating the effect of re-exports on the appearance of market dependence between producer-nations and terminal-markets. We focus on lobster as a case example because it is a high-value commodity that is traded worldwide and it is of particular sociocultural and economic importance in North America, where it supports thousands of small-scale fishers (Steneck et al., 2011; Stoll et al., 2016). We also use this case because it speaks to, and illustrates, the growing role of China in the global seafood economy. Our analysis highlights the dynamic nature of seafood trade routes and shows how market dependencies change with time. The approach also quantifies the masking of market dependencies created by indirect seafood trade routes. Evidence of such masking suggests that teleconnected vulnerabilities are being obscured, creating an environment where risk of surprise to producer-nations is likely exacerbated.

MATERIALS AND METHODS

Trade Data

Data behind the seafood trade route analysis are derived from the United Nations Comtrade database, an online portal of international trade statistics (United Nations, 2017). We use the 6-digit Harmonized System (HS) codes for fresh (030622) and frozen (030612) lobster. These codes include American (*H. americanus*) and European lobster (*H. gammarus*), but not any of the species of rock and spiny lobster or Norway lobster (*Nephrops norvegicus*). Data for prepared and preserved lobster products are not included, since it is not possible to distinguish between the different species of lobster in this data.

Producer-nations and their annual landings were identified using the FAO Global Capture Production database (FAO, 2017). Trade statistics were then extracted from the UN Comtrade database for all nations trading lobster from 2006 to 2015. Any country trading lobster which was not identified by FAO as a producer is treated as a re-exporter. Focusing on re-exported product allows us to distinguish between nations that are terminal markets and those that effectively serve as intermediaries. In using this approach, we make several assumptions that warrant explicit acknowledgment. First, our analyses are based on the assumption that trade data provided in the UN Comtrade database are accurate. We recognize that this may not always be the case, yet UN figures are the most widely accepted data currently available. This most likely means that our results provide an under-estimate of the issue, since any inaccuracies in the data would further obscure dependencies between producer-nations and terminal markets. Another assumption relates to the delineation of trade routes. Throughout our analysis we are liberal in our designation of direct trade, which we define as trade occurring between producer-nations and non-producer nations. This assumption overlooks instances in which producer-nations themselves engage in re-export activities by importing and then re-exporting product that they did not harvest[1]. This assumption is necessary because the UN Comtrade database does not provide information about country of origin, making it impossible to trace the flow of product within a nation. This assumption also likely underestimates the masking of trade routes.

Network Analysis

Seafood trade often involves nations that act as "middlemen" in the supply chain, importing and then subsequently re-exporting product. This results in indirect linkages between nations, creating dependencies that are sometimes difficult to identify if focus remains primarily on direct trade (i.e., trade between a producer and a non-producer). As a result, they are rarely accounted for in assessments of fisheries resilience or sustainability.

We begin to address this issue by mapping seafood trade routes from producer-nations to terminal markets and evaluating the extent to which re-exporting intermediaries obscure the magnitude of true producer-market relationships, referred to here as market dependency. This approach, which is based on network analysis, thus measures the true dependence of producer nations on terminal markets over time, and provides a method for systematically assessing the extent of teleconnectivity created through seafood trade routes.

To examine the role of seafood re-exports and evaluate their masking effect we use a network approach. Specifically, we use weighted eigenvector centrality in the R package igraph. This is a common network metric that describes the relative importance of individual nodes based on their position in a network and the centrality of adjacent nodes (Bonacich, 1987). In other words, eigenvector centrality allows us to characterize the "global" prominence of a node (nation) in the network depicting the global trade of lobster (as opposed to "local" prominence, which measures such as degree centrality will do). The methodology relies crucially on two steps.

First, we measure the eigenvector centrality of nations engaged in lobster trade worldwide from 2006 to 2015 by calculating their centrality using only direct trade relationships (i.e., producer nation exports) for each year. We refer to this as Direct Trade Network (DTN). While this provides an assessment of the relative importance of producer nations and importers, the focus on direct trade does not allow us to evaluate the role of non-producing nations, which often import product for re-export rather than domestic consumption (or a combination of both).

To capture re-export—which is instrumental for uncovering any potential masking effects of terminal markets by falsely assuming trade diversification—we calculate the eigenvector centrality of nations engaged in global lobster trade (yearly, for the same time period), including both direct trade *and* re-exported trade. We refer to this as All Trade Network (ATN).

We arrive at the masking effect of re-exporting seafood by deducting eigenvector centrality values calculated in the first step by those calculated in All Trade Network (ATN).

To assess changes in the importance of trading nations over time, and thus evaluate if the evolution of trade patterns has reduced or increased the masking effect, we then order these centrality scores arrived at for each year (2006–2015) to get a rank for each country in both DTN and ATN. We do this to evaluate how the relative importance of nations changes over time, both in terms of direct trade and re-exporting patterns. We calculate this change by first standardizing the ranks (accounting for the different numbers of trade partners in DTN and ATN) and then subtracting the output of DTN from ATN using the equation:

$$R_{\mathrm{ATNt1}} - R_{\mathrm{DTNt2}}$$

where R_{t1} equals the rank of country R in ATN at time (t) and R_{t2} is the rank of country R in DTN at the same time (t). Standardization of ranks was done by letting all nations with non-existent values for any DTN or ATN (a result of them not being involved in trade during this time period) assume the lowest rank + 1 for that time period. In simple terms, all nations not trading in any particular year therefore tie for last place.

Finally, to determine the functional role of each trading nation—either as an intermediary or terminal market—we calculate the difference between in- and out-degree centrality in the ATN network. This allows us to differentiate between the countries who import for domestic consumption (in-degree would be high, while out-degree virtually null), and those functioning as re-exporting hubs (the difference between in- and out-degree would be minimal).

RESULTS

We find that market dependencies between producer-nations and terminal-markets for lobster are consistently masked, but the degree of distortion of true market dependencies varies between nations and across regions (**Figure 1**). Between 2006 and 2015 the

[1]Trade between the United States and Canada provides an example of this dynamic. Both countries land lobster, but also trade with each other.

underestimation of this market dependency (based on re-export) ranges from 7 to 14% of total traded value per year. As we discuss in the subsequent section, this finding is conservative.

Calculation of the change in rank order between DTN and ATN allows us to assess changes in the importance of trading nations over time, and thus evaluate if the evolution of trade patterns has reduced or increased the regional masking effect of interest. **Figure 2** shows the cumulative change in rank of nations over time between the two trade networks, presented per geographic region. This change reflects the aggregate relative masking of true market dependency when only accounting for direct trade. While this masking is notable in the trade network in all regions except North America, it is most pronounced in Asia[2]. Asia is consistently the region with the largest change in rank when contrasting only direct trade with directly traded and re-exported volumes over time, indicating a strong masking effect in this region, which results from the existence of prominent trade hubs and also large terminal-markets that are receiving re-exported product. Specifically, we find that 11 nations in Asia change ranks between DTN and ATN by at least 5 positions. By contrast, only 1 nation in Europe changes by more than 5 positions in rank (Iceland +25).

To calculate the magnitude of masking created by re-exports (**Figure 3**) we assess the annual discrepancy between eigenvector centrality for DTN and ATN per region. Accounting for re-exports (ATN), we find that the cumulative eigenvector centrality of European nations decreases annually from a high of 0.45 in 2007 to <0.25 in 2015 (−44%), indicating their declining importance in the global trade of lobster. This downward trend is contrasted by the cumulative change in eigenvector centrality of Asian nations. Between 2006 and 2015, centrality increases by 278%, from 0.11 to 0.32, explained by a rise in trade by several Asian nations. In particular, South Korea (+170%), Vietnam (+3,397%), Hong Kong (+256%), and China (+3,047%) all become more central nodes in the lobster trade network during the 10-year study period. The difference between DTN and ATN among European nations is relatively small, and between 2012 and 2015 is virtually non-existent. However, we find evidence that there is consistent masking in Asia from 2006 to 2015 (−7% per year) (**Figure 3**).

China provides an illustrative example of how seafood trade routes with intermediary trading nations contribute to masking true market dependencies and exposure to risk linked to these. While China's expanding appetite for lobster has been well-documented, particularly in association with the Chinese New Year and Guanggun Jie (Singles' Day), estimates in both the media and the scholarly literature consistently under-represent the magnitude of the Chinese market by underplaying the role that trade intermediaries play in routing product to China (e.g., Fabinyi, 2017). In 2015, producer-nations exported US$154.8 million worth of lobster directly to China, but an additional US$29.1 million[3] worth of product was routed to China through re-export by other nations, indicating that China's actual import of lobster was 19% larger than conventional estimates based on direct trade. This lobster is distributed to China by way of seven primary intermediaries: Thailand (THA), Hong Kong SAR (HNK), Indonesia (IDN), India (IND), Philippines (PHL), Malaysia (MYS), and Sri Lanka (LKA). This stands in contrast to Europe, where re-export appears to be <2%.

DISCUSSION

Teleconnectivity or the coupling of seemingly disparate processes and places is thought to expose fishers to risks that prior to intensive global trade were not of major importance (Crona et al., 2015b). This article examines the role that seafood trade intermediaries play in obscuring market dependencies for lobster and provides a method for assessing teleconnectivity via trade–arguably a first step in identifying and understanding the surprises and potential vulnerabilities associated with such telecoupling (c.f. Adger et al., 2009; Liu et al., 2013).

We find that despite the participation of an increasing number of nations in the global trade of lobster, many of these countries function primarily as intermediaries, thereby masking true terminal-market dependency. More research is needed to understand the extent to which trade routes are masking market dependencies in other fisheries, as lobster market dynamics are not necessarily representative of other species. However, consistent with other recent research on global seafood trade, we find that Asia is becoming an increasingly important market for fisheries products and has recently overtaken Europe as the largest market outside North America (e.g., Villasante et al., 2013). Our findings also show that the apparent diversification that is occurring as a result of increased seafood trade obscures the growing dependency that lobster-producing nations have on key markets, of which one of the largest is China.

Further research is needed to more fully understand the risks associated with the masking created by seafood trade routes. However, one hypothesis is that this pattern could further accentuate teleconnected vulnerabilities by setting producer-nations up for surprise in the marketplace. In the case of lobster, the seasonality of both landings and the market as well as quality of lobsters being landed (soft-shell vs. hard-shell) accounts for some of the change in ex-vessel lobster price, but there have also been several points in the 25 years when prices dropped suddenly, causing socioeconomic hardship in coastal communities where they are harvested. In the United States, for example, the ex-vessel price for lobster has had three punctuated drops observed in 2001, 2008, and 2011. In each case, these episodes were described as "crises" on account of the socioeconomic impacts (and general anxiety) that they caused fishers. Indeed, the stress associated with these price drops was so severe that it reportedly led to several outbreaks of violence among industry members (Acheson and Acheson, 2010). What ties these episodes together is that unforeseen trade dynamics—as opposed to a change in

[2]The consistent top rank of North America means that no change in rank is observed over time and signals that the masking effect is null for this region.

[3]Re-exported trade represented 35% of the total value in 2014.

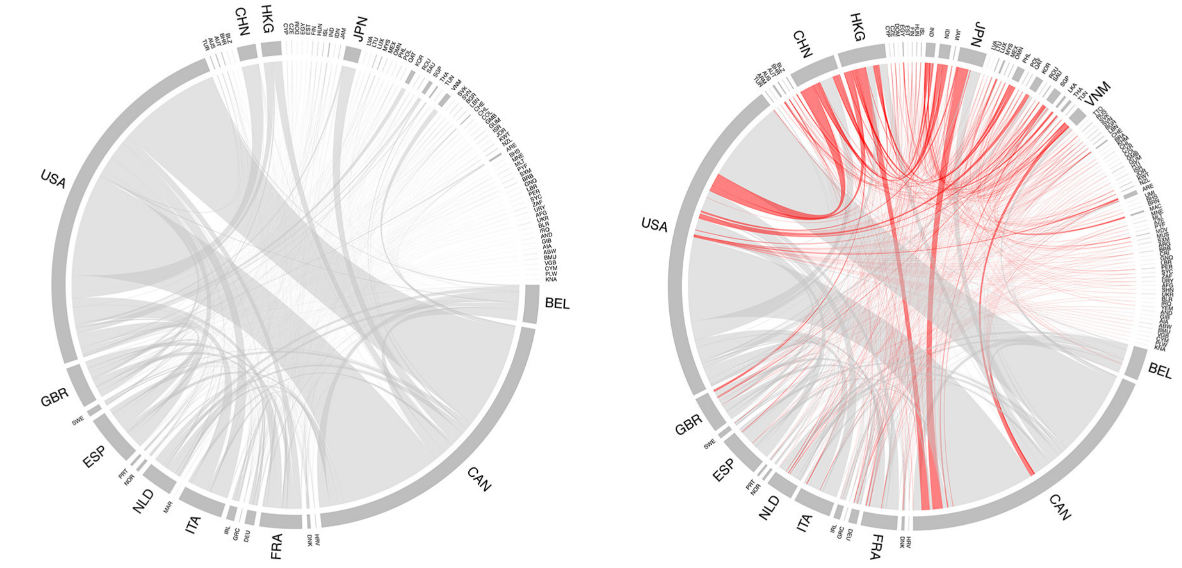

FIGURE 1 | Direct trade and re-export of *Homarus* spp. Global (2015) (Left) trade of *Homarus* spp. from producer-nations accounting for direct trade only. (Right) All trade of *Homarus* spp. including re-export (red). Width of edges between nations indicates relative value (US$) of trade.

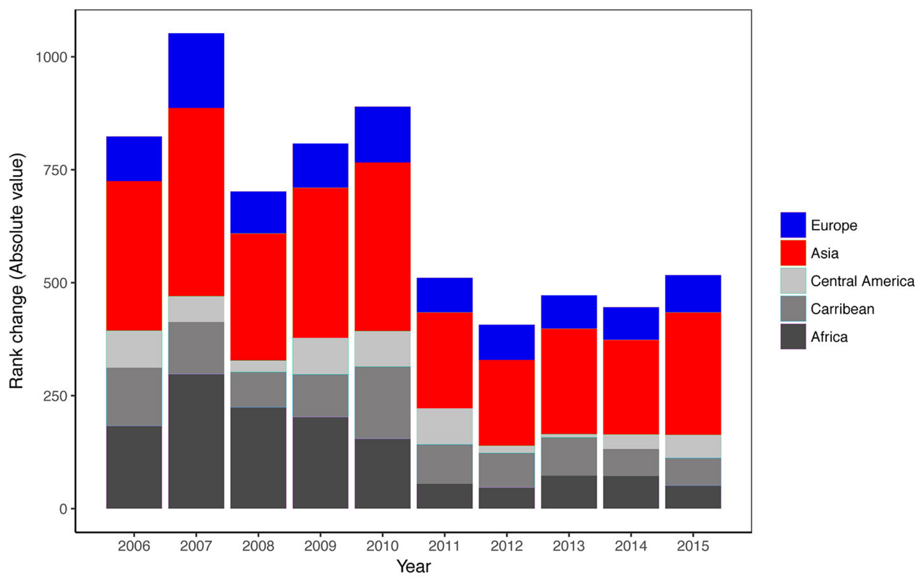

FIGURE 2 | Relative degree of masking of true market dependence by region. Values are based on total change in rank order (aggregated by region) when comparing eigenvector centrality scores based on direct, and combined direct and re-exported lobster trade statistics. Note that North America is not visible in the graph as it consistently ranks as the most important node in the network and rank does not change.

the status of the lobster fisheries alone—played a key role driving the change in price. In 2001, traders were unable to physically distribute as much product due to the downsizing of aircrafts in the wake of the terrorist attacks on the World Trade Center in New York City; in 2008, global economic instability led to less demand for luxury products worldwide; and in 2012, processors in Canada were unable to keep pace with supply. This coupling between price and trade dynamics highlights the vulnerability that producer-nations can be exposed to through trade and underscores the need for understanding and anticipating these vulnerabilities and their origins.

The risk associated with trade is particularly relevant for producer-nations that rely heavily on export markets like China, which have political structures that facilitate abrupt and broad-scale policy changes. These changes can, and have, taken many forms. For example, scholars have documented that the Chinese

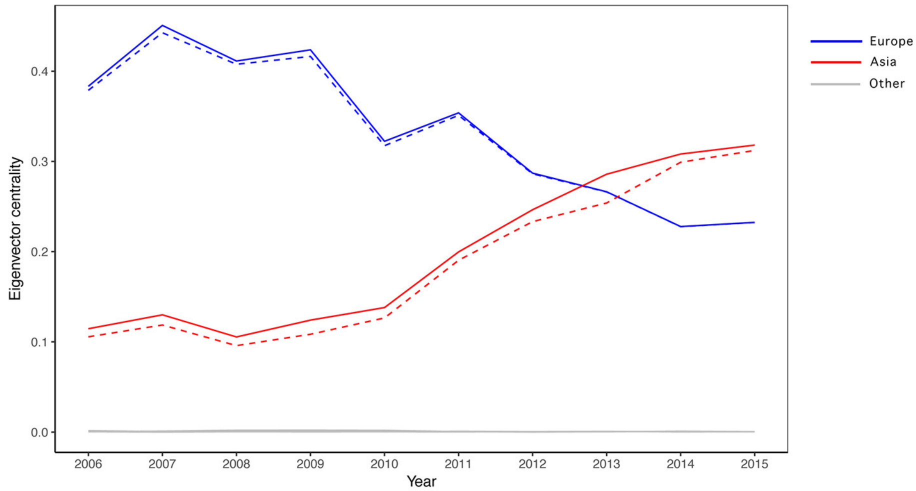

FIGURE 3 | Total eigenvector centrality of regions between 2006 and 2015. Solid lines denote values based on all trade and hashed lines represent trade without re-exports results.

government placed an economic sanction on Norwegian salmon after a Nobel prize was awarded to dissident Liu Xiaobo (Chen and Garcia, 2016). In another instance, the Chinese government banned geoducks and other shellfish from the Northwest Pacific region due to concerns about paralytic shellfish poisoning and inorganic arsenic (NOAA, 2014). The point here is not to make China the culprit as it represents an increasingly valuable market in the global seafood economy, but to highlight the vulnerability created by market dependencies in general, particularly in situations that can lead to abrupt market changes. Not being able to clearly see these dependencies and anticipate change has the potential to amplify such vulnerabilities. This finding, though here specifically explored for lobster, is likely to be relevant for other seafood commodities and sectors, given that re-exporting seafood is a relatively common practice.

Monitoring market dependencies will require greater attention to the movement of product around the world, including that which is re-exported by non-producer nations. Our current capacity to do this, however, is significantly limited by two compounding factors. First, the Harmonized System (HS), which was established in 1988 as a way to standardize the global trade of commodities, is not conducive for traceability because the 6-digit trade codes that are used largely lack species-level resolution (Chan et al., 2015)[4]. The HS codes for *Homarus* spp. represent somewhat of an exception in that they only include two species (American and European lobster) that are relatively constrained (geographically), but even this analysis is limited. Much more commonly, though, HS codes aggregate species in ways that make it impossible to make even rough estimates of trade patterns. For example, all of the approximately 60 species of rock lobster that are harvested worldwide are lumped into a single set of HS codes. Being able to accurately delineate seafood trade routes for most species therefore will not be possible until trade data is collected at the species-level along with information about the origin of harvest.

Second, our ability to discern trade routes and understand market dependencies is hampered by incomplete data and gray and illegal seafood trade. We see signs of this in the lobster trade data, which likely has the effect of underestimating the masking of dependencies that we report in this paper. For example, in 2015 Vietnam did not report any re-export of lobster to China. We do not know why this data is not in the UN Comtrade Database, but given that US$67.2 million worth of lobster was exported to Vietnam and Vietnam is a well-known gray trading hub for seafood into China (Barclay et al., 2016), it is likely that some portion of this product ended up in China. Such gray trade would therefore mean that our results underrepresent the real-world importance of the Chinese market. There are also several other sources of potential error that add uncertainty to our estimate. Hong Kong SAR, for example, imported US$81.2 million worth of lobster in 2015, making it among the largest importers of lobster worldwide. Yet it only reported US$5.5 million worth of lobster trade to China. Though lobster is certainly consumed in Hong Kong SAR, it is quite likely that a portion of the remaining product also ends up in China by way of gray or illegal trade since Hong Kong SAR has a well-documented history of being a strategic waypoint for seafood trade into China (Akamine, 2005; To and Shea, 2012; Eriksson and Clarke, 2015).

We have focused on the role that seafood trade routes play in obscuring teleconnectivity and therefore potentially masking vulnerabilities for small-scale producers around the world. We emphasize this point because it is unrepresented in the literature on small-scale fisheries and seafood trade. However, ultimately, complex trade routes that mask connectivity also have implications for ongoing discussions about food safety, labeling (including widespread mislabeling that occurs in many

[4] Chan et al. (2015) report that only 9.9% of fisheries products with HS codes are reported at the species level

locations), certification (which requires traceability), taxes and tariff collection, implementation and enforcement of CITES laws, and marine resource sustainability in general (see e.g., Bailey et al., 2016; Cawthorn and Mariani, 2017).

DATA AVAILABILITY

The datasets analyzed for this study can be found in the United Nations COMTRADE Database [https://comtrade.un.org] and FAO Global Capture Production Database [http://www.fao.org/fishery/statistics/collections/en].

AUTHOR CONTRIBUTIONS

JS and BC conceived of the research. JS and EF prepared and organized the data. JS conducted the analyses and wrote the draft. BC, MF, and EF provided edits and feedback.

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Discriminating Catch Composition and Fishing Modes in an Artisanal Multispecies Fishery

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Many small-scale fisheries are multi-species, and the catch composition can vary according to available habitats, fishing modes, and fisher groups. Here, we applied novel analyses for understanding the factors affecting differences in catch composition among fishers, which should be useful for planning regulatory measures and fishery development initiatives. Interviews with 235 artisanal fishers in Fiji were used to analyse how fishers' catch composition of 22 species of sea cucumbers varied across geographic scales (locations and villages within locations), genders, and fishing modes. Venn diagrams illustrated that gleaning and SCUBA diving were practiced to varying extents among locations and genders, whereas fishers used breath-hold diving more uniformly across the fishery. Segmented bubble plots revealed spatial variations in catch composition across the fishery. A PERMANOVA analysis found that species catch composition varied most across the two geographic scales and, secondarily, among fishing modes and between men and women. Gendered differences in catch composition were variable from one village to another, and so should not be generalized. SIMPER analyses showed that gleaners and SCUBA divers caught significantly different suites of sea cucumber species. Species threatened with extinction were among those typifying catches of SCUBA divers. Our novel graphical techniques are useful for visualizing fishing modes and catches across other fisheries. Artisanal fisheries may exhibit strong heterogeneity in catches at multiple spatial scales. Planning of regulatory measures that limit certain fishing modes or species should take into account the likely differential impacts on different fishing communities and genders.

Keywords: small-scale, artisanal, sea cucumber, invertebrate, species composition, gleaning, diving, fishing gear

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INTRODUCTION

Artisanal and small-scale fisheries are a significant source of food, employment, tradition and cultural identity in coastal communities around the world (Berkes et al., 2001; Kittinger, 2013; Batista et al., 2014). Small-scale fisheries make up 25% of the world's catch and have grown rapidly in the last decades (Pauly and Charles, 2015; Zeller et al., 2015). These fisheries have the potential to seriously deplete nearshore marine resources (Bender et al., 2014; Purcell et al., 2014b; Samoilys et al., 2017), despite unsophisticated fishing gears and vessels compared to commercial fisheries (Piroddi et al., 2015; Munga et al., 2016). An artisanal fishery is a type of small-scale fishery in which simple or traditional fishing methods are used (Berkes et al., 2001; Batista et al., 2014). Artisanal fisheries include examples for which the catch is sold for domestic or international markets.

Typically, artisanal fisheries use multiple gears and fishing strategies, at the same or different times of the year, to target a wide variety of invertebrates and demersal and pelagic fishes (McClanahan and Mangi, 2004; Batista et al., 2014). Many of these multispecies fisheries have operated for millennia, with various degrees of sustainability (Cesar et al., 1997; Campbell and Pardede, 2006; Tuda and Wolff, 2015). Understanding species targeted in different locations by different types of fishers will pinpoint populations of species that might be more over-exploited or known to be at risk of extirpation.

The capacity to withstand ongoing fishing pressure varies among wild stocks, and some species are known to be vulnerable to extinction (Dulvy et al., 2003). Hence, there is a general consensus that multispecies fisheries should be managed with regulations that are species-specific, such as catch quotas and minimum legal size limits (Jennings and Polunin, 1996; Purcell, 2010; Samoilys et al., 2017). Clearly, data on who is catching which species are valuable for communicating such regulations to the right user groups and for understanding the impacts of regulations on different types of fishers.

A few management measures are already widespread in small-scale fisheries, including marine reserves, promotion of alternative livelihoods, and gear-based management (McClanahan and Mangi, 2004; Cinner et al., 2009; Jennings, 2009). However, measures must be appropriate to the specific characteristics, needs, and challenges of the fishery (Samoilys et al., 2017). Fishing mode, fishing gear, gender, age group, and trip frequency all affect the magnitude and species composition of the catch, and should be understood if management is to be effective (Pelletier and Ferraris, 2000; Kittinger et al., 2015; Olopade et al., 2017).

Gear types and fishing modes can also vary significantly between genders and regions, even when the same species are being targeted (Isaac et al., 2015; Rahman et al., 2016). Moreover, these factors tend to interact. For instance, the type of vessel will affect the fishing grounds that can be accessed, and therefore also the species composition of the area fished (Pennino et al., 2016). In many cultures, men and women tend to use different methods and gears, influencing the species they can access (Lambeth et al., 2014; Santos, 2015; Purcell et al., 2016a).

Here, we present novel graphical and analytical approaches to assess variations in catch composition among fishers in a multispecies artisanal fishery linked to international markets: the sea cucumber fishery in Fiji. Sea cucumbers are harvested worldwide, predominantly in small-scale artisanal fisheries, as a high-value commodity for export to Asian dried seafood markets (Purcell et al., 2013; Eriksson et al., 2015). They are an ideal case study to develop diagnostic tools to assess catch composition because multiple species are often targeted in the same region, using multiple methods (Toral-Granda et al., 2008; Eriksson et al., 2010; Purcell et al., 2016a). Fishing methods include gleaning (collection by hand in shallow water), breath-hold diving and SCUBA diving (Choo, 2008; Eriksson et al., 2010; Muthiga and Conand, 2014; Purcell et al., 2016a). Such methods are typical of some artisanal shellfish fisheries in Latin America (Castilla and Defeo, 2001; Naranjo Madrigal and Salas Márquez, 2014) and in the Pacific Islands (Gillett, 2011).

The sea cucumber fishery in Fiji is operated by men and women fishers using artisanal fishing strategies (Purcell et al., 2016a), and fishery-dependent and fishery-independent data indicate over-exploitation of stocks (Pakoa et al., 2013; Mangubhai et al., 2017). Previously, we showed that men and women used gleaning, breath-hold diving and SCUBA diving with differing frequency across the Fijian fishery as a whole; a higher proportion of women gleaned than men, and very few women used SCUBA (Purcell et al., 2016a). Catch composition tended to differ between men and women, although the effects of fishing modes and finer geographic scales on catch composition were not examined.

The Fijian sea cucumber fishery has been one of the largest among Pacific Islands in terms of production volume (Kinch et al., 2008). Exports of dried sea cucumber (bêche-de-mer) have averaged ~250 tones p.a. over the past 15 years prior to a fishery moratorium in 2017 (Pakoa et al., 2013; Govan, 2017). Nearly all of the harvested sea cucumbers are exported and only a small amount of certain species (e.g., *Holothuria scabra*) are sold and consumed locally (Pakoa et al., 2013; Mangubhai et al., 2016; Purcell et al., 2016b). Tropical sea cucumbers occupy a range of reef and shallow lagoon habitats, accessible by the different fishing modes, and sale prices vary greatly among species (Purcell et al., 2012, 2017; Mangubhai et al., 2016). As with many other sea cucumber fisheries in Oceania, the products constitute a primary or secondary income source for a majority of fishers who collect them (Purcell et al., 2016b).

In this study, we interviewed 235 fishers to gather data on the frequency of catch of 22 species of sea cucumbers in Fiji. Our novel graphical approaches offer a more informative way to conceptualize spatial variations in fishing modes and catch composition than traditional graphs or tables. We then applied multivariate analyses to examine factors most affecting the variations in catch composition among fishers. Further analyses typify the species caught by fishers in distinguishable groups. By examining catch composition across multiple spatial scales, fishing modes and gender, the study contributes to an understanding of differential fishing impacts among fishers and informs management decisions for these and other small-scale fisheries.

METHODS

Fishery Context and Study Sites

The sea cucumber fishery in Fiji was operated solely by artisanal fishers operating predominantly from rural villages. Previously, we showed that fishers had a wide range of ages, and consisted of men and women using gleaning, breath-hold diving and SCUBA diving to collect sea cucumbers by hand (Purcell et al., 2016a). A total of 27 sea cucumber species were harvested in the fishery, and fishers always collected multiple species based on availability of habitats and their fishing strategies (Pakoa et al., 2013; Purcell et al., 2016a). Sea cucumbers are not by-catch or discards of other fisheries in this case because they exist in reefal areas inaccessible to trawls and other mobile fishing gears. The fishery was regulated by a single minimum legal size limit across all species and a prohibition on the use of SCUBA gear to collect sea cucumbers, except for fishers in some villages that had been granted exemptions by the Ministry of Fisheries (Pakoa et al., 2013).

In consultation with Fiji's Ministry of Fisheries, eight locations (sub-regions) were chosen to give a broad sampling design: Yasawa group, Bua, Cakaudrove, Vanua Balavu, Lau group (south), Kadavu, Taveuni and Ra. We collected data in 35 villages (between 3 and 5 villages within each location) in which fishers were collecting sea cucumbers. Due to fears of resource depletion, the fishery was closed in 2017 by a long-term national moratorium.

Sampling and Data Collection

Data were collected from February–September 2014 using questionnaire-based interviews. Apart from consulting the village headman and village elders, a "snowball" technique was used to locate current sea cucumber fishers. We also used a gender-inclusive approach, in which women fishers were interviewed where possible to ensure their representation in surveys. At the time of the study, best estimates indicated that around 8,000 fishers were collecting sea cucumbers in Fiji (Purcell et al., 2018a). Fishers were interviewed irrespective of their age, whether they fished part-time or full-time or just collected sea cucumbers when fishing other resources, and the fishing mode(s) they used. An average of 6.7 fishers ($\pm$1.8 s.d.) were interviewed in each village, with a total of 235 fishers across all locations.

The interview surveys of fishers were approved (Southern Cross University: ECN-13-279) for ethical human research and overseas research in accord with the Australian National Statement on Ethical Conduct in Human Research 2007. In Fiji, the Ministry of Education, Heritage and Culture granted an additional approval (RA01/14). In each village we also sought and obtained authorisation from the chiefs or village headmen for conducting the interviews. An information sheet, given to each interviewee, explained the project, funding, research uses of data, and that their responses were voluntary and confidential. Fishers gave written consent prior to the interviews.

Questions from a structured questionnaire (see Purcell et al., 2016a, Supplementary Material therein) were posed to fishers during the interviews, which lasted 40–60 min. Interviews took place in fishers' homes or in an open place within villages. To make sure fishers had understood the questions we repeated or asked them in an alternative way, and photographic identification sheets of all harvestable species were used to confirm local names of sea cucumber species used by fishers. An interpreter translated questions and responses when a foreign researcher conducted the interview. Among other questions, the questionnaire asked about how frequently they caught each of 22 species of sea cucumber, on a scale of "often," "sometimes," "seldom," or "never," which were later converted to rank frequencies of 3, 2, 1, and 0, respectively. We asked fishers about the fishing mode(s) they used to harvest sea cucumbers within the past year, which could be one or a combination of gleaning (wading on sand flats and reef flats), breath-hold diving, and SCUBA diving. Hookah gear was not used by any fisher in Fiji. Given the guarantee of confidentiality, fishers disclosed their illegal use of SCUBA gear to collect sea cucumbers in some areas where it was prohibited.

Data Analyses

Fishers might have practiced gleaning, breath-hold diving, SCUBA diving or a combination of two or three of these fishing modes in the year prior to the interviews. Thus, we constructed Venn diagrams to illustrate spatial variations in the proportion of fishers using different fishing modes in each location. Varying sizes of bubbles simultaneously illustrate the proportions of fishers in each location practicing each fishing mode and the various combinations of modes. We firstly tabulated the numbers of fishers using each fishing mode (SCUBA, gleaning, breath-hold diving) and combinations of modes in each location. These location totals were entered into the fields in the online web application BioVenn (Hulsen et al., 2008) to generate the Venn diagrams for each location. Transparency of the diagrams was adjusted using Photoshop CS5.1, and each was sized to a common scale on a map. We used Venn diagrams as a novel method for visualizing variations in the use of three fishing modes among locations in a fishery. This graphical tool is useful when 2–4 fishing modes are used and shows the proportion of fishers using one or more modes; this overlap is otherwise difficult to visualize with graphics such as histograms.

Segmented bubble plots were prepared using PRIMER v7 software to illustrate the average catch frequencies of the most commonly caught sea cucumber species from each location. This graphical tool "displays several variables on the same plot as different sized segments of a circle, in differing color and segment position for the differing variables" (Clarke and Gorley, 2015)—in this case species of sea cucumbers. Average frequency ranks for each species within each location were calculated (see Table S1) and the 10 species caught in greatest frequency among locations were selected. More than 10 species would have yielded unwieldy plots. The Bray-Curtis resemblance matrix of capture frequency data from the 10 species was ordinated using a metric Multi-Dimensional Scaling (mMDS) within PRIMER7 based on the Kruskal fit scheme and 50 repeats (Clarke and Gorley, 2015). Metric MDS was suited because, in this case, the segmented bubble plots illustrate the average values of ranks for each species in each location (Clarke and Warwick, 2014). The segmented bubbles for each location in geographical space were of interest here, rather than the ordination plot itself in multidimensional space which would likely be confusing to resource managers. Input data for the overlay bubble segments were the ranked frequency of capture for each species of sea cucumber for each fisher. The segmented bubbles for each location were then adjusted for transparency in Photoshop CS5.1 and overlaid on a map.

Statistical analyses were undertaken using PRIMER7 software (Clarke and Gorley, 2015). Not all species were harvested by fishers at all sites and we did not find women to interview in some villages and locations, but PERMANOVA is robust for such data (Anderson et al., 2008). A six-factor PERMANOVA analysis was conducted on the Bray-Curtis resemblance matrix from the original data on rank frequencies of each of the 22 species in our questionnaires. We employed Type III sums of squares, which is suited for designs with nested factors (Clarke and Gorley, 2015). Data among species were on the same rank scale and were not skewed, so needed no standardization or transformation. The fixed factors were gleaning, breath-hold diving, SCUBA diving, gender, and location, while village was a random factor nested within locations. Some interaction terms were not testable owing to insufficient data combinations for those tests.

Following significant results ($\alpha = 0.05$) from the PERMANOVA analysis, one-way Similarity of Percentages (SIMPER) analyses were conducted to determine the sea cucumber species characterizing the catch within each location, and to characterize fishers who used gleaning or not, and fishers who used SCUBA diving or not. For each analysis, the cumulative contribution cut-off was specified as 50%.

RESULTS

Spatial Variation in Fishing Modes

Use of the three different fishing modes by fishers clearly varied significantly among the eight locations in Fiji (**Figure 1**). Breath-hold diving was by far the most commonly used fishing mode, and was practiced by most men and most women. Fishers who used SCUBA tended, on average, to be younger (33 y ± 1 y s.e.) than fishers who did not use SCUBA (38 y ± 1 y s.e.). The depth range for breath-hold divers was about 1–20 m, whereas SCUBA divers told us they frequently dived to depths of 20–50 m (also see Pakoa et al., 2013).

Gleaning was used by 45% of fishers overall, and was employed by few fishers (<10%) in the southern Lau group. In that area, islands were relatively small and the reef habitats were chiefly subtidal. Similarly, relatively few fishers (10–30%) used gleaning on islands around Vanua Balavu and the Yasawa Group (**Figure 1**). In only one of the eight locations (Kadavu) was gleaning used as the sole method by a substantial proportion of fishers. Our graphical analysis shows that fishers who gleaned tended to also use breath-hold diving to collect sea cucumbers at some times, but individual fishers rarely (only 5 cases) reported catching sea cucumbers by both gleaning and SCUBA diving.

SCUBA diving was most commonly used in Bua province, where 39% of fishers used this method. SCUBA diving was used by a small proportion (<20%) of fishers in in the Yasawa group of islands, Taveuni, Lau group and Kadavu. Based on our sampling, SCUBA diving apparently was not used by sea cucumber fishers in Ra, Cakaudrove, or Vanua Balavu (**Figure 1**). Some fishers used more than one method, which brings the total percentages of the three fishing modes to more than 100%.

Variation in Catch Composition

While the 10 most commonly harvested species in Fiji (mentioned earlier) were collected in all eight study locations, the average contribution of each species to catches varied significantly among locations (**Table 1**, **Figure 2**). For example, on average, *Holothuria coluber* and *H. edulis* were caught "rarely" in Vanua Balavu and southern Lau Group, but fishers in the north-western locations reported catching them "sometimes" to

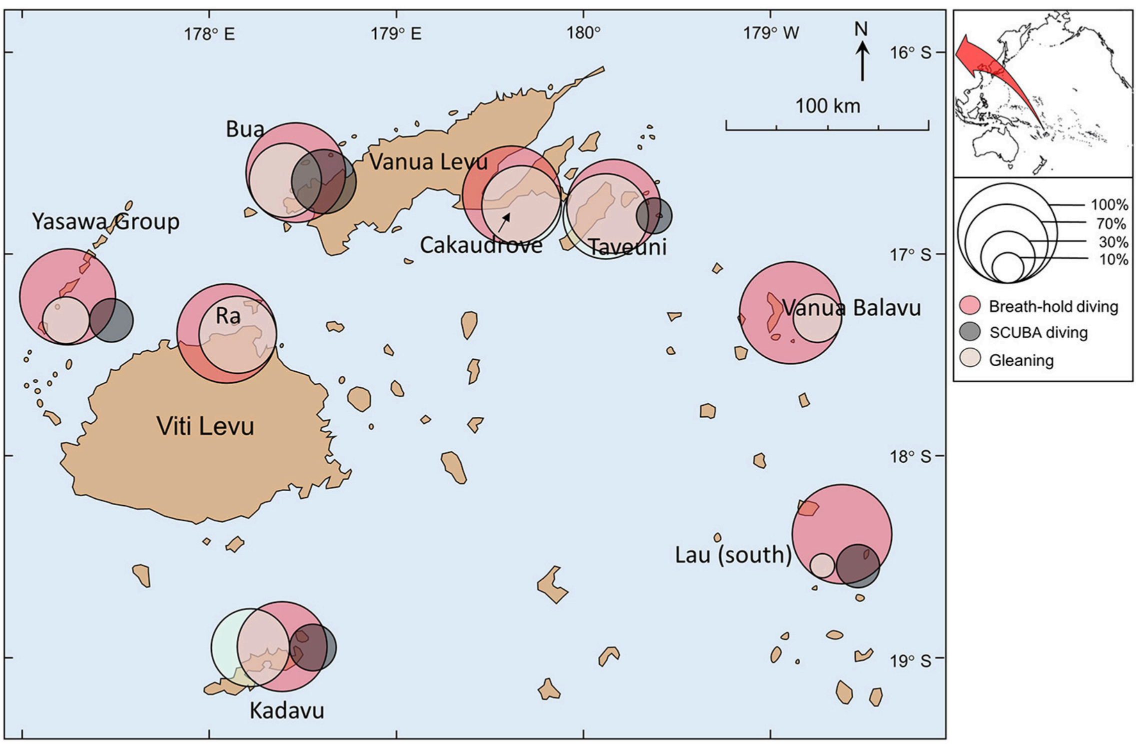

FIGURE 1 | Map of Fiji islands with Venn diagrams illustrating overlap in three fishing modes (gleaning, breath-hold diving, and SCUBA diving) for each of the eight study locations. Bubble area for each fishing mode is proportional to the percentage of fishers using that mode; overlap denotes fishers using a second or third fishing mode at certain times to collect sea cucumbers. The fact that some fishers used more than one method brings the total percentages to above 100%.

TABLE 1 | Statistical results from PERMANOVA analysis of catch composition among fishers with different fishing modes, genders, and among locations and villages within locations.

Source	df	SS	MS	Pseudo-*F*	*P*(perm)
Gleaning (Gl)	1	16,555	16,555	9.77	**0.001**
Breath-hold diving (Br)	1	1,234	1,234	1.29	0.097
SCUBA diving (SC)	1	13,721	13,721	6.12	**0.001**
Gender (Ge)	1	9,892	9,892	6.64	**0.001**
Location (Lo)	7	39,802	5,686	3.52	**0.001**
Village within Location [Vi(Lo)]	26	40,609	1,562	3.71	**0.001**
Gl × Br	1	1,281	1,281	1.75	0.104
Gl × SC	1	771	771	0.98	0.447
Gl × Ge	1	314	314	0.61	0.489
Gl × Lo	7	5,730	819	1.58	0.054
Br × Ge	1	820	820	1.23	0.304
Br × Lo**	5	4,074	815	1.27	0.278
SC × Ge	1	802	802	1.23	0.279
SC × Lo**	4	3,575	894	1.13	0.407
Ge × Lo**	6	3,434	572	0.76	0.761
Gl × Vi(Lo)**	17	8,132	478	1.14	0.214
Br × Vi(Lo)**	6	3,628	605	1.44	0.078
SC × Vi(Lo)**	4	2,857	714	1.70	0.051
Ge × Vi(Lo)**	7	5,993	856	2.04	**0.004**
Gl × Ge × Lo**	1	531	531	1.07	0.429
Gl × Ge × Vi(Lo)**	2	1,033	517	1.23	0.273
Res	133	55,957	421		
Total	234	220,750			

*Only the testable main effects and interactions are included. Significant p-values are in bold. **Denotes interactions for which one or more levels of one of the factors is not included in the test because data did not exist (i.e. women fishers or a fishing mode was not present in one or more locations or villages).*

"often"; *H. coluber* had the largest range of ranks (0.2–3.0). *Bohadschia vitiensis* were collected at a similar frequency over all eight locations (range of ranks: 2.3–2.9). *Holothuria lessoni*, a species list as Endangered by the IUCN, were collected at the lowest frequency throughout most locations (0.1–0.3; only Ra had a rank of 0.6); while *H. atra*, a low-value species, was collected with high frequency (1.5–3.0) in most locations (Table S1, **Figure 2**). The different sea cucumber species are not seasonally abundant (as with some finfish) but fishing strategies might differ seasonally somewhat for certain fishers. So some caution is needed since the inherent bias of different times in which surveys are conducted could potentially influence the differences among locations.

The PERMANOVA analysis of all 22 sea cucumber species revealed significant differences ($p < 0.001$) in catch composition between fishers who gleaned and those who did not, between fishers who used SCUBA gear and those who did not, and between locations and villages within locations. Breath-hold diving was not compared in further analyses because the use of this fishing mode did not significantly discriminate catches among fishers ($p = 0.097$; **Table 1**). There were significant differences in average catch composition between men and women but those differences varied among villages (interaction-$p = 0.004$) (**Table 1**). The PERMANOVA indicated that 14% of the overall variation in catch composition was explained by fishing methods, 18% by differences among locations and 18% by differences among villages (combined difference of 50%).

The SIMPER analyses of fishing methods revealed that *Holothuria atra*, *H. edulis,* and *Stichopus chloronotus* were three species typifying catches of fishers who gleaned for sea cucumbers and distinguished them from non-gleaners (**Table 2**). The non-gleaners were distinguished most by catching *Actinopyga lecanora* and *A. miliaris*, which were harvested infrequently by gleaners; *A. miliaris* was also harvested infrequently by SCUBA divers, and typified catches of breath-hold divers. Fishers using SCUBA diving were distinguished most by harvesting *A. lecanora*, *H. fuscogilva*, *T. ananas,* and *T. anax*, which are species mostly inhabiting deeper waters. Fishers using SCUBA gear also had the highest group similarity (65%) in catch (frequency) composition— i.e., they tended to catch similar species to one another, more so than fishers within other fishing-mode groups.

We also found large variation in group similarities of fishers within locations (**Table 3**). At the extremes, catch frequencies of fishers in Vanua Balavu were 79% similar to other fishers in that location, whereas catch frequencies were just 48% similar among fishers in Taveuni. Species typifying the catches differed among locations, but *H. atra*, *B. vitiensis*, *B. argus* were nearly always among the key species contributing to the similarity of catches among fishers within each location (**Table 3**).

DISCUSSION

Understanding Fishing Modes in Artisanal Fisheries

This study illustrates that even within a small-scale multispecies fishery, fishing modes can vary greatly among locations and genders. Geographic variation in fishing modes is partly explained by variation in nearby habitats accessible to village fishers, and also by differences in fishing history, socioeconomic factors, and management contexts among locations. In other fisheries, the type of vessel available to fishers determines their fishing grounds and fishing strategies (Isaac et al., 2015). We found that the use of gleaning and SCUBA diving was location- and gender-specific. Many of the commercially important sea cucumber species occupy shallow subtidal habitats in 1–10 m depth (Purcell et al., 2012). The prevalence of animals in depths that can be accessed by breath-hold diving and the extensive shallow fishing grounds in Fiji explains the relatively uniform use of this fishing mode across fishers.

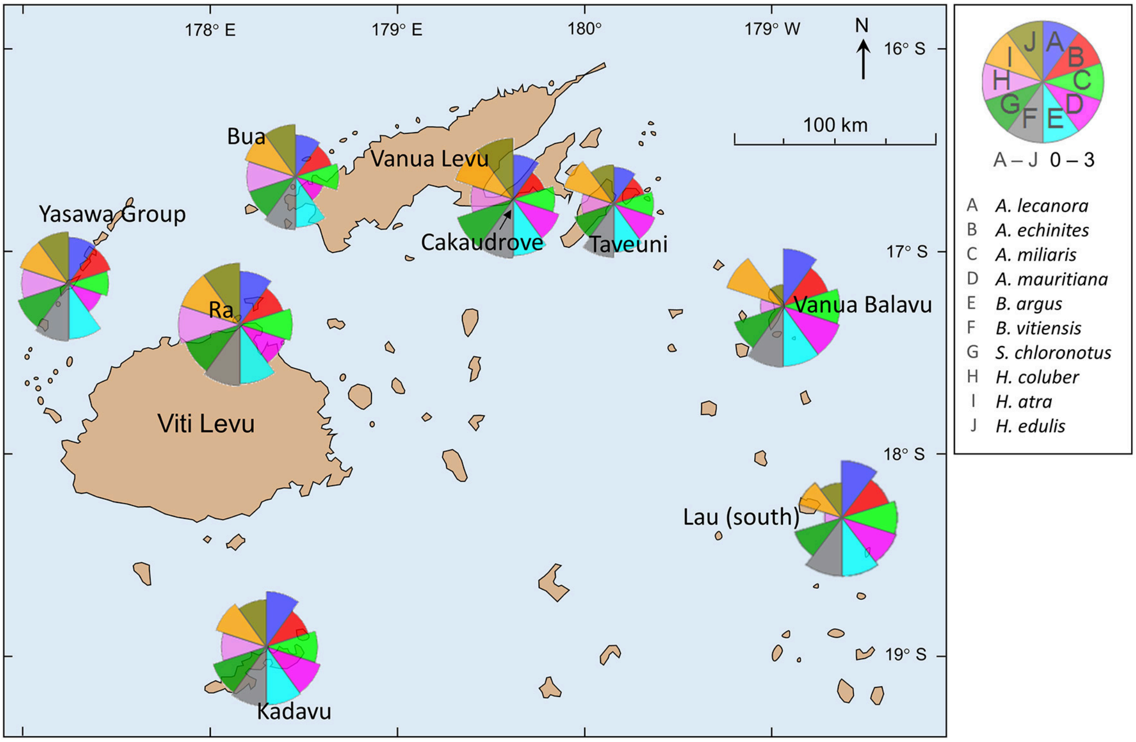

FIGURE 2 | Map of Fiji islands with segmented bubble plots illustrating variations among locations in catch composition of the 10 most commonly harvested species. Length of each segment is proportional to the average rank (0–3) frequency of capture per location for each species based on questionnaire responses from fishers. Refer to Supplementary Material Table S1 for the full list of species.

TABLE 2 | SIMPER analysis showing species responsible for the first 50% of similarities between fishers who used or did not use gleaning or SCUBA methods.

Species	Similarity contribution (%)			
	Gleaners	Non-gleaners	SCUBA fishers	Non-SCUBA fishers
Holothuria atra	14.4	7.0		11.9
Bohadschia vitiensis	12.8	12.7	10.1	13.1
Bohadschia argus	10.9	11.7	12.0	11.1
Stichopus chloronotus	10.7	6.0		9.6
Holothuria edulis	9.0			7.0
Actinopyga lecanora		9.7	10.6	
Actinopyga miliaris		7.5		
Holothuria fuscogilva			8.1	
Thelenota ananas			7.9	
Thelenota anax			6.5	
Average group similarity (%)	59.0	62.1	64.8	60.6

The average similarity of all samples within each grouping is given in the bottom row.

Our findings suggest that regulatory measures that control one fishing mode will probably affect fishers in different locations to varying extents within small-scale fisheries. This is true of regulations that affect specific gears and vessel types, as well as area closures (Pennino et al., 2016; Samoilys et al., 2017). For example, the use of SCUBA for collecting sea cucumbers was fully banned in Fiji after our surveys (Mangubhai et al., 2017) and our study informs us that fishers would be mostly affected in Bua. In contrast, fishers in Ra, Cakaudrove, and Vanua Balavu, where SCUBA diving is rarely used, would have been unaffected by that regulation. SCUBA is often used in locations where shallow stocks of sea cucumbers have been depleted (Eriksson et al., 2010; Friedman et al., 2011) and can itself exacerbate over-exploitation across all fishery (Eriksson et al., 2012; Pakoa et al., 2013). Thus, the frequency of use of SCUBA across locations in a fishery (while of course considering habitat availability) offers insights to areas where depletion of resources is most likely.

Assisting fishers to cope with changes in fishery regulations is important for compliance (Arias et al., 2015), and an understanding of variations in gear use among fisher groups should inform this process. The large geographic and gendered variation in fishing modes in this study implies that management measures restricting certain fishing modes will inconsistently affect different villages. Understanding where different fishing modes are used should help managers to gauge likely socioeconomic impacts of management regulations. The full ban on SCUBA in Fiji after our surveys would have mostly affected young men, since they were the primary users of this fishing mode. Knowledge about gendered variation in fishing modes aids the design of training programs on fishing (Katikiro

TABLE 3 | SIMPER analyses of catch similarities within study locations.

Region	Group similarity (%)	Key species	Similarity contribution (%)
Ra	71.19	*H. coluber*	10.03
		H. edulis	9.98
		H. atra	9.96
		B. vitiensis	9.65
		S. herrmanni	8.99
		B. argus	8.54
Kadavu	61.56	*B. vitiensis*	11.37
		B. argus	10.58
		A. mauritiana	10.14
		S. chloronotus	9.15
		A. lecanora	8.34
		H. atra	0.97
Bua	56.87	*H. atra*	11.56
		B. vitiensis	10.83
		H. edulis	9.85
		B. argus	9.49
		S. chloronotus	9.33
Cakaudrove	72.76	*H. atra*	13.55
		H. edulis	13.05
		B. vitiensis	11.74
		S. chloronotus	11.64
		B. argus	9.98
Taveuni	47.93	*B. vitiensis*	16.67
		H. atra	15.76
		B. argus	11.89
		A. mauritiana	7.93
Lau Group (south)	64.56	*B. argus*	14.36
		B. vitiensis	13.06
		A. lecanora	11.78
		A. mauritiana	10.14
		A. miliaris	9.75
Yasawa Group	65.79	*B. vitiensis*	13.13
		B. argus	11.52
		S. chloronotus	9.25
		H. edulis	7.77
		H. atra	7.53
		S. herrmanni	6.45
Vanua Balavu	79.42	*B. vitiensis*	9.97
		B. argus	9.35
		A. mauritiana	9.24
		H. atra	9.14
		A. miliaris	8.17
		A. lecanora	8.07

et al., 2015). For example, the results of our survey show that awareness programs about SCUBA should mostly be targeted at men, and training or awareness about damage to reefs from gleaning (e.g., turning over boulders in search of animals) should not only be targeted at women.

The Venn diagram approach used in this study could be used to illustrate variation in the use of gleaning, breath-hold diving, and compressed-air diving in other fisheries (e.g., Castilla and Defeo, 2001; Eriksson et al., 2010; Naranjo Madrigal and Salas Márquez, 2014). Similarly, the approach could serve in illustrating variations in the use of fishing gears for finfish such as speargun, hand line, traps, and net gears in East African artisanal fisheries (Davies et al., 2009; Daw et al., 2011), and gleaning, hook-and-line, and spearfishing in Pacific Island fisheries (Gillett, 2011).

Correlates of Catch Composition in Artisanal Fisheries

Significant variation in catch composition of sea cucumber species at small spatial scales (among villages within locations), genders and fishing modes shows that fishers within multispecies small-scale fisheries can have widely differing impacts on different species. Indeed, a fishery in southern Portugal found that gill nets and longlines caught significantly different compositions of species within similar fishing grounds (Erzini et al., 2010). Since different fish and invertebrate species attract a broad spectrum of different sale prices (Thyresson et al., 2013; Purcell et al., 2017), variation in catch composition also flows to variation in incomes and fishing strategies chosen by fishers. This is common to many small-scale multi-species artisanal fisheries. For example, in the elasmobranch fishery in Baja California, long-lived species with lower fertility have largely disappeared from catches, and fishing modes have been adapted to catch smaller species that remain abundant (Smith et al., 2009). In our study, the species most typifying the catches reported by gleaners are known to be shallow-water species (Conand, 1989; Purcell et al., 2012) that tend to have a relatively low market value (Purcell et al., 2018b). In contrast, species found to typify catches of SCUBA divers were deeper water species, and most are moderate- to high-value. Thus, SCUBA divers might not need to fish as often as gleaners to earn the same income. Similar trends were found for spearfishers who used hookah, rather than snorkel, to catch finfish in Chile (Godoy et al., 2016).

Understanding the species harvested most frequently by fishers presents one useful basis for planning lists of permissible species as a regulatory measure (Purcell et al., 2014a; Mangubhai et al., 2017). Species permissible for exploitation should ideally include some accessible to each fishing mode allowed in the fishery, so that each fisher group still has some species they can harvest. In this case study, fishery managers could, for example, select the top six species contributing most to similarity in catch among gleaners, non-gleaners, SCUBA divers and non-SCUBA divers as the candidates for a shortlist of permissible species in the fishery.

In data-poor fisheries, where fishery-dependent data from landing surveys or interviews with fishers are lacking, predicting the impact of management measures on catches is difficult (Kittinger et al., 2015). For example, certain species might be banned for collection or excluded from shortlists of permissible species, differentially affecting men, and women fishers in different areas. Our findings support the idea that stocks of different species will be impacted to varying extents based on the fishing modes used by fishers. Bans on SCUBA have been advocated in sea cucumber fisheries, such as the one in Fiji, in order to limit health risks to fishers and the depth range that species can be collected (Pakoa et al., 2013). Our analysis shows that such bans will also ease fishing pressure on certain species and shift pressure on other species if fishers revert to other fishing modes rather than exit the fishery.

This analysis helps to identify how different groups of fishers affect sea cucumber species of conservation interest. None of the species most typifying catches of gleaners and non-SCUBA divers are listed by the IUCN as threatened with extinction, whereas three species typifying catches of SCUBA divers (*Holothuria fuscogilva*, *Actinopyga miliaris*, *Thelenota ananas*) are either vulnerable or endangered with extinction (Conand et al., 2014). Similarly, fishers using SCUBA or hookah were targeting deep-water species of high value such as white teatfish *H. fuscogilva* in Papua New Guinea (Friedman et al., 2011), and small-scale fishers use SCUBA gears to target other endangered species such as black teatfish *H. nobilis* in fisheries off the coast of East Africa (Eriksson et al., 2012). Since four of the seven endangered species are considered deep-water species, the strong impact of SCUBA diving on threatened species should justify bans on compressed-air diving to collect sea cucumbers. Sea cucumbers may have different sensitivities to environmental stress and recruitment fluctuations, and some species have particular habitat requirements that makes them naturally rarer than others (Conand et al., 2014). How the vulnerability of individual species to other stresses interacts with fishing pressure remains to be resolved. This study provides clear justification that regulations on fishing modes could, in part, act as conservation measures.

AUTHOR CONTRIBUTIONS

SP, WL, and ST conceived the research. SP, WL, and ST conducted the fieldwork. SP and NF analyzed the data. SP, ST, NF, WL, and DC wrote 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.2018.00243/full#supplementary-material

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Behavior Change Interventions to Reduce Illegal Fishing

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Illegal fishing is a serious problem that threatens the sustainability of fisheries around the world. Policy makers and fishery managers often rely on the imposition of strict sanctions and relatively intensive monitoring and enforcement programs to increase the costs of illegal behavior and thus deter it. However, while this can be successful in fisheries with sufficient resources to support high levels of surveillance and effective systems for imposing penalties, many fisheries lack the resources and requisite governance to successfully deter illegal fishing. Other types of governance systems, such as customary marine tenure and co-management, rely more on mechanisms such as norms, trust, and the perceived legitimacy of regulations for compliance. More generally, the absence of such social and psychological factors that encourage compliance in any fishery can undermine the efficacy of an otherwise effective and well-designed fishery management system. Here we describe insights from behavioral science that may be helpful in augmenting and securing the effectiveness of conventional deterrence strategies as well as in developing alternative means of deterring illegal fishing in fisheries in which high levels of surveillance and enforcement are not feasible. We draw on the behavioral science literature to describe a process for designing interventions for changing specific illegal fishing behaviors. The process begins with stakeholder characterization to capture existing norms, beliefs, and modes of thinking about illegal fishing as well as descriptions of specific illegal fishing behaviors. Potential interventions that may disrupt the beliefs, norms, and thought modes that give rise to these behaviors, along with those that encourage desirable behaviors, can be developed by applying principles gleaned from the behavioral science literature. These potential interventions can then be tested in artefactual experiments, piloted with small groups of actual stakeholders and, finally, implemented at scale.

Keywords: illegal fishing, compliance, behavior change, behavioral science, interventions, small-scale fisheries, social norms

INTRODUCTION

Illegal fishing – defined here as the intentional disregard of fishery regulations – occurs all around the world, in fisheries of all sizes, and with all types of target species. Many countries and international bodies (e.g., the Food and Agriculture Organization of the United Nations) have recognized illegal fishing as an important problem threatening fishery sustainability (FAO, 2002;

Pitcher et al., 2008; Agnew et al., 2009; Le Manach et al., 2012). In some small-scale fisheries and low-governance areas it is among the most significant issues faced by fisheries that are often already stressed by over-harvesting, pollution, and other anthropogenic impacts (Sumaila et al., 2006; Hauck, 2008; Österblom et al., 2011). These fisheries generally have the least capacity to address illegal fishing.

Data on the frequency and degree of illegal fishing are limited (Bergseth et al., 2015), making it difficult to understand the full extent and impact. However, it is clear that highly regulated, well-enforced fisheries have a relatively low incidence of illegal fishing (Agnew et al., 2009) and many achieve high compliance with regulations such as Total Allowable Catch (TAC) limits (Grimm et al., 2012). Other fisheries achieve compliance mainly by imposing social costs (e.g., shame), generating trust in the authorities responsible for regulating the fishery and in the efficacy of the regulations themselves [which depends strongly on how regulators and enforcers interact with fishers: (Hønneland, 2000; McClanahan et al., 2006)], and aligning compliance with ethical or moral values, etc. (Gezelius, 2002, 2004; Nielsen, 2003; Eggert and Lokina, 2010; Jagers et al., 2012), often in the context customary marine tenure or co-management governance systems (McClanahan et al., 2006; Viteri and Chávez, 2007). However, many fisheries lack most or all of these mechanisms to increase the economic, social, and psychological costs of illegal fishing or to motivate compliance with economic, social, and psychological rewards (Kuperan and Sutinen, 1998; Arnason, 2013). As a result, such fisheries typically experience high levels of illegal fishing (Hilborn et al., 2005; Beddington et al., 2007; Agnew et al., 2009). Illegal fishing can be especially devastating for small-scale fisheries where participants are highly dependent on resource extraction for livelihood support and food security (Hauck, 2008; Worm et al., 2009).

We reviewed the literature on the factors that contribute to illegal fishing, and on interventions aimed at changing undesirable behavior in order to examine the potential for such interventions to supplement fishery enforcement efforts and achieve higher compliance with regulations in more fisheries. We also describe a process that has been used to design and implement behavior change interventions in other sectors, modified for developing interventions to reduce illegal fishing.

THE DETERRENCE APPROACH

Illegal fishing is a complex issue, driven by an interacting array of economic, institutional and social factors (Gallic and Cox, 2006; Hauck, 2008). Historically, policy makers and fishery managers have attempted to deter illegal fishing by imposing sanctions on offenders and by strengthening monitoring and enforcement programs (Sumaila et al., 2006; Hauck, 2008; Arias and Sutton, 2013) which increases the cost of illegal behavior or reduces the costs of legal behavior (Kuperan and Sutinen, 1998; Sumaila et al., 2006). The theory of compliance underlying this approach posits that all individuals are rational decision-makers who aim to maximize their utility, and that individual actors break the rules only when the benefits of doing so outweigh the costs (Becker, 1968; Branch et al., 2006; Sumaila et al., 2006; Keane et al., 2008). This concept was adopted from classical economic theory, and serves as the basis for the deterrence model. Researchers have focused on finding the optimal level of fines or sanctions that should be imposed, given a certain probability of detection (e.g., Sumaila et al., 2006), to reduce the prevalence of illegal behavior.

According to the deterrence model, perfect monitoring, enforcement, and prosecution, coupled with sufficiently severe penalties, should prevent illegal fishing from occurring. A handful of case studies from fisheries around the world with 100% observer coverage and strong enforcement measures have demonstrated dramatically reduced illegal fishing (Ainsworth et al., 2008; Burnett et al., 2008; Alaska and British Columbia groundfish case studies in Bonzon et al., 2013). Moreover, even if monitoring and enforcement are imperfect, illegal fishing should be reduced, as long as sanctions are adequate, the likelihood of getting caught is sufficiently high, and fishermen are acting rationally (Becker, 1968).

However, in many fisheries the fines associated with violating fishing regulations are not large enough to provide a significant deterrent, as courts are typically hesitant to impose sanctions for fisheries violations that may seem excessive in comparison to what are perceived as more serious crimes (Sutinen and Kuperan, 1999). The cost of achieving enforcement levels resulting in the optimal probability of detection is often prohibitive, especially in relation to fisheries revenues. Actual levels of enforcement are often determined largely by this cost of implementation rather than by the levels required to deter illegal behavior (Arnason, 2013). Several studies have found that the actual likelihood of detection while violating a fishery regulation is often close to zero (Kuperan and Sutinen, 1998).

In small-scale fisheries, limited funding and capacity, often in the context of corruption, poverty, and/or organized crime regimes, sometimes leave fishery managers with few effective tools for addressing the problem of illegal fishing. Indeed, in many of the world's fisheries, and particularly in small-scale and/or developing world fisheries, effective, reliable monitoring and enforcement are rare (de la Torre-Castro, 2006; Hauck and Kroese, 2006; Gutiérrez et al., 2011).

If fishermen act only in their economic self-interest, an obvious solution to this quandary would be to seek more cost-effective ways to strengthen enforcement and increase penalties for detection. However, decades of research in several disciplines, including cognitive and social psychology, sociology, biology, anthropology, and behavioral economics, have yielded many important insights into the drivers of human behavior suggesting this approach may not always be effective (Sutinen and Kuperan, 1999; Fowler, 2005; Velez et al., 2005; de la Torre-Castro, 2006; Sumaila et al., 2006; Hauck, 2008; Keane et al., 2008; Mazar et al., 2008; Thaler and Mullainathan, 2008; Bose and Crees-Morris, 2009; Jagers et al., 2012; Kraak et al., 2014; von Essen et al., 2014). Findings from these scientific disciplines challenge the three core assumptions of the standard economic model of human behavior: that humans act and make decisions rationally, have boundless willpower, and are motivated solely by self-interest (Thaler and Mullainathan, 2008). Instead, humans have many cognitive biases, are influenced by context and social factors, hold individual and cultural values, and are often driven by beliefs and perceptions that do not accurately reflect reality.

Rather, most humans are predictably irrational actors (Ariely, 2008) whose actions are sometimes driven by deliberative reasoning but more often by automatic mental processes or affect, often outside of awareness (Weber, 2013). A more realistic model of compliance (the "behavior change model") based on this understanding of human behavior would posit that a range of factors – including economic self-interest as well as social norms, perceptions, beliefs, and information – influences decisions about whether to engage in illegal behavior, and that the most important drivers of illegal behavior are context dependent. Hence, efforts to increase compliance should address whichever factors most strongly drive illegal behavior in a particular context.

EVIDENCE-BASED STRATEGIES TO COMBAT ILLEGAL FISHING

Illegal fishing behaviors are likely to be more varied and complex than the rational actor model of human behavior would indicate (Sutinen and Kuperan, 1999; Fowler, 2005; Velez et al., 2005; de la Torre-Castro, 2006; Hauck, 2008; Kraak et al., 2014; von Essen et al., 2014). Research into human behavior, decision-making, and compliance indicates that individual levels of risk tolerance, perceptions of regulation legitimacy, levels of trust and mistrust, preferences for avoiding detection, self-perceptions, wealth, knowledge or understanding of the likelihood of being caught, as well as social, moral, and other contextual factors all play roles in determining whether or not an individual will violate a regulation (see literature cited in Keane et al., 2008: Becker and Stigler, 1974; Polinsky and Shavell, 1979, 1990; Kaplow, 1990; Malik, 1990; Bebchuk and Kaplow, 1992; Sutinen and Kuperan, 1999; Hønneland, 2000; Nielsen, 2003; Tyler, 2006; as well as Sumaila et al., 2006; Hauck, 2008; Mazar et al., 2008; Bose and Crees-Morris, 2009; Jagers et al., 2012; Kraak et al., 2014). Modeling and empirical studies have shown that such factors can be at least as important as economic considerations in driving illegal behavior (Velez et al., 2005; Sumaila et al., 2006; Tyler, 2006; Lopez et al., 2012; Kraak et al., 2014).

Several important insights have emerged from research suggesting interactions between fishery actors likewise influence cooperation and rule breaking (see literature cited in Keane et al., 2008: Andreozzi, 2004; Dawes, 1973; Hamilton and Axelrod, 1981; Tsebelis, 1989; Mesterton-Gibbons and Milner-Gulland, 1998; Fehr and Gächter, 2002; Gezelius, 2002, 2004; Fowler, 2005). For example, the ways that enforcement officers interact with fishers can have a strong impact on compliance (Tsebelis, 1989; Hønneland, 2000; Tyler, 2006; Sundström, 2012). One field study, for example, revealed that when fishers perceive enforcement officers to be fair, incorruptible, and respectful, they are more likely to comply with regulations (Hønneland, 2000). Modeling studies have demonstrated that in situations where resource users and enforcers are likely to interact multiple times, increasing the reward to enforcement officers for detecting illegal activity may not reduce the number of offenses; in fact, it may actually reduce the effort devoted to monitoring (Tsebelis, 1989; Andreozzi, 2004). This counter-intuitive outcome results from the fact that rewarding enforcers for catching violators may incentivize them to reduce their monitoring in order to encourage more flagrant illegal behavior, which enforcers can more easily detect to reap the benefits (Tsebelis, 1989; Andreozzi, 2004).

Under certain conditions – for example, when leadership is strong, trust is high, and social capital is high (Gutiérrez et al., 2011; Turner et al., 2016) – fishers tend to engage in self-enforcement, monitoring and reporting on or otherwise stopping the illegal behaviors of others (Fehr and Gächter, 2002; Fowler, 2005; van Hoof, 2010). Repeated interactions among self-enforcing resource users may increase cooperation (Hamilton and Axelrod, 1981) and empirical studies have shown that repeated interactions also increase community support for punishment of non-cooperators (Fehr and Gächter, 2002; Fowler, 2005). However, some modeling studies suggest that the shared benefits of communal self-enforcement (e.g., stewardship of resources) may not be sufficient to motivate enforcement over the long term without additional payments or incentives to monitor (Mesterton-Gibbons and Milner-Gulland, 1998).

DESIGNING BEHAVIORAL SCIENCE-BASED INTERVENTIONS TO REDUCE ILLEGAL FISHING

Research from behavioral science disciplines has guided successful interventions to change behavior in many sectors, ranging from voting behavior (Issenberg, 2010; Neri et al., 2016), savings and investment behavior (Fertig et al., 2015), to health behavior such as health screenings (Hallsworth et al., 2016; Matjasko et al., 2016), and prejudice (Aboud et al., 2012). These have often been implemented when changes in policy, the law or social structures were not feasible or not effective. In this context, an intervention is an action meant to produce a specified change in cognition, affect or behavior in a target. Here we focus on designing and using such interventions to reduce illegal fishing. Such interventions are not, of course, a panacea for ending illegal fishing. They are not likely to be necessary in fisheries with high levels of surveillance and strong enforcement capacity. Neither are they likely to produce strong enough incentives in the absence of surveillance and enforcement to achieve high compliance. They may be most useful for extending the mechanisms that result in high compliance rates observed in customary marine tenure and some co-management systems (McClanahan et al., 2006; Viteri and Chávez, 2007), such as trust in leadership, perceived legitimacy of regulations, and social norms to fisheries that lack such mechanisms.

Successful behavior change initiatives rely on a deep understanding of what motivates undesirable behavior, as well as of how to identify and overcome any barriers to the desired behaviors (Michie, 2008; Butler et al., 2013; Kraak et al., 2014). Human minds rely on heuristics to interpret information and to make decisions when information is scarce or cognitive resources are low, which results in cognitive biases (Gilovich et al., 2002; Kahneman, 2003). Thus the way information is framed, the methods through which it is transmitted, and certain contextual attributes can strongly impact how people respond.

Some fishery management systems (i.e., Rights Based Management systems) are designed to motivate compliance by making it possible for fishermen to directly benefit from behaviors such as complying with a catch limit, in addition to the use of surveillance and penalties. Recent studies have shown that well designed rights based management systems can result in higher collective compliance rates (Grimm et al., 2012), behaviors consistent with increasing catch value rather than volume, and other behaviors that result in improved fishery outcomes (Costello et al., 2008; Gutiérrez et al., 2011; Newman et al., 2015). However, cases of unanticipated and undesirable fishery outcomes in rights based fisheries such as excessive quota lease rates (Pinkerton and Edwards, 2009), undesirable levels of quota consolidation (Casey et al., 1995; Grafton, 1996; Eythórsson, 2000; Yandle and Dewees, 2008), and undesirable distributions of benefits (Grafton, 1996; Guyader and Thébaud, 2001; Hauck, 2008; Carothers, 2011; Olson, 2011; Brown et al., 2017) indicate that the full suite of incentives and motivations at play in these systems need to be considered in order for these systems to achieve a variety of conservation, economic, and social goals.

Several other aspects of fishery management are already based on an understanding of human motivation and behavior. For example, fisheries observers are used on board many commercial fishing vessels not only to record catch data, including illegal take, but also to serve as a constant disincentive to engaging in illegal behaviors (Pramod et al., 2014). Participatory, community-based resource science and management can increase compliance by increasing the perceived validity of regulations (Ostrom, 1990; Hønneland, 2000; Nielsen, 2003; Hauck and Kroese, 2006; Tyler, 2006; Viteri and Chávez, 2007). This can be an especially effective means of improving compliance in small-scale and low governance settings (Hauck, 2008; Worm et al., 2009). Thus, fisheries managers are increasingly engaging fishermen in their science and management processes so that they are more likely to understand the importance of maintaining catch limits (Hartley and Robertson, 2006; Armstrong et al., 2013). However, results depend on other contextual variables, including the extent to which laws and regulations in general are deferred to (Anferova et al., 2005; Hauck and Kroese, 2006; Keane et al., 2008; Velez, 2011).

There appears to be substantial opportunity to build on these examples and improve compliance with fishery regulations, particularly in low governance and low capacity fishery contexts. This will require a better understanding of fisher responses to policies and regulation, designing policies and regulations to better elicit desired behaviors, and interventions that can enhance more conventional tools intended to reduce illegal fishing.

ADDRESSING THE DRIVERS OF ILLEGAL FISHING

While there is both a theoretical (Hønneland, 2000; Sumaila et al., 2006) and empirical (Fehr and Leibbrandt, 2011; Velez, 2011) basis for the design of behavioral science-based interventions, cases in which well-established methodologies from the behavioral sciences have been used to design and implement such interventions appear to be rare. In the remainder of this paper, we discuss some of the most powerful non-monetary drivers of illegal fishing that have been documented in the literature. We then describe a generalized process for designing interventions that target these drivers in order to reduce illegal fishing behaviors. In an effort to increase the rigor and robustness of the solutions generated through our process, we combine social science methods with empirical evaluation and testing methods, as has been advocated by other authors (e.g., Tantia, 2017). Because the drivers at play in a given fishery, as well as the interventions that will be effective, will depend to a significant degree on the specific social, economic and political context of the fishery, this process is designed to result context-specific solutions.

We have organized the following behavioral science-based intervention examples into three categories based on the main drivers they aim to address: (1) those related to self-interest; (2) those related to personal perceptions and beliefs, including perceived social norms; and (3) those related to information (or the lack thereof). Within each of these categories, there are two basic types of behavior change interventions: (1) changing internal drivers of undesirable behavior such as beliefs and values; and (2) removing barriers to the expression of desirable behaviors. See **Table 1** for a summary of these categories, along with some example interventions. Existing research on compliance, norms, risk-taking, altruism, and other topics can inform the design of both types of interventions. Behavioral science-based interventions can also improve group dynamics and increase cooperation and social cohesion (Hamilton and Axelrod, 1981; Fehr and Gächter, 2002; Fowler, 2005; Tyler, 2006; Velez et al., 2006; Lopez et al., 2012), both of which are vital features of effective community-based management systems (Gutiérrez et al., 2011).

Self-Interest

Drivers of behavior related to self-interest are those that involve physical or emotional benefits to the individual or their communities. The most straight-forward of these in the context of illegal fishing is the profit motive. Obviously, there are often significant financial benefits associated with illegal fishing which may be challenging to address through behavioral interventions. Here, we review studies that have revealed a number of other types of self-interest drivers that may be more amenable to behavior change interventions.

The relative influence of the profit motive compared with other motivations will likely vary among fisheries. For example, it may be that the social status resulting from financial gains from illegal fishing is as important a driver as the actual profits.

TABLE 1 | Categorized behavioral drivers of illegal fishing, potential methods to investigate, and potential intervention examples.

Illegal fishing driver category	Illegal fishing driver	Potential methods to investigate	Examples of actions based on the behavioral interventions
Self- interest	Increase profits or social status or improve reputation	Using existing data on the communities, or existing information, further more targeted data gathering methods can be used. Informal interviews of representatives of individuals displaying the target behavior (e.g., the actual fishers) and of different stakeholder groups; literature reviews; surveys, especially techniques designed to investigate potentially sensitive topics by maintaining the respondent's confidentiality, such as Randomized Response Technique (RRT) (Lensvelt-Mulders et al., 2005); power mapping; social network analysis; ethnography; town halls; focus groups. See Step 1 in **Figure 1**.	Education campaign making the long-term negative implications of illegal fishing more immediate and salient or reducing social and psychological rewards could potentially alter people's attitudes and behaviors around illegal fishing.
	Safety and protection		Creation of a truly anonymous reporting hotline.
	Resistance to change out of desire to preserve identify or tradition		Campaigns to tap into pride in self/community (Butler et al., 2013). Making legal fishing something to be proud of, or support notion of working for common good (Day et al., 2014).
	Meeting immediate survival needs in the face of poverty		Program to deliver information about the impacts of illegal fishing or to clarify what the regulations that allows individuals to access materials intermittently [including via text messaging (Mullainathan and Shafir, 2013; Castleman and Page, 2016; National Science and Technology Council, 2016), games, or even soap operas (Silberner, 2016; Vansen, 2016)] than extended courses that require high mental bandwidth and large amounts of time.
Perceptions and beliefs	Fishing illegally because of belief others are doing so	To develop and test interventions, a rich methodological history exists in the experimental branches of sociology, psychology, political science, economics and marketing research.	Changing perceptions by highlighting legal fishing activity. Communicating low incidence of illegal behavior.
			Telling stories of where other fisheries have benefited from complying with regulations (Kraak et al., 2014).
	Perceived lack of legitimacy of regulations	Randomized control trials and field experiments can help hone the intervention and adapt them to the sociocultural realities of the targeted communities.	Messaging campaigns to educate about damaging impacts of illegal fishing. Co-creating regulations with fishers to increase legitimacy.
			Highlighting role of fishers in collecting data/designing regulations.
	Lack of trust between enforcers and fishers	See Steps 2 through 4 of **Figure 1**.	Create forum where enforcement agents and fishers can interact.
Information	Lack of knowledge about regulations		Simple, clear rules communicated through appropriate channels.
			Education about purpose of regulations, process for designing them, and mechanisms through which they are intended to work (Pollnac et al., 2010).
	Lack of information about consequences of illegal fishing		Education campaigns designed to make these impacts salient.

Similarly, there may be reputational benefits from illegal fishing. For instance, violating the regulations may allow fishers to catch more or larger fish, thereby making them appear to be more skilled or experienced than their peers. This social status benefit can also prevent community members from reporting violators (e.g., von Essen et al., 2014). Fishers may also take personal pride in maximizing their daily catch, or in coming home with a full boat, potentially driving them to exceed their quotas or otherwise violate fishing regulations.

Another important dimension to consider in self-interest is time. Most people have a well-documented cognitive bias toward prioritizing short-term needs and benefits over long-term costs and impacts (Weber et al., 2007; Gifford, 2011). Thus, making the long-term negative implications of illegal fishing more immediate and salient or reducing social and psychological rewards could potentially alter people's attitudes and behaviors around illegal fishing. Safety and protection are also important self-interest drivers that could potentially influence illegal fishing behaviors (Corbett, 2005). Fishers may experience pressure to engage in illegal behaviors, or at the very least to turn a blind eye to it, lest they be seen as an informant by a powerful individual or group. This can be an especially significant factor in settings where the illegal actors are functioning like an organized criminal group, as opposed to isolated actors (Österblom et al., 2011).

Some fishermen are motivated by a desire to preserve a sense of identity or tradition. Such fishermen may be resistant to changing their behavior in the face of new regulations (Hviding, 1996; McGoodwin and Nations, 2001; Pollnac et al., 2001, 2012; Eder, 2005; Blount, 2007; Gupta, 2007; Weeratunge et al., 2014). Interventions can be designed to either take advantage of such an interest in preserving or reinforcing identity, or to change them where necessary. For example, Rare, a conservation NGO, has designed effective conservation interventions that tap into pride in one's self, place, or community with campaigns and capacity building programs (Butler et al., 2013). Such interventions are being used to improve uptake of the notion that legal fishing is something to be proud of, that one's community is a place where people work together for a common good that is larger than one's self, or that one's knowledge is being used to inform the design and implementation of the regulations may be effective (Day et al., 2014).

Finally, illegal fishing often occurs in communities dealing with poverty; fishers violate rules in an effort to meet the basic needs of their families (de la Torre-Castro, 2006). Poverty has been linked to a set of cognitive processes that have come to collectively be known as the "scarcity mindset," wherein (among other effects) the mental processes necessary to consider and value one's own long-term needs are impeded by the immediate and pressing drive to meet one's short-term needs (Shah et al., 2012; Mani et al., 2013; Mullainathan and Shafir, 2013). Experimental results suggest that the "scarcity mindset" causes people to make sub-optimal or irrational decisions. When individuals are in the scarcity mindset they likely do not have the mental bandwidth to engage in efforts to conserve fish stocks, even if such efforts could generate higher yields in a few years.

While the reduction of poverty is the long-term solution, other measures may be effective in increasing cognitive bandwidth to lengthen planning horizons and/or reduce discounting (i.e., placing a smaller value on future benefits than on current benefits), such as short-term measures to alleviate pressing food security or cash flow issues. This problem of low cognitive bandwidth can also be addressed by improving the way in which programs aimed at increasing compliance with fishery regulations are implemented. Because impoverished people often lack a safety net, engagement in educational or capacity building programs can often be disrupted by small problems such as a sick child (Mullainathan and Shafir, 2013). A program to deliver information about the impacts of illegal fishing or to clarify what the regulations are might be more effective in this context if it allows individuals to access materials intermittently [including via text messaging (Mullainathan and Shafir, 2013; Castleman and Page, 2016; National Science and Technology Council, 2016), games, or even soap operas (Silberner, 2016; Vansen, 2016)] than extended courses that require high mental bandwidth and large amounts of time.

Perceptions, Beliefs, and Norms

Often, the decision to engage in illegal fishing is motivated by individual perceptions, beliefs, values, or social norms (Velez et al., 2005, 2006; Sumaila et al., 2006; Tyler, 2006; Lopez et al., 2012).

Belief in the legitimacy of regulations and of fishery management authorities is a key factor in compliance. If there is no faith in the efficacy of the regulations, or in the science that serves as the basis for regulation – whether as a result of corruption, lack of information, or other factors – compliance is also likely to be low (Sutinen and Kuperan, 1999; Hatcher et al., 2000; Tyler, 2006; Levi et al., 2009; Arias, 2015; Turner et al., 2016). Increasing the perceived legitimacy of regulations is one of the most powerful means for increasing compliance (Hønneland, 1999, 2000; Sutinen and Kuperan, 1999; Tyler, 2006; Viteri and Chávez, 2007). Some factors that may impact the perceived legitimacy of regulations include: involvement of fishers in the regulatory process; similarity of enforcement agents to fishers; effectiveness of regulations; visibility of benefits resulting from regulations; equity of management outcomes; perceptions of corruption in governing institutions; perceptions of efficacy of governing institutions and regulations; and procedural justice (Hatcher et al., 2000; Hønneland, 2000; McClanahan et al., 2006; Levi et al., 2009; Arias, 2015; Turner et al., 2016).

Creating deference to regulations, resulting in voluntary compliance, as opposed to coercing compliance (Tyler, 2006; Viteri and Chávez, 2007), results in greater durability and resilience of legal behaviors over time. For example, if enforcement diminishes due to budget cuts, compliance levels may remain high when there is deference (Tyler, 2006). Others have found that willingness to comply with regulations voluntarily is inversely proportional to the level of top-down control in a system. This is because such control signals mistrust, reducing intrinsic motivations such as reciprocity and the desire to "be a good citizen" (Bowles, 2008; Richter and van Soest, 2012).

Using behavioral interventions to increase deference may help to break the vicious cycle wherein top-down control in response to low compliance results in mistrust, which leads to more violations, thereby leading to calls for even stronger controls and signaling even greater mistrust (Kraak et al., 2014). Creating forums in which enforcement agents can interact with fishers and community members outside of the high-tension atmosphere of an inspection encounter may generate mutual respect and understanding, reducing the perception that the enforcers are "outsiders" or "others," which can in turn increase compliance (Hønneland, 2000; von Essen et al., 2014). Skillful facilitation may be necessary to elicit a constructive dialog (Pollnac et al., 2001).

Likewise, the perception that other fishers are violating fishing regulations can decrease legitimacy and be a strong driver of non-compliance behavior (Kuperan and Sutinen, 1998; Bova et al., 2017; Bergseth and Roscher, 2018). This is particularly true when the payoff from compliance for an individual depends on the assurance others will also comply (Nielsen, 2003). Chronic violation of regulations may decrease the perceived legitimacy and effectiveness of the regulations, weakening the moral and social obligations of those fishing legally to continue doing so (Viswanathan et al., 1997). One study found that fishers who perceived that other fishers were violating fisheries regulations were themselves 8% more likely to violate (Hatcher et al., 2000).

Social norms – people's perceptions of what other people do or should do (Cialdini et al., 1990; Miller and Prentice, 2016) – are considered to be among the most powerful drivers of human behavior (Cialdini et al., 1990, 1991; Reno et al., 1993; Cialdini and Trost, 1998; Sober and Wilson, 1998; Kallgren et al., 2000; Boyd and Richerson, 2006; Schultz et al., 2007; Goldstein et al., 2008; Allcott, 2011; Gneezy et al., 2016) and have been identified as important drivers of legal and illegal fishing behavior (van Sittert, 1993; Hatcher et al., 2000; Sumaila et al., 2006; Hauck, 2007, 2011; Thomas et al., 2016; Bova et al., 2017). Fishers who have been complying with regulations may engage in illegal fishing when they perceive that their peers are doing so. There may be a high degree of community acceptance or even support of illegal behavior, based on, for example, a belief that this type of behavior is part of what defines the community, or that it is a form of protest against illegitimate regulations or corrupt enforcement actors. Fishers may be motivated by a desire to rebel against laws and regulations that are perceived to be oppressive (Nielsen and Mathiesen, 2003; Fabinyi, 2007; Hauck, 2007, 2008; von Essen et al., 2014). Educating individuals about the damaging impacts of illegal fishing can be improved by focusing on how these behaviors can negatively impact the whole community and future generations. It may be that community members and fishers believe illegal fishing to be a "victimless crime" (Smith and Anderson, 2004; Hardin, 2009), especially if stocks are still relatively healthy. Thus, clearly identifying the victims as the fishers' own friends and neighbors may be a powerful intervention.

In addition, community members and other fishers who are friends, family, and neighbors of fishers who engage in illegal fishing may not wish to turn them in because they see these illegal actors as members of their own group. This in-group dynamic can be especially problematic if enforcement agents are also members of the same communities as illegal fishers. If these attitudes have persisted long enough, this may result in permissive social norms and a "culture of rule breaking," in which breaking the rules is acceptable (Branch et al., 2006).

Just as they can drive illegal behavior, replacing social norms that reinforce illegal behavior with norms that strengthen legal fishing can be among the most effective and long-lasting interventions (van Sittert, 1993; Kuperan and Sutinen, 1998; Sutinen and Kuperan, 1999; Eder, 2005; de la Torre-Castro, 2006; Sumaila et al., 2006; Hauck, 2007, 2011; Weeratunge et al., 2014). Because the perception of the norm drives behavior (as opposed to the actual conditions in the fishery) (Prentice and Miller, 1993; Miller and Prentice, 2016), interventions may need to focus on increasing alignment between perceived norms and reality. For example, if the vast majority of fishermen in a community actually comply with their catch limits but there is a widespread perception that most people do not, individuals may exceed their quotas even if their individual preference is to comply. Communicating and making salient the actual low incidence of the illegal behavior would disrupt this perception and perhaps prevent this kind of illegal fishing.

Messaging campaigns using social norms which describe a desired behavior as common among a target audience's peers can effectively motivate that behavior in the target audience (Goldstein et al., 2008). Behavioral interventions designed to change this perception may highlight the prevalence of legal fishers or the scarcity of illegal fishing in a given community. Framing new regulations as "tried and tested" in other, similar governance contexts, such as telling stories of similar fisheries where complying with regulations has led to benefits for communities, may be a successful strategy (Kraak et al., 2014).

Information and Knowledge

Many fishery management initiatives are based on the assumption that the provision of information will result in desired behaviors. This assumption that information will alter behavior is sometimes referred to as the information deficit model. This is probably seldom the case, because there are many other factors that determine behavior (Butler et al., 2013; Sutton and Rao, 2014). In fact many efforts to change behavior solely by providing information have failed, and sometimes result in perverse outcomes such as increased poaching (Bergseth et al., 2017). However, strategies that provide information are often important components of behavior change strategies and there are many insights from behavioral research that can be applied to improve the effectiveness of communication.

Simple, clear rules communicated to fishers through the appropriate channels are more likely to be followed (for example, summaries of rules printed on waterproof cards handed out at sea; articles in fishing magazines or local newspapers) than are complex rules communicated through channels that are ignored by fishers (for example, posted on government websites or published in lengthy reports) (Bose and Crees-Morris, 2009; Jagers et al., 2012; Thomas et al., 2016). Some illegal fishing behaviors are also motivated by unfounded beliefs or misinformation. For example, fishers may believe that catching more fish will always result in higher revenues and profits, when in fact this is often not the case: fishing too hard can create market gluts that drive down the price of each individual fish caught, and overfishing for an extended period can cause the stock to collapse. Participatory processes in which stakeholders identify such dynamics together can result in improved common understanding, which in turn can result in the co-creation of interventions to disrupt the adverse dynamics. For example, in 2012 a participatory systems-mapping exercise revealed that high catch rates – which were believed by many fishers to be essential for maintaining sufficient fishing revenues – were causing price collapses in the Upper Gulf of California curvina (croaker) fishery. Based on this information, community purchase agreements and a price floor were implemented to regulate catch volumes and boost compliance with the quota system, which in turn stabilized prices and increased overall revenues (EDF de Mexico, 2015).

Education about the purpose of regulations, the process through which they were designed, and the mechanisms through which they are intended to work can increase compliance (Pollnac et al., 2010). Participatory processes in which fishermen co-create the regulations may be even more effective (Ostrom, 1990; Hatcher et al., 2000; Keane et al., 2008; Karr et al., 2017). If fishers are included in the process of collecting data and/or designing the regulations, an education campaign that highlights this role and the value of their input may significantly increase the perceived legitimacy of the management system and instill a sense of ownership in it.

Fishers and community members may also lack information on the likely consequences of illegal fishing, and how illegal behaviors may impact themselves and their communities. Some forms of common illegal fishing practices, such as dynamite and cyanide fishing, can have immediate and visible negative impacts on the target ecosystem and community. Other forms of illegal fishing, however, such as exceeding individual quotas or fishing in key habitat areas, may have negative impacts that take longer to manifest, or that only arise from the aggregate behavior of many individuals. These types of impacts can seem abstract or intangible; people often struggle to make optimal decisions about abstract concepts or with imperfect information (Gilovich et al., 2002; Weber, 2006). Education campaigns that make these types of impacts more salient may help reduce illegal fishing. However, as mentioned above, the provision of information alone is rarely sufficient to change behavior (Butler et al., 2013; Sutton and Rao, 2014), and must be presented in ways that inspire emotional responses to the problem (Weber, 2006; Butler et al., 2013). Coupling information provision with other interventions aimed at producing motivation to engage in the desired behavior and at removing barriers to behavior change may also be necessary.

DESIGNING AND IMPLEMENTING BEHAVIORAL INTERVENTIONS TO REDUCE ILLEGAL FISHING

The prevalence of illegal fishing in small-scale fisheries lacking the resources and systems to implement traditional deterrence methods, along with the failure of those methods to deter illegal fishing in many fisheries in which they are implemented, calls for new approaches and tools. Here, we draw on several design processes[1] that have been used to change behavior in other sectors (e.g., healthcare, finance, public policy, international development, ethics, and advertising) to describe a step-by-step process for designing empirically supported behavioral interventions specifically targeted to reduce illegal fishing.

The process can be summarized in the following five steps (and see **Figure 1**):

(1) Gain an in-depth understanding of the community and context in order to identify relevant actors, types of problematic behaviors, and possible drivers.
(2) Develop hypothetical interventions.
(3) Experimentally test hypothetical interventions.
(4) Pilot interventions based on the mechanisms identified.
(5) Scale-up tested interventions, and set up systems to monitor, evaluate, and adjust.

Step 1: Gain an In-Depth Understanding of the Community and Context to Identify Relevant Actors, Types of Problematic Behaviors, and Possible Drivers

Understanding the context of illegal fishing is essential for identifying conditions that enable illegal fishing and for interpreting the results of surveys and experiments. Important contextual attributes include the manner in which policies are implemented, how relevant actors interact, how decisions are made at various levels of society, the role of fishing in the community's political, economic, social, and cultural spheres, the values, beliefs, and behaviors of all relevant stakeholder groups, and the general scope of illegal fishing.

There are a variety of methods for gaining an understanding of community context. Informal interviews of representatives of different stakeholder groups may suffice. This information can be supplemented with a literature review. Surveys, power mapping, social network analysis, ethnography, town halls, focus groups, and other social science methods can also be used if time and resources allow[2].

These same social science methods can also be used to gather information on the relevant illegal fishing acts and each actor group's contributing behaviors. Survey techniques

[1] Including the Behavioral Design guidance presented in (Tantia, 2017); the REVISE principles to change unethical behavior (Ayal et al., 2015); the Behavioral Economics Guide (Samson, 2017); the MINDSPACE mnemonic (Dolan et al., 2010, 2012); the Field Guide to Human Centered Design (Brown, 2009; IDEO, 2015); and the Root Solutions process (root-solutions, 2017).

[2] The "Field Guide to Human Centered Design" (IDEO, 2015) provides an extensive set of tools and methods that may be useful in conducting effective and comprehensive community surveys/interviews.

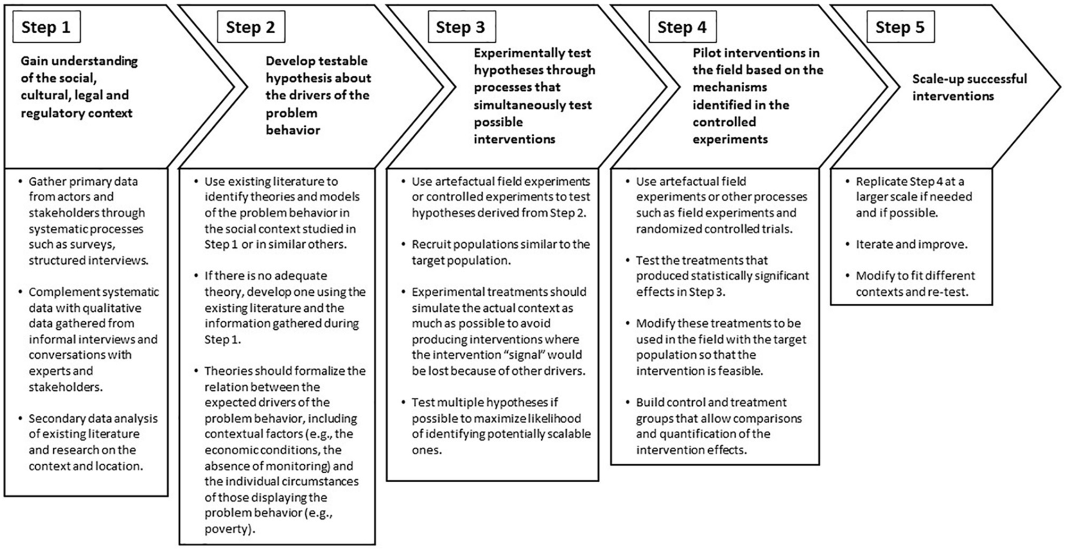

FIGURE 1 | Flow diagram of five step process for designing and implementing empirically supported behavioral interventions to reduce illegal fishing.

designed to investigate potentially sensitive topics (like illegal fishing) by maintaining the respondent's confidentiality, such as Randomized Response Technique (RRT) (Lensvelt-Mulders et al., 2005), will be especially useful in this step.

Illegal fishing is typically comprised of many different behaviors with many different drivers. Illegal behaviors may include fishing without a permit, fishing in restricted areas or at restricted times, fishing for protected species, fishing with illegal gears, failing to report or underreporting catches, among others.

Relevant actors include fishermen and those who may influence fishing behavior. Vessel or gear owners may condone, encourage, or even demand that their boats participate in illegal fishing. Those involved in transporting, distributing, and selling fish may help deliver protected species or illegally sized fish to market. Enforcement officers may not report illegal fishing they witness taking place, or may simply avoid witnessing such illegal activity. Judges may reduce fines to a negligible amount. Family and community members may not report illegal activities to authorities. Each of these actor groups and their relevant behaviors should be considered in the design of interventions. Targeting an intervention at a group other than the fishers themselves could possibly be the most effective means of eliciting the desired change.

Survey results and literature review can illuminate the drivers of specific illegal fishing behaviors. The next step will be to determine which behaviors to prioritize, given available resources and the desired scope of the intervention. Workshops designed to describe specific illegal behaviors and assign potential drivers to them can be effective.

Step 2: Develop Hypothetical Interventions

To generate hypothetical interventions, a theory (or theories) of change can be developed that describes how the behavioral drivers identified in Step 1 can be addressed to ultimately reduce illegal fishing. Developing theories of change helps ensure that those designing a hypothetical intervention share an underlying understanding of the relevant context and various dynamics at work. It is an important step, because interventions that seem generalizable may fail to remain relevant in a particular fishery upon closer examination of the theory of change (Margoluis et al., 2013).

Theories of change can be informed by a literature review, information gathered in Step 1, and local knowledge. Several types of interventions have been shown, either empirically or via modeling studies, to be effective for reducing illegal behaviors (e.g., Hamilton and Axelrod, 1981; Tsebelis, 1989; Sutinen and Kuperan, 1999; Fehr and Gächter, 2002; Gezelius, 2002, 2004; Andreozzi, 2004; Fowler, 2005; Velez et al., 2005; Sumaila et al., 2006; Tyler, 2006; Lopez et al., 2012; Kraak et al., 2014; von Essen et al., 2014). In addition, certain principles for changing behavior have been articulated based on experiments and field experience (e.g., Dolan et al., 2010; Ayal et al., 2015; Samson, 2017). Thus, there is an abundant and growing body of research that can be drawn from to identify a compelling theory of change and develop hypothetical interventions.

Step 3: Experimentally Test Hypothetical Interventions

Once potential interventions have been developed to address a particular behavior associated with illegal fishing, the next step is to experimentally test the efficacy of those interventions. To do so, artefactual field experiments [wherein samples are drawn from the population that would be used in a larger field study (Velez et al., 2006; Fehr and Leibbrandt, 2011; Lopez et al., 2012; Gneezy et al., 2016)], or laboratory experiments that use samples of individuals from each target actor group can be conducted to test the effectiveness of each intervention – compared to each other as well as a control treatment if possible – at modifying attitudes and changing behaviors. If it is not possible to test experimental interventions on the target audience (due to concerns about influencing the target audience ahead of the full implementation of the intervention, for example), then an alternate but highly similar audience can be used (Samson, 2017). In addition, given available time and resources, preliminary experiments with small numbers of participants can be conducted in a separate community to test intervention variations and refine experimental protocols before implementing the full-scale experiment in the target community. Behavior change might not be captured as a change in actual illegal fishing, but rather through an analogous behavior in a simulation; for example, through reductions in cheating behaviors in a game-based experiment. Common pool resource (CPR) games are often used to test the effects of hypothetical interventions on participants in a simulated fishery. Experimental interventions could include mock fishing scenarios, simulated framing and messaging campaigns, the provision of feedback on the effects of illegal fishing, or many other types of interventions designed to address drivers identified in surveys and interviews. Experimental treatments that simulate real world variations and challenges can be used to test the robustness of interventions to some extent.

Step 4: Pilot Interventions Based on the Mechanisms Identified

Once interventions have been tested experimentally, those with demonstrated efficacy (in the experimental setting) at shifting behaviors in the desired direction should be piloted with small groups under real-world conditions in the target community. This step is crucial because behavioral interventions that are effective in experimental settings may not be effective in real-world settings, where efforts may be undermined by countless confounding factors that were not accounted for in the experiment. For example, it is easy to convey information, such as the aggregate catch of all fishers, to the participants in an experiment. It may, however, be significantly more difficult to get that same information to all members of a fishing community within the requisite amount of time. Similarly, experimentation may reveal that allowing participants to generate their own fishing rules is effective in reducing illegal behaviors, but it might not be politically possible to implement an intervention that involves having fishers re-design the actual regulations with which they must comply. The purpose of the pilot stage, therefore, is to clarify how the interventions that worked in the experimental phase can be implemented in the real world, and to identify problems that arise in the field before they are implemented at a larger scale, requiring more resources and capacity.

Depending on the intervention and the results of the experiments in step 3, piloting may require multiple "conditions" to test different versions ("treatments") of each intervention in the real-world environment. Depending on available resources, each version of the intervention should be replicated on multiple sample populations as well, if possible. In addition, control groups should be included (Martin et al., 2012; Monitoring Design Before-After Control-Impact, 2017). At this step, the efficacy of the interventions can be measured directly with surveys conducted before and after interventions are carried out, and with direct observations of behavior, although it is likely that only short-term process indicators can be measured during this pilot phase (e.g., immediate reductions in the presence of non-permitted fishers on the water, or indicators of earlier steps in the theory of change, such as shifts in knowledge or attitudes). Longer-term outcome indicators (e.g., community-level metrics such as reductions in seasonal catch above quotas or official reports on the prevalence of illegal fishing) should be used to measure success of the large-scale implementation (in the next step).

Step 5: Scale-Up Tested Interventions, and Set Up Systems to Monitor, Evaluate, and Adjust

If the pilots demonstrate efficacy, and after any necessary modifications are made to the design based on the results, then the interventions are ready to be implemented on a broad, community-wide scale.

A deliberate scaling strategy should be developed, rather than simply depending on the effectiveness of the intervention to result in broader uptake (Battista et al., 2017). A key step will be to determine what scaling up interventions will entail in terms of actual logistics and policy. These will vary greatly among interventions: for example, they may be minimal if the intervention consists of participation in a CPR game that illustrates dynamics that lead to illegal fishing in order to change beliefs about illegal fishing. Some interventions can be scaled very simply, for example by increasing the number of monitors showing aggregate catch at landing sites. However, some interventions such as campaigns to change social norms or the use of more participatory processes to increase the legitimacy of regulations may require many more resources, policy changes, and even the formation of new relationships or changes in existing relationships.

These kinds of changes may lead to unforeseen challenges. For example, if interventions involve the implementation of a program that rewards community members who report illegal fishing, conflicts may form between adjacent areas of the community that failed to emerge in the pilot stage (e.g., if one part of the community has a disproportionately large number of illegal fishermen).

Thus, except in limited circumstances, scaling up interventions from pilots to the entire community is likely to lead to unexpected dynamics (World Health Organization and ExpandNet, 2011; Management Systems International, 2012; Sutton and Rao, 2014; Battista et al., 2017). This is generally an unavoidable part of changing a social and economic system. When challenges do arise, it is critical to document them and any changes made to the intervention in order to accurately evaluate its efficacy in the following step. Changing interventions prematurely will confound efforts to analyze the efficacy of the intervention, but may be necessary depending on context.

Evaluation of the performance of behavior change interventions is critical, from beginning to end (Woodhouse et al., 2016; Battista et al., 2017). Measurable indicators of the desired behavior changes should be chosen and evaluated prior to implementation to generate baseline data. Many of the same indicators used for evaluating the efficacy of interventions in experiments and pilot projects can be used to assess the efficacy of community-wide interventions. These can include process indicators that reflect intermediate changes that precede actual outcomes such as reductions in illegal fishing (e.g., increased cooperation in reporting and monitoring programs, or the purchase of legal fishing gears). In addition, indicators of actual outcomes (i.e., reductions in illegal fishing behavior) should also be measured at the community-wide scale to ensure illegal fishing has actually been reduced. It is important to measure changes in similar communities not receiving interventions, if possible.

Reductions in illegal fishing can often be measured using standard fisheries data collection methods, including catch logs, reports from patrols, at-sea or electronic observer data, etc. In some cases, new data streams will be required to measure behavior change; for example, individual catch records would be necessary for measuring the efficacy of an intervention aimed at changing individual fishing or reporting behavior. These can be complemented by social science techniques, e.g., surveys with fishermen and community members regarding the frequency and intensity of the illegal fishing taking place. Progress should be measured against specific, quantitative objectives for each indicator that are established before implementation. If these objectives are not being met, project managers can then investigate what is undermining the intervention's effectiveness, and propose solutions to get them back on track.

DISCUSSION AND CONCLUSION

There is an urgent need to reduce illegal fishing, especially in fisheries where illegal fishing may be threatening livelihoods and food security in dependent communities, and where resources for bolstering surveillance and enforcement are limited. Moreover, corruption, lenient penalties, and other problems constrain the efficacy of enforcement systems in many fisheries around the world. There is evidence that behavioral factors related to perceptions and beliefs, self-interest, and information or the lack thereof can also drive illegal fishing activities. Hence, interventions aimed at addressing these drivers can supplement enforcement efforts or prompt compliance where enforcement is inadequate to reduce illegal fishing activity. Furthermore, such interventions may prove to be even more effective if implemented in concert with each other, so that multiple drivers of the behavior are targeted at once. For example, efforts to improve access to information can be paired with messaging/framing campaigns targeted toward relevant perceptions and beliefs in order to increase knowledge while simultaneously generating motivation, a technique which has proven effective for eliciting change (Butler et al., 2013; Sutton and Rao, 2014).

Significant research has been conducted on behavioral science-based interventions that may be useful to marine conservation and management (Reddy et al., 2017), and there is much room to improve outcomes through the application of these lessons. However, as behavior change is context- and actor-dependent, a systematic process for developing solutions to illegal fishing tailored to specific fishery contexts is needed.

We posit that effective interventions to reduce illegal fishing behaviors in any setting can be developed and implemented by using the 5-step process described here, which is derived from well-established methods that have been used to change behavior in many other sectors. This process entails developing a deep understanding of the target communities and includes steps to characterize illegal fishing behaviors and their drivers, develop theories of how undesirable behaviors can be changed, test potential interventions with experiments, pilot and adjust interventions, and fully implement interventions, as well as to monitor, evaluate, and adjust interventions to ensure their ongoing effectiveness.

We are not recommending that conventional, command-and-control regulations and enforcement systems designed to deter illegal fishing, where they already exist, be replaced by a behavioral approach. Instead, we seek to highlight the conditions under which deterrence methods can be complemented through the application of behavioral science, and suggest approaches to improve compliance. Behavioral science-based interventions can improve the efficacy and uptake of conventional regulations, improving the levels of compliance and deference, as well as their resilience over the long term (Tyler, 2006). Combining behavioral interventions with increased surveillance to increase detection probability, for example, may be highly effective for reducing illegal fishing because both the monetary and non-monetary drivers of the illegal behaviors are targeted (Hønneland, 2000; Sumaila et al., 2006; Velez et al., 2006). Furthermore, efforts to reveal and reduce corruption, which can themselves benefit from the lessons of behavioral science, can go a long way toward reducing the systemic drivers of illegal fishing (Becker and Stigler, 1974; Hønneland, 1999, 2000; Sutinen and Kuperan, 1999; Dietz et al., 2003; Sumaila et al., 2006; Tyler, 2006; Hauck, 2007; Österblom et al., 2011; Sundström, 2012; von Essen et al., 2014). For these reasons, behavioral interventions may be particularly useful in small-scale and low-governance fisheries that lack resources for high levels of surveillance and enforcement.

AUTHOR CONTRIBUTIONS

WB contributed to the development of the novel method presented in the manuscript and also was the lead author of the manuscript. RR-C was the lead in developing the novel method presented in the manuscript, and provided multiple reviews and edits of the manuscript text. SS contributed to the background literature review presented in the manuscript, and also provided a number of complete reviews. JF, ME, and DL-K contributed to the development of the novel method presented in the manuscript and the initial draft. RF contributed to development of the novel method presented in the manuscript and the initial draft, and provided multiple reviews and edits.

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Toward Ecosystem-Based Assessment and Management of Small-Scale and Multi-Gear Fisheries: Insights From the Tropical Eastern Pacific

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Small-scale fisheries (SSF) remain a largely under-assessed and overlooked sector by governments and researchers, despite contributing approximately 50% to global fish landings and providing food and income for millions of people. The multi-species, multi-gear and data-poor nature of SSF makes implementation of traditional single-species management approaches – like catch-quotas or size limits – particularly challenging and insufficient. A more holistic approach is thus required, which demands assessment of ecological impacts. Here we carried out an estimation of selected ecological indicators of the impact of fisheries (mean length, maximum body size, mean trophic level, trophic and spatial guilds, threatened species and landed by-catch) based on the nominal catch of different gears in three representative SSF along the Colombian Pacific using landings data collected in multiple years (2011–2017). Results showed that taxonomic, size-based, functional and conservation features of the nominal catch vary greatly with geographical location and gear type used. Overall, handlines and longlines tend to select larger sizes and higher trophic levels than nets, but they also catch a higher proportion of intrinsically vulnerable species and species of conservation concern. This challenges the idea that more selective gears have overall lower ecological impacts. In contrast, nets target a wider size range – although focusing on small or medium sized fish – and include a higher diversity of trophic and spatial guilds, which could arguably be considered a more "balanced harvest" type of fishing that retains ecosystem structure and functionality. Bottom trawls, though, exhibited a relatively high percentage of landed by-catch, an undesirable feature for any fisheries in terms of sustainability. We propose that the assessment of a suite of ecological indicators, like those implemented here, should be included as part of periodic evaluations of multi-gear and multi-species SSF in tropical coastal areas, as a practical step toward ecosystem-based fisheries management.

Keywords: Colombia, ecological indicators, ecosystem approach to fisheries, gear-based management, tropical fisheries, catch composition

INTRODUCTION

Small-scale fisheries (SSF) are widely recognized for their contribution to nearly half of global landings and for the multiple socio-economic benefits they provide to coastal communities (Andrew et al., 2007; Béné et al., 2010; FAO, 2015). However, this fisheries sector remains largely under-assessed and overlooked by governments and researchers (Salas et al., 2007, 2019; FAO, 2015; Purcell and Pomeroy, 2015). Management of SSF in tropical developing countries is generally constrained by insufficient government funding, lack of political will, open access regimes, multiple and scattered landing sites and low participation of resource users in decision making (Andrew et al., 2007; Salas et al., 2007; Kato et al., 2012). Traditional management approaches like catch-quotas and size limits for target species exhibit several practical difficulties when tried to be implemented in multi-gear and multi-species tropical SSF (Salas et al., 2007; Purcell and Pomeroy, 2015). Furthermore, the establishment of catch-quotas, one of the most common management measures, depends on reliable assessments of the target stock size and condition of main target species but these type of assessments are often hindered by low quality of the data available, high uncertainties underlying length-frequency catch data and lack of knowledge of basic growth and reproduction features of target species (Froese, 2004; Cope and Punt, 2009; Ramírez et al., 2017; Herrón et al., 2018).

In the past two decades a shift in fisheries management has been observed from a single-species approach – in which the main objective was to obtain maximum sustainable yields (*MSY*) of target species – to a more holistic approach that also considers the impacts of fishing at the community and ecosystem level, for which two main frameworks are commonly used: the Ecosystem Approach to Fisheries – EAF (Garcia, 2003) and the Ecosystem-Based Fisheries Management – EBFM (Pikitch et al., 2004). Both frameworks take into account the undesired effects of fishing on ecosystems due to the inherent selectivity of the fisheries for a particular size range and/or taxonomic group; these effects may include impacts on biodiversity, taxonomic composition, population abundance, size structure, trophic structure and trophic dynamics of biological communities (Pauly, 1984; Jennings and Kaiser, 1998; Arias-González et al., 2004; Pikitch et al., 2004). To detect such impacts, several ecological indicators have been proposed based on empirical or model-derived evidence of their potential to adequately inform of fishing impacts. These indicators often relate to basic ecosystem's attributes such as: species richness and diversity, biomass, relative abundance of specific target or non-target groups, size structure, trophic level, structure and dynamics of the food web (Rochet and Trenkel, 2003; Fulton et al., 2005; Jennings, 2005; Jennings and Dulvy, 2005; Link, 2005; Shin et al., 2005). Current scientific advice for fisheries management in the European Union, for example, incorporates assessment of indicators such as: mean length of the fish community, proportion of predatory fish in the community, catch-based marine trophic index, proportion of discards in the fishery, among others ["IndiSeas" project – Coll et al. (2016)]. Other approaches to holistically assess fisheries and examine fishing impacts at the ecosystem level are mass-balanced trophic models, which require knowledge of trophic relations, as well as detailed data on diet composition and fishing effort that are not always available for coastal tropical systems [but see for example: Bacalso and Wolff (2014); Rehren et al. (2018), and Tesfaye and Wolff (2018)].

Here we examine the composition of the nominal catch of the multi-gear and multi-specific SSF of the Colombian Pacific coast to assess geographic or gear-related differences in selected indicators used as proxies of the potential ecological impacts of current fishing practices. Our analyses used a unique set of landings data from recent years (from 2011 to 2017) collected at three coastal zones of the Colombian Pacific with different environmental, socio-economic and fisheries management regimes. Finally, we discuss the potential benefit of implementing a periodic monitoring of ecological indicators to assess and manage SSF under an ecosystem-based approach.

MATERIALS AND METHODS

Study Area

The Colombian Pacific coast is part of the tropical eastern Pacific region and it is located in the western side of the country bordering with Panama (7° 13′ 21″N, 77°53′25″W) and Ecuador (1° 27′ 48″N, 78°51′43″W), and stretching for approximately 1,300 km (Correa and Morton, 2010) (**Figure 1**). The northern coastal sub-region extends for approximately 335 km of coastline south of the Panama border and is characterized by rocky and sandy shores, and relatively small mangrove forests [ca. 50 km^2, Velandia and Díaz (2016)]. This sub-region has a narrow continental shelf (1–15 km) and a low human population density [6 people*km^{-2}, DANE (2011)]. In contrast, the central coastal sub-region of Buenaventura, which encompasses approximately 150 km of coastline south and north of the city of Buenaventura, is dominated by mangrove forests [ca. 220 km^2; Mejía-Rentería et al. (2018)], alluvial plains, river deltas and estuaries. These seascapes are also the dominant ones in the remaining Colombian Pacific southern coast up to the border with Ecuador. The Buenaventura sub-region has a wider continental shelf (32–52 km) and a higher human population density [70 people*km^{-2}, DANE (2011)] mainly due to the presence of the main city port of the entire Colombian Pacific (Buenaventura city).

Within the northern sub-region, there are two management areas declared in recent years: (1) an Exclusive Artisanal Fisheries Zone or ZEPA, for its Spanish acronym, and (2) a regional marine protected area (Tribugá – Integrated Regional Management District or DRMI for its Spanish acronym), declared recently by the Colombian fisheries authority and by the regional environmental authority, respectively (AUNAP, 2013; CODECHOCO, 2014) (**Figure 1**). These two management zones cover ca. 1,600 km^2 of coastal and marine habitats (Velandia and Díaz, 2016) and complement conservation efforts by the adjacent National Natural Park Utría established in 1987 (PNN, 2006), which includes a marine area of ca. 132 km^2. Current fishing practices inside the marine area of the National Park are

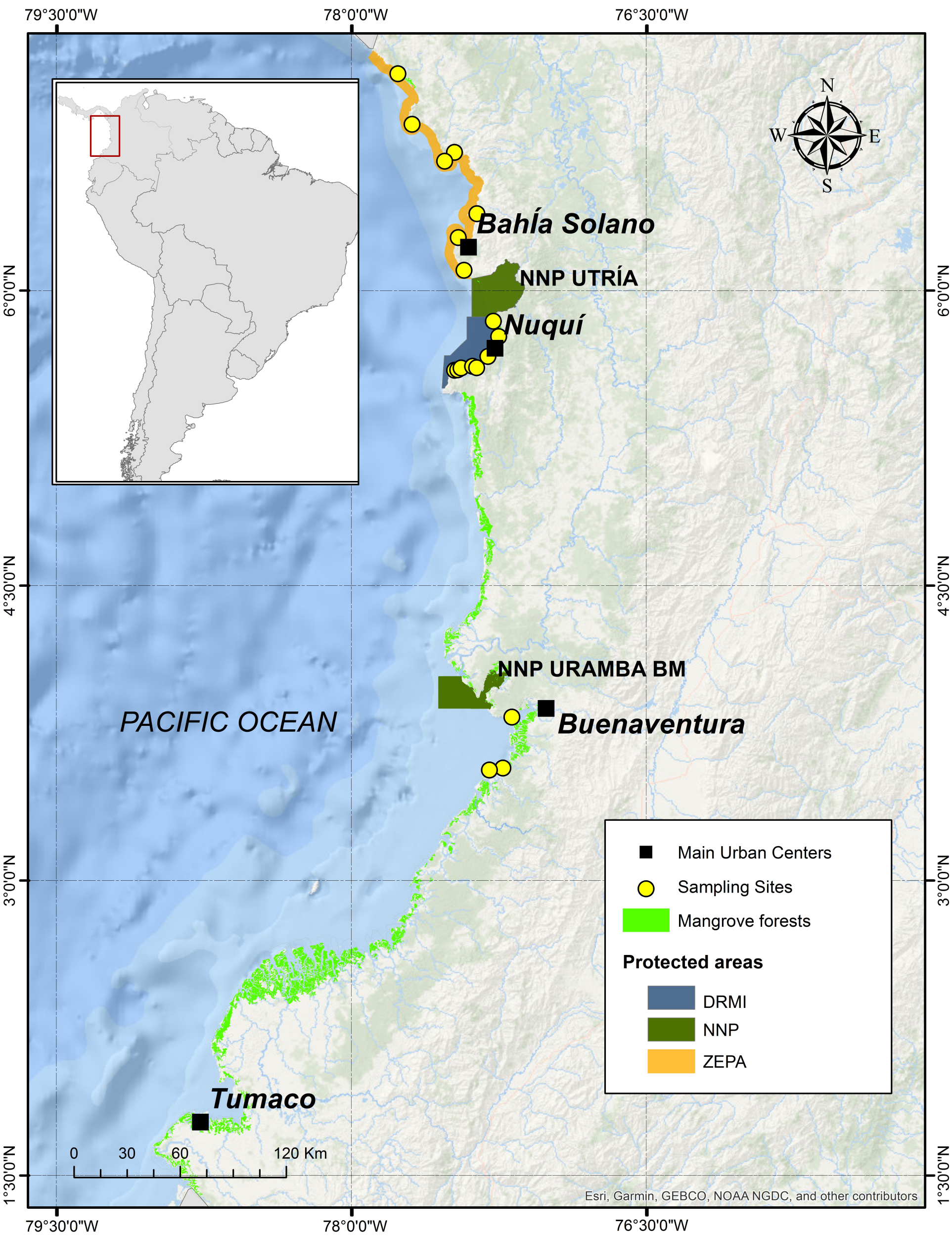

FIGURE 1 | Colombian Pacific coast with location of the three coastal zones included in this study: ZEPA, Tribugá (DRMI + National Natural Park Utría) and Buenaventura. Location of sampled landing sites, National Natural Parks and mangrove forests within the three coastal zones are also shown.

similar to those within the DRMI (PNN, 2011) and therefore we considered the Park's area as part of the same coastal zone, referred to hereafter as Tribugá.

Fishing Gears

At least 13 different main types of fishing gears have been reported in the Colombian Pacific SSF (Saavedra-Diaz, 2012) and eight of those are used by fishers at some or all of the three coastal zones studied here. These eight gears are: handlines, longlines (bottom), gillnets (including lobster nets), bottom trawls, purse seines, beach seines, cast nets and spear guns. Cast nets are mostly used to collect bait (such as sardines or anchovies) used in longlines or handlines and therefore the catch derived from this gear is rarely landed. Spear guns are used by a very low number of fishers while beach seines are more commonly used by family groups in the coastal communities. However, these two gears (spear guns and beach seines) contributed to <1% of the nominal catch recorded within each zone (**Figure 2**) and therefore were not included in further analyses. The main characteristics of the five gears that account for most of the catch are summarized in **Table 1**, including a sub-classification of gillnets based on the net material and on their mesh size. Given that lobster nets are a type

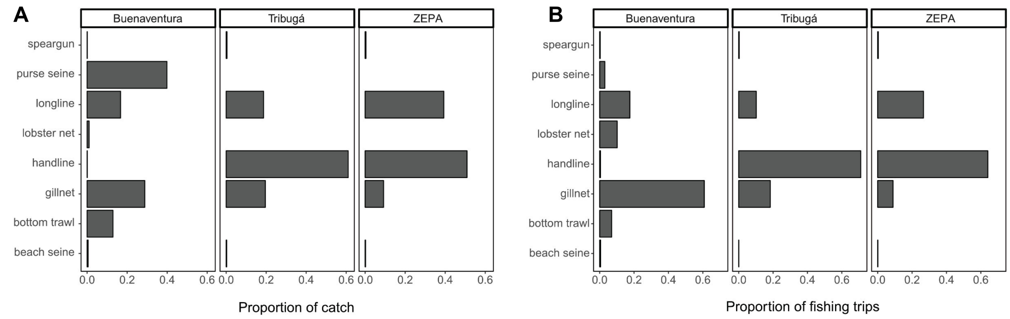

FIGURE 2 | Relative contribution to the catch in terms of biomass **(A)** and to the number of sampled fishing trips **(B)** by each gear type used in the SSF at three coastal zones of the Colombian Pacific. Sampling periods and landing sites included in each coastal zone are described in Section "Materials and Methods."

of gillnet targeted on a specific taxonomic group (Palinuridae) and include the use of bait, we treat them here as a separate type of gear. Detailed technical specifications of these gears and how they are used in the Colombian Pacific can be found in Saavedra-Diaz (2012) and Puentes et al. (2014).

TABLE 1 | Characteristics of gear types and subtypes that contribute most to total SSF landings at the three zones of the Colombian Pacific included in the present study.

Gear type	Gear subtype	Hook/ mesh size	Number of fishers	Main features
Handlines		5–9	1–2	1–10 hooks. Use bait.
Longlines		5–10	2–3	Bottom longlines. 500–2,000 hooks. Use bait.
Gillnets	Small-mesh	≤2.75″	2	1–12 pieces of nylon net (each piece: 180 m*1.8 m), used drifting or fixed to bottom.
	Medium-mesh	3–5″	2	
	Large mesh	≥5″	2–3	
	Lobster net	4″	1–2	2–6 pieces of multifilament net (each piece: 150–180 m*1.8 m). Use bait.
Bottom trawls		0.5–1″	2	Multifilament net of 8–10 m*2–3 m dragged over the sea floor at shallow areas. Small-scale equivalent of industrial otter-trawler.
Purse seines		2–2.5″	10–14	Small-scale encircling multifilament net, operated by two boats. Used only in the first 3–4 months of the year. Fishing grounds located 8–10 nautical miles from the coast.

Data Collection

In the ZEPA and Tribugá coastal zones, a community-based fisheries monitoring program was implemented from 2011 to 2016 by the regional non-government organization (NGO) MarViva Foundation[1]. Local observers were trained and hired to collect data at landing sites within each coastal community (Díaz et al., 2016; López-Angarita et al., 2018). Monthly visits were made by staff from the NGO to verify data quality and species identification. Data gathered through this monitoring program and used in the present study include data from nine landing sites located in ZEPA (2011–2013) and nine landing sites located in Tribugá (2011–2013 and 2016). At the Buenaventura coastal zone a similar community-based monitoring scheme was adopted by the authors of this study to collect data from August 2016 to July 2017 at three representative landing sites (**Figure 1**). Data gathered at landing sites included: date, common name of landed species, weight landed per taxa to the nearest 0.05 kg, catch status (e.g., whole, gutted), fishing gear type and fishing method. Also, total length of fish (or disk width in rays) and total length of invertebrates to the nearest 0.5 cm were measured in a representative sample of the catch (20–30%). All fish species were identified to the lowest taxonomic level possible following identification guides available for the region (Keen, 1971; Fisher et al., 1995; Acero, 2004; Marceniuk and Acero, 2009; Robertson and Allen, 2015).

Taking into account the collective ownership and management of the land occupied by Afro-descendent communities along the Pacific coast of Colombia (Law 70 of 1993), formal agreements with the Boards of the Community Councils Los Riscales, Los Delfines, Cupica, Juradó, Cajambre and Bazán-Bocana (in charge of the coastal areas where this study took place) were made by either MarViva Foundation or by the first author, whereby written informed consent was obtained. Additionally, meetings with fishers' representatives (locally elected leaders of fishers associations) were held at each coastal community to explain the objectives and methods of the project prior to the beginning of field activities. Approval from an external ethical committee was not required by local legislation for research collecting fisheries data at landing sites.

[1] www.marviva.net

TABLE 2 | Size-based, functional and conservation indicators used here for the assessment of the catch of SSF in the Colombian Pacific.

Indicator	Description	Rationale	Associated reference
Mean length	Mean length of all species in the catch	Given that fisheries is size selective and normally targets the adult phase of target species, it is expected that mean length in the catch decreases with increased fishing effort.	Jennings, 2005; Jennings and Dulvy, 2005; Link, 2005; Rochet and Trenkel, 2003; Shin et al., 2005
Mean maximum body size (*MBS*)	Weighted mean of the maximum size that the species in the catch can have in their lifetime.	Species with larger body size, higher longevity and age at maturity and lower growth rates have higher vulnerability to fishing and therefore are more likely to experience overfishing under sustained or increased fishing effort.	Smith et al., 1998; Jennings et al., 1999; Pitcher and Preikshot, 2001; Denney et al., 2002; Dulvy and Reynolds, 2002; Greenstreet and Rogers, 2006; Cheung, 2007
Mean trophic level (*MTL*)	Weighted mean of the trophic level of the species in the catch (*sensu* Pauly et al., 1998)	Given that fisheries tend to target larger fish/species with high trophic levels it is expected that mean trophic level in the catch will decreased with increased effort.	Pauly et al., 1998; Jennings et al., 2002; Pinnegar et al., 2002; Guénette and Gascuel, 2012; Shannon et al., 2014; Gascuel et al., 2016
Trophic guilds	Relative abundance of species belonging to these trophic guilds: herbivore, invertivore, omnivore, piscivore, and planktivore	Following the rationale for MTL, it is expected that increased fishing will lead to a decrease in the proportion of piscivore species (or other guilds) in the catch.	Caddy and Garibaldi, 2000; Link et al., 2002; Rochet and Trenkel, 2003
Spatial guilds	Relative abundance of species associated to a habitat in the water column: demersal, bentho-pelagic and pelagic	Given the intrinsic selectivity of the fisheries (gear, season, or spatially induced) it is expected that the proportion of pelagic and/or demersal species will change with increased fishing effort.	Caddy, 2000; Caddy and Garibaldi, 2000; Pitcher and Preikshot, 2001; Link et al., 2002; Rochet and Trenkel, 2003; Fulton et al., 2005
Threatened categories	Relative abundance of endangered species based on categories established by IUCN (www.iucnredlist.org)	Endangered species should be avoided as target or by-catch of commercial fisheries to allow their populations to recover.	Degnbol and Jarre, 2004; Rochet and Rice, 2005; Shin et al., 2010
Landed by-catch	Relative abundance of species that are not intentionally targeted and usually discarded	Removal of non-target species can cause a decrease in the population abundance of those species but also ecological effects on the ecosystem such as food-web disruption or habitat destruction	Alverson et al., 1994; Rochet and Trenkel, 2003; Fulton et al., 2005; Link, 2005; Shin et al., 2010; Collie et al., 2017

Rationale for its use as proxies of ecological fishing impacts and related literature are also indicated.

Data Processing and Analyses

Considering that 80% of fish were not landed whole, but gutted (42.6%), beheaded (2.2%), gutted and beheaded (31.4%) or as trunks (3.4%), weight corrections factors based on FAO (2000) were applied to landed weight for more accurate estimates of live weight removed per taxon. For some taxonomic families of small-sized species of relatively low market value (e.g., Acanthuridae and Muraenidae) there was partial or no data available on conversion factors. We assigned a conversion factor of 1.1 to those cases, being this value the most common reported as conversion factor for gutted weight across taxa (FAO, 2000). Large sting rays (*Hypanus* spp.) that could not be weighted were measured and disk-widths were later converted to total weight based on literature values for the two species involved (Ehemann et al., 2017). A table with all correction factors used per taxon is included as part of the (**Supplementary Table S1**). Landings data converted to live weight is technically known as "nominal catch" (FAO, 2018) which does not include discarded specimens (live or dead) that are not brought to landing sites. For practical reasons we will refer here to the nominal catch as "catch." After weight conversion was performed, as described above, relative weight per taxa (species, genus, or family) was calculated based on the catch (kg) per taxon divided by the total catch (all taxa combined) within each coastal zone.

To explore potential inter-annual differences in the catch composition of the coastal zones of Tribugá and ZEPA, we carried out cluster and non-metric multi-dimensional scaling analyses (nMDS) to compare relative weight within landing sites among years of those species that contributed to 95% of the catch at each landing site.

Size-based, functional and conservation indicators related to the composition of the catch were estimated and assessed among coastal zones and fishing gears. A list of the selected indicators is presented in **Table 2**, along with a brief description and the rationale behind their current global use as proxies of ecological fishing impacts. Mean total length (cm) in the catch was estimated across taxa for each gear within each coastal zone and visualized through violin plots. Maximum body size (cm), trophic level, trophic guild and spatial guild were assigned to all species registered in the landings based on data available on FishBase (Froese and Pauly, 2017), the Smithsonian Tropical Eastern Pacific Fish Guide (Robertson and Allen, 2015) and SeaLifeBase (Palomares and Pauly, 2018). Additionally, published values from local studies (Criales-Hernandez et al., 2006; Castellanos-Galindo et al., 2017) were used to assign trophic levels to some invertebrate species for which information could not be found on international databases. Trophic guilds categories used were: herbivore, invertivore, omnivore, piscivore and planktivore, while categories of spatial guilds used were: demersal, bentho-pelagic and pelagic.

Conservation threat status was assigned to species based on regional and national assessments that follow the International Union for the Conservation of Nature's (IUCN) Red List standards (IUCN, 2017). National assessments used are those carried out in Colombia in recent years for marine fish species (Chasqui et al., 2017), marine invertebrates (Ardila et al., 2002) and reptiles (Morales-Betancourt et al., 2015); the last one was included taking into account the rare occurrence of some species of sea turtles in the catch. Information on regional assessments was based on Polidoro et al. (2012). The categories used are: Not Evaluated (NE), Data Deficient (DD), Least Concern (LC), Near Threatened (NT), Vulnerable (VU), Endangered (EN), and Critically Endangered (CR). Definitions and criteria used for each category can be found at www.iucnredlist.org.

An additional classification of the taxa registered in the catch was made based on their current use or importance to fishers and markets. Three categories were considered for this purpose: "commercial," for those species of commercial interest, "local use" for those species that are not sold to external markets but are locally consumed or used as bait, and "by-catch" for those species that are not intentionally targeted and are usually discarded before reaching the landing site. However, when the size of the individuals was not so small (approximately >25 cm) or when fishers did not carry out the sorting process of the catch while they were on-board, some of that by-catch made it to the landing site and we will refer to that portion of the catch as "landed by-catch." In the case of bottom trawlers, fishers generally brought the last haul completely unsorted and separated from the rest of the catch, so we could use that haul to estimate landed by-catch. The classification of species in the above mentioned categories was based on Díaz et al. (2016) and on interviews made to local fishers of the coastal zone of Buenaventura by the first author (unpublished data).

Mean trophic level (*MTL*) of the catch for each gear category (*g*) at each coastal zone was estimated using the formula described by Pauly et al. (1998):

$$MTL\left(g\right) = \sum_{s=i}^{n} Wig^{*}TLi / \sum Wig$$

Where *Wig* is the biomass (total weight) of species *i* caught by gear *g*, and *TLi* is the trophic level of species *i* for *n* species. In a similar way we estimated mean maximum body size (*MBS*) per gear type at each zone, replacing *TL* in the previous formula for *MBS*. Generalized linear models (GLMs), using a logarithmic link function and a quasi-poisson distribution, were used to assess differences in mean length, *MTL* and mean *MBS* among gear types and zones. When statistical differences were detected within either factor or their interaction, pairwise comparisons were carried out using the "emmeans" R Package, based on least-square means and adjusted *p*-values following Tukey tests (R Core Team, 2017; Russell, 2018).

RESULTS

A total of 40,035 one-day fishing trips were sampled accounting for 1,823.2 tons of estimated biomass in the catch and 515,243 specimens measured. The proportion of the catch contributed by each fishing gear differed among ZEPA, Tribugá and Buenaventura (**Figure 2**). Hook-based gears contributed the most to the catch in ZEPA and Tribugá, while net-based gears dominated in Buenaventura. The relative contribution made by each gear to the total biomass was similar to the proportion of fishing trips per gear in ZEPA and Tribugá, but not so in Buenaventura, where a very large biomass contribution was made by purse seine nets despite the relatively low number of fishing trips recorded for that gear type (**Figure 2**). Total biomass (kg), number and estimated percentage of fishing trips sampled per gear type at each zone are presented in **Table 3**.

TABLE 3 | Total biomass in the nominal catch (i.e., live weight converted from landed weight, as described in section "Materials and Methods") of SSF, number of fishing trips sampled and estimated percentage of trips sampled per gear type at landing sites of the three coastal zones of the Colombian Pacific included in the present study (n.d., no data available on total number of trips).

Zone	Gear type	Biomass (kg)	Number of fishing trips sampled	Percentage of fishing trips sampled
ZEPA	Beach seine	2,057.6	7	n.d.
	Gillnet	86,435.7	875	87%
	Handline	481,009.8	6,302	78%
	Longline	370,961.4	2,620	67%
	Spear gun	3,951.5	32	n.d.
Tribugá	Beach seine	1,383.9	21	n.d.
	Gillnet	158,752.0	5,345	92%
	Handline	493,520.3	20,672	76%
	Longline	151,412.0	2,974	70%
	Spear gun	3,476.2	95	n.d.
Buenaventura	Beach seine	343.8	6	n.d.
	Bottom trawl	9,358.8	77	21%
	Gillnet	20,799.7	669	42%
	Handline	77.5	5	n.d.
	Lobster net	750.9	112	45%
	Longline	12,068.7	193	62%
	Purse seine	28,835.5	33	47%
	Spear gun	77.7	4	n.d.

Taxonomic Composition of the Catch

179+ species belonging to 80 families were identified as part of the catch of the SSF of the three coastal zones of the Colombian Pacific. However, this number of species is probably an under-estimation of the richness of the catch considering that 66 common names of mostly rare species (i.e., low relative abundance in the catch) were not assigned to any taxonomic category and 31 of them were only identified to genus or family level, resulting in a total of 276 different common names registered in the catch of the three coastal zones.

95% of the biomass in the catch was accounted for by 24 families and 72 species (**Figure 3** and **Supplementary Figure S1**). Mackerels, tunas and bonitos (Scombridae) contributed between 20 and 30% of the annual catch at all zones, indicating an overall importance of this family in the SSF of the entire Colombian Pacific coast. Jacks (Carangidae), cusk eels (Ophidiidae), groupers (Serranidae) and snappers (Lutjanidae) were also important

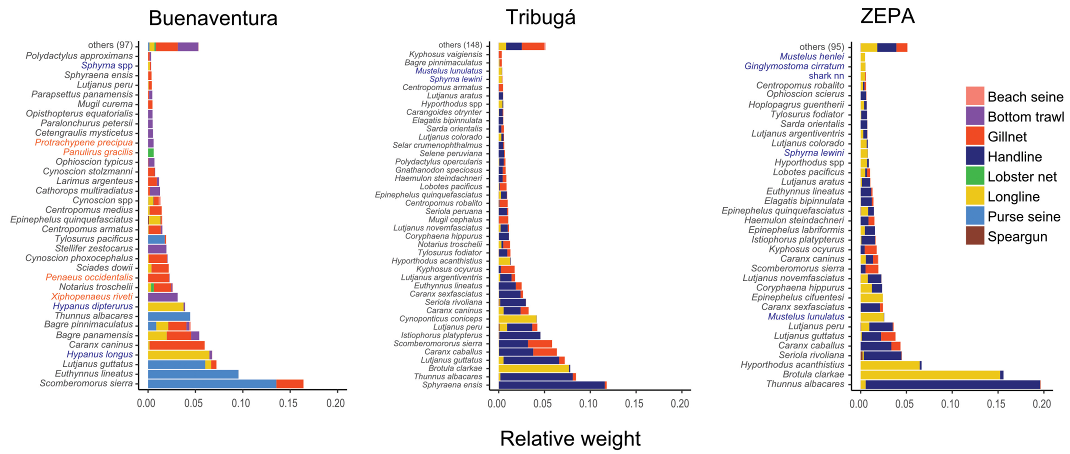

FIGURE 3 | Relative weight of taxa in the catch of the SSF at three coastal zones of the Colombian Pacific: ZEPA, Tribugá, and Buenaventura. Taxonomic identity is indicated for those taxa that contributed 95% to total catch and relative catch contribution by each gear type is illustrated. Elasmobranch species (sharks and rays) are shown in blue font, crustaceans in orange and bony fish in black.

in the landings of ZEPA and Tribugá while in Buenaventura, catfishes (Ariidae), whiptail stingrays (Dasyatidae) and drums or croakers (Sciaenidae) followed Scombridae in the relative abundance ranking (**Supplementary Figure S1**). A higher number of species (41) accounted for 95% of the catch in Tribugá than in Buenaventura and ZEPA (35 species each) (**Figure 3**). The distribution of the relative abundance of species shows a more even pattern in the catch of Tribugá than that of ZEPA, where two dominant species (*Thunnus albacares* – Scombridae and *Brotula clarkae* – Ophidiidae) contributed to 35% of the catch. Invertebrate species, mainly shrimps (Penaeidae) and lobsters (Palinuridae), were abundant in Buenaventura, but not so in ZEPA or Tribugá. Additionally, several shark species were relatively abundant in ZEPA and Tribugá compared to Buenaventura (**Figure 3**). A complete list of the taxa recorded in the catch of each zone, with their absolute and relative weight, is included in the (**Supplementary Table S2**).

Results from the cluster and the nMDS analyses showed that there were not distinctive inter-annual differences related to species composition of the catch at the landing sites sampled in ZEPA and Tribugá (**Supplementary Figure S2**). Based on records of daily fishing activity in Tribugá and ZEPA collected by MarViva during their monitoring program (Díaz et al., 2016) and the information available from the Colombian fisheries authority[2], there was no evidence of changes in fishing effort made by the small-scale fleet in those areas during the past 10 years. We thus used the combined catch data for all years of each of these coastal zones for subsequent analyses.

Size-Based Indicators of the Catch

Overall, most specimens at all zones were <100 cm of total length (**Figure 4**) with longlines in ZEPA capturing on average larger size classes (**Table 4**), even though the largest specimens were caught by handlines in Tribugá (e.g., the sailfish species *Istiophorus platypterus* reaching >400 cm TL; **Supplementary Figure S3**). In contrast, bottom trawls in Buenaventura exhibited a high relative abundance of small-sized individuals with a narrow unimodal distribution of length. The catch of this gear was composed mainly of the target small shrimps species Pacific seabob – *Xiphopenaeus riveti* and titi shrimp – *Protrachypene precipua*, and other non-target small-sized invertebrates and juvenile fish of several species (**Figures 3**, **4**). Lobster nets and gillnets in Buenaventura had most of their catch toward the lower side of the overall length range observed in this study (**Figure 4** and **Table 4**). Results from the GLM conducted with the entire catch (all species included) showed that mean length in the catch within the same gear type was statistically different among zones, with ZEPA showing higher mean length in the catch than Tribugá and Buenaventura for gillnets and longlines, and also for handlines when compared to Tribugá ($p < 0.001$ in all cases). Mean length was also statistically different among gears within the same zone: in Buenaventura, mean length of purse seines was higher than that of all other gears whereas mean length of bottom trawls was lower than all the other gears ($p < 0.001$ in all cases). In Tribugá and ZEPA, longlines had a significantly higher mean length in their catch compared to handlines and gillnets ($p < 0.001$ in all cases).

Handlines and longlines showed the largest maximum body size (*MBS*) of the species in the catch, with mean values above 130 cm in all cases (**Figure 5** and **Table 4**). Mean *MBS* of the entire catch of handlines was statistically higher ($p < 0.001$) in ZEPA than in Tribugá. In the case of longlines, Buenaventura showed higher mean *MBS* than ZEPA and Tribugá, related to the high relative abundance of stingrays (*Hypanus* spp.) in the catch of longlines of that central coastal zone, although the mean *MBS* was only statistically different when compared to ZEPA ($p = 0.02$). On the other hand, gillnets appear to target species of medium *MBS* at all three zones with mean values close to 80 cm and statistical differences found between Tribugá and Buenaventura ($p = 0.01$). Bottom trawls had a significantly

[2]http://sepec.aunap.gov.co/

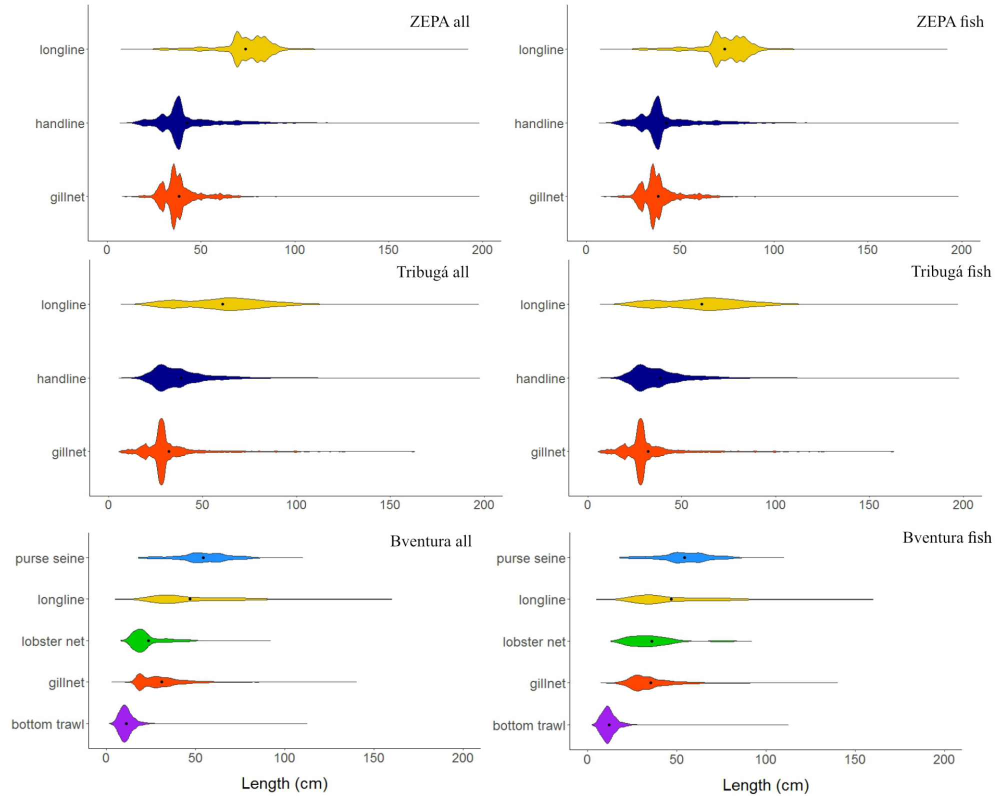

FIGURE 4 | Length distribution of the entire catch (up to 200 cm) and of the fish portion of the catch of SSF per gear type at three coastal zones of the Colombian Pacific: ZEPA, Tribugá, and Buenaventura (abbreviation: Bventura). Black dots indicate mean values. A similar plot of the length distribution of the catch up to the maximum length observed at each zone is included as part of the **Supplementary Figure S3**.

TABLE 4 | Mean estimated values ± standard deviation for total length, maximum body size and trophic level of the catch at the three geographical zones studied here: Buenaventura, Tribugá, and ZEPA.

		All species in the catch			Only fish species in the catch		
Zone	**Gear**	**Total length**	**Maximum body size**	**Trophic level**	**Total length**	**Maximum body size**	**Mean trophic level**
Buenaventura	Bottom trawl	11.26 ± 4.89	33.26 ± 39.01	3.24 ± 0.70	11.99 ± 5.20	41.96 ± 45.26	3.63 ± 0.48
	Gillnet	31.18 ± 13.18	77.02 ± 33.91	3.88 ± 0.59	35.35 ± 12.75	81.66 ± 31.12	4.00 ± 0.42
	Lobster net	23.61 ± 11.50	55.70 ± 51.88	3.78 ± 0.51	36.08 ± 14.09	86.47 ± 68.76	4.3 ± 0.34
	Longline	46.93 ± 21.94	169.93 ± 85.65	3.75 ± 0.35	47.01 ± 21.92	169.93 ± 85.65	3.75 ± 0.35
	Purse seine	54.48 ± 14.18	119.53 ± 63.67	4.21 ± 0.31	54.48 ± 14.18	119.53 ± 63.67	4.21 ± 0.30
Tribugá	Gillnet	32.03 ± 15.67	86.02 ± 47.89	3.91 ± 0.56	32.03 ± 15.67	86.47 ± 68.76	3.91 ± 0.56
	Handline	39.77 ± 23.80	151.16 ± 95.65	4.17 ± 0.27	39.77 ± 23.80	151.16 ± 95.65	4.17 ± 0.27
	Longline	60.66 ± 21.91	141.64 ± 64.44	3.91 ± 0.20	60.66 ± 21.91	141.69 ± 64.44	3.91 ± 0.20
ZEPA	Gillnet	38.43 ± 10.73	83.24 ± 46.29	3.98 ± 0.38	38.43 ± 10.73	83.24 ± 46.29	3.98 ± 0.38
	Handline	42.73 ± 18.10	184.57 ± 97.55	4.25 ± 0.26	42.73 ± 18.10	184.57 ± 97.55	4.25 ± 0.26
	Longline	73.86 ± 14.05	133.35 ± 72.27	3.90 ± 0.21	73.86 ± 14.05	133.53 ± 72.60	3.90 ± 0.21

Estimated values are shown for both the total catch (all species included) and for the fish portion of the catch, excluding invertebrates and reptiles (i.e., sea turtles).

smaller mean *MBS* than all other gears except for lobster nets ($p < 0.01$ in all cases).

Paired comparisons based on the entire catch within each coastal zone revealed that in Buenaventura, longlines had higher *MBS* than all other gears, except for purse seines ($p < 0.001$ in all cases), while bottom trawl had lower *MBS* than all other gears except for lobster nets ($p < 0.01$ in all cases); none of the other paired comparisons was statistically significant in Buenaventura. In ZEPA, handlines exhibited a significantly higher *MBS* than longlines and gillnets ($p < 0.001$ in both cases). In Tribugá mean

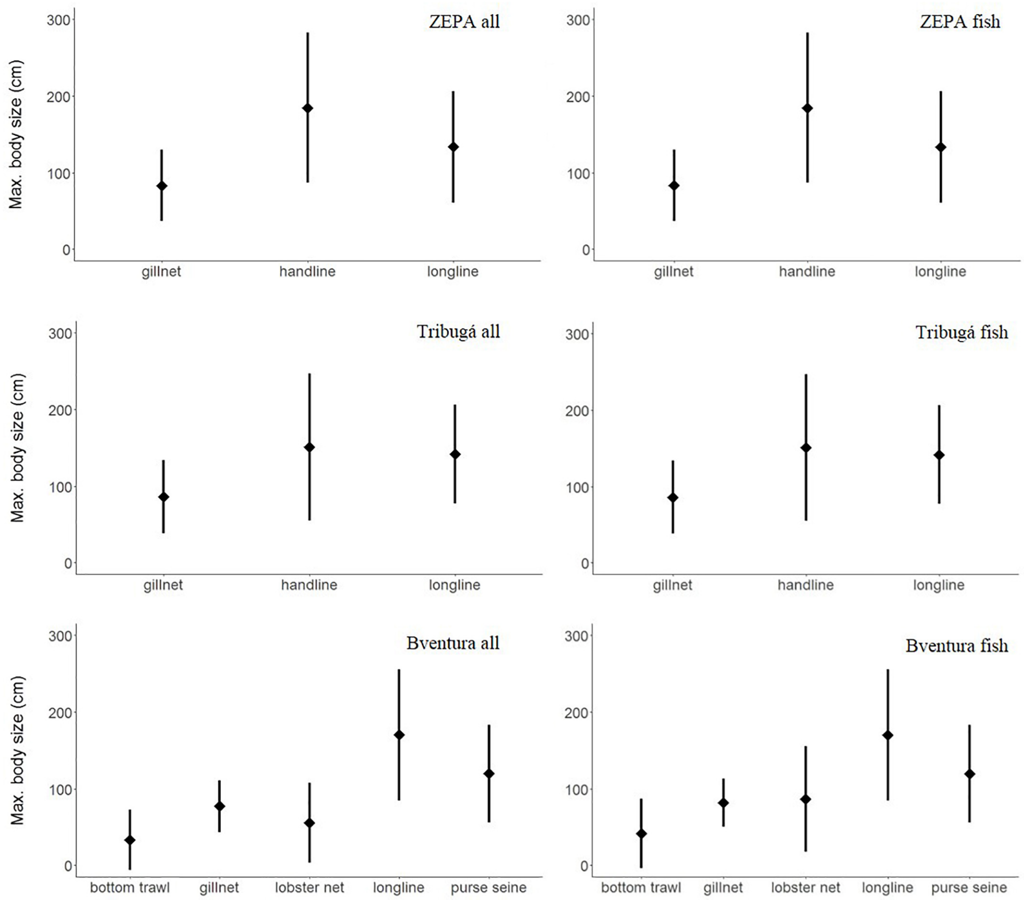

FIGURE 5 | Weighted mean and standard deviation of maximum body size of the entire catch and of the fish portion of the catch of SSF per gear type at three coastal zones of the Colombian Pacific: ZEPA, Tribugá, and Buenaventura (abbreviation: Bventura).

MBS of gillnets was lower than that of handlines and longlines ($p < 0.001$ in both cases), but mean *MBS* values of the two hook-based gears, i.e., longlines and handlines, were not significantly different between each other.

For bottom trawls, gillnets and lobster nets in Buenaventura invertebrates accounted for 34, 8, and 56% of the catch, respectively. To assess the influence of shrimp and other small invertebrates on the estimates of size-based indicators, we estimated mean length and mean *MBS* for the fish portion of the catch, i.e., excluding all invertebrates and other non-fish species (i.e., sea turtles) from the data set prior to analyses. As expected, values of both size-based indicators, especially of *MBS*, increased for bottom trawls, lobster nets and gillnets in Buenaventura (**Table 4**) but had no effect in other gears of that coastal zone nor in the estimates derived from Tribugá and ZEPA, where invertebrates and reptiles accounted for only 0.03 and 0.01% of the catch, respectively. GLMs conducted for the fish portion of the catch showed the same statistical differences in total length among zones and/or gears observed previously for the whole catch, except for the difference between gillnets and lobster nets in Buenaventura which was not significant this time ($p = 0.98$). In contrast, the results of the pairwise comparisons of *MBS* values based on the fish portion of the catch showed that differences among zones or gears previously observed for the entire catch were no longer significant. In particular, mean *MBS* of the fish caught with gillnets was not statistically different between Buenaventura and Tribugá ($p = 0.12$) and within Buenaventura mean *MBS* of longlines and lobster nets were not statistically different ($p = 0.34$) from each other.

Functional Indicators of the Catch

Mean trophic level of the entire catch (all species included) was very similar across gears and zones, with mean values lying above 3.5 for all cases except for bottom trawls in Buenaventura that exhibited the lowest mean value, while handlines and purse seines exhibited the highest values (**Figure 6** and **Table 4**). Statistically significant differences among gears within the same coastal zone were only found between *MTL* of handlines and longlines within ZEPA ($p < 0.01$).

Following the rationale explained above for size-based indicators and considering the general positive relationship between a species body size and its trophic level (Romanuk et al., 2011), we also estimated *MTL* for the fish portion of the catch only. Similarly to the findings related to mean length

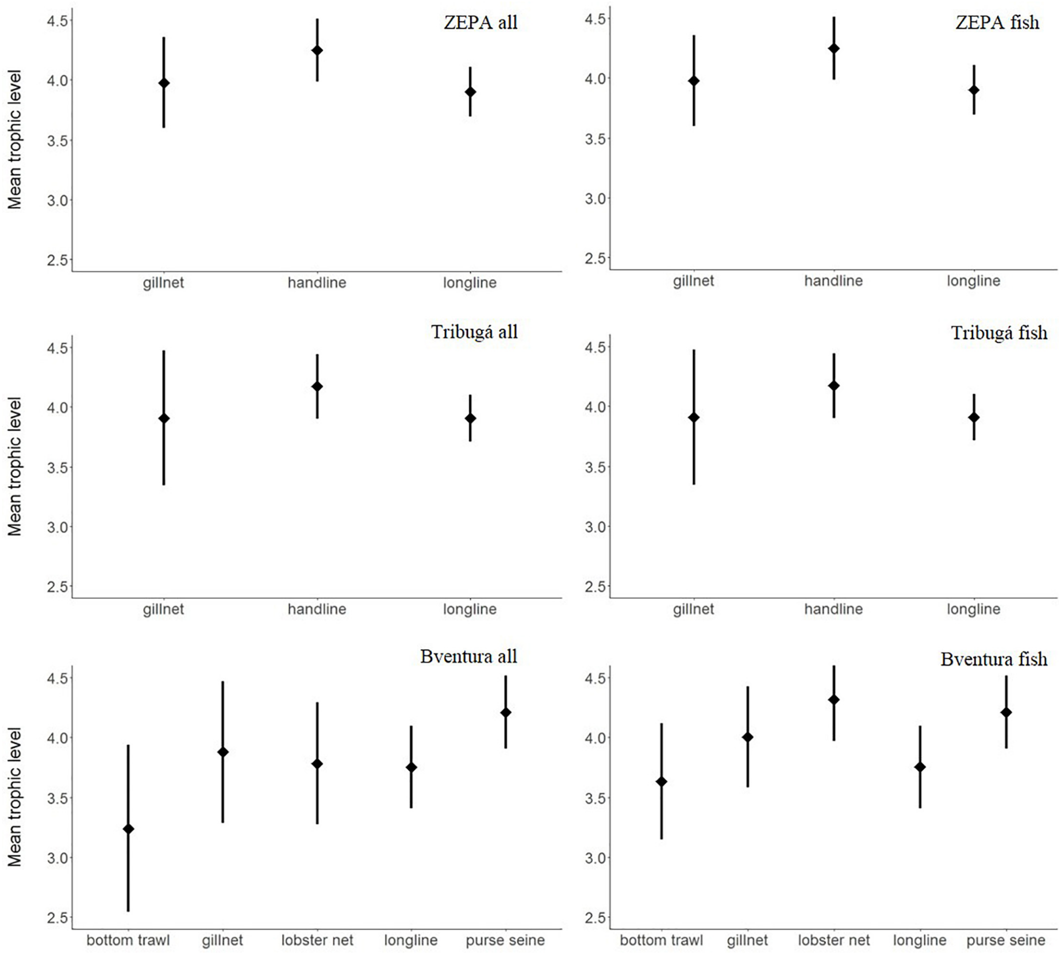

FIGURE 6 | Weighted mean and standard deviation of trophic level of the entire catch and of the fish portion of the catch of SSF per gear type at three coastal zones of the Colombian Pacific: ZEPA, Tribugá, and Buenaventura (abbreviation: Bventura).

and *MBS*, there was an increase – although relatively smaller – in the estimated values of *MTL* for bottom trawls, gillnets and lobster nets in Buenaventura (**Figure 6** and **Table 4**). The small increase resulted in the difference between *MTL* of gillnets from Buenaventura and gillnets from Tribugá being no longer significant ($p = 0.24$).

Results of the relative abundance of trophic guilds corroborated that high trophic level guilds (piscivores and invertivores) are dominant in the catch of most gears across zones, except for bottom trawls, the gear that showed the highest diversity of trophic guilds (**Figure 7**). Also worth noting is the higher relative abundance of invertivores in the catch of longlines in Buenaventura compared to that of Tribugá and ZEPA for the same gear, where piscivores accounted for more than 90% of the catch.

In terms of spatial guilds, demersal species were dominant in Buenaventura for all gears except for purse seines, contrasting with the results from ZEPA and Tribugá where pelagic species had a higher relative abundance in the catch of gillnets and handlines while longlines caught more demersal and bentho-pelagic species (**Figure 7**). The overall proportions of species belonging to different spatial guilds was similar between ZEPA and Tribugá for the same type of gear: gillnets, handlines or longlines.

Conservation Indicators of the Catch

Based on the regional assessment of IUCN's Red List, the three coastal zones have Least Concern (LC) as the predominant category of the biomass in the catch (54–73%), while threatened categories (Vulnerable – VU, Endangered – EN and Critically Endangered – CR) represented less than 1% of the biomass. The relative weight of species classified as Near Threatened (NT) was higher in ZEPA than in the other two zones with handlines being the gear that contributed most to that difference (**Table 5**). When the same analysis was based on the national assessment (Colombian's red lists assessments), Not Evaluated (NE) and Near threatened (NT) were the dominant categories in the catch of all zones – with ZEPA exhibiting the highest relative abundance of NT species – while Data Deficient (DD) and LC had overall low values. Based on the national assessments, the relative weight

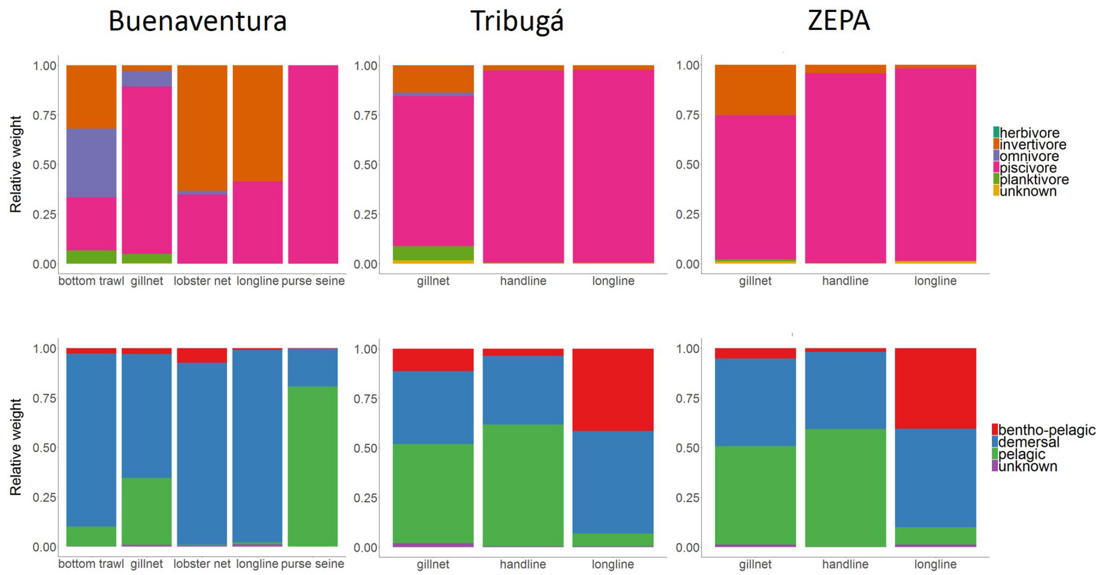

FIGURE 7 | Proportion of trophic guilds and spatial guilds per gear type in the catch of SSF at three coastal zones of the Colombian Pacific: ZEPA, Tribugá, and Buenaventura.

TABLE 5 | Proportions of threatened or non-threatened taxa in the catch of SSF of the Colombian Pacific.

		Not classified				Non-threatened categories						Threatened categories					
		unknown		NE		DD		LC		NT		VU		EN		CR	
Zones	**Gears**	**Reg**	**Col**	**Reg**	**Col**	**Reg**	**Col**	**Reg**	**Col**	**Reg**	**Col**	**Reg**	**Col**	**Reg**	**Col**	**Reg**	**Col**
Buenaventura	Bottom trawl	0.02	0.02	0.33	0.90	0.03	0.01	0.62	0.04	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00
	Gillnet	0.03	0.03	0.08	0.66	0.01	0.05	0.88	0.00	0.00	0.12	0.00	0.14	0.00	0.00	0.00	0.00
	Lobster net	0.02	0.02	0.01	0.96	0.55	0.00	0.38	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.01	0.01
	Longline	0.05	0.05	0.00	0.47	0.65	0.07	0.30	0.00	0.01	0.04	0.00	0.37	0.00	0.00	0.00	0.00
	Purse seine	0.00	0.00	0.00	0.29	0.00	0.05	0.88	0.00	0.12	0.66	0.00	0.00	0.00	0.00	0.00	0.00
Tribugá	Gillnet	0.04	0.04	0.10	0.69	0.01	0.03	0.83	0.02	0.02	0.21	0.00	0.01	0.00	0.00	0.00	0.00
	Handline	0.01	0.01	0.02	0.63	0.01	0.02	0.83	0.02	0.13	0.33	0.01	0.00	0.00	0.00	0.00	0.00
	Longline	0.03	0.03	0.00	0.34	0.65	0.01	0.29	0.01	0.01	0.56	0.00	0.05	0.02	0.00	0.00	0.00
ZEPA	Gillnet	0.07	0.07	0.14	0.58	0.00	0.01	0.78	0.00	0.00	0.34	0.00	0.00	0.00	0.00	0.00	0.00
	Handline	0.01	0.01	0.03	0.48	0.02	0.02	0.57	0.01	0.37	0.49	0.00	0.00	0.00	0.00	0.00	0.00
	Longline	0.03	0.03	0.00	0.17	0.43	0.02	0.44	0.01	0.08	0.59	0.00	0.17	0.02	0.00	0.00	0.00

Species classification were based on regional assessments (Polidoro et al., 2012) (Reg) and national assessments produced by the Colombian government (Col) for marine fish species (Chasqui et al., 2017), marine invertebrates (Ardila et al., 2002) and reptiles (Morales-Betancourt et al., 2015). Categories used are: Not Evaluated (NE), Data Deficient (DD), Least Concern (LC), Near Threatened (NT), Vulnerable (VU), Endangered (EN), and Critically Endangered (CR), based on: www.iucnredlist.org. Taxa which could not be identified to species level and therefore could not be assigned to a specific category where classified as "unknown."

of species under category VU was higher in the catch of ZEPA and Buenaventura, mostly due to the presence of species caught with longlines (e.g., stingrays). Overall, the relative abundance of threatened or near threatened categories in the catch was higher when based on national assessments than when the analysis was based on IUCN's regional assessments.

Landed by-catch species, those that are not commercialized or locally used, were only a conspicuous proportion of the catch of bottom trawls where they accounted for >30% of the catch (**Table 6**). For the rest of the gears, landed by-catch was below 3% and more than 75% of the catch corresponded to commercially important species. In ZEPA and Tribugá, 20% of the catch of gillnets is locally consumed or used as bait, instead of sold to local or external markets.

DISCUSSION

Our results showed clear differences in the catch composition among the three coastal zones and, particularly, between the northern rocky-dominated coast (Tribugá and ZEPA) and the central estuarine and mangrove-dominated coast (Buenaventura)

TABLE 6 | Proportions of categories related to fishers' use of the species registered in the catch of SSF in the Colombian Pacific.

Zones	Gears	Commercial	Local use	Landed by-catch	Unknown
Buenaventura	Bottom trawl	0.55	0.10	0.36	0.00
	Gillnet	0.90	0.09	0.01	0.00
	Lobster net	0.93	0.05	0.02	0.00
	Longline	0.98	0.01	0.01	0.00
	Purse seine	1.00	0.00	0.00	0.00
Tribugá	Gillnet	0.77	0.21	0.00	0.02
	Handline	0.96	0.03	0.00	0.00
	Longline	0.76	0.23	0.00	0.00
ZEPA	Gillnet	0.78	0.21	0.00	0.01
	Handline	0.98	0.02	0.00	0.00
	Longline	0.96	0.03	0.00	0.01

"Commercial" refers to species that are usually sold to local or external markets, "local use" to those species that are not sold but are locally consumed or used as bait, and "landed by-catch" to those species that are not intentionally targeted and that are usually discarded. Taxa which could not be identified to species level and could not be assigned to a specific category where classified as "unknown".

of the Colombian Pacific. Some of the observed differences were related to the interaction between gear type and geographical location of the coastal zones.

Despite being in a traditionally data-poor tropical SSF context, our data sets, produced by a non-government organization and by an academic research project, included higher sampling frequency, sample size and geographic coverage than normal government fisheries data (Ramírez et al., 2017; Herrón et al., 2018). Community-based fishing monitoring schemes (as those followed in the present study) are therefore useful and likely more effective and less expensive ways of monitoring fisheries resources in typical SSF like the ones evaluated here. Overcoming some limitations in these schemes like the correct differentiation of certain species and common names within certain taxonomic groups, e.g., groupers, sharks, is something that will require further attention in the future (Castellanos-Galindo et al., 2018).

Size-Based and Functional Indicators

In the management areas established in the northern coastal zones, a higher selectivity of fishing gears has been promoted based on the assumption that gillnets tend to catch a higher proportion of immature fish and have higher by-catch rates than hook-based gears (Vieira et al., 2016; Ramírez-Luna and Chuenpagdee, 2019). Our results confirmed a lower mean length in the catch of gillnets when compared to longlines and handlines in ZEPA and Tribugá. However, fisheries selectivity is influenced not only by the gear used but also by spatial and temporal patterns of resource distribution (Maunder et al., 2014; Sampson, 2014). Therefore, the observed differences reflect not only the inherent selectivity of gears but also the location of the fishing grounds used by each gear. Particularly in ZEPA, longline fishers use deeper grounds located at greater distances from the shore, whereas gillnets tend to fish in areas closer to shore (Velandia and Díaz, 2016). A higher abundance of larger/older individuals in deeper habitats has been widely reported for many fish species and has been attributed to ontogenetic changes, although recent evidence indicate that this "deepening" could also be associated to increased fishing pressure in shallower areas (Frank et al., 2018). Distance to shore and depth of fishing grounds could also explain the higher mean length observed in the catch of purse seines in Buenaventura compared to other gears in the same zone (**Figure 4**). Purse seines are used at fishing grounds located further offshore (8–10 nautical miles) than other gears (unpublished data) and target mostly pelagic species (**Figure 3**). Bottom trawls – which exhibited the lowest mean length in the catch of all zones even when invertebrates are removed – have the smallest mesh size of all nets (0.5″) and are used in near-shore, shallow waters (unpublished data), targeting mainly two small-sized shrimp species (*X. riveti* and *P. precipua*). Continued monitoring of mean length in the catch complemented by spatial analyses of fishing grounds could provide more information regarding the factors explaining the observed differences and the potential long-term impacts of different gears on the size-structure of fish and invertebrate communities.

Our results of maximum body size (*MBS*) in the catch indicate that longlines and handlines are targeting larger body-sized species that are more vulnerable to overfishing due to their life history characteristics (Jennings et al., 1998; Cheung, 2007) (e.g., sailfish, tunas, and sharks, **Figure 3**), while bottom trawls are targeting species that could potentially withstand more fishing pressure and/or recover more rapidly (e.g., shrimps, other small invertebrates and small-sized fish species). Particularly in Buenaventura, longlines had a significantly higher *MBS* than the rest of the gears, probably linked to the fact that large-sized stingrays of the genus *Hypanus* were an important part of the catch of this gear (**Figures 3**, **5**).

Targeting a relative high proportion of small-sized specimens has been suggested as a way of improving overall yields while maintaining the structure of the natural ecosystem, under the concept of "balanced harvest" (Kolding et al., 2015b), an approach that contradicts traditional management measures like imposing size limits for target species to avoid fishing immature individuals thus preventing growth and recruitment overfishing (Beverton, 1992; Myers and Mertz, 1998; Froese, 2004). Despite being more aligned to the principles of EBFM, critics of the balanced harvest approach have also argued that there are many practical difficulties of implementing such harvest scheme, particularly a drastic shift in consumers' seafood preferences toward new species and sizes (Charles et al., 2015; Froese et al., 2015; Garcia et al., 2015).

Similarly to size-based indicators, *MTL* of the catch has been used as an indicator of ecological fishing impacts as it is expected to decrease with increasing fishing pressure [Pauly et al., 1998; Jennings et al., 2002; Pinnegar et al., 2002; Gascuel et al., 2016, but see Sethi et al. (2010)]. However, *MTL* has been criticized as an indicator of ecosystem condition since it can be largely influenced by external economic factors, such as market demands (for species and sizes) and by environmental variability that alters the dynamics of primary productivity and the recruitment of planktivore species (Caddy et al., 1998; Caddy and Garibaldi, 2000; Branch et al., 2010). Nevertheless, *MTL* may still be a suitable indicator for the state of a fishery system, if fishing pattern and external factors remain constant over time and only fishing effort increases (Shannon et al., 2014). Our estimates of *MTL* were fairly similar across gears and coastal zones and showed that SSF in the Colombian Pacific are extracting mainly high trophic level species of the system. This is corroborated by the high proportion of piscivores and invertivores in the catch of most gears across all zones, with the exception of bottom trawls that exhibited the highest diversity of trophic guilds in the catch (**Figure 7**).

These results go in line with a worldwide pattern of fishing that has focused on high trophic levels (Kolding et al., 2015a). *MTL* values observed here (overall mean: 3.9) are higher than *MTL* values reported in tropical SSF of the Western Indian Ocean [2.3–3.6, Rehren et al. (2018); Tuda et al. (2016)], the Caribbean [3.3–3.5, Arias-González et al. (2004)], the Indo-Pacific [2.4–3.7, Bacalso and Wolff (2014)] and other localities in the tropical eastern Pacific [2.5–2.9, Zetina-Rejon et al. (2003) and Díaz-Uribe et al. (2007)]. However, values of trophic level per species used in this study correspond to the adult phase of the species (FishBase, Froese and Pauly, 2017) and do not necessarily correspond to the actual trophic level of the size classes harvested per species. This can impose biases in the estimates of mean *MTL* of the catch (Caddy et al., 1998; Reed et al., 2016). In the future, local studies on the diet composition of target species should be conducted and used to estimate trophic levels per size class of main target species.

Differences observed in the proportion of spatial guilds across zones and gears seem best explained by location and habitat type. In ZEPA and Tribugá, coastal zones characterized by narrow continental shelves and few estuaries, pelagic and bentho-pelagic species dominated the catch (**Figure 7**). In contrast, fishing gears in the mangrove-dominated and estuarine area of Buenaventura caught mainly demersal species, except for purse seines, the only gear that operates further off-shore. Therefore, observed differences in proportions of spatial guilds do not seem to offer at this point an unequivocal indication of potential geographical or gear-based differences in fishing impacts but future assessments of temporal trends of this indicator might indicate changes in fishing effort or in the natural abundance of the resources (Caddy, 2000; Pitcher and Preikshot, 2001; Link et al., 2002).

Conservation Indicators

Based on regional assessments of the threatened status of species (Polidoro et al., 2012), most of the catch of SSF in the Colombian Pacific does not currently face major extinction risks, which could be interpreted as a sign of a sustainable fishery. However, the diagnosis is different when the national assessments are used (Ardila et al., 2002; Morales-Betancourt et al., 2015; Chasqui et al., 2017), since a large proportion of the biomass in the catch corresponds to Nearly Threatened (NT) species (**Table 5**). Based on the national red lists, longlines' catch is conformed partly by species classified as Vulnerable (VU) in Buenaventura (37%) and in ZEPA (17%), mainly attributed to the presence of rays, stingrays and sharks. However, national assessments of commercially important species have generally been based on stock assessments with limited landings time-series or with poor spatial coverage. This could impose biases and is a common situation in data-limited tropical SSFs assessments (Costello et al., 2012; Ramírez et al., 2017; Herrón et al., 2018). On the other hand, the high proportion of Not Evaluated (NE) species in the catch of SSF, based on national assessments (**Table 5**), highlights the need to collect data on the status of natural populations based also on fishery-independent surveys.

By-catch and discards have also been considered to be meaningful indicators of the potential ecosystem impacts of fishing (Fulton et al., 2005; Link, 2005). They are increasingly being monitored and regulated in fisheries of developed countries [e.g., Landings:Discards ratio from the IndiSeas project, Coll et al. (2016)]. The high proportion of landed by-catch of bottom trawls observed here (36%) suggests a higher ecosystem impact of this fishing gear compared to other gears currently used. Bottom trawling has long been identified as a fishing method that can cause a variety of ecological impacts, such as: reduced abundance of non-target species, reduced diversity of the benthic community, sediment resuspension, disruption of nutrients cycles, changes in primary productivity, destruction of habitat and changes in trophic dynamics of the demersal and benthic communities (Collie et al., 2000, 2017; Olsgard et al., 2008; Dell et al., 2013). Fisheries authorities in Colombia banned the use of bottom trawls more than 10 years ago (INCODER, 2004) but fishers continue to use it since there is low enforcement capacity and high market demand for the main target species (small-sized shrimp species). On the other hand, a recent study on the effects of small-scale bottom trawling in similar estuarine environments in Brazil found that observed differences in the structure of macrofaunal communities seemed to be more related to natural variability than to the degree of trawling impact (Ortega et al., 2018). These authors discussed whether those communities could be adapted to a highly dynamic and frequently disturbed estuarine environment, which could also be the case of the benthic communities in Buenaventura that have sustained a bottom trawl fishery for more than 30 years. Specific studies on the dynamics of the catch of bottom trawls involving on-board monitoring and surveys of natural benthic communities will provide valuable inputs for management decisions regarding the continuation of the ban currently established on this gear or, perhaps, a transition toward fishing effort regulation.

CONCLUSION

Analyses of the catch through the lens of ecological indicators provide alternative paths for the assessment and monitoring of SSF that complement the traditional single-species assessment methods and provide insights into potential ecological impacts of fishing. Observed differences in taxonomic composition of the catch and in the proportion of gears used among coastal zones most likely reflect the deep knowledge of small-scale fishers about the temporal and spatial distribution of resources (Saavedra-Diaz, 2012; Purcell et al., 2018). Hook-based gears (handlines and longlines) tend to catch larger sizes and higher trophic levels than nets, but they also include a higher proportion of species that are more vulnerable to fishing impacts and/or have higher conservation concerns. These findings challenge the generalized notion that more selective gears have overall lower ecological impacts. In contrast, net-based gears catch wider size ranges – although tend to focus on small-size classes – and include a wider representation of species, trophic and spatial guilds, which could arguably be considered a more "balanced harvest" type of fishing that retains ecosystem functionality (Garcia et al., 2015). Using the data presented here, a preliminary snap-shot assessment of the gears (**Supplementary Table S3**) suggests that there is not one ideal or "green" fishing gear since each gear harvests a specific size and/or functional component of the system and therefore will affect that component more severely than other gears. The rapid assessment also shows that the same type of gear can have different ecological impacts when used in different environmental contexts, e.g., the differences in the proportion of trophic and spatial guilds in the catch of longlines in Buenaventura compared to that in ZEPA.

Ecological indicators to assess the impacts of fisheries are most useful when assessed on a temporal timeframe and used simultaneously, taking into account that no single indicator can adequately inform on its own about the status or trends of a complex ecological system (Link et al., 2002; Shin et al., 2010; Coll et al., 2016). Additionally, the criteria to assess the degree of ecological impact of the gears must be aligned with fisheries management and conservation objectives that sometimes have conflicting long-term goals (Link, 2002). For example, targeting large individuals is usually considered a sound fisheries management measure on the basis of avoiding juveniles in the catch and allowing individuals to reproduce prior to being harvested. However, fish species that attain large body sizes are generally those that are more fecund (Barneche et al., 2018) and more vulnerable to overfishing compared to small-sized fish species, potentially facing higher extinction risks (Jennings et al., 1998; Cheung et al., 2005; Cheung, 2007).

In order to better inform management decisions related to ecological impacts imposed by different fishing gears, medium to long-term monitoring of the relative effort of each gear and of the metrics associated to ecological indicators is needed. We propose that simple ecological indicators, such as those used in this study, be included as part of annual assessments of multi-gear SSF in tropical countries where data and management capacities are limited. In this way, a systematic evaluation of the potential impacts of fishing at the community and ecosystem level could be developed and facilitate the transition toward EBFM.

DATA AVAILABILITY

The datasets generated for this study are available on request to the corresponding author.

AUTHOR CONTRIBUTIONS

PH, GC-G, and MW conceived and designed the analyses. PH and JD collected the data. PH, GC-G, and MS performed the analyses and produced the final figures. All authors discussed the results and contributed to the writing of the final 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.2019.00127/full#supplementary-material

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Connecting a Trophic Model and Local Ecological Knowledge to Improve Fisheries Management: The Case of Gulf of Nicoya, Costa Rica

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Trophic models of the Ecopath with Ecosim (EwE) type and local ecological knowledge (LEK) have widely been applied to fisheries assessment and management. However, there are no specific methodologies describing how LEK from local fishers can be incorporated with the scientific data from the models in the context of ecosystem-based fisheries management. To our knowledge this is the first contribution exploring a systematic integration of LEK with EwE modeled output. An EwE food web model of the Nicoya Gulf ecosystem constructed 20 years ago and recently revisited by the authors and collaborators, was used in workshops to stimulate discussion among local stakeholders regarding changes in the marine ecosystem. For this study, 58 artisanal fishers were recruited to eight workshops. To assess the LEK, we documented the discussions, and the qualitative data were analyzed with quantitative frequency of responses to identify trends. Next, we systematically compared the changes in the fishery over time through an analysis of similar, complementary, and contradictory information across knowledge systems. In general, the analysis across systems reflected changes in species composition of the catches, paralleled by a harvest reduction in high-trophic-level species, as well as economic losses due to a shift in harvesting low-value species and due to an increase in operational costs. Particularly, we identified (1) similar pieces of information that delivered the same message, providing robust evidence of changes in the social–ecological system; (2) information complementary to each other, which together provided a broader picture (descriptors and attributes) of the changes of some fishing resources; and (3) conflicting pieces of information that indicated mismatches between sources of knowledge, which might suggest the cause of management problems. This study demonstrated how integrating knowledge systems can enhance our understanding of the state and changes in ecosystems, helping to improve fisheries management. We also found that an EwE model can be

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an effective communication tool to be used with fishers and to promote discussion and engagement. Our aspiration is to bring new and replicable tools to the policy interface in Latin-American fisheries, based on both stakeholder participation (including LEK) and the best scientific information available.

Keywords: small-scale fisheries, ecosystem-based approach for fisheries management, Ecopath with Ecosim, trophic model, local ecological knowledge, connecting knowledge systems, Gulf of Nicoya, science–policy interface tools

INTRODUCTION

In recent years, resource managers have increasingly focused on fishery-driven changes in ecosystem structures and trophic relations, since fishery-induced changes in biomass at one trophic level have been shown to affect the whole ecosystem (Pauly et al., 2000). Food web models of the Ecopath type have been used as efficient tools for presenting the interactions and changes in the food web as a result of fishing (Christensen and Pauly, 2004), and have also allowed managers to predict tentative changes in the future with the Ecosim tool (Pauly et al., 2000; Christensen and Walters, 2004). If one seeks to identify realistic measures for fisheries management, it is important to understand both the ecosystem context, in which the fishing activities take place, and the preferences or motivations underlying the fishers' behavior (Bacalso et al., 2013). While modeling tools have widely been applied for ecosystem-based fisheries assessment (Christensen and Walters, 2005), there are as of yet very few examples in the literature of their application with fishers (Power et al., 2004), despite the fact that their participation and knowledge in the decision-making process have often been shown to enhance sustainable management (Paramor et al., 2005; Pita et al., 2010; Mackinson et al., 2011; Msomphora, 2015; Leite and Pita, 2016). There are quite a few studies that are using Ecopath with Ecosim (EwE) with local fishers and other stakeholders in surveys (Paramor et al., 2005; Bacalso et al., 2013) as well as in workshops (Power et al., 2004; Paramor et al., 2005; Armada et al., 2018). The need to create synergies across scientific and local knowledge systems is engrained in the objectives of the Sustainable Development Goals (SDGs) and other international initiatives but has been limited in the global science–policy interface (Mackinson, 2001; Tengö et al., 2014), including the Latin-American tropical context (Salas et al., 2007; Begossi, 2015; Saavedra-Díaz et al., 2015).

Understanding environmental problems and their impacts on the ecosystem and its services, is crucial for societal decisions and for the development of adaptation strategies (Dietz, 2013). However, assessment may be difficult and complex, and any decision can present uncertainties (Kenter et al., 2011). Scientific data, if communicated adequately, have the potential to inform people and to help individuals in the process of weighting alternatives (Dietz, 2013). It has been shown, however, that scientific knowledge and the perception of local stakeholders are often disconnected in public decision-making, which may eventually lead to management measures that are not supported by or complied by the local stakeholders (Mackinson et al., 2011; Dietz, 2013; Msomphora, 2015). As Mackinson et al. (2011) point out, the scientific findings and the perspectives of people need to be integrated in decision-making if the desired outcome is to utilize the best scientific information available and to harmonize it with the public's beliefs about how the world works to improve the management of resources. The same principles should apply for the management of fisheries as well (Mackinson et al., 2011; Saavedra-Díaz et al., 2015; Fujitani et al., 2018).

Approximately 95% of catches in Costa Rica come from the Pacific Coast, and 8% of landings come from the artisanal fleet (Biomarcc-SINAC-GIZ, 2013). In particular, several important fishing grounds are within the Gulf of Nicoya (GoN; Wolff et al., 1998), a tropical estuary at the Pacific coast of the country (**Figure 1**). The GoN supports around 2,000 small-scale artisanal fishers, who mainly use nets to fish and fish to support their families (Pachecho-Urpí et al., 2013; Ross-Salazar, 2014). The gulf has exhibited different forms of fishery management, including spatial and temporal closures (Salas et al., 2007), such as a yearly fishing closure of 3–4 months, for the protection of small pelagic species' reproductive peak events: Whiteleg shrimps (*Litopenaeus* spp.), small pelagic fish species (Cupleiformes), snapper (*Lutjanus* spp.), and corvinas (*Cynoscion* spp. and other species); and feeding grounds for barracudas (*Sphyraena ensis*; Proyecto Golfos, 2012). Other management tools used are licenses, fishing permits, and gear restrictions (Salas et al., 2007), especially in the so-called "marine responsible fishing areas" (AMPRs for its Spanish acronym). The latter were implemented in response to local initiatives of co-management (García Lozano and Heinen, 2016).

Despite the management measures in place, challenges remain, such as fishing without a license, the use of prohibited mesh sizes by gillnet fishers (<3 inches; Ross-Salazar, 2014), the illegal use of "rastras" (a type of artisanal trawling), and the bycatch associated with both rastras and semi-industrial trawling. Fishing inside no-take areas or during closures is also a recurrent problem (Proyecto Golfos, 2012). The limited participation of governmental institutions in activities of surveillance and control of illegal fishing complicates the situation and contributes to an increasing number of fishers and fishing intensity on resources (Salas et al., 2007). The control of minimum catch sizes for target species has legally been implemented to protect juveniles. However, while this management measure can potentially be controlled at the market, it has been observed that the great variety of species caught has made enforcement difficult or compliance confusing to fishers (Purcell and Pomeroy, 2015).

For Costa Rica, there are ecological data and analyses (e.g., growth, catches, fishing gears, recruitment, reproduction, and diets analysis) that come from traditional fisheries stock

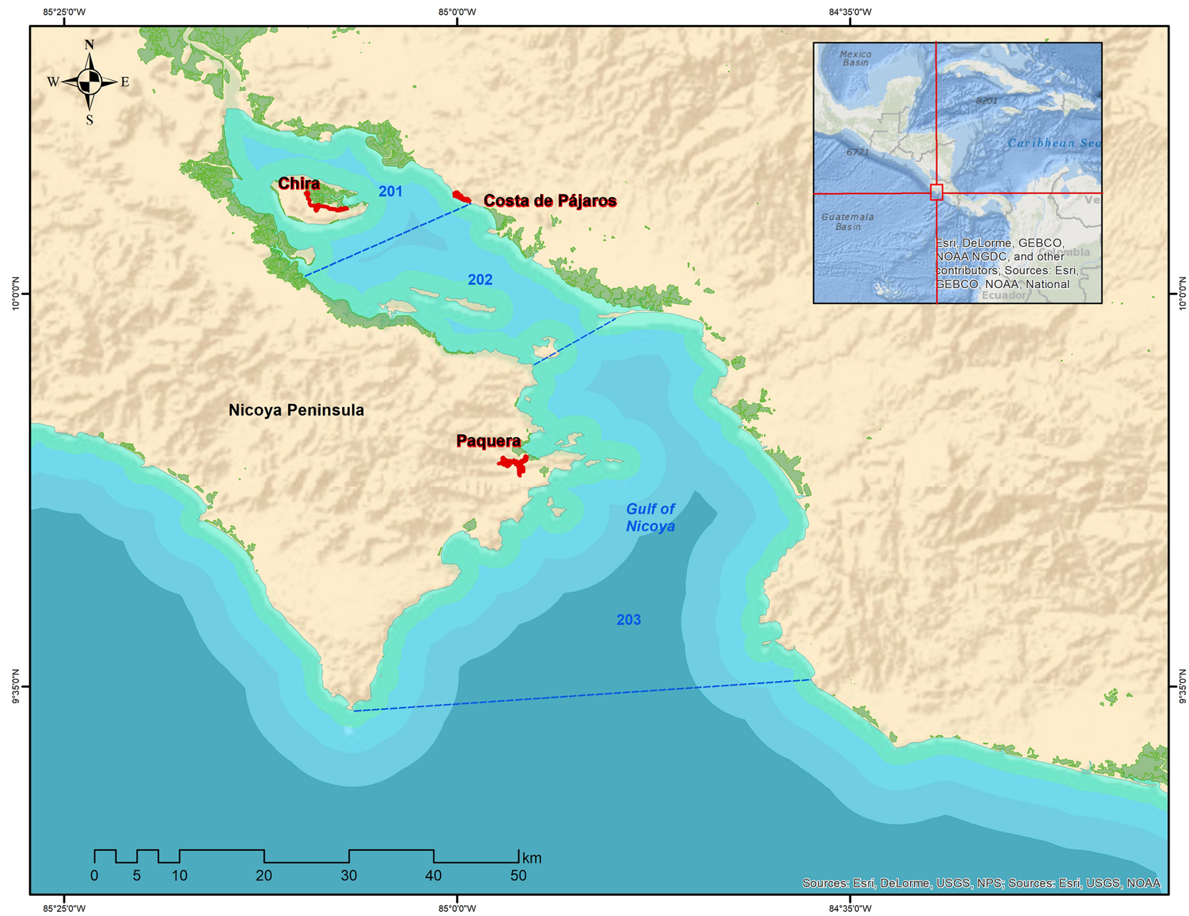

FIGURE 1 | Gulf of Nicoya (GoN) located on the Pacific coast of Costa Rica. The Gulf is sectored by Incopesca into areas 201, 202, and 203 based on species composition and fishing gears used (Marín-Alpízar and Vásquez, 2014). The three focal points selected for this study along the gulf were Isla Chira (inner area), Costa de Pájaros (inner-intermediate area), and Paquera-Tambor (outer area).

assessments, and some of this information has been summarized in recent technical reports (Biomarcc-SINAC-GIZ, 2013; Marín-Alpízar and Vásquez, 2014). However, as Marín-Alpízar and Vásquez (2014) stated, over the years, few efforts have been made to develop a holistic description and understanding of the ecosystem (Wolff et al., 1998; Alms and Wolff, 2019). On the other hand, the lack of coordinated effort between fishery stakeholders, researchers, and authorities/decision makers aggravates the situation (Proyecto Golfos, 2012). Many management initiatives do not work because stakeholders are not (or do not feel) involved in the processes (Msomphora, 2015). Moreover, the dynamics of fishing efforts are driven either by ecological (catch composition, environmental changes, etc.) or social drivers (fishers' behavior and cultural and economic aspects; Naranjo-Madrigal and Bystrom, 2019), which are not well understood. The disconnection between different social and ecological systems, scattered sources of knowledge, and the lack of inclusiveness is usually reflected in poor policy measures (Mackinson, 2001; Dietz, 2013). In general terms, overfishing is a major threat in the GoN engrained in the high fishing effort and great diversity of fishing gears employed (Pachecho-Urpí et al., 2013). The overexploitation of fishery resources is also a result of the poor coordination among different actors of society and the corresponding systematic integration of their knowledge (Mackinson, 2001; Salas et al., 2007).

A portrayal and modeling of the GoN ecosystem and its fisheries was described about 20 years ago by Wolff et al. (1998), who used a functional trophic modeling (EwE) approach to integrate ecological and fisheries data of the gulf. Recently, the gulf has been revisited by the authors and collaborators to update the model with current data (Alms and Wolff, 2019) and to contrast the state of the gulf ecosystem between these two decades. The basic input parameters gathered to create the model (Alms and Wolff, 2019) are from the Costa Rican monthly artisanal landing statistics (Incopesca), for the main target groups of fisheries, for each zone of the GoN. These statistics are considered the best scientific information available. When comparing the system models 20 years apart, some changes could clearly be distinguished: (1) species composition of the catches has changed significantly over the years, paralleled by a harvest reduction in high-trophic-level species; and (2) economic losses have increased due to a shift in harvesting low-value species and due to an increase in operational costs. The models have facilitated a connection between the available fisheries' and ecological data (Wolff et al., 1998; Alms and Wolff, 2019).

While the EwE models are based on available ecological and fisheries information (Pauly et al., 2000) and thus appear as a promising starting point for taking management decisions in the GoN (Alms and Wolff, 2019), it is also important to evaluate and consider the state of the ecological knowledge of local stakeholders with regard to the fishing system in the Gulf, as a means to link and better understand the social and ecological drivers involved in the dynamics of fishing efforts and environmental decisions of artisanal fishers (Naranjo-Madrigal and Bystrom, 2019). The concept and applications of local ecological knowledge (LEK) seem important to be included in this context (Begossi, 2015). There are various cases in the literature that attempt to connect local and scientific knowledge, under the assumption that different knowledge systems can contribute to an enriched picture, which is useful for the sustainable management of ecosystems (Mackinson, 2001; Mackinson et al., 2011; Tengö et al., 2014). Synergies across knowledge systems can improve the understanding of environmental conditions, its changes, and possible adaptation strategies (Mackinson et al., 2011; Tengö et al., 2014).

The aim of this paper was to use scientific information of EwE in participatory workshops to integrate fisher's LEK with modeled output for the GoN, with the premise that connecting these two knowledge systems can enhance our understanding of the state and changes in the ecosystem and help to improve fisheries management. For the purpose of this study on LEK, fishers were asked about how they perceive the state and use the local natural/fishing resources, which of the resources are important for their livelihoods, and how the ecosystem and target resources have changed over the course of time (1990s–2010s). Similar applications and definitions of LEK are found in other studies that manage fisheries in the Latin-American region (Begossi, 2015). Particularly, EwE results were used to stimulate discussion among local stakeholders regarding observed changes in the marine ecosystem. The discussions were documented and the qualitative data were analyzed and presented by frequency of responses to identify the predominant topics and trends while assessing LEK. Systematically and qualitatively, we compared the changes in the fishery over time through an analysis of similarities, complementarities, and contradictions across knowledge systems (Tengö et al., 2014). The outcomes of this study are expected to contribute to a new narrative of decision-making in fisheries management, based on both stakeholder participation and scientific evidence.

MATERIALS AND METHODS

Study Site

The GoN (**Figure 1**), located on the Pacific coast of Costa Rica, has an area of 1,550 km^2, a length of 80 km, and a width of 50 km. It is considered one of the largest tropical estuaries in Central America (Wolff et al., 1998). The Gulf contains several islands and important spots of biodiversity. Of the 214 species of fish (Proyecto Golfos, 2012), more than 50 are commercially important (Lobo-Calderón et al., 2012). Proyecto Golfos (2012) summarizes a list of coastal marine species reported in the GoN, including 200 species of polychaetes, 10 species of stomatopods, 95 species of decapods, 37 species of copepods, five species of cetaceans, and breeding areas for hammerhead sharks (*Sphyrna lewini*), among other species. The presence of well-developed mangrove areas, corals in the outer Gulf (Proyecto Golfos, 2012), nesting beaches for the Pacific ridley sea turtle (*Lepidochelys olivacea*), and feeding grounds for hawksbill turtles (*Eretmochelys imbricata*) and green turtles (*Chelonia mydas*) also brings conservation value to the Gulf (CREMA, 2014).

Because of the high productivity of the GoN, it is considered one of the most important estuaries in the region (Wolff et al., 1998; Alms and Wolff, 2019), and the fisheries are considered as the main economic activity (Wolff et al., 1998) on which more than 60% of the gulf's population depend (Marín-Cabrera, 2012). Costa Rica's artisanal fishers use mainly fishing nets, but also bottom and drifting longlines and handlines (Marín-Cabrera, 2012). An additional 10% of the gulf's fishers generate their income from manual shellfish harvesting (Marín-Cabrera, 2012). Moreover, two semi-industrial fleets operate in the gulf (sardine purse seiners and shrimp trawlers; Ross-Salazar, 2014).

According to its bathymetry and oceanographic conditions, the GoN can be divided into three different sectors: the inner, the middle, and the outer Gulf (Marín-Alpízar and Vásquez, 2014; **Figure 1**), named zones 201, 202, and 203, respectively, by the Costa Rican institute of fisheries, Incopesca. The division is based on species composition and the fishing gears used. Some species have reproductive sites in the inner and middle areas of the GoN (e.g., croakers and shrimps) from where they migrate to external areas when maturing; there are movements in the opposite direction of certain species as well (Proyecto Golfos, 2012). The inner gulf is defined as an area of priority by Incopesca, because of its importance in the reproduction and nursery of commercially important fish species and shrimps (Marín-Cabrera, 2012; Proyecto Golfos, 2012).

Considering the diverse conditions within the gulf, for this study, three focal points were selected along the GoN (**Figure 1**): (1) Isla Chira (north internal region, 10°05′33,84′′N–85°09′01,07′′W); (2) Costa de Pájaros (north intermediate region, 10°06′02,66′′N–84°59′42,68′′W); and (3) Paquera-Tambor (southwest external region, 9°49′05,53′′N–84°56′00,51′′W). These three points were considered to geographically represent the diversity of extended artisanal fisher communities located along the GoN and at the same time to effectively embody common aspects among the sites, for example, similar target resources such as small pelagics (sardines, anchovies *Centengraulis mysticetus*, *Ophistonema* spp.), shrimps (white shrimp *Litopenaeus* spp., Pacific sea bob shrimps ∼titi *Xiphopenaeus riveti*), snapper (spotted rose snapper *Lutjanus guttatus*, Colorado snapper *Lutjanus colorado*), and corvinas/croakers (whitefin weakfish ∼queen *Cynoscion albus*, Tallfin croaker ∼agria *Micropogonias altipinnis*, weakfish ∼aguada *Cynoscion squamipinnis*, and various species; Alms and Wolff, 2019) and the generalized use of gillnet as a fishing gear.

Study Overview

First, we conducted a pre-workshop where a questionnaire was applied, and artisanal gillnet fishers were recruited to these workshops. Next, we conducted workshops using the information from the EwE model of the GoN as input for discussions on the changes in the fishing system over time, and for assessing LEK. Data from the workshops were analyzed by coding the most frequent words used by respondents into individual themes to identify trends and relevant topics. Finally, we qualitatively compared the state of the resources according to the EwE model output and LEK of the fishers. Evidence from the model and LEK was compared in terms of the interactions found across both sources of knowledge, as information that is similar, complementary, or contradictory to each other (Tengö et al., 2014).

The core of the study was conducted from May to July 2017, as this is a 3-month period of fishing closure in the inner and intermediate zones of the gulf, created for the protection of the reproductive peak events of target resources (small pelagic fish species, shrimps, snapper, and corvinas). Given that fishers from internal zones are usually not involved in any fishing activity during the closure, it was expected that fishers would have more availability to participate and engage. Before running the official survey, exploratory visits to the study sites were performed during January to March 2017 to establish contacts with community leaders and fishing association presidents.

In each community, we sought and obtained authorization from the presidents of the fishing associations for conducting the interviews and workshops. In the current research, we asked participants for prior informed consent and explained to them the project and the use of the data. Their responses were voluntary and confidential, and all people involved in the study had the possibility to drop out at any time. Data handling took place in an anonymized form, and it was made sure that it is impossible to identify particular individuals. The focus of the study was the small-scale artisanal fishers who used gillnet gears and owned a fishing license from Incopesca. Those fishers that worked for someone who had a license were also considered. We were interested in people who were living in the area for more than 5 years and who have about 5 years of experience as a fisher. A list of fishers' names matching these criteria was provided by the presidents of the fishing associations, so it was possible to contact participants during the study in their houses or at the local fish market.

Pre-workshop Questionnaire Administration

The questionnaire was pretested with the fisher community leaders to measure the performance of the instrument. This allowed us to reformulate some sections for language, precision, and clarity. We avoided unfamiliar technical terms such as fishing effort, marine resource, and sustainable fishing and used instead clear expressions for the study population. During the questionnaire administration, a minimum of 10 people were interviewed per community in the expectation that at least 5 participants would be attending the workshops. The conversations were facilitated in small groups (Macmillan et al., 2002).

The general characteristics of the artisanal gillnet fishers who were interviewed and their availability to be part of a workshop were examined *via* the questionnaire (**Supplementary Material**). The first part of the questionnaire was designed to obtain information on the socioeconomic and demographic characteristics and fishing practices of the respondents. The second part of the questionnaire identified the willingness of the fishers to participate throughout the entire process. Each interview session lasted an average of 30 min (Leite and Gasalla, 2013) with 86 questionnaires performed; 34.5% of the fishers interviewed were from Costa de Pájaros, 32.8% from Isla Chira, and 32.8% from Paquera-Tambor. In this study, we presented results for the three sites and for the fishers who met our selection criteria and attended the workshops ($N = 58$). Most of the attendees were male (82.8%) with an average age of 41 years (**Supplementary Material**); the age of the majority (24.1%) range from 26 to 32 years.

An Ecopath With Ecosim Model as a Means to Assess the Local Ecological Knowledge

To assess the local fishers' knowledge about changes in the fishing ecosystem over time, workshops were held in each focal area (**Figure 1**). Eight workshops were conducted, and 58 fishers participated.

In order to adequately communicate information to the fishers, the understanding of the EwE model output by the moderators was essential. Our interdisciplinary team (EwE modeling, behavioral economics, and fisheries ecology) met to address this aspect and to plan the sessions that would be presented in the workshops. The lectures and activities were pretested in a pilot workshop (Leite and Gasalla, 2013) with artisanal fishers in the gulf, and it was found that the simulations of the models needed to be translated into basic graphs and illustrations to facilitate participants' interaction, as other authors have also pointed out (Armada et al., 2018). In the official workshops, the major findings of the study were explained by a facilitator and an assistant using visual aids (graphs and illustrations). Likewise, the names of the species were presented to the fishers using common names and images to confirm recognition (Leite and Gasalla, 2013). The lecture slides used in the workshops are provided in the **Supplementary Material**.

For the purpose of this paper, the following changes in the fishery over time (1990s–2010s; Alms and Wolff, 2019) were explained to the participants: (1) an overall increase of 20.9% in the total fishing catches, for both artisanal and semi-industrial catches; (2) a severe decrease in the catches of shrimps and corvinas (60 and 35%, respectively) in the 2010s; (3) changes from shrimp-dominated catches (1990s) to sardine-dominated catches and small demersal fish (e.g., small corvinas and small sharks, among others).

The reduction in catches of corvinas and shrimps led to additional changes (Alms and Wolff, 2019): (4) a decline in the commercial value of the catches (almost 50%) compared to that in the 1990s. Although shrimps still represent the largest contribution (39%) of the total value, an important percentage of the economic value (35%) is currently provided by species of lower commercial price, as in the case of small demersal (28%; e.g., small corvinas) and small pelagic species such as sardines and anchovies (7%). Other species of higher trophic levels only contribute small percentages, such as snappers (9%), large corvinas (9%), and catfish (5%). (5) Eighty percent of corvinas caught in the 2010s had not reached the size of maturity and were thus small individuals of lower market prices. (6) There are changes in corvinas and shrimps in terms of the species composition of the catches. While the capture of whitefin weakfish and tallfin croaker has increased, the catches of other corvina species have diminished by 35%. Likewise, there was a severe decrease in the catches of coastal shrimp species, including the white shrimp and the Pacific sea bob shrimp ∼titi.

An overview of the impact of different fishing fleets on the species was presented to the fishers. The artisanal gillnet fleet seems to have the strongest negative impact on different species in the ecosystem, together with predatory species, large drums, mackerel, barracuda, and catfish (Alms and Wolff, 2019). Also, the concepts of food webs, ecosystem, and trophic level (Christensen and Walters, 2004) were described to the participants, with specific examples of existent species in the GoN. This allowed our team to introduce the antecedents and logic of the trophic model of the GoN (Alms and Wolff, 2019), including the EwE 6.4.4 software used to create it (Christensen and Walters, 2004). Subsequently, we encouraged the participants to reflect on the information received and on the changes in the fishery system, to discuss it in groups (Power et al., 2004), and to make a presentation with an overview of their perceptions to the rest of the participants. Attendees were stimulated to participate equally during the activities. Their opinions and comments were registered through photographs, notes, recording relevant discussions, and collecting the materials used in the presentations (Saavedra-Díaz et al., 2015). Workshops were conducted at sites of easy access to participants, such as community centers, restaurants, and schools (Sánchez-Jiménez et al., 2014), and were based on previously published methodologies for consultation processes (Power et al., 2004; Paramor et al., 2005; Sánchez-Jiménez et al., 2014; Armada et al., 2018).

Analysis of Data From Workshops and Interactions Across Ecopath With Ecosim and Local Ecological Knowledge

The data of the questionnaires were used to create a respondent's profile in terms of socioeconomic and demographic characteristics and fishing practices of the participants (**Supplementary Material**). Later, the qualitative data from the workshops were coded into individual themes according to the most frequent words used by respondents (Paramor et al., 2005) and presented with the percentage (%) of people referencing key subjects along with specific quotes (Ward et al., 2017). The most recurrent topics mentioned were catch, abundance of fishing resources (mainly shrimps, corvinas, and large predatory species), fishing effort, economic efficiency, and impact of fishing fleets on the marine resources.

Then, we used the key themes identified to explore interactions between the two sources of knowledge (scientific and local). We followed a modified version of the concepts described in Tengö et al. (2014) and focused on the state and changes over time of the resources of shrimps, corvinas, sardines, and large predators. Systematically and qualitatively, we compared (Gilchrist et al., 2005) the changes in the fishery over time through an analysis of similar, complementary, and contradictory information across knowledge systems. Similarity in information is understood here as two sources of knowledge that provide the same message with the exact same or very similar words. We defined complementary as different pieces of information that are unique to each knowledge system, but when combined can better describe a situation or enrich a message. Information that is contradictory to another piece of information presents opposite messages on the same topic.

For the analysis of similarities, complementarities, and contradictions across knowledge systems, descriptors and attributes (information derived from the LEK and the model) were used to describe the state and changes of resources (Mackinson et al., 2011). Attributes such as biomass, catch per unit of effort (CPUE), and abundance were used to create a descriptor for the state of the marine resources. CPUE, an index of the amount of fish caught per unit time spent fishing using a particular gear, was calculated from data reported in workshops, using the kilograms of catch per day with one gillnet (**Supplementary Material**). Economic descriptions were elicited using attributes like profits, commercial importance, and prices. Other descriptors such as fishing effort and the impact of fishing gears on species were included.

RESULTS

The respondents' profiles are summarized in tables (**Supplementary Material**), revealing that the income for most of the interviewees lays between ₡200,000 and 300,000 Costa Rican colones (1 EUR: 611 Costa Rican colones as of survey year); 36.8% said they earn ₡200,000. This amount oscillates around the minimum monthly salary for Costa Rica in 2017 (256,000: EUR 419.10). Importantly, most respondents (81%) depend solely on fishing, while the remaining (17.5%) combine fishing with other activities, specifically tourism, which suggests that there is a vast number of fishers with monthly salaries below the minimum. In the range of ₡80,000 to 110,000 falls the basic expenses (monthly bills and food) of 23.6% interviewees, but it is noteworthy that the expenses varied among fishers, and, for example, 18.2% require a minimum of ₡200,000 to 300,000 to cover their basic needs. The balance between income and expenses seems to be influenced by the number of family dependents (between 0 and 7 with an average of 3.3 dependents) and other expenditures beyond the basics (e.g., formal or informal loans to buy a fishing boat).

Gillnet is the primary fishing activity for 66.7% of the respondents, while 26.3% interlaces gillnet with hook fishing and

7% interchanges it with line fishing. Corvina fishing is the main activity for most of the respondents and usually is combined with other activities such as fishing for shrimps (20%) and snappers (15%). Additionally, the results of the interviews indicated that 40.4% of the people are fishing 6–9 h per day almost daily (56.9%).

Discussions in workshops concerning changes in the fishing ecosystem over time were used to understand the LEK. The qualitative data helped to identify dominant topics and trends in relation to abundance of fishery resources (shrimps, corvinas, and large predatory species), fishing effort, profitability, and impact of fishing fleets on the marine resources. Then, the key themes identified in the workshops were used to examine the interactions across LEK and the food web EwE model. We focused on the state and changes over time of the resources of shrimps, corvinas, sardines, and large predators, and we compared the information of both systems of knowledge considering the similarities, complementarities, and contradictions.

Trends With Shrimps and Corvinas (Local Ecological Knowledge)

The resources of shrimps and corvinas were indicated as highly abundant in the past, while their abundance has decreased over the course of time (**Figure 2A**). This is nicely summarized by the following statements from a fisher: "In old times, there were more croakers, you could hear them everywhere" (Isla Chira-workshop, 17th June 2017). A participant in the same workshop specified that at around 1993, "a shrimp fever took place all over the island" because of its great abundance and the high fishing activity. In the case of corvinas, data for the 2010s show that certain species of this family were not present any longer, while others had recovered. A significant reduction in catches of corvinas was reported, ranging from 70–90 kg in the 1990s to only 20–30 kg in the 2010s, for a single day of fishing. A reduction was also reported for shrimps, from 30–39 kg in the past to only 5–9 kg today per day of fishing.

Participants indicated that shrimps and corvinas were geographically widely distributed in the past, contrasting with the restricted distribution reported for present times (**Figure 2A**): "In the past you could fish shrimps and corvinas everywhere, now you have to go to deeper waters and different places to find them" (Isla Chira-workshop, 8th June 2017). With respect to shrimps, their current distribution is restricted. Low abundance for certain species of shrimps was also mentioned.

In terms of commercial aspects, the answers of the participants reflect a medium use intensity of commercial species and low to medium prices of corvinas/shrimps in the earlier 1990s, and a greater commercial use and higher prices for both groups at the end of the 1990s and during the 2010s (**Figure 2B**). Fishers reported that at the beginning of the 1990s, and in earlier times, shrimps were so abundant that they were also used as bait. The valuable corvinas were directly sold or were exchanged for plantains, a crop grown in other distant areas, and particularly difficult to find on the islands. In the 2010s, despite the increased commercial use and higher prices for both species, the profits were reported as relatively low. If one considers the reported size reductions of corvinas and shrimps caught (**Figure 2C**), low incomes can be more easily explained, since small specimens do not receive as high prices in the market as large ones. In line with their perceptions, only 20–29 individual shrimps were needed in the 1990s to make a kilogram, while 40–49 individual shrimps are needed in currently. Corvinas were commonly around 2 kg in size in the 1990s, while currently, one to four individuals are necessary to obtain a kilogram of corvina.

In the 1990s, the most commonly used gillnets mentioned by fishers had mesh sizes of 3.5 and 3.0 inches (**Figure 2D**). During the 2000s, 2.75 and 2.5 inches were the most commonly used gillnet mesh sizes (especially after 2005), even though they are illegal. In general, illegal fishing, through the use of gillnets with mesh sizes of 2.5 inches and "rastras" (a type of artisanal trawling), was widely reported in the early 2010s up to now. Another widely used fishing gear reported during the 2010s is the semi-industrial trawl, labeled as a non-selective method with high levels of bycatch.

As stated by fishers, in the 1990s, there were almost no fishing regulations compared to the 2000s (**Figure 2D**), when Marine Areas of Responsible Fishing (AMPRs) and minimum landing sizes (larger than the size at first maturity) were created with the aim of sustaining the fishing resources and ecosystems. However, the fishers still expressed that there are high levels of illegal fishing and confusion with regard to the legal size limits of species, since there are multiple species being caught, each with different size regulations.

Trends With Other Commercial Species and Large Predatory Species (Local Ecological Knowledge)

For several large predators, the fishers' reports point to a great decrease or absence in the waters of the gulf (**Figure 3**). This is also the case for the sierra fish (ray, *Pristis* spp.) and hammerhead sharks (*Sphyrna lewini*); however, some fishers still indicate the presence of sierra fish in coastal waters. Barracuda (*Sphyraena ensis*) was mentioned as a highly abundant species in the 1990s and a low-abundant species in the 2010s. In the case of jacks (*Caranx* sp.), the reports went from high to low abundance. In the case of groupers, the picture is diffused, with the presence and recovery of the cabrilla species (*Epinephelus* spp.) barely mentioned. Also, one non-commercial species for which information was provided is the bottlenose dolphin (*Tursiops truncatus*), reported as practically absent at present. As indicated by the fishers consulted, mackerel (*Scomberomorus sierra*) was classified as almost absent in the areas where they fished in the 2010s. Participants mentioned that the gillnet fishing sector generates less profits out of the harvest of this species. For the 1990s, it was suggested that there was a high abundance but low commercial importance of mackerel for gillnet fisheries as well (**Figure 4D**).

Species of catfish (*Bagre panamensis*) were reported as present in the 1990s and of high commercial importance, while they were almost absent and slightly commercially important in the 2010s (**Figure 4A**). Snappers (*Lutjanus* spp.) were identified as highly abundant and profitable in the past. However, catch went down from 20 to 29 kg in the early 1990s to 5–9 kg per

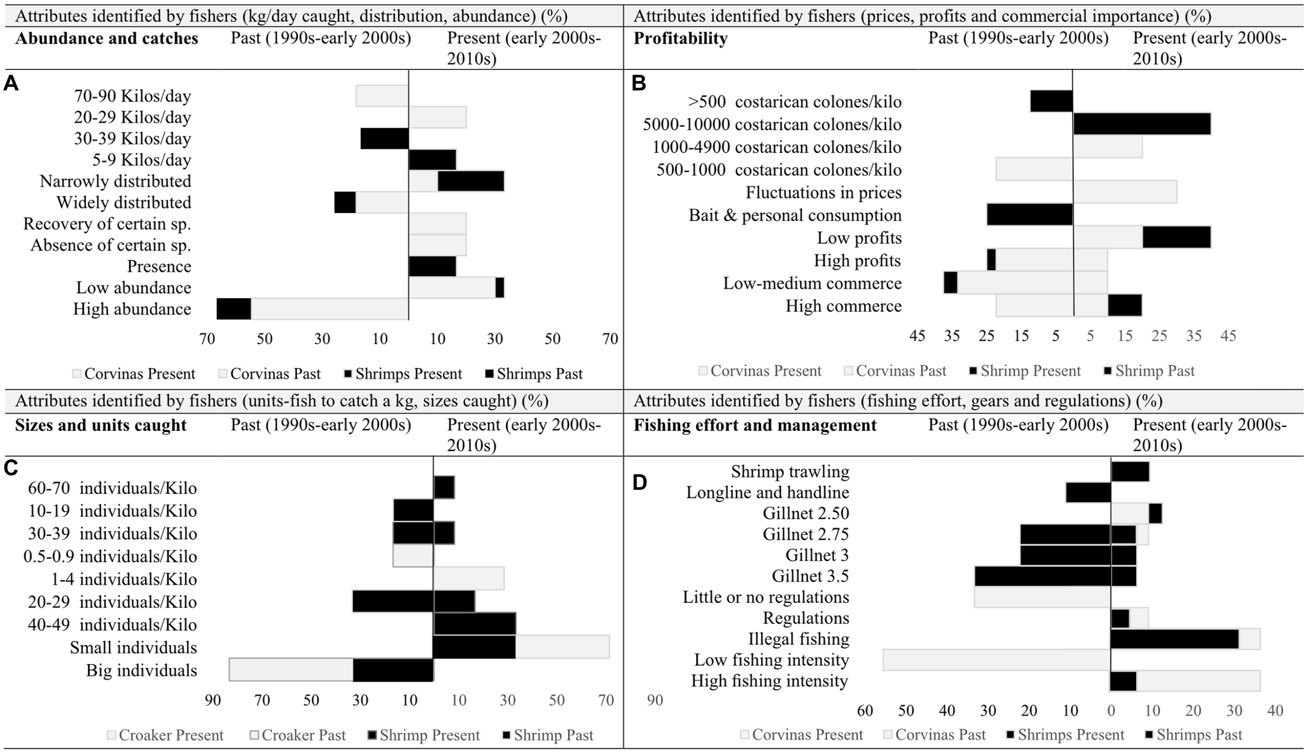

FIGURE 2 | Predominant topics and attributes identified in the focus groups related to the state of shrimps and corvinas [1990s and (or) 2000s]. Percentage of responses (%). Topics: **(A)** abundance/catches, **(B)** profitability, **(C)** sizes, and **(D)** fishing effort/management.

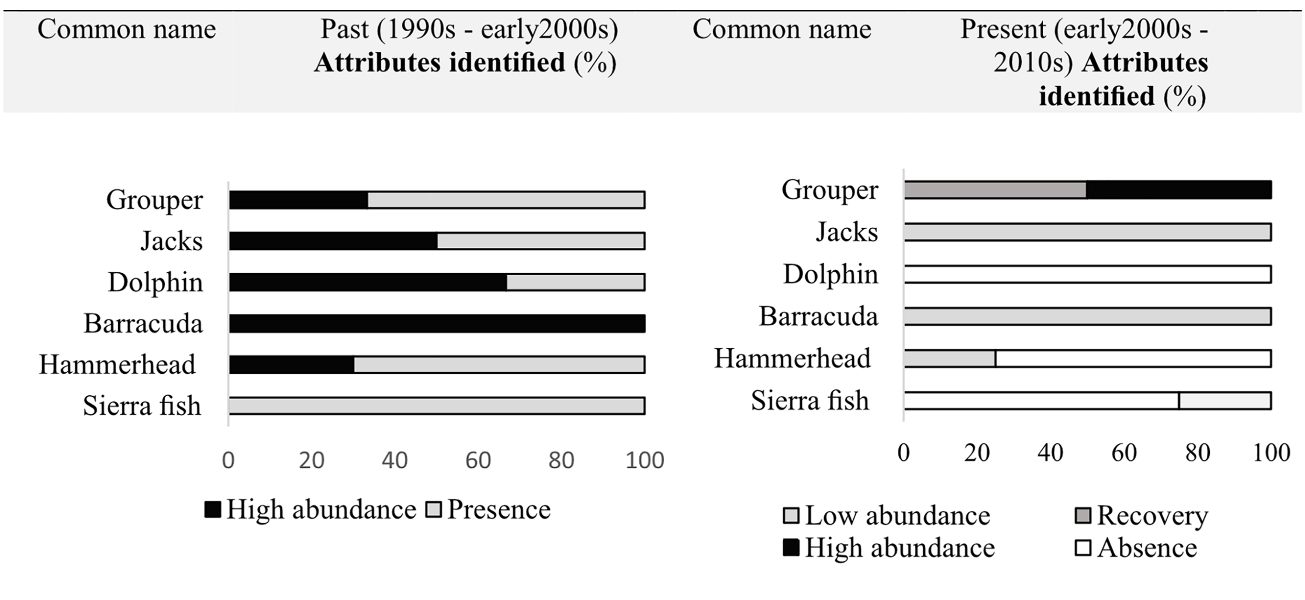

FIGURE 3 | Local ecological knowledge (LEK) about temporal changes in the state of large predatory species according to artisanal fishers consulted in the GoN (% of responses).

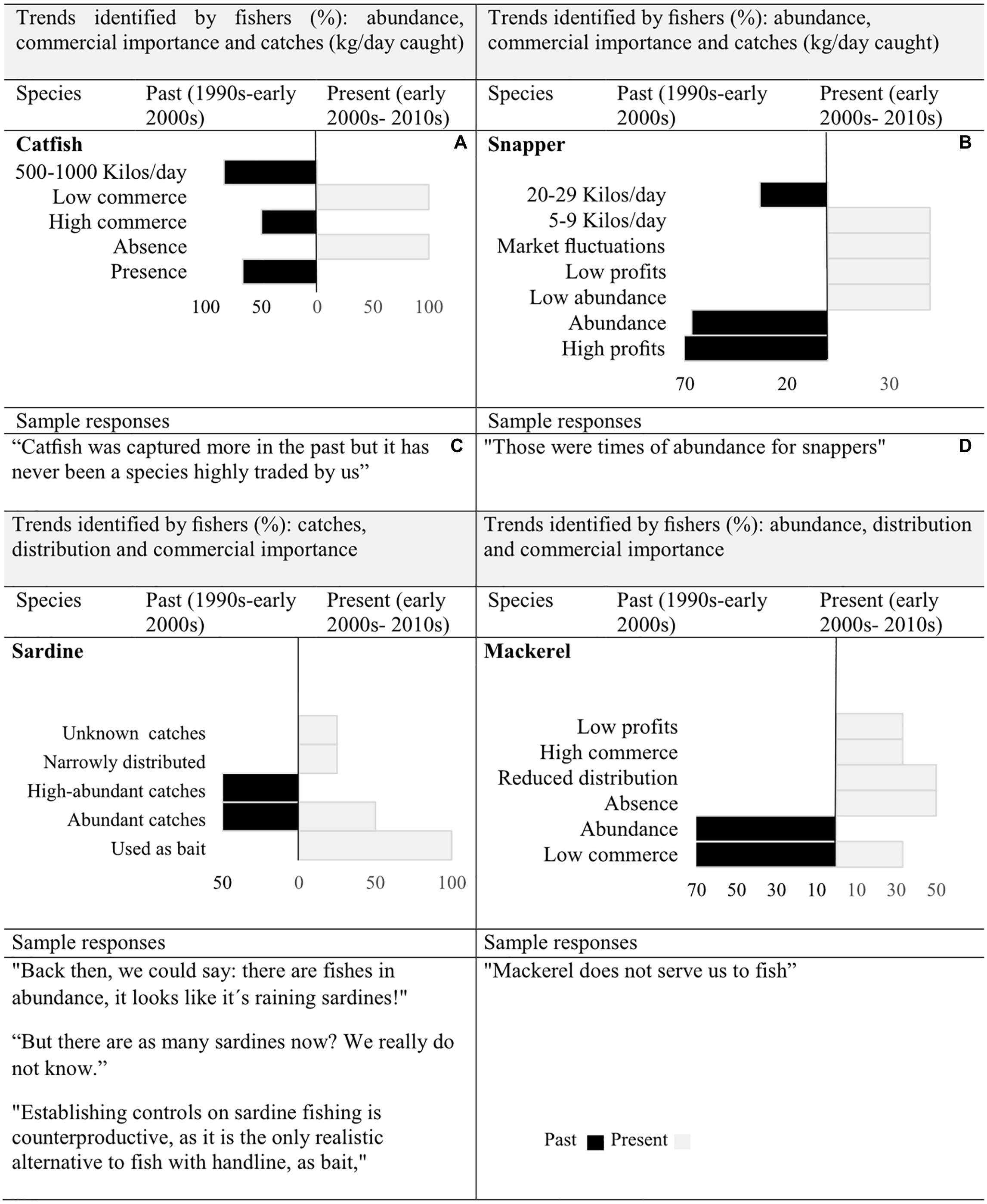

FIGURE 4 | Summary trends of four important commercial species in GoN as reported in the focus groups by participants: **(A)** catfish, **(B)** snapper, **(C)** sardine, and **(D)** mackerel (% of responses).

day in the 2010s (**Figure 4B**). Moreover, fluctuations in the market have been influencing low profits associated with the commercial importance of snappers, according to the majority of fishers consulted.

We found an interesting case with sardines (*Opisthonema* spp.), since according to the fishers, its catches were abundant in the past (1990s), but the current state, in the 2010s, is unknown for participants (**Figure 4C**). Fishers mentioned that Incopesca authorities suggested to significantly reduce sardine fishing. Some people assumed that the management measure was proposed due to a decrease in the catches of the species; however, there was no agreement and certainty among participants regarding this affirmation. Currently, sardines are widely used as bait by fishers; therefore, some other fishers consider that catches of sardines remain as abundant as in the past.

Similarities Across Systems of Knowledge

Similar information (**Table 1**) is reflected in the reports that indicate peaks in the catches of shrimps and corvinas in the 1990s with a severe decrease (60 and 35%, respectively) in the 2010s. The catches of shrimp and corvinas were widely distributed in the 1990s along the gulf, predominantly in the inner area (Zone 201). A restricted distribution of catches is suggested for both species in the 2010s, with most of the catch originating in the outer part of the gulf (Zone 203). In the case of corvinas, the current dependence on only two species (compared to seven species in the 1990s) and smaller specimens reveals changes in the species composition of the catches and a decrease from large to small demersal individuals. For both sources of knowledge in the 2010s, fishing effort of corvinas increased mainly in the intermediate area, while the fishing effort for shrimps decreased.

The model and LEK agreed that the first signals of stock reductions of large drums and shrimps were observed in the 1990s, associated to a growing commercial importance of the species at the end of the decade. At the same time, the increasing pressure of gillnet fishing on the resources, explained by the expanding illegal fishery (80% of gillnet fleets), negatively impacted the resources in the 2010s. The impact of semi-industrial trawling on shrimps and corvinas due to bycatch was identified in both knowledge systems.

Complementarities Across Systems of Knowledge

It was possible to identify descriptors of abundance by integrating different attributes from the two systems of knowledge (from LEK and EwE), such as biomass (from EwE), CPUE (from LEK), and subjective abundance (from LEK). Attributes such as profits, commercial importance, and prices were used as descriptors of profitability (the **Supplementary Material** contains details of the attributes and descriptors used). The combination of data thus provides evidence of changes in the abundance of shrimps and corvinas from a high (1990s) to a low abundance (2010s), and economic changes from high (1990s) to low profitability (2010s) of its fishing activity (**Table 2**).

The two sources of information combined also suggest significant reductions in the harvest of high-trophic-level species (mackerel, barracudas, sharks, and rays). Specifically, in the 2010s, local fishers report a decrease in the catches of large predators including the absence of certain groups such as sharks and sierra fishes. Similarly, for the description of the profitability of shrimp and corvina fisheries, there is an accordance between both knowledge systems, which point to the economic losses in the 2010s paralleled by a shift in the harvest from high- to low-value species (**Table 2**).

According to the EwE model, shrimps accounted for the vast majority of the total value of artisanal and semi-industrial fleets in the 1990s and still represented the largest contribution to the artisanal fleets in the 2000s but experienced a strong decline in the total catch and value. The two systems of knowledge integrated suggest that the inshore resources have been decreasing, greatly affecting the artisanal fishers, since this fleet is not able to compete with the semi-industrial fishing fleet, which has larger vessels and capacities to go fishing further out to sea. For the artisanal fishery, small corvinas represent the largest contribution in the catch, and currently, just two species are sold as a high-quality product: the whitefin weakfish (*Cynoscion albus*) and the Stolzmann weakfish (*Cynoscion stolzmanni*). The rest of the species are small and sold in low-value classes.

Finally, it was also found that the temporal impact (1990s vs. 2010s) of different fishing fleets on some fishing resources is better explained when the two knowledge systems are complementary, as it presents an overall picture. That is the case of information about the impact of the semi-industrial fleet on shrimps. The data for the 1990s were obtained by combining LEK and the EwE knowledge. For the 1990s, the model alone shows the impact of different fishing fleets on large predators, as well as a negative impact by artisanal gillnet, longline, and semi-industrial shrimp fleets. The details of the gillnet fleets' impact on shrimps and corvinas were provided by the fishers since the model does not differentiate at that level. Fishers identified a growing commercial importance at the end of the 1990s with the extensive use of gillnets with mesh sizes of 3 and 3.5 inches, and a continued increase in gillnet impact on the resources in the 2010s, especially illegal fishing with mesh sizes of 2.5 and 2.75 inches.

Contradictions Across Systems of Knowledge

There are also contradictory pieces of information between the EwE and LEK (**Table 3**). For example, despite the significant increase in the commercial importance of corvinas reported at the end of the 1990s by local fishers, they indicated that the fishing effort on this resource was low during that time. This is counter to the model, which indicates a high fishing effort since the 1990s.

The model shows considerably higher catches of sardines in the 2010s than in the 1990s, with a change from shrimp-dominated catches in the 1990s to sardine dominated catches, and a peak of catches in the early 2000s. The model also detects a declining trend in the catch of sardines since 2008. In this regard, the LEK is unclear about the current state of the sardine catches, with some fishers believing that its catches are abundant as it is commonly seen and used as a bait to fish corvinas.

DISCUSSION

There are few efforts attempting to address the lack of systematic integrated information on small-scale fisheries (Salas et al., 2007). This also applies to the fisheries of the GoN, Costa Rica, where a dissociation between sources of knowledge, mainly from local stakeholders, scientists, and decision makers, has been identified. The approach followed in this case study, examined the potential of using the scientific findings of an EwE model to stimulate discussion among fishers regarding observed changes in the marine ecosystem, and from this, obtain insight on the LEK. The

TABLE 1 | Similarities across two systems, local ecological Knowledge (LEK; this study) and scientific knowledge (EwE; Alms and Wolff, 2019).

Descriptor	Similarities							
	Shrimps		Corvinas		Sardines		Large predators	
	Past (1990s–early 2000s)	Present (early 2000s–2010s)	Past (1990s–early 2000s)	Present (early 2000s–2010s)	Past (1990s–early 2000s)	Present (early 2000s–2010s)	Past (1990s–early 2000s)	Present (early 2000s–2010s)
Catches	• Peaks in catches, 30–39 kg/day[EwE and LEK] • Widely distributed inshore/offshore resources (more catches in the inner part)[EwE and LEK]	• Severe decline catches (+60%, 5–9 kg/day), especially Pacific sea bob[EwE and LEK] • Narrowly distributed catches white shrimps[EwE and LEK]	• –Peak in catches, 70–90 kg/day[EwE and LEK] • Widely distributed inshore/offshore resources (more catches inner part)[EwE and LEK] • Largest contribution of catches relies on five commercial species of corvinas[EwE + LEK]	• Decline in the catches, (20–29 kg/day)[EwE and LEK] • Narrowly distributed. Catches (+) in the outer parts, more than half[EwE and LEK] • Changes in species of the catches. Two species out of seven species are the largest contribution in the catches. Five commercial species of corvinas declined in 35%[EwE and LEK]	×	×	×	×
Fishing effort	×	Fishing effort (–)[EwE and LEK]	×	Fishing effort (+) in the intermediate area[EwE and LEK]	×	×	×	×
Fishing fleets impact on species	Initial impact of artisanal gillnets on shrimps (gillnets, growing commerce at the end of 1990s[EwE and LEK])	• Illegal fishing (80%), impact of artisanal gillnets on shrimps[EwE and LEK] • Shrimp biomass (–)[EwE and LEK]	Initial impact of artisanal gillnets on corvinas, with gillnets and a growing commerce at the end of the 1990s[EwE and LEK]	Continued impact of artisanal gillnets on corvinas (both EwE and LEK; 80% illegal fishing)[EwE and LEK]	×	×	Initial impact on predators (semi-industrial), at the end of the 1990s[EwE and LEK]	Varied bycatch of large predators by semi-industrial shrimp fleet[EwE and LEK]

TABLE 2 | Complementarities across two systems, LEK (this study) and scientific knowledge (EwE; Alms and Wolff, 2019).

Descriptor	Complementarities							
	Shrimps		Corvinas		Sardines		Large predators	
	Past (1990s–early 2000s)	Present (early 2000s–2010s)	Past (1990s–early 2000s)	Present (early 2000s–2010s)	Past (1990s–early 2000s)	Present (early 2000s–2010s)	Past (1990s–early 2000s)	Present (early 2000s–2010s)
Abundance	Prominent EwE^{b} LEK^{c} LEK^{a}	Visible reduction EwE^{b}, LEK^{b} EwE^{c}, LEK^{c} LEK^{a}	High EwE^{b} LEK^{c} LEK^{s} LEK^{a}	Low EwE^{b} LEK^{c} LEK^{s}, EwE^{s} LEK^{a}		×	Presence, high LEK^{a}	• Less high trophic levels: mackerel, barracudas, sharks, and rays EwE^{b} • Absence/less large predators LEK^{a}
Catches	×	×	×	×	×	×	×	Less large predators (EwE^{c}). Narrowly distributed (LEK^{c})
Profitability	High profitability EwE^{pro}, LEK^{pro} LEK^{ci}, LEK^{pri}	Low profitability EwE^{pro}, LEK^{pro} LEK^{ci} LEK^{pri}	High profitability LEK^{pro} LEK^{ci}, LEK^{pri}	Low profitability LEK^{pro}, EwE^{pro} LEK^{lc}, LEK^{pri}	×	×	×	×
Fishing fleets impact on species	Initial and growing impact of artisanal gillnets on shrimps (gillnets 3–3.5 inches) LEK	• Artisanal fleet impact on shrimps (illegal nets 2.5–2.75 inches). LEK • Semi-industrial catches: shrimp (1990s), sardine (2000s) EwE	Initial and growing impact of artisanal gillnets on corvinas, 3–3.5 inches LEK	Continued impact of artisanal gillnets on corvinas, mainly illegal with 2.5–2.75 inches LEK	×	×	Large predators impacted by artisanal gillnet, longline and semi-industrial shrimp fleets EwE	• Artisanal fleets reduce impact on sharks/rays EwE • Longline and semi-industrial shrimp fleet: impact (++) on large predators EwE

Descriptors for specific fishing resources, using and combining attributes informed by both sources of knowledge. The descriptor of abundance was created using different attributes: biomass (b), catches per unit of effort (c), size (s), and abundance (a). The descriptor of profitability was created using attributes such as profits (pro), level of commercial importance (lc), and prices (pri) (see the ***Supplementary Material*** *for details in the attributes).*

TABLE 3 | Contradictions across two systems, LEK (this study) and scientific knowledge (EwE; Alms and Wolff, 2019).

	Contradictions					
Descriptor	**Shrimps**		**Corvinas**		**Sardines**	
	Past (1990s–early 2000s)	**Present (early 2000s–2010s)**	**Past (1990s–early 2000s)**	**Present (early 2000s–2010s)**	**Past (1990s–early 2000s)**	**Present (early 2000s–2010s)**
Catches	×	×	×	×	• Medium catches (shrimp dominated)[EwE] • Peak catches in early 2000s[EwE] ×	• Higher catches (change to a sardine dominated)[EwE] • Declining trend in catch-2008[EwE] • Unknown/abundant[LEK]
Profitability	×	×	×	×	×	×
Fishing effort and fishing intensity	×	×	• High[EwE] • Low[LEK]	×	×	×

two knowledge systems (the scientific and the local) were later compared systematically and qualitatively to identify similarities, complementarities, and contradictions across information. The aim was to integrate the two sources of information to enhance our understanding of the state and changes in the ecosystem and to help improve fisheries management. Additionally, we identified other advantages resulting from this systematization related with the engagement of the fishery participants.

Connecting Systems of Knowledge

Multiple examples in the academic literature show how synergies across knowledge systems have allowed for a better understanding of ecosystem and natural resource management (Mackinson, 2001; Gilchrist et al., 2005; Leite and Gasalla, 2013; Beaudreau and Levin, 2014; Danielsen et al., 2014; Fujitani et al., 2018). As a first step, the scientific findings of the EwE model of the GoN were presented and discussed among local fishers, illustrating a process of integration of knowledge through validation, whereby one knowledge system is incorporated into another (Tengö et al., 2014; Msomphora, 2015). Since it has been demonstrated that both types of knowledge can augment each other, the next step taken was to assess interactions across systems (Mackinson et al., 2011), as an example of cross-fertilization of knowledge (Tengö et al., 2014).

The analysis of the interactions across systems of knowledge demonstrates that the fishers' perceptions on the past and current state of the fisheries–ecosystem presented strong similarities with the core findings of the EwE model, especially in relation to the following aspects: (1) there was a severe decrease in the catch of shrimps and corvinas in the 2000s, paralleled by (2) significant changes in the species composition of the catches of corvinas over the years and a reduction in their sizes. (3) The first signs of reduction in the catches of large drums and shrimps were visible especially at the end of the 1990s, due to growing commerce and use of gillnets. (4) The usage of gillnets increased in the 2010s, and illegal fishing was indicated as a predominant activity. (5) In the 2010s, fishing efforts toward corvinas increased in area 202, and fishing efforts toward shrimps decreased.

In general, a growth in the use of gillnets was widely reported from the early 2000s up to now by both sources of information. This trend may be related to the greater intensity of fishing that has most probably led to a depletion of larger specimens in the population, resulting in the predominance of smaller individuals in the catches, a process described as fishing down the web (Pauly et al., 1998; Alms and Wolff, 2019). Like the example above, we found similar pieces of information that delivered the same message, helping to foster stronger confidence in the conclusions and providing robust evidence of changes in the social–ecological system of the Gulf.

There is information identified as complementary to each other, because together they provide a broader picture (descriptors and attributes) of the changes of certain fishing resources. The examination across the model and the LEK revealed that it was possible to generate descriptors of abundance and profitability for specific fishing resources using and combining attributes informed by both sources of knowledge (Mackinson, 2001). When combined, the following changes in the fishing system were highlighted: (1) changes over time in the abundance of shrimps and corvinas from high to low abundance; (2) significant reductions in the harvest of high-trophic-level species (mackerel, barracudas, sharks, and rays); (3) economic losses due to a shift to harvesting low-value species (predominance of small individuals and changes from shrimp- to sardine-dominated catches); and (4) revenues decreased due to higher operational costs to catch offshore resources—the inshore resources diminished, and the artisanal fishers were not able to compete for the more distant resources with the semi-industrial fishing fleet because of limitations in vessels and transportation capacities (Alms and Wolff, 2019).

Characteristics such as abundance, biomass, catch per unit effort and profits, commercial importance, and prices seem to be adequate attributes when comparing changes in a fishery system, according to both the local fishers and the scientific perspectives. With respect to the temporal changes (1990s–early 2000s vs. early 2000s–2010s) caused by different fishing fleets on some fishing resources, most of the information was provided by the model, suggesting that there are elements of information more suited to a specific knowledge system. However, when systematic scientific knowledge is complemented with available LEK, it is possible to see an overall and enriched image (Tengö et al., 2014).

Contradictory pieces of information, on the other hand, were detected among the EwE model and the fishers' perceptions: (1) reduction in the catches of sardines since the late 2000s was identified by the model but not by the fishers. (2) Despite the reduction in catches, the high prices in the market for large pelagic fish make the activity profitable for the semi-industrial fleet, as discussed above. However, this does not apply for the artisanal fleet that operates with smaller vessels with restricted ranges and lower fishing capacities. (3) Increase in the fishing effort toward corvinas was not detected by local stakeholders but was shown by the model data. The latter result suggests that fishers possibly perceive a decrease in fishing efforts as an explanation of the reduction in the catches of corvinas over time.

Some authors raise the point that it is important not to ignore the disagreements between different sources of knowledge provided by diverse systems and stakeholders, since doing so could lead to an artificial consensus (Leite and Gasalla, 2013). The conflicting information between LEK and the EwE model found in this case study has generated new insights with the potential to be acknowledged at the decision-making level. We suggest that the mismatches between LEK and scientific knowledge could indicate the source of management and enforcement problems. For instance, in the case of the sardine, local stakeholders perceive abundant catches from the early 2000s up to now, while the model shows a declining trend in the catches since 2008. During the focal groups' activities, it was often stated that sardines are the only realistic alternative to fishing corvinas with handlines (the second most common activity in the artisanal fishing sector besides gillnet fishing). As a result, a conflict arises since reducing or avoiding fishing sardines, as authorities recommend, is difficult to enforce, and artisanal fishers do not see a need to reduce sardine fishing.

As Tengö et al. (2014) identified, and in light of the interactions between the EwE model and the LEK described so far, it is possible to note how using multiple evidence types can generate different valid and useful knowledge, but together improve our understanding of the state and changes in the fisheries systems, as well as the implications for the well-being of humans. Another area where connecting systems of knowledge would potentially be fruitful is in relation to the control of minimum catch sizes for target species. This regulation has been implemented in the GoN as an output control measure to protect juveniles with possibilities to enforce it at the market. Fishers mentioned this topic during the group discussions and expressed confusion concerning the legal-size limits of some species of corvinas, due to the large number of other species caught and the different size regulations in place for each one. The control of catch sizes is possibly creating a regulatory environment where the burden of compliance is high, yet the reason for complex regulations is unclear for some fishers. Thus, there seems to be a need for better communication with local fishing stakeholders about the reasoning behind ecosystem-based management alternatives.

General Conclusion and Management Implications for the Gulf of Nicoya

It has been broadly recommended that scientists engage more directly with fishery management (Mackinson et al., 2011; Purcell and Pomeroy, 2015), combined with the use of LEK as a source of information (Fischer et al., 2015). However, the integration of systems of knowledge is complex and requires specific strategies of communication and methods (Leite and Gasalla, 2013). Despite the abundant literature on the importance of LEK in fisheries (Fischer et al., 2015) and the multiple examples using food web models in management schemes (Pauly et al., 2000; Christensen and Walters, 2004, 2005), there are no specific methodologies describing how LEK can be systematically incorporated with scientific data in the context of ecosystem-based fisheries management (Leite and Gasalla, 2013). The method we propose is, to our knowledge, the first contribution exploring a systematic integration of a food web model of the EwE type with the assessment of fishers' LEK. As we have demonstrated, using multiple types of evidence together, can expand our understanding (Tengö et al., 2014) of the state and changes in ecosystems, helping to improve fisheries management.

As Armada et al. (2018) stated, we also found that an EwE trophic model can be an interactive and effective communication tool to use with artisanal fishers to promote initial discussions on changes in the fishing ecosystem over time and, from there, to gather their perceptions about these multifaceted and sensitive topics. After the workshops, our team learned that information of this kind should be presented using basic images and graphics, moving gradually from the most basic to the most intricate information.

The primary purpose of this study was the systematic connection of the two systems of knowledge, to improve fisheries management. The added advantage from integrating the information was the engagement from those using the resources and who participated in the workshops. As of yet, there are only very few practical applications of a food web model to engage stakeholders for fisheries management with EwE modeled output (Power et al., 2004; Paramor et al., 2005; Bacalso et al., 2013; Armada et al., 2018), and to our knowledge, there are no reports of this kind in the Latin American region or in the GoN. Most participants stressed the importance of the current participatory process regarding the information received and how they relate to it, and they also mentioned the need for considering their opinions and perceptions. This could include making regulations more transparent and potentially more streamlined. The representation of local stakeholders in the management process can potentially help contribute to levels of trust, two-way knowledge exchange, and legitimacy in developing sustainable fishing options (Power et al., 2004; Pita et al., 2010; Mackinson et al., 2011; Msomphora, 2015; Leite and Pita, 2016; Fujitani et al., 2017).

Fishery management in the GoN has rarely followed an ecosystem approach, and the interaction between species and the effect of the different fishing fleets (and fishing effort) on the ecosystem has not been adequately considered (Alms and Wolff, 2019). We note that the authorities' suggestions of reducing or avoiding sardine fishing are related to the type of gillnets used during the activity (non-selective and small mesh sizes) rather than because of worries about the state of the sardine stock. However, sardines are an important source of food for various predators, including sharks and rays (Alms and Wolff, 2019), functioning as a link in the food web (Wolff et al., 1998; Alms and Wolff, 2019). In this respect, the adequate management of sardines should be a topic of further discussion and clarification with local fishers. Catches of shrimps (same trophic level as sardines; Baum and Worm, 2009) have decreased significantly over the past two decades, causing a severe reduction in the total value of the catches as well as effecting the Gulfs' ecosystem (Alms and Wolff, 2019). Since the different life stages of shrimps are key food items for a great variety of species, their progressive decline in abundance over time will definitely cause a great system impact and therefore requires further research and management.

It is important to emphasize that the reduction in the inshore resources mentioned by the fishers and described in Alms and Wolff (2019) has resulted in a decrease in the revenues of artisanal fishers, who are unable to compete with the semi-industrial fishing fleet for offshore resources because of vessel size, travel distance, and storage capacity. The same holds true for those (alternative) species that migrate to cooler and deeper waters (Biomarcc-SINAC-GIZ, 2013).

The management problems of the gillnet fisheries in the GoN are complex. Most of the interviewed fishermen are only engaged in fisheries, lacking alternative income sources (Fernández-Carvajal, 2013). The use of prohibited nets (pores less than 3 inches) and the increase in the size and number of nets are common features of this type of fishery, and even illegal fishing gears such as rastras and artisanal fences are being employed (Marín-Alpízar and Vásquez, 2014). The development of economic alternatives to fishing in the Gulf thus seems imperative (Biomarcc-SINAC-GIZ, 2013). However, fishing is a deeply rooted activity among fishers, and a transition to other jobs is often difficult, especially for older fishers (Fernández-Carvajal, 2013), which is the case of many of our workshop participants with more than 10 years of fishery experience. As a result, one important challenge is to choose those alternatives that deliver the best trade-offs to the gillnet fishing sector while maintaining the health of the ecosystem (Biomarcc-SINAC-GIZ, 2013), and ensuring that these alternatives are accepted by a critical number of fishers (searching for consensus).

As revealed by our study, the model and its features as a holistic tool for ecosystem description and scenario simulation, were useful to both fishers and fishery managers, to address some of the multiple challenges in the GoN. We are confident that this exercise contributed to identifying and filling gaps in the knowledge on the fisheries system of the GoN (Mackinson et al., 2011). We hope that this study will also stimulate future collaborations of fishers (Power et al., 2004), as part of a cumulative and iterative learning process (Tengö et al., 2014).

Our study suggests that the workshop-mediated integration of LEK and scientific data reduced conflicts between stakeholders and may help to foster the compliance of fishers (Leite and Gasalla, 2013; Msomphora, 2015). Management proposals that local resource users do not agree or comply with will be hard-pressed to meet management goals (Fujitani et al., 2012). We hope that the outcomes of this study can contribute to new narratives of decision-making in the GoN based on stakeholder participation (including the LEK) and the best scientific evidence available.

DATA AVAILABILITY

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

This study follows the standards of good scientific practice outlined by the German Science Foundation. The protocol was assessed for ethical human research by the Ombudsperson, who is the point of contact for good scientific practice at the ZMT, the institute for which authors conducted the research.

AUTHOR CONTRIBUTIONS

AS-J, MF, DM, AS, and MW conceived the research. AS-J conducted the field work, accompanied in some opportunities by MF, AS, and MW. AS-J analyzed the data in collaboration with MW and MF. AS-J wrote the draft of the paper. All authors participated in the improvement and revision of the document.

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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.2019.00126/full#supplementary-material

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Fishers' Local Ecological Knowledge (LEK) on Connectivity and Seascape Management

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In developing countries where data and resources are lacking, the practical relevance of local ecological knowledge (LEK) to expand our understanding of the environment, has been highlighted. The potential roles of the LEK varies from direct applications such as gathering environmental information to a more participative involvement of the community in the management of resources they depend on. Fishers' LEK could therefore be useful in order to obtain information on how to advance management of coastal fisheries. Many targeted fish species migrate between habitats to feed, spawn or recruit, connecting important habitats within the seascape. LEK could help provide answers to questions related to this connectivity and the identification of fish habitat use, and migrations for species and areas where such knowledge is scarce. Here we assess fishers' LEK on connectivity between multiple habitats within a tropical seascape, investigate the differences in LEK among fisher groups and the coherence between LEK and conventional scientific knowledge (CSK). The study was conducted in 2017 in Zanzibar, Tanzania, a tropical developing country. One hundred and thirty-five semi-structured interviews were conducted in six different locations focusing on fish migrations, and matching photos of fish and habitats. Differences between fisher groups were found, where fishers traveling further, exposed to multiple habitats, and who fish with multiple gears had a greater knowledge of connectivity patterns within the seascape than those that fish locally, in single habitats and with just one type of gear. A high degree of overlap in LEK and CSK was found, highlighting the potential benefits of a collaboration between scientists and fishers, and the use of LEK as complementary information in the management of small-scale fisheries.

Keywords: small-scale fisheries, seascape, fish migrations, data-poor, participatory research, coral reef, mangrove, seagrass

INTRODUCTION

Small-scale fisheries are critically important for the provision of food security and sustained livelihoods, especially in developing tropical countries (FAO, 2012; Unsworth et al., 2018b). However, many marine coastal systems are intensely and synergistically affected by human activities and fish stocks have declined globally at an alarming rate, calling for management actions

(Pauly and Zeller, 2016). Many fisheries appear to be failing in achieving yields or conservation goals where healthier oceans supporting more fish, feeding more people, and improving livelihoods are prioritized (Karr et al., 2017; Unsworth et al., 2018a).

Within the marine conservation community there is considerable interest in combining local and scientific knowledge to achieve management objectives. However, few studies have examined the merits and caveats of local ecological knowledge (LEK) or have shown how combining both knowledge systems would result in better management outcomes (Hamilton et al., 2012). In developing countries, where data and resources often are lacking, authors have highlighted the practical relevance of LEK in order to obtain useful information (Taylor et al., 2011; Silvano and Begossi, 2012; Thornton and Scheer, 2012). Since biologists do not always have the means or funds of gathering knowledge on ecological systems directly, the classical approach to management of natural resources, which is solely based on scientific knowledge, is destined to be unsuccessful (Davis and Ruddle, 2010). Although rare, examples suggest that the inclusion of LEK and the involvement of local fishers, increases the chances of success (Ruddle, 1995; Shephard et al., 2007; Nenadovic et al., 2012). Conventional scientific knowledge (CSK) is gained from data collected according to a scientific design and theoretically interpreted (Mackinson, 2001; Gaspare et al., 2015). LEK, on the other hand, is accumulated over one's lifetime from observations and hands-on experience in interacting with ecological systems and utilizing natural resources for one's livelihood (Olsson and Folke, 2001). Another aspect of LEK, which can also be denoted as indigenous or traditional ecological knowledge (IEK or TEK), is that it is also a cumulative body of knowledge that transcends generations, through cultural transmission and can often be associated with elders within the local community (Berkes et al., 2000; Johannes et al., 2000; García-Quijano, 2007; Davis and Ruddle, 2010). Fishers can provide novel information on the biology and ecology of species and help answer questions related to the identification of fish habitat use, nursery areas and migrations of species where such knowledge is scarce (Begossi et al., 2016). Le Fur et al. (2011) demonstrated that fishers in West Africa were able, collectively, to develop maps of nursery locations including specific details for each estuary. Moreover, fishers identified periods during which mature adults migrated toward spawning grounds and periods of juvenile recruitment. This information is crucial in fisheries management and can also be used in the establishment of marine protected areas (MPAs), particularly to determine the location and size of protection to maximize conservation, biodiversity, and fishery benefits. LEK was also compared with scientifically gathered data showing that the two data sets were similar (Le Fur et al., 2011), highlighting collaboration between scientists and fishermen and the use of LEK as complementary information.

Tropical seascapes are comprised of a mosaic of habitats including mangroves, seagrass meadows, macroalgal beds and coral reefs (Ogden, 1988). Many coral reef fishes, targeted by the local fishers, migrate to seagrass and mangrove areas to feed during dusk or dawn or during tidal fluctuations (Dorenbosch et al., 2004; **Figure 1a**; Unsworth et al., 2007). Similarly, many fishes utilize these adjacent habitats as nursery areas before migrating to coral reefs as adults (Berkström et al., 2013a; **Figure 1b**). These migrations transfer nutrients and energy between the ecosystems within the seascape and contribute to a shifting biomass that accumulates within the organisms throughout their different life stages (Berkström et al., 2012; Hyndes et al., 2014). Several species also undergo reproductive migrations, gathering in large schools in spawning areas (Claydon, 2004). The connectivity between different habitats where the species cover their full life cycle is important for the replenishment of fish stocks and the provisioning of ecosystem services vital to local human populations. Research on seascape connectivity suggests that connectivity can effectively increase the resilience of marine ecosystem functions and services (Mumby, 2006; Olds et al., 2013) and has recently been highlighted as important in the management of aquatic resources (Berkström et al., 2012; Nagelkerken et al., 2015; Sheaves et al., 2015; Olds et al., 2016). Although the tropical seascape supports a high biomass of fish in total, species-specific biomass is relatively low, causing artisanal fisheries to target several fish species by using many types of gears (Garcia-Quijano, 2015). Tropical fishers have thus adapted to this by incorporating different fishing methods across local habitats in order to try and maintain high levels of yields. Also, with fish stocks depleting, fishers have to move further to exploit more productive fishing grounds (García-Quijano, 2007). Since LEK is acquired by an individual's hands-on-experience and observations of the environment in which they work, heterogeneity of ecological knowledge between fishers can arise between different groups of fishers (Crona, 2006; Crona and Bodin, 2006). Furthermore, Davis and Wagner (2003) highlighted the importance of identifying "experts" when researching LEK, in order to be able to use the most reliable and comprehensive LEK in fisheries management. The present study therefore sets out to distinguish whether there are differences in LEK between different groups of fishers that: (i) utilize single and multiple habitats, (ii) fish locally (within 5 km of their village) or distantly (>5 km away from their village), (iii) use different types of fishing gears, and (iv) fish in ancestral fishing grounds or not. Furthermore, LEK is compared with CSK on connectivity from the same area. It is hypothesized that fishers utilizing multiple habitats, move to fish, use multiple gears and fish in ancestral fishing grounds will have more comprehensive LEK than those that fish in single habitats, fish locally, use single gears and fish in non-ancestral fishing grounds.

MATERIALS AND METHODS

Study Area

The study was conducted on Unguja Island within the Zanzibar archipelago, Tanzania, off the coast of East Africa. It is the main island of the archipelago and is most commonly referred to as Zanzibar. Zanzibar is surrounded by rich marine resources from the Western Indian Ocean (WIO), where small-scale artisanal fishing and tourism take place. The fishery applies a variety of fishing techniques targeting a large number of species (Jiddawi and Öhman, 2002). The tropical seascape around

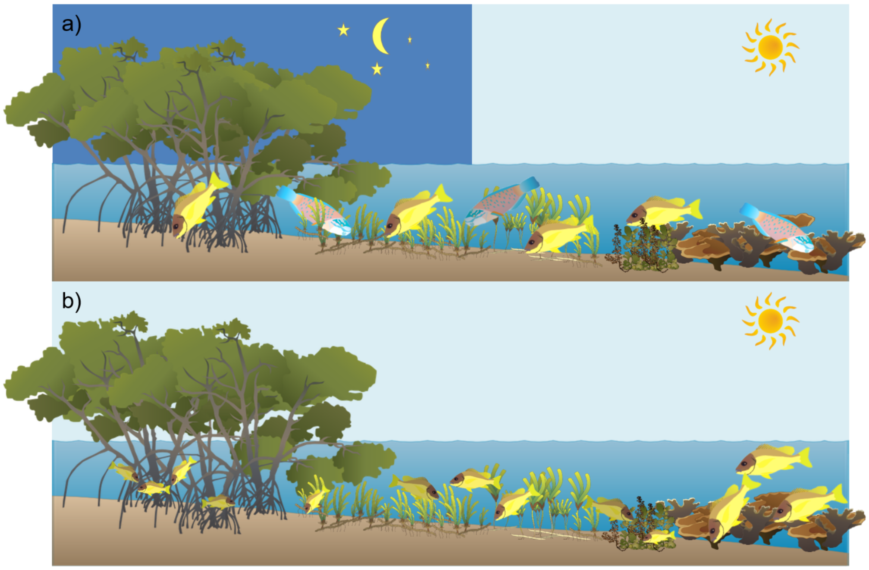

FIGURE 1 | Schematic illustration adopted from Berkström (2012) showing **(a)** dial and tidal foraging migrations between coral reef, macroalgae, seagrass, and mangrove habitats and **(b)** ontogenetic migration of juvenile coral reef fish between the above-mentioned habitats within tropical seascapes. Image symbol courtesy of the Integration and Application Network, University of Maryland and Stina Tano.

Zanzibar is comprised of multiple habitats including mangrove forests, seagrass meadows, macroalgal beds, and coral reefs (Berkström et al., 2012; Khamis et al., 2017). It experiences large tidal fluctuations of up to 4m and is subjected to the northeast (*kaskazi*) and the southeast (*kusi*) monsoon seasons (McClanahan, 1988). The study was conducted in six locations: two sites located in the north-west part of the island, two sites in Menai Bay, the south-west part of the island and two sites on the eastern side of the island (**Figure 2**).

Data Collection

Data on LEK was collected through semi-structured interviews with local fishers between September and November 2017. The interviews were conducted in Uroa, Ungunja Ukuu, Paje, Fumba, Nungwi, and Makoba (**Figure 2**). Fumba and Unguja Ukuu were chosen because both these locations are situated in Menai Bay, where scientific information on connectivity has previously been collected (Berkström et al., 2012; Berkström et al., 2013b; Tano et al., 2017). These areas were also chosen because they are comprised of multiple habitats (mangroves, seagrass, macroalgae, and coral reef).

A questionnaire was used for gathering information from local fishers. Interviews were conducted in Kiswahili via an interpreter and after conducting interviews in each village the answers were translated to English by the same interpreter. For each site, a beach recorder was used to find fishers willing to be interviewed. A minimum of 20 interviews were performed at each site. First, questions were asked to gather the demographics of the respondents. Second, questions were asked to gather data on LEK about habitat use and connectivity of selected species of fish. Three general questions regarding different types of fish migrations between habitats (diurnal/feeding, spawning, and ontogenetic) were asked. This section also contained pictures of fish species (juveniles and adults) and different habitats for the respondent to match the fish species to the habitats in which they are found. An array of fish species was included that either use single or multiple habitats. Toward the end, an open dialogue was held to better understand the level of ecological knowledge that the respondent possessed. Lastly, respondents were asked how they gained their knowledge that they demonstrated in the interview.

Data Description

There were four variables of interest; type of fisher (local or distant), habitat usage (single or multiple), ancestry (if forefathers fished in the area), and gear usage. Based on the distance they moved to fishing grounds, fishers were classified as either local (<5 km), or distant (>5 km). Ancestry described if the respondents have been fishing in an area for generations or are new to the area. Gear usage was divided into five categories: multiple gears and the individual single gears dema traps, handlines, nets, and spears/sticks. Fishers that used either drag nets, seine nets, gill nets or mosquito nets or a combination of nets were classified under the general term "nets." Fishers were also classified as either using a single habitat to fish in or multiple habitats to fish in. Fishers who said that they used multiple habitats, but where the second habitat was "open ocean" were changed to single habitat users.

Connectivity knowledge was assessed by asking three questions regarding diurnal/feeding, ontogenetic and spawning migrations. Respondents were asked if they knew of fish that move between habitats to feed, spawn or live in as juveniles, and were also asked to give examples. The more "yes" answers to the three questions represented a higher knowledge on connectivity

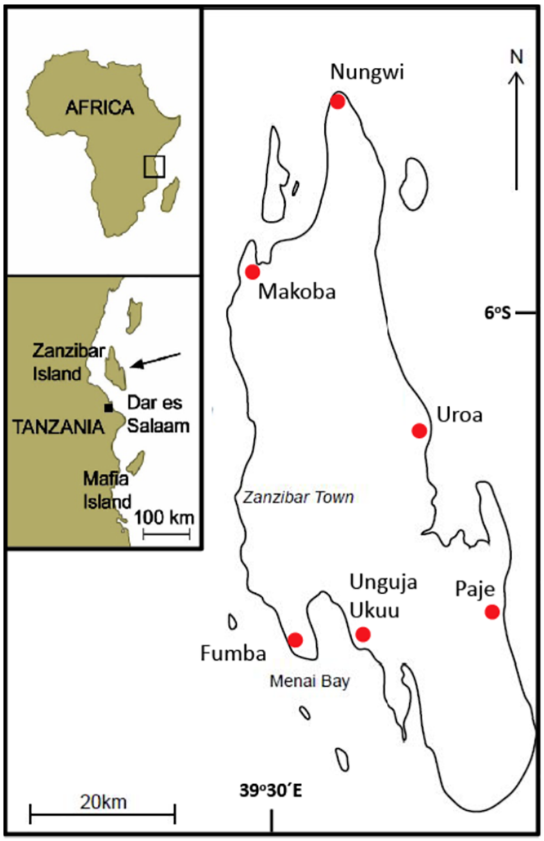

FIGURE 2 | Map of Zanzibar off the east coast of Tanzania. The locations of the six sites, where interviews were conducted, are indicated with red markers.

and were scored (0–3). A score of "0" represented that all three questions were answered with a "no."

Ecological data on habitat use and connectivity by fish in Menai Bay (Berkström et al., 2012, 2013b; Tano et al., 2017) was used to compare CSK data with LEK data by local fishers. Four habitats within the tropical seascape were in focus: (1) coral reefs, (2) seagrass meadows, (3) macroagal beds, and (4) mangroves. However, it was challenging to be certain that the local fishers were distinguishing between seagrass and macroalgae, therefore the two habitats were combined and referred to as submerged aquatic vegetation (SAV). Habitat scores were allocated to each fish species, which corresponded to the number of habitats used by each fish species. LEK habitat scores represented that of which the fishers were aware of and CSK habitat scores represented that of which the scientific community were aware of. Mean LEK habitat score was calculated for each fish species by averaging all the respondent's answers for each fish species. The total number of fishers that mentioned that a particular fish species was present in one of the three habitats (coral, SAV, and mangrove) was also recorded. If more than 25% of fishers stated that a particular fish species was seen in a habitat, then that fish species was deemed to occur there. The fish species might occur in that habitat if 10–25% of fishers stated that they do. If less than 10% of fishers stated that they do occur, they were deemed not to occur there. In order to verify that the LEK data for habitat score can be counted on, an index of inaccuracy was created (**Supplementary Figure S1**).

Data Analysis

Difference in LEK scores between type of fisher, fisher's habitat usage and gear choice were analyzed with permutational multivariate analysis of variance (PERMANOVA). The assumptions of normality were not met so data was fourth root transformed. The PERMANOVA was performed on unbalanced data, although PERMANOVAs are robust in dealing with unbalanced data (Anderson, 2001). However, to make sure that differences found were not due to unbalanced data, data points were randomly taken out by using the "RANDBETWEEN (1;135)" function in Excel to get equal data sets for the different groups of fishers. PERMANOVA tests were rerun with the reduced, equal sample sizes. The results were similar, confirming that all of the data could be used in the analysis. The PERMANOVA test was performed using 999 permutations under a reduced model. A non-metric multi-dimensional scaling (nMDS) ordination with Euclidean dissimilarity index was performed in order to see patterns in the multivariable data. A Wilcoxon signed-rank test with continuity correction was used to compare the differences between the mean habitat scores for the different knowledge sources (CSK and LEK) and the different subcategories of LEK (migratory and local fishers, multiple, and single habitat users).

RESULTS

Demographics

In total, 135 fishers were interviewed. The respondents were all male and between the ages of 17 and 75 years. On average, there were more respondents in the age class 25–34 years of age. Eighty-four percent of respondents had a formal educational background, whether it was primary education (23%), secondary education (59%), or tertiary education (2%). Most of the respondents had children (74%) and out of those respondents; 1–3 children (41%), 4–6 children (31%), or 7+ children (28%). For fishing gear, handlines and nets were more commonly used by fishers, as well as combinations of different fishing gears. Out of the total number of respondents, there were more fishers that utilized multiple habitats ($n = 101$) than a single habitat ($n = 21$). There were also more fishers that fished in non-local fishing grounds (i.e., distant fishers, $n = 72$) than fishers that fished locally ($n = 50$). Respondents' knowledge of their environment was gained mainly through: hands-on experience (63%), experienced and shared knowledge (29%), and fishing seminars and formal education (8%) (**Figure 3**).

Differences in LEK Between Fishers

There were differences between fishers with regards to type of fisher (distant/local), habitat usage (single/multiple), and gear usage. More than half of the respondents received the highest LEK score that can be allocated. There were significant differences in LEK scores between multiple and single habitat

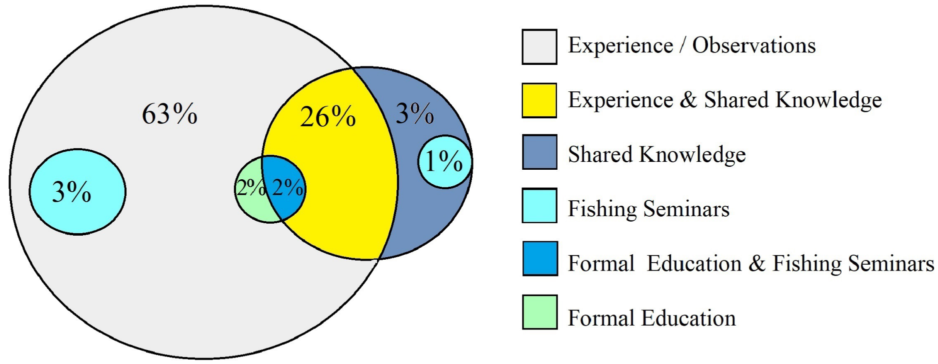

FIGURE 3 | Venn diagram showing the methods of knowledge acquisition on fish ecology/biology by fishers.

TABLE 1 | A PERMANOVA table based on Euclidean dissimilarity for LEK data between different groups of fishers in Zanzibar, Tanzania.

Source	df	SS	MS	Pseudo-F	P (perm)
Type of fisher	1	2.3109	2.3109	3.7768	0.061
Habitat usage	1	8.8271	8.8271	14.427	0.005*
Ancestry	1	0.3725	0.3725	0.6087	0.64
Gear usage	4	9.0053	2.2513	3.6794	0.027*
Type of fisher × Habitat usage	1	0.9987	0.9987	1.6322	0.248
Type of fisher × Ancestry	1	0.0846	0.0846	0.1383	0.935
Type of fisher × Gear usage	4	2.856	0.7140	1.1669	0.387
Habitat usage × Ancestry	1	0.6709	0.6709	1.0964	0.393
Habitat usage × Gear usage	4	3.21	0.8025	1.3116	0.326
Ancestry × Gear usage	4	1.9333	0.4833	0.7899	0.672
Type of fisher × Habitat usage × Ancestry	1	0.7874	0.7874	1.2869	0.317
Type of fisher × Habitat usage × Gear usage	4	2.7932	0.6983	1.1412	0.406
Type of fisher × Ancestry × Gear usage	4	2.6206	0.6551	1.0707	0.469
Habitat usage × Ancestry × Gear usage	4	1.9482	0.4871	0.7960	0.651
Res	4	2.4475	0.6118		
Total	39	40.866			

* *indicates significance.*

users [$F_{(1,39)}$ = 14.427; p = 0.005] and between fishers using different gears [$F_{(4,39)}$ = 3.679; p = 0.027, **Table 1**]. On average, fishers using single habitats had higher LEK scores than those fishing in multiple habitats. Dema trap fishers had the lowest LEK scores, whereas the other fishing gear users had similar LEK scores. Local fishers generally had higher LEK scores compared to distant fishers, however there was no significant difference found between the two types of fishers [$F_{(1,39)}$ = 3.777; p = 0.061, **Table 1**]. There was no significant difference found for ancestry [$F_{(1,39)}$ = 0.609; p = 0.64] and no interactions were found between the different variables (**Table 1**). On average, fishers knew less about spawning migrations compared to diurnal and ontogenetic migrations. A similar trend was seen across the different types of fishers, habitat usage, ancestry and gear usage.

Differences in LEK and CSK

There were significant differences found between CSK and LEK (**Table 2**). On average, CSK had higher habitat scores than LEK (**Supplementary Table S1**). There was a significant difference between CSK and LEK in multiple, single, local, and distant fishers (**Table 2**). It was also found that distant fishers had higher scores than local fishers and that multiple habitat users had higher scores than single habitat users (**Table 2**).

Local ecological knowledge and Conventional scientific knowledge corresponded with each other regarding the fish

TABLE 2 | A table showing results from a Wilcoxon signed-rank test with continuity correction comparing mean habitat scores between local ecological knowledge (LEK) and conventional science knowledge (CSK).

Source	V-value	*p*-value
CSK vs. LEK	1101.5	$1.425e^{-07}$
CSK vs. LEK (Local)	1141.5	$1.408e^{-08}$
CSK vs. LEK (Migratory)	1050	$2.204e^{-06}$
CSK vs. LEK (Multiple)	1087	$3.164e^{-07}$
CSK vs. LEK (Single)	1123	$4.143e^{-08}$
CSK (Local) vs. LEK (Migratory)	66	$8.851e^{-08}$
CSK (Multiple) vs. LEK (Single)	390	0.0428

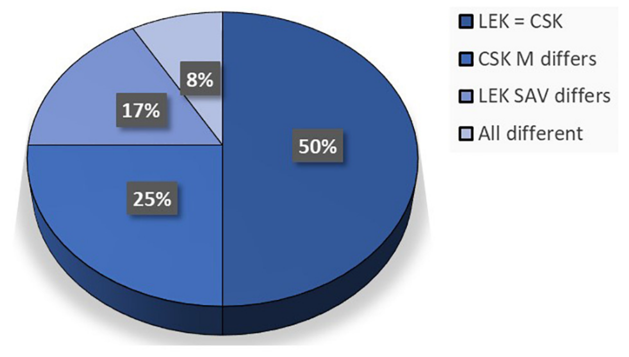

FIGURE 4 | Pie chart depicting the relation between LEK and CSK regarding fish habitat use. The habitats that are used by different species of fish data obtained from scientific literature (CSK) (Berkström et al., 2012; Tano et al., 2017) compared with that obtained from interviewing local fishers (LEK) in Zanzibar, Tanzania. Fishers were shown pictures of different fish species and different habitats, and were asked to point to habitats that each individual fish species were found in. C, corals; SAV, submerged aquatic vegetation; M, mangroves. "CSK M" refers to scientific data regarding the mangrove habitat, "LEK SAV" refers to local fisher's data regarding the SAV habitat. "All different" means that more than one LEK habitat did not match the CSK habitats.

species that utilized coral reef habitats (**Figure 4**). LEK stated that SAV habitats were utilized by all the fish species that were shown, which did not correspond to CSK for some of the fish species. Most of the species that occur in mangroves, known by CSK, did not correspond with LEK (**Figure 4**). However, for the fish species *Sphyraena flavicauda* (barracuda) both CSK and LEK stated that it occurred in mangroves (**Supplementary Table S1**).

DISCUSSION

A large majority of fishers demonstrated high knowledge of fish migrations between various habitats around Zanzibar. Knowledge on feeding and ontogenetic migrations were the highest while less was known about spawning migrations. At least half of the fishers had similar knowledge about connectivity as that of scientists. However, LEK on connectivity, differed between different groups of fishers. To our knowledge, this is one of the first studies to specifically assess fishers' LEK on connectivity between multiple habitats within a tropical seascape. However, other studies have touched upon the topic of connectivity related to spawning migrations (Robinson et al., 2004; Silvano et al., 2006), fish habitat use (García-Quijano, 2007; Valdés-Pizzini and García-Quijano, 2009; Silvano et al., 2010; Gaspare et al., 2015), and comparison of habitat maps created by local fishers with satellite images (Aswani and Lauer, 2006b; Aswani and Vaccaro, 2008; Lauer and Aswani, 2008, 2010; Selgrath et al., 2016). The results from the present study may be highly valuable due to the lack of studies from Africa, with only 2–8% of the published articles on marine LEK from this region (Thornton and Scheer, 2012). The majority of studies have focused on North America and Oceania. Furthermore, tropical seascapes have a high diversity of target species for which the biological and ecological knowledge is limited (Silvano et al., 2006).

Differences in LEK Between Fishers

Overall, there were differences between all of the fisher groups except for those that fish in ancestral fishing grounds or not. When asked whether fish migrate to feed, spawn or during ontogeny, significant differences in LEK were found between fishers that fish in multiple and single habitats, and between fishers that use different types of gears. In contrast to what was hypothesized, single habitat users had higher LEK scores, meaning they knew more about fish migrations, than that of multiple habitat users. It was thought that multiple habitat users would have greater knowledge on seascape connectivity than single users, due to the fishers interacting with many different habitats within the seascape when fishing and at the same time developing localized knowledge based on those interactions, experiences, and observations. A possible reason for this result may be due to social intergroup dynamics, where ecological knowledge on fish migrations and fishers' own experiences might be shared freely between the two different groups. Crona and Bodin (2006) found that fishers, despite fishing in different areas, had similar knowledge to each other due to frequent relations. However, at a more detailed level, multiple habitat users did have on average a greater knowledge of fish habitat usage than single habitat users when asked to match photos of individual fish species with photos of habitats. Even though the knowledge is shared between the two groups of fishers, the knowledge that is conveyed might consist of general behaviors of fish rather than detailed information on fish ecology, which may explain observed differences. A similar consensus can be seen in fishers that are grouped by fishing gears used. Fishers fishing with basket traps (*dema*) on average knew the least about fish migrations, which may be explained by the nature of how the fishing gear is utilized. Fishers can have a minimum of 5 basket traps and a maximum of 10 basket traps left at different sites in an area for long hours in order to increase catch probability (Jiddawi and Öhman, 2002). Since this method of fishing allows fishers to leave the trap at a particular time and then return to the trap after a few hours, fishers might not be very observant of fish behaviors during this period, unlike fishers that use gears that require the fisher to be present and vigilant at all times during the fishing period (e.g., fishers that use nets, handlines, spear/sticks and a combination of gears). Furthermore, handline and multiple gear fishers typically catch coral reef dwelling fishes that also utilize multiple habitats, e.g., fishes from the family *Lutjanidae* and *Lethrinidae* (Jiddawi and Öhman, 2002) and may therefore have a greater knowledge on the ecology of these families. A similar result was reported by Crona (2006), where groups of fishers were distinct from each other based on the type of gear that was utilized. Deep-sea fishers and seine-net fishers had the broadest concept on fish migrations, and in extension seine-net fishers also acknowledged the population dynamics of sea urchins, declining seagrass meadows and fish abundances (Crona, 2006).

When asked general questions about fish migrations, there were no significant differences found between fishers that fished locally and distantly, and those who fished in ancestral fishing grounds and those who did not. However, when asked to match photos of fish species with habitats in which they are found, significant differences were found between local, and distant fishers. As hypothesized, distant fishers knew more about connectivity, in terms of fish migrations, than local fishers on this more detailed level. This is in accordance with Crona and Bodin (2006), who also found that distant fishers were the most knowledgeable. This may be explained by distant fishers moving from one seascape to another, acquiring information on more fish species with varying habitat requirements compared to fishers that are more restricted to areas adjacent to their villages (Jiddawi and Öhman, 2002). Their experience of interacting with these multiple seascapes in different areas and with the fish species could add to their knowledge on fish ecology and on connectivity in general. On the other hand, this may differ in different seascape settings depending on which habitats are available within the local fishing grounds. If all habitats are present within the local fishing grounds, local fishers may be expected to acquire a deeper knowledge on connectivity than distant fishers since they spend more fishing time within their local seascape and less time traveling.

Tropical fish migrations occur on a daily, seasonal or annual basis and within an individual fisher's lifetime (Berkström et al., 2012). Hence, the result of having no difference found between fishers that fished in ancestral fishing grounds and those who did not may be due to fishers observing the different types of migrations (diurnal/feeding, spawning, and ontogenetic) that fish undergo over their lifetime and do not necessarily depend on ancestral knowledge to know whether fish migrate or not.

Differences in LEK and CSK

Since conventional science is currently the presiding epistemological knowledge system that is widely used in resource management plans (Davis and Ruddle, 2010), LEK on connectivity was compared with CSK from the same area. CSK was collected in Zanzibar by scientists during a number of field trips where fish communities and habitats were studied directly during diving and snorkeling excursions (Berkström et al., 2012; Berkström et al., 2013b; Tano et al., 2017). LEK was found to correspond with CSK in 50% of the respondents' answers, while LEK and CSK were completely different in only 8% of answers. This indicates that, even though there was a significant difference found between the two different epistemological knowledge systems due to the different approaches of acquiring ecological knowledge, both LEK and CSK can be used to complement each other. This was in accordance with other studies comparing LEK and CSK on fish biology and ecology in Tanzania (Gaspare et al., 2015), Brazil (Silvano et al., 2006, 2010; Silvano and Begossi, 2012; Begossi et al., 2016; Lima et al., 2017), and the Philippines (Selgrath et al., 2016). Multiple research papers advocate that local knowledge should be used in conjunction with scientific knowledge (Berkes et al., 2000; Johannes et al., 2000; Garcia-Quijano, 2015). However, Davis and Ruddle (2010) emphasized the point that LEK needs to be assessed for accuracy and validated with CSK. In the present study, the main discrepancy was between LEK and CSK on fish in mangrove habitats for 25% of the fish species. For these, LEK indicated that fish did not use mangrove habitats while CSK indicated that they did. This discrepancy may be explained by the fact that none of the fishers that were interviewed actively fished in mangrove habitats. Fishers would not have had observational experience with mangrove dwelling or migratory fishes and hence reflecting the lack of knowledge regarding this habitat. As García-Quijano (2007) stated: "fishers' knowledge and experience are based on thousands of hours "sampling" local ecosystems with their fishing gear" and hence the lack of connectivity knowledge in mangrove habitats is likely due to the lack of "sampling" this habitat with their fishing gear.

Regarding SAV habitats (seagrass and macroalgae), LEK stated that fish utilized SAV habitats and CSK stated the opposite for 17% of the fish species. This may be due to fishers grouping seagrass and macroalgae together under the general idea that they are vegetation growing underwater and not distinguishing between the two. Furthermore, scientific surveys of fish in the seascape are likely to underestimate the number of fish species present due to field sampling only capturing a snapshot in time. For the fish species *Gerres oyena* (common silver-biddy), fishers overwhelmingly underscored the habitats that this particular fish uses, due to majority of fishers indicating that this particular species used sand habitats as its primary habitat. Although Berkström et al. (2012, 2013b) and Tano et al. (2017) (from which the scientific fish data was taken) only looked at fish species that utilized coral, seagrass, macroalgae and/or mangrove habitats, Allen and Erdmann (2012) concurred that common silver-biddy do indeed utilize sandy bottoms in sheltered waters near coral reefs. The fishers also indicated that the species might occur in coral and SAV habitats, which was similar to that of CSK stating that they do occur in those habitats.

Combining LEK and CSK for Natural Resource Management

Tropical local resource users are constantly feeling the ramifications of increased anthropogenic pressures on the tropical seascape and are experiencing decreased fish stocks and catching smaller sized fish (Jiddawi and Öhman, 2002). Fisheries management is, however, complex and often lacks accurate and viable data due to the costs and inaccessibility of areas to biologists (Garcia-Quijano, 2015). The present study highlighted that local resource users are knowledgeable in ecological processes and more importantly are familiar with fish migrations and the key habitats that different species of fish utilize, which could be used in fisheries and seascape management as well as providing valuable information for the design of MPAs. Information on fish connectivity within the seascape will facilitate in the siting of MPAs, which habitats to include, and what size and spacing is needed to maintain healthy fish populations (Johannes et al., 2000). A few studies in Turks and Caicos Islands (Close and Brent Hall, 2006) and in the Solomon Islands (Aswani and Lauer, 2006a,b; Lauer and Aswani, 2008) have coupled LEK and benthic mapping with a geographical information system (GIS) to aid in fisheries management and the implementation of MPAs. Aswani and Lauer (2006a) showed how indigenous people assisted in the design of MPAs by identifying marine habitats and related resident taxa on aerial photos which were then incorporated into a GIS database along with dive surveys from the same area. Converting fishers' knowledge and socioecological behavior into geo-spatial data, aids in designing and implementing resource management strategies in a cost-effective and participatory way, bridging the gap between LEK and CSK (Aswani and Lauer, 2006b).

Although some progress toward the inclusion of LEK and bottom-up management systems have occurred, fishers' knowledge has long been ignored by scientists, policy-makers, and governance institutions (Hind, 2015). Some of this lack of inclusion is likely an issue of utility. Natural scientists have found it difficult to integrate a knowledge culture, which is often qualitative and in non-standard format and different from their own (Soto, 2006). However, Valdés-Pizzini and García-Quijano (2009) showed that Puerto Rican fishers think in the same ecological way as fisheries scientists and managers by coupling fish species to different habitats. Furthermore, Begossi et al. (2016) found that fishers in Brazil classify fish taxonomy by the generic level and in a similar hierarchical fashion as that of scientist, analogous to the *Linnean* classification of genus. The fishers were also able to give detailed knowledge on fish diets, facilitating scientists with gaps in food-web ecology. Similarly, the fishers in the present study demonstrated relevant ecological knowledge by matching fish species to habitats and acknowledging fish migrations. As fisheries science and management evolve, current perceptions about fishers' knowledge and their role in this area need to change (Baelde, 2007). LEK may not only fill scientific knowledge gaps, complementing CSK, but also contribute to higher success in fisheries management by making local resource users feel important and included in the process. The inclusion of LEK can also improve the political position of small-scale fishers which is often a disadvantaged stakeholder group for access to coastal resources (García-Quijano, 2007). Carmack and Macdonald (2008) argued that where focus and scale of inquiry is the same, collaborative research should take science and LEK as equals. This "conscience" approach assumes that both CSK and LEK is valid within its own set of rules and neither replaces the other. In this way the joint enquiry will have a joint focus on what is important for the local natural resource users.

In conclusion, it was deemed that the local fishers of Zanzibar had a high knowledge of connectivity which led more toward a general understanding of connectivity than an in-depth knowledge of connectivity, which scientists possess. However, the knowledge that local users possess (LEK) would aid fisheries management with valuable information regarding fish ecology and behaviors when used in conjunction with the knowledge gained from scientists (CSK). Results suggest differences between fisher groups, where fishers traveling further, exposed to multiple habitats, and fish with multiple gears have a greater knowledge on connectivity patterns within the seascape than those that fish locally, in single habitats and with just one type of gear. This should be recognized when finding "experts" within the local fishing community to consult in fisheries management. We suggest that a co-management approach to devising and implementing management proposals that incorporates both epistemological knowledge systems of LEK and CSK regarding seascape connectivity, would increase the effectiveness of natural resource management in aquatic environments.

DATA AVAILABILITY

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

All participants provided written informed consent to participate in this study. In Tanzania, at the time of the study, no ethics approval was required. No ethics approval was required in Sweden based on the nature of the interview data and the fact that the data was collected and analyzed outside of Sweden.

AUTHOR CONTRIBUTIONS

All authors conceived the research. MP conducted the fieldwork and analyzed the data. CB and MP wrote the draft. LN and NJ provided edits and feedback.

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SUPPLEMENTARY MATERIAL

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Inclusive Management Through Gender Consideration in Small-Scale Fisheries: *The Why and the How*

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In a world in which ocean degradation is widespread and aggravated by the effects of climate change, there is a need to contribute with new management approaches to ameliorate the situation. Here, inclusive management is proposed as such an alternative. This contribution argues that including all genders in the management process is needed and the inclusion itself can generate new ways to solve problems. An assessment of findings from literature of the positive aspects when considering gender in environmental governance is presented and related to the specific situation of small-scale fisheries (SSF). These positive findings are explained in terms of (1) Participation, (2) Space, actors and activities, (3) Economic power, and (4) Equity and environmental stewardship. Further, a practical approach is taken and a model for gender inclusion in coastal/ocean management for SSF is presented and illustrated with a case of seagrass SSF in East Africa. The central argument is that in view of ongoing coastal/ocean degradation and the moderate governance and management success, it is worth trying management approaches that *consciously* and *explicitly* consider gender and diversity of actors. This will bring central actors (e.g., women not previously considered) into the management process and will provide the base for better governance and policy reform.

Keywords: gender, gender and environment, small-scale fisheries, coastal management, ocean governance, marine spatial planning, seagrass conservation, Zanzibar

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INTRODUCTION

In the current situation of ocean/coastal degradation as well as the uncertainty of human fate due to climate change (IPCC, 2018) it is urgent to provide new angles and solutions to ocean/coastal problems. In this contribution, the benefits of adopting an inclusive ocean/coastal management approach, which incorporates gender aspects for small-scale fisheries (SSF), are presented. Inclusive management is defined here as any management initiative that strives toward sustainability while *consciously and explicitly* considering the diversity of actors who have a stake in the social-ecological system. Inclusive management considers men, women, children, elders and minorities. This approach is a new proposition and, as such, is not yet tested although it shares commonalities with established participatory approaches and co-management as well as with inclusive development (Koralagama et al., 2017). The main particularity of this approach is that it brings to the table "gender analysis" for governance and management enhancement (de la Torre-Castro et al., 2017). The key argument is that given previous experiences, it seems fruitful to have a gender perspective in SSF governance, management and conservation. This contribution develops the argument using knowledge from the vast field of gender and environment and through the author's own experience working with gender and SSF associated with seagrasses in East Africa. This research does not cover each idea presented on gender and environment nor all schools of thought and ways to approach it. Instead, the focus of the contribution is on exposing the various positive arguments for gender inclusion, which provide evidence for ways in which governance, and management approaches can be improved, and policy reformed.

The contribution draws attention to the importance of increasing the diversity of actors and voices involved in order to improve SSF governance and management. The article is organized as follows; first, key aspects related to gender are introduced, then arguments from the literature which support gender and diversity are presented, this is followed by the presentation of a hands-on generic model to accommodate and study gender in ocean/coastal areas with SSF and a specific application of the model to the case of SSF associated with seagrasses in Zanzibar, Tanzania. The article ends with conclusions and thoughts for the future.

KEY GENDER ASPECTS

At a basic biological level, human beings are sexual organisms (male or female). Exemptions, however, do exist and in some countries, law recognizes a "third sex" (for example in South Africa and Australia); other countries have an even more complex view of the issue. Here, the focus is on men and women, but the same arguments can be extended to minorities if wanted/needed.

For humans, which are in essence complex creatures, sex is not enough to understand behavior; *and behavior is a key variable for understanding natural resource use and management.* As such, considering gender has deep policy implications. Gender is useful as it refers to the cultural, normative and social attributes of being a man or a woman. There are different definitions of gender, but all of them incorporate the social construction of being a man or a woman and the power differences associated to them. The history of the concept can be traced all the way back to Plato and later on to John Stuart Mill, and in the 1970s and 1980s to Catharine MacKinnon and Andrea Dworkin (Nussbaum, 1999). Gender takes into consideration the contextual factors framing actions, attitudes, aspirations, capabilities, etc. of a man or a woman (Harding's, 1986; Gregson et al., 1997). It also considers what is expected from different sexes from a societal perspective. In addition, gender considers the interrelationships between and within categories; who has power to do what, how and why, who benefits and who do not. As such, gender analysis is a powerful tool to understand society and identify areas that need improvement (Davis and Nadel-Klein, 1992; Jackson, 1994; Bennett, 2005; Sprague, 2005).

During the last decades, gender has gained importance due to the historical inequalities between men and women (e.g., Bryson, 2003; Lykke, 2009). There is an honest effort to try to reverse such inequalities, and although concrete results have been moderate and not as tangible as desired, advances have been achieved and practically all important high level global institutions consider gender as central to their own organization and areas of work (e.g., UN, EU, UNDP, WB, etc.).

In relation to SSF, the FAO voluntary guidelines for SSF (FAO, 2015) includes a section on gender equality. The text makes clear that discrimination against women in SSF should be challenged and that gender mainstreaming should be an integral part of SSF policy. A whole handbook for implementation was created 2 years later (FAO, 2017). These recent events will certainly bear fruit in the coming years, especially as the number of scholars working with gender and SSF seems to be growing (see for example Vol. 17, in Maritime Studies Journal 2018).

ASSESSING THE LITERATURE FOR POSITIVE FEATURES OF GENDER INCLUSION: *THE WHY*

This section presents the *positive* aspects found (in the literature and in author's experience) when including a gender perspective in environmental policy, governance and management[1]. The section is organized into the following categories; (1) Participation, (2) Space, actors, and activities, (3) Economic power, and (4) Equity and environmental stewardship.

Participation

Participation is one of the major reasons to include women in management efforts. How fair, effective and realistic can management be when excluding half of the population? Different projects show that including gender in management and allowing women to participate in decision-making, monitoring, implementation and evaluation is positive (e.g., Westermann et al., 2005; Agarwal, 2010; Barclay et al., 2017). One of the main arguments put forward in the literature is that women have different types of knowledge, observations, experiences and interpretations that may enrich management and provide new perspectives when analyzing problems and when tailoring solutions (e.g., World Bank [WB], 2010, 2015; Klugman et al., 2014). Women's participation also leads to a different kind of leadership that can facilitate the navigation of difficult policy issues (UNEP, 2015). Women's participation, and gender analysis more generally, are matters of justice and equity (Di Chiro, 2008) and may lead to the recognition of different arenas in which different actors (co-) work and (co-) produce, as well as the different contributions by different actors, for example in terms of conservation efforts, marketing, direct extraction, etc. Participation has also been a way to foster emancipation and empowerment and in some cases has led to building coalitions between different and previously disaggregated groups (e.g., Kleiber et al., 2015). It has created a novel and open space for networking (Arora-Jonsson, 2014) and not seldom has expanded the focus of the problems from environmental management to broader societal issues (e.g., Onyango and Jentoft, 2011; Arora-Jonsson, 2014). Participation is considered a key point for future sustainability agendas (Agenda 2030, 2015).

Space, Actors and Activities

Obviously, in order to manage a system, knowledge about the system is a prerequisite (Kooiman et al., 2005; Schultz et al., 2007).

[1] For a view, also discussing negative gender experiences and challenges see Arora-Jonsson (2014).

From a social-ecological perspective, social and ecological parts of a system are equally important and thus, relevant information about both is needed. First, a social-ecological mapping or inventory is needed (Schultz et al., 2007). It is important to have information about the characteristics of the ecosystems in question, together with the resource users and their relation to management plans. In addition, it is critical to know/understand images, norms and attitudes in the local context (Song et al., 2013). Women have been largely excluded as users and stewards of natural resources, at least in contemporary approaches to resource management taking place in different governmental agencies. It is possible to find examples of matriarchies and traditional or local ecological management systems, but these have not been dominating lately.

In coastal management, Diamond et al. (2003) advocates for a gender perspective. Adding a "gender lens" in SSF will provide a clearer picture of the whole system (Williams, 2008). It is critical to know who is doing what in the coastal zones (in specific ecosystems and within larger seascapes). This includes information about the roles of the people using the different coastal spaces, the resources used and the relations of power over places and resources. People *work* in the various ecosystems of the coastal zones. This work can be defined as "the active labor-based interaction of human beings and the material world" (Menon, 1991). Women and men perform different activities. Men normally "fish" as their main occupation (sometimes combined with other activities) while women normally have many roles such as invertebrate collector, fisherwoman, trader, processor, etc. (Weeratunge et al., 2010). Without doubt, mapping the actors, resources and activities will increase the general knowledge of the coastal zone and help in the identification of critical management and policy gaps. It will provide a visualization and understanding of the work and movement of people. For example, in Mayotte, aerial pictures taken at different times and seasons were used to investigate the activities and uses in the intertidal areas. The gendered differentiated practices can be analyzed in such a way too. Recent mapping of seascapes has been an important tool to identify key ecosystems and areas of conservation (Palafox-Juárez and Liceaga, 2017). One issue that becomes clear when working with gender and coastal resources is the lack of existing gender-disaggregated data (Williams, 2002; Bennett, 2005; FAO, 2012; Fröcklin et al., 2013; Kleiber et al., 2015). In some parts of the world, attention to gender aspects is higher and has been very positive particularly in community-based management; see for example, initiatives taking place in the Pacific, South East Asia and East Africa ([2,3] and Fröcklin et al., 2018, respectively).

Having clear information about defined spaces, actors, activities and their overlap may facilitate the acquisition of such data. Spatial analysis also has the potential to reveal issues of environmental justice; who has access to the most valuable resources and ecosystems? Why are specific patterns found? Who decides what? In what way? How do the decisions and interrelations at the household level affect the use of coastal spaces and resources and vice versa?

[2]https://www.spc.int/resource-centre

[3]www.genderaquafish.org

Studies considering natural and social domains have received much attention in gender and environment (e.g., Rocheleau et al., 1996) but actual *mapping and linking* between the ecological and the social dimensions have not been prominent in the literature. It can be argued that in gender and environmental studies there is bias toward consideration of the social side rather than the ecological side. There is also a bias about studied systems; gender and environment research has tended to focus on forests, fresh water provision and disaster management and far less on ocean/coastal systems and their associated fisheries (SSF or others). Studies that have considered space, actors and activities have found that gender is a key factor that cannot be ignored in management and policy (Thyresson et al., 2013; de la Torre-Castro et al., 2017; Drury O'Neill and Crona, 2017; Picaulima et al., 2017; Drury O'Neill et al., 2018).

Economic Power

At the core of gender studies, analyses of economic inequalities are found. Historically, men have been seen as breadwinners and women as caretakers of the household and children. A key focus in feminism is to achieve women's economic independence and, as a consequence, the power of decision-making. Boserup's work (Boserup, 1970) constitutes a keystone study. Boserup analyzed the economic contributions of women and linked them to development. Since then, a common result of research in this area has been the clear existence of economic asymmetries between men and women dealing with natural resources (e.g., World Bank [WB], 2012, 2015). These economic concerns have been reflected in paradigms of thought from women in development (WID) to women and development (WAD) and later to gender and development (GAD); it is beyond the objective of this article to review all of them (see for example Rathgeber, 1990), but suffice to say that economic inequality has been given a lot of attention. Issues of economic inequality are important in both developed and developing nations. Naturally, the World Bank addresses this agenda (World Bank [WB], 2006, 2010, 2012). In general, economic equality and gender integration in labor and markets is highly beneficial (Cotter et al., 1997). In addition, women's missing potential in development can be considered a deep loss (Duflo, 2012). Economic development normally decreases inequality and benefits the whole society but specially women. So, still policy interventions are needed to assure gender equality (Duflo, 2012).

Recent research in SSF found that economic asymmetries are a common feature in both finfish and shellfish associated SSF and constitute huge management challenges (Barclay et al., 2018; Drury O'Neill et al., 2018). Fröcklin et al. (2013) analyzed the market activities of fish traders and concluded that economic gender inequalities were present in the system, but additionally that, gender insensitive policies masked the feedback needed for learning and adaptive management by missing key actors, in this case women fish traders and their activities. A recent study also shows that, globally, women are commonly economically active in the coastal zones, but their contributions are neither registered in official records nor recognized by society (Kleiber et al., 2015). In SSF it is thus necessary to analyze what the critical assets are, not only in terms of direct ecological goods (such as fish and shellfish) but also in terms of conservation or potential ecosystem services that may provide higher revenues (for example as carbon sinks or as sites for ecotourism). Linked to the point above on mapping, who has the access to assets and resources with higher economic value and how the distribution of wealth looks like? Who has the access to markets and information? How can economic development be created in an equal and just way? Therefore, integrating economic aspects and gender in analysis of SSF will highlight the aspects explained above. There is also a need to go beyond the gender/ecosystem link and analyze the whole living situation, especially in tropical rural communities, paying attention to both productive and reproductive work, and from the individual level to whole household dynamics. The potential of gender inclusion for progress toward a green economy and overall sustainable development has also been identified (Agarwal, 2012).

Environmental Stewardship and Equity

Ecofeminism has argued that there is a natural connection between women and environment (e.g., King, 1983; Shiva, 1989). This school of thought argues there is a naturalistic caring inclination; since women are "birth givers" and have an intimate connection with children it is argued that this is extended to nature. Because of pregnancy and childcare, women also are less likely to move; and therefore considered as the primary actors in environmental care with high levels of local ecological knowledge. Ecofeminism has been criticized and marginalized for its essentialism and lack of stringent analysis (e.g., Jackson, 1993; Jackson, 1994; Leach, 2007). However, Thompson (2006), revising the early work of Merchant (1980) argues for a reevaluation of ecofeminism. Thompson's argument is that ecofeminism's central thesis is still valid; since it explains the commonalities of human (women) and nature domination that stem from positivistic science and capitalism. The objective of this section is not to defend ecofeminism, but to problematize and link to empirical studies showing that in many cases women *do* care for the environment. Women have been shown to: be more supportive to wildlife (Arjunan et al., 2006); improve forest management (Agarwal, 2009a,b); promote positive collective action and social norms for better management (Westermann et al., 2005); include more ethical aspects for holistic management (Lauber et al., 2001); and to be more cooperative in different settings with environmental importance (Revollo-Fernandez et al., 2016). Elderly women have also been found to be crucial to retaining and passing down traditional ecological knowledge (Singh et al., 2013). It has also been found that women university students have smaller ecological footprints than male counterparts (Medina and Toledo-Bruno, 2016), women engage in more pro-environmental behaviors (Hunter et al., 2004) and in countries with higher proportion of women in their parliament, the likelihood of ratification international environmental treaties increases (Norgaard and York, 2005). Ecofeminism and Political Ecology have emphasized the role of women as leaders in conservation. This type of strong leadership with local resistance has also been found in coastal systems; in Peru, for example, women were leaders to defend shrimp farming developments through grassroots mobilizations (Veuthey and Gerber, 2012).

However, the reasons for caring about the environment may vary, and in many cases fulfill material and work needs (Jackson, 1993; Dankelman, 2001). Additionally, there is little information about the actual impacts of those actions on the environment (positive or negative). Evidence presented by Agarwal from forests in India and Nepal is positively convincing (Agarwal, 2010), but other studies have not found clear links between women and better environmental conditions or conservation (e.g., Nugent and Shandra, 2009). A review of ecological restoration and gender found positive evidence that integrating gender in restoration efforts giving higher efficiency and effectiveness, but as gender is generally not taken into consideration in restoration, it is difficult to draw overall conclusions (Broeckhoven and Cliquet, 2015). In development, women are often considered as agents of change and drivers of sustainable development (e.g., Braidotti et al., 1994; UNEP, 2015). But there is a warning here; women are already facing the so called "double burden" of work and household duties (or the "triple burden" of productive, reproductive and community work according to Moser, 1989). Should they take one more task of being better environmental stewards? Dankelman (2001) answers with a clear *no*; "care for the environment should not be added to the long list of tasks for which women are already responsible." Here, gender analysis is useful to place the burden (and joy) of environmental care in more equitable terms. It may also open up the possibility of addressing inequitable food security and childcare provision. Women have had enormous responsibility related to food security and meeting wider societal needs (Boserup, 1970), especially in fisheries where they play a key role in poverty alleviation and provision of high quality protein (Harper et al., 2013; Béné et al., 2016). Gender analysis may help to identify areas in which men can contribute more. Needless to say, this implies a reconsideration of management, conservation and policy, in which both men and women and their interrelations are important, as well as how those interrelations relate to the environment. This new way of linking gender, management, conservation and policy necessarily deals with equity and justice, and clearly links to the first point of participation.

ACTIONABLE RECOMMENDATIONS. A SOCIAL-ECOLOGICAL MODEL FOR GENDER INCLUSION IN OCEAN/COASTAL SSF MANAGEMENT: *THE HOW*

While the previous section uncovers the positive aspects of using gender in environmental management and governance, it says little about the practical way to do it and about the difficulties of working with gender. Some of the difficulties when working with gender are explained briefly below.

Gender is not completely unproblematic (Hawkins et al., 2011; Arora-Jonsson, 2014); there are methodological, ideological and philosophical challenges when working with gender. At the core, the main difficulty is defining what gender really is (Arora-Jonsson, 2014), considering the context and posing adequate relevant questions (Scott, 2012). Gender has to be understood in its historical context. While the concept was created to avoid biological determinism, recent work problematizes the indivisibility of the biological and the socio-cultural. There is a need for new categorizations that allow us to deal with duality without falling into old simplifications (for a discussion see for example Lykke, 2009). Another difficulty when working with gender is that gender is not a static category, rather a process changing over time and space. This conceptualization becomes useful to analyze history and transformation and to dive deeper into interrelations between gender, the physical environment and socio-cultural processes (Nightingale, 2006). In addition, gender research has been shifting the focus of the analysis. It has been argued that gender analysis has moved the focus from men to women and then to men again. However, Kabeer (1994) refutes this dilemma, stating that gender analysis is not in opposition to highlighting the oppressed gender (normally women) and inequalities. She makes a parallel with class analysis in which the situation of the poor and disadvantage is naturally emphasized and argues that, therefore, there is no real tension between gender analysis and a fight for women's rights and emancipation.

In coastal/marine environments, studies of gender are scarce, so the initial focus needs to be around mapping and characterization of the social-ecological setting. As basic knowledge is acquired, steps toward more complex social-ecological analysis can be taken. Here, a practical approach is adopted by providing a generic model to integrate the different aspects of the management process into a comprehensive unit including gender. How to go on? How a can a researcher or a management agency work with these factors in a hands-on way? The intention of the model is to facilitate the process and to consider the whole setting, incorporating biophysical, ecological, social and economic elements. The model is built upon layers of knowledge that are superimposed on each other (similar to a GIS model). It departs from the biophysical reality and builds on complexity with higher levels of social understanding and interrelations between humans-nature and humans-humans. To acquire knowledge about the different layers, different epistemologies can be used. The challenge for the researchers and/or managers is to link and understand the rich information in a holistic way. **Table 1** presents the different layers and key aspects of the model. Parts of the model has been applied for the case of SSF associated with seagrasses in Zanzibar, Tanzania. A brief presentation of the case and the novel information that the inclusion of gender provided for management enhancement is given after the table.

GENDER IN SMALL-SCALE FISHERIES ASSOCIATED WITH SEAGRASSES

The model (**Table 1**) has been partially applied to the case of SSF associated with seagrasses in Zanzibar, Tanzania. The knowledge generated corresponding to the different model layers can be found in specific publications (Fröcklin et al., 2012/Seaweed farming and farmers' health, 2013/Fish traders, 2014/Invertebrate collection, 2018/Small-scale innovations; Nordlund et al., 2014/Invertebrate collection; de la Torre-Castro, 2012/Governance; de la Torre-Castro et al., 2017/Gender analysis and seascape). Here, only the main findings and benefits of including gender in SSF research are highlighted and illustrated.

Seagrasses are an important fishing ground all over the world (Nordlund et al., 2018) in which SSF are highly represented. Particularly in Zanzibar, Tanzania, they provide a large amount of ecosystem goods and services, such as seagrass associated fish and invertebrates, bait for fishing, fishing grounds and substrate for seaweed farming. Other services were the use of seagrass as fertilizers, for traditional medicine and in cultural activities (de la Torre-Castro and Rönnbäck, 2004). Since seagrasses are part of larger biophysical units (i.e., seascapes) providing an even larger amount of services, the characterization of the seascape was a major part of the gendered social-ecological analysis and was done through transects, satellite pictures, aerial pictures and observation in selected places in Zanzibar (de la Torre-Castro et al., 2017). Mapping of the people allowed the collection of disaggregated data on men and women and using interviews and diaries enabled the performance of a thorough gender analysis. The key factors for understanding the gendered social-ecological situation were: (1) To have a spatial view of resources and resource users along the seascape, (2) To identify the key goods and services that differ between men and women, (3) To identify key ecosystems for subsistence and income provision, and (4) To identify management gaps and/or biases (see **Table 1**). The seascape characterization provided the first layer of knowledge (the biophysical space and its condition with related natural resources). The mapping of the people and the management options were then superimposed on this (layers 2, 3, and 4). The result provided a robust understanding of the situation. The most important management result was that men-dominated activities – in this case, coral-associated SSF - are the ones given attention and are backed up economically by governmental agencies (**Figure 1**). In addition, gendered inequalities were found in income. In almost all cases, men earned more than women for all coastal/marine related activities. Another key finding was that the importance and perception of ecological goods and services was also gendered (recently the gendered nature of ecosystem services has been highlighted e.g., de la Torre-Castro et al., 2017; Fortnam et al., 2019; Nagoli et al., 2019). Women participation in management and decision-making was low and inequalities were found not only in economic terms but also in terms of household chores distribution, traded fish, access to markets, etc.

Specifically in relation to management of seagrass meadows, it was found that management plans tend to focus on men and finfish fishing in corals, whilst in fact, many of the activities with the greatest impact on seagrass meadows were women-related in form of invertebrate collection (Nordlund et al., 2010; Fröcklin et al., 2014), growing of red seaweed over the meadows (Fröcklin et al., 2012) and subsistence fisheries (Williams, 2002; Matsue et al., 2014; de la Torre-Castro et al., 2017). Fröcklin et al. (2014) showed that collection activities could cause negative changes in invertebrate populations in a relatively short time span (e.g., 5 years). Seaweed farming

TABLE 1 | A generic social-ecological model for inclusive management through gender integration in ocean/coastal settings with associated small-scale fisheries (SSF).

Layer of knowledge	Possible methods to acquire information	Key issues and comments	Strengthen "positive" gender aspect (see Assessing the Literature for Positive Features of Gender Inclusion: *The Why*)
1. Mapping and characterization of the seascape	Transects, aerial pictures, satellite photographs, etc. Ecological studies of ecosystems and associated species Social-ecological inventories Focus is on gaining knowledge about the biophysical component	Knowledge about the basin and key ecosystems and species is needed	Space
2. Mapping and characterization of resource users	Photographs, ethnographic research (e.g., following people in their daily activities), interviews, focus groups, participatory mapping, analysis of data loggers (e.g., fisher boats and fishing grounds, counting men and women on board and their roles), activity diaries Focus is on knowledge about disaggregated resource users, activities and ecosystem goods and services of relevance	Knowledge about who is doing what along the seascape is needed, identification of key activities, ecosystems and resources used Identification of key gendered goods and services	Space, actors and activities
3. Gender analysis	Different types of interviews, observation, different constellations of focus groups, historical analysis, analysis of socio-cultural context, ethnographical analysis, sociology, political science methods, political ecology, different feminist school of thought, Women and Development approaches, Livelihoods approach There are no simple recipes to analyze gender. Each case is unique. Focus is on disentangling who **has power** to do what and why, and posing relevant questions. Examples of key questions: What is the explanation for the resource and ecosystem use observed? What are the gendered relationships vis-à-vis nature? What are the interrelations between women and men? How do activities in the coastal zone relate to the household? What are the societal restrictions for each gender? What are the societal expectations for each gender in this particular context? What are the institutions in place reinforcing inequality?	Harding's (1986) typology can be used as a heuristic tool for this analysis. This typology comprises three categories: *Gender structure* which relates to the working activities resulting in a division of labor (see section about mapping above). *Gender symbolism*, which encompasses the socio-cultural factors defining what, is perceived as feminine or masculine. *Individual gender* which concerns how identity is constructed and how it may change over time. This approach has been very useful as the three categories are clear and the analysis provides a strong basis with which to gather initial knowledge about the gendered situation in coastal areas. After having this knowledge base, further steps may include other types of more complex analysis, for instance using intersectionality.	All combined This is the main contribution of "inclusive management" and "social-ecological" gender analysis Economic analysis should be included here to analyze inequalities
4. Integration of information	Interdisciplinary analysis, complexity analysis, use of GIS (Geographical Information Systems), including participatory GIS; participatory methods (to understand the current situation), participatory scenario building (to understand possible futures and areas for transformation); analysis of norms, images, views and mental models Focus on linking the previous layers of information	Diversity of knowledge and actors is needed for the integration	Participation Equity
5. Tailoring management plans	Integration of information into existing management structures (e.g., Integrated Coastal Zone Management, Marine Spatial Planning, Ecosystem based management, MPAs, etc.), a total change in management approach may also be needed, but that transformation is more costly to carry out (in both time and resources)	Measures to reduce the identified inequalities in participation, access to resources, access to economic benefits, conservation and planning	Participation Equity
6. Implementation	Participation, co-management, adaptive co-management, community based-management; etc.	Identify key actors and positions to implement the measures, set clear objectives, indicators of success and time targets	Participation Environmental stewardship and equity
7. (Re-) Evaluation and iteration	Performance analysis, participatory methods, gradual model adjustment	Analyze the performance, continue if positive, adapt and change if negative. Evaluate in a holistic manner both biophysical indicators and social indicators with special focus on gender and equity. Managers should always provide feedback to the actors	Participation Equity

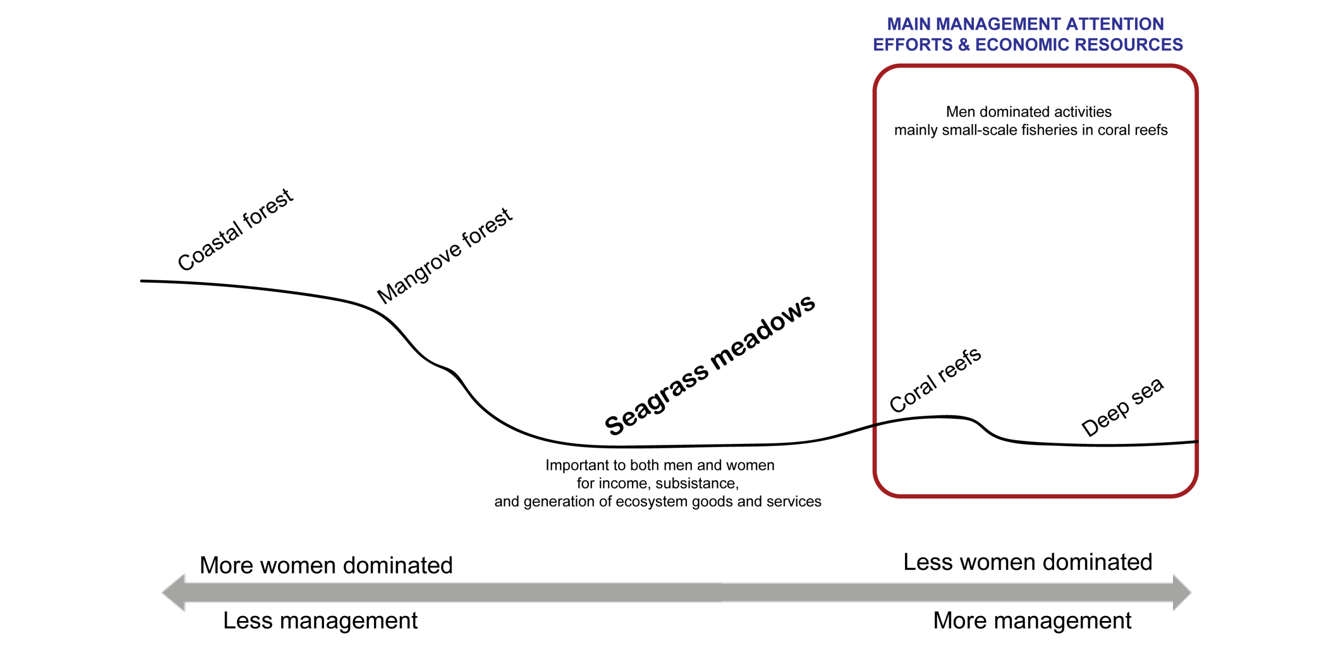

FIGURE 1 | The tropical seascape with differential gender domination and SSF management efforts in Zanzibar, Tanzania. Data from de la Torre-Castro et al. (2017).

of red Euchemoid species is traditionally done over seagrass meadows (de la Torre-Castro and Rönnbäck, 2004) and negative effects have been identified for seagrasses and macrofauna (Eklöf et al., 2005); farms hinder potential seagrass biomass increase, especially in tall and large seagrass species (Eklöf et al., 2006b) and they change seagrass fish community composition (Eklöf et al., 2006a). In addition to the ecological changes, farming had a detrimental effect on farmers' health (Fröcklin et al., 2012) and income provision was too low to be able to break poverty traps (de la Torre-Castro et al., 2017).

Gender inequalities were found in access to ecosystems and management focus (management was always androcentric), but seagrasses were of high value to both men and women and, relative to other ecosystems, provided good income generation (de la Torre-Castro et al., 2017). The study also shows that women have a strong spirit of entrepreneurship. Literature has found that women are normally "motors" of economic development (e.g., Jerneck, 2018). There is a lot to do in this regard and attention has been given to, for instance, the role of women in fish markets (Fröcklin et al., 2013) and for the whole fish value chain (Drury O'Neill and Crona, 2017). Fish associated with seagrasses seem to dominate catches in the Western Indian Ocean, so these points are central to policy (e.g., Wanyonyi, 2018).

In terms of seagrass conservation, both men and women were concerned for their status. However, the need to perform economic activities that in many cases damage the meadows (e.g., aquaculture, fishing with drag-nets) hinders conservation. Here the intersectionality perspective (Crenshaw, 1991; Lykke, 2009 chapter 5); could be of great value. Intersectionality refers to the analysis of how gender and other categories such as class, race, etc. interact, and it has been identified as a key issue for future research in gender and environment (Hawkins et al., 2011; Nightingale, 2011; Ravera et al., 2016). In tropical seagrasses settings, problems of gender and poverty are deeply intertwined. In temperate settings, other issues like gender and education may play an important role.

For seagrass ecosystems in general, there is an imbalance between knowledge of the ecological system vs. the social one. There is a lot of knowledge about the ecology of seagrass meadows, but relatively little about their fisheries and other types of societal goods and services (Nordlund et al., 2018). The gendered social-ecological analysis proposed here is just at the beginning, thus replication of these type of studies is urgently needed for the improvement of management and for policy reform.

The research described above covered the three first layers of knowledge and partly the fourth layer of the model (see **Table 1**). However, the next layers require cooperation with local people, managers and civil society organizations. Scientific research alone is not enough to fulfill the whole management cycle, which includes other actors than researchers and other processes than just scientific enquiry. Managers, resource users, organizations, testing and reevaluation are structures and processes of management cycles. There is a need to include scientific work in formal management processes in new and productive ways. Research-financing bodies can play an important role supporting initiatives linking science with real management situations.

CONCLUSION

As discussed above, dealing with gender and coastal/marine management is a complex task putting high demands on the way SSF should be handled. Gender inclusion in governance, management and policy requires a new way of thinking and significant knowledge about how to understand gender both *vis-à-vis* nature and social relations. There are no simple ways to perform social-ecological analyses that integrate gender. In this text, it is argued that gender inclusion seems to be positive for promoting ocean/coastal sustainability. The text provides the basis for this argument; *the why*, based on evidence of previous experiences with other systems (e.g., forestry, water, agriculture, etc.) where gender inclusion has been positive and desirable, The inclusion of women has been found to be positive in terms of participation; space, actors and activities; economic power, as well as equity and environmental stewardship. Based on this knowledge, it is concluded that "inclusive management" which integrates gender and the involvement of women might be a way forward to help to address the bad situation of ocean/coastal resources. Inclusive management is considered here as any management option that *explicitly* and *consciously* considers a diversity of actors (and the first obvious ones are men and women). Knowing *the why* is necessary but not sufficient; there is also a need to address *the how*. This contribution provides an organized way to address gender integration for management enhancement and policy reform. A social- ecological model to understand gender is proposed as a hands-on way to work with inclusive management and to facilitate gender analysis. The model is built by superimposing layers of knowledge in which gender analysis is embedded. The social-ecological nature of the model, by considering both social/cultural factors and the access to and use of ecosystems and ecological resources, makes it a good candidate to facilitate the understanding of gendered situations and to visualize management and policy reform.

A FEW WORDS ABOUT THE FUTURE

As the "Anthropocene" continues unfolding, instability, shocks and disturbances are expected to increase (e.g., Steffen et al., 2011). New institutions and environmental management regimes are urgently needed to curb degradation and boost optimism. In this regard, resilient systems are needed in order to be able to tackle disturbance. Since resilience is enhanced by diversity (e.g., Folke et al., 2004) adding gender has great potential to facilitate progress toward positive pathways.

However, gender and resilience research is still in its infancy. Two recent studies reach opposite conclusions; one states that it is better to maintain a pluralistic approach and diversity of methods, i.e., not only using resilience thinking (Kawarazuka et al., 2017), whilst the other study advocates for linking resilience and critical feminist social theory (Iniesta-Arandia et al., 2016). There is a clear need to develop more gender research in Natural Resource Management and link to key approaches such as resilience, vulnerability, limits of growth and the relatively new approach for Earth sustainability, i.e., the planetary boundaries (Steffen et al., 2015).

For SSF it is imperative to advance gender knowledge. Quantitative as well as qualitative data is needed. Quantitative studies are crucial for economic analysis for example, while qualitative research, for example in the form of rich narratives, are key for in-depth understanding of the gendered social-ecological situation. SSF are context specific, but in the contemporary world, they are connected to global markets and peoples' lifestyles. So cross-scale considerations are needed too. Moreover, since a vast majority of SSF take place in the tropics, clear links to the Sustainable development goals (SDGs) are necessary (Agenda 2030, 2015). In this regard, the most obvious links are between goal no. 14 "Life below the water" and goal no. 5 "Gender equality." As gender research in SSF grows stronger, the FAO voluntary guidelines for SSF (FAO, 2015) will gain in legitimacy and knowledge acquisition, bringing a positive development for global SSF's future.

AUTHOR CONTRIBUTIONS

MdlT-C conceived the idea, wrote the whole manuscript, and analyzed the literature.

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Securing a Just Space for Small-Scale Fisheries in the Blue Economy

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The vast developmental opportunities offered by the world's coasts and oceans have attracted the attention of governments, private enterprises, philanthropic organizations, and international conservation organizations. High-profile dialogue and policy decisions on the future of the ocean are informed largely by economic and ecological research. Key insights from the social sciences raise concerns for food and nutrition security, livelihoods and social justice, but these have yet to gain traction with investors and the policy discourse on transforming ocean governance. The largest group of ocean-users – women and men who service, fish and trade from small-scale fisheries (SSF) – argue that they have been marginalized from the dialogue between international environmental and economic actors that is determining strategies for the future of the ocean. Blue Economy or Blue Growth initiatives see the ocean as the new economic frontier and imply an alignment with social objectives and SSF concerns. Deeper analysis reveals fundamental differences in ideologies, priorities and approaches. We argue that SSF are being subtly and overtly squeezed for geographic, political and economic space by larger scale economic and environmental conservation interests, jeopardizing the substantial benefits SSF provide through the livelihoods of millions of women and men, for the food security of around four billion consumers globally, and in the developing world, as a key source of micro-nutrients and protein for over a billion low-income consumers. Here, we bring insights from social science and SSF to explore how ocean governance might better account for social dimensions of fisheries.

Keywords: Blue Growth, conservation, economic, development, human-rights, ocean governance

INTRODUCTION

The world's coasts and oceans offer vast opportunities to support economic development and are increasingly prominent in the discourse on global environmental futures (Lubchenco et al., 2016). A critical challenge for adapting ocean governance for the 21st century is to balance competing interests, to realize economic potential while avoiding irreversible environmental change. Simultaneously, ocean governance transformations must ensure that the human rights of those who depend on the sea for their livelihoods are respected, that benefits of growth are equitably distributed and that human well-being of coastal and marine-resource dependent people is maintained or enhanced (Leach et al., 2012). This is the "safe and just space" that defines the scope for sustainable development more broadly (Dearing et al., 2014). Small-scale fisheries (SSF) provide a powerful example of the way in which contemporary changes to ocean governance are balancing, reconciling and trading off multiple interests and objectives.

In developing countries oceans support 47 million women and men engaged in small-scale fishing and fish-trading (World Bank et al., 2012). However, SSF are increasingly squeezed by industrial fishing fleets and large-scale aquaculture servicing global seafood buyers, the establishment of no-fishing reserves for conservation, coastal development and industrialization of seascapes, and the pursuit of mineral wealth (Bavinck et al., 2017; Said et al., 2017; **Figure 1**). The economic promise of oceans has captured the attention of conservationists, business leaders, funders, governments, and multi-lateral organizations including the United Nations and the World Bank. This is illustrated by an uptick in global ocean-focused conferences that have previously framed conservation as the leading agenda, which now emphasize a focus on the "Blue Economy" (Bennett, 2018). The "Blue Economy" and "Blue Growth" agendas frame the ocean as the new economic frontier. For example, the now annual World Ocean Summit, hosted by *The Economist* (the most recent one took place in Abu Dhabi in March 2019) is attended by business leaders, big international conservation non-government organizations and economists who aim "*to deepen engagement with the private sector and particularly private capital's involvement with the ocean*" (Project AWARE, 2018) with a vision of "*an ocean in robust health and a vital economy*." The Blue Economy aims to tap into the estimated USD 24 trillion in potential goods and services (i.e., energy generation, mining, tourism, maritime transport, aquaculture, and capture fisheries), derived from the world's oceans, and to balance industrialization of oceans with environmental protection (Hoegh-Guldberg et al., 2015; The Economist, 2015). Initiatives framed around the Blue Economy or Blue Growth purport that economies, societies and marine environments will all benefit; however, the logic for reaching these win:win:win outcomes through the strategies described has been contested (Silver et al., 2015; Barbesgaard, 2018; Brent Z.W. et al., 2018). It has been argued that these same strategies have not led to environmentally sustainable and equitable outcomes on land (e.g., Clark et al., 2018), so there is little reason to expect them to perform better at sea.

Oceans provide broad-based public goods; the governance strategies and management practices proposed in Blue Economy initiatives may lead to, or accentuate, inequitable capture of these goods to generate private wealth for a relative few (Béné et al., 2010). There are concerns expressed by small-scale fisher groups that the Blue Economy agenda undervalues social objectives, and in doing so threatens the basic imperative of providing both livelihoods and affordable, nutrient dense food for those who need it most (e.g., Pamalakaya-Pilipinas, 2015). To date, considerations of food security and human rights have not been front and center in high-level dialogue around the Blue Economy. Small-scale fishers have been notably underrepresented (e.g., World Ocean Summit held in 2017; Our Oceans Conference held in 2018) considering that SSF employ more women and men than all other ocean economic sectors combined (World Bank et al., 2012; OECD, 2016)[1]. This imbalance has raised considerable concern from small-scale fisher associations, other civil society groups, social scientists and development practitioners (Brent Z.W. et al., 2018). These actors have spear-headed strong resistance to ocean initiatives that were viewed as driving economic reforms (WFFP and WFF, 2013) and more recently those specifically aligned to the Blue Economy agenda (Pamalakaya-Pilipinas, 2015; Brent Z. et al., 2018; World Forum of Fisher Peoples, 2018).

The Blue Economy and other initiatives frame transformation as necessary to "fix" an ocean that is in an environmentally degraded and economically underperforming state. Here, we offer three additional considerations for the Blue Economy, or other initiatives grounded in 'environmental crisis' and 'untapped economic frontier' narratives. Firstly, we explain why market-based trajectories of change put forward as part of the Blue Economy pose risks to the benefits that SSF provide to society. Second, we emphasize SSF as uniquely placed to produce and distribute food and income to those whose nutritional and financial needs are greatest. Finally, we call for more meaningful uptake of well-developed inclusive governance principles by engaging emergent governance platforms to ensure that the course navigated is one toward sustainable, equitable and just ocean futures.

BLUE GROWTH TRADE-OFFS

As the use of ocean and coastal resources and space intensifies, and particularly as the idea of Blue Growth and the Blue Economy takes a prominent place in policy discourse, the need to identify and manage tradeoffs becomes increasingly urgent. Governance of the oceans is frequently represented as failing, and SSF are often portrayed as disparate, disorganized and dysfunctional (Cunningham et al., 2009), or as intensely exploitative and environmentally destructive (Vincent and Harris, 2014). Indeed, ocean governance propositions must account for the adverse social and ecological impacts that SSF can have (Johnson, 2006), and poverty and low human well-being that reside within some

[1] There are an estimated 60 million workers engaged in SSF (World Bank et al., 2012) while other sectors combined employ ca. 31 million (OECD, 2016).

FIGURE 1 | Small-scale fisheries, amidst contemporary pressures on coastal systems and ocean space. **(A)** In developing countries fish caught by SSF are an important source of protein and essential micro-nutrients – often in these contexts nutritional alternatives are limited. Men, and women, are active in SSF harvesting, post-harvest processing and marketing [Wade Fairley (copyright – used with permission), Malaita Province, Solomon Islands, 2012]. **(B)** Informal fisheries market chains contribute to livelihoods of hundreds of millions of people [Dominyk Lever (copyright – used with permission), Cambodia, 2004]. **(C)** Despite the growth of aquaculture, people in developing countries continue to rely on SSF, and will so for decades to come [Edward Burtynsky (copyright – used with permission), Luoyuan Bay, Fujian Province, China, 2012]. **(D)** In many regions SSF exist within increasingly contested ocean and coastal space [Jamie Oliver (copyright – used with permission), 2008, Penang, Malaysia]. **(E)** SSF can adapt to marine developments [Lorelei Stevens (copyright – used with permission), Commercial Fisheries News, River Thames, United Kingdom, 2013]. **(F)** but also can be squeezed out by expansive development or privatization [Edward Burtynsky (copyright – used with permission), Lee County, FL, United States, 2012].

SSF systems (Béné,, 2006). To balance this perspective, small-scale fishers are also considered for their potential as resource stewards (Bennett et al., 2018) and as small-scale entrepreneurs whose aggregate activities have "multiplier" effects in local and regional economies (Bavinck, 2014). In this section we draw attention to the risks that emerge from either "crisis" or "new economic frontier" narratives, and the Blue Economy tactics proposed.

Currently, a dominant policy response to improve governance is marine spatial planning to delineate ocean space and allocate it among different sectors (Jones et al., 2016; Said et al., 2017; Bennett, 2018). Marine spatial planning defines spaces for industrial development, for fishers, energy, land reclamation for development (Ding et al., 2014), and marine reserves that separate conservation from other uses (Ehler and Douvere, 2009). While marine spatial planning is a practical strategy to manage multiple uses, there are risks in how spatial allocation plays out politically (Kerr et al., 2015; Jones et al., 2016). These risks include marginalization of small-scale fishers from decision processes, and in the allocation of space for tourism and conservation, for example (Segi, 2014; Hill, 2017). Technical or evidence-based approaches are valuable to planning, yet can be misused in ways that, rather than highlighting tradeoffs and identifying winners and losers, promote the appearance of being benign and apolitical (Li, 2007). Yet, research suggests that marine spatial planning, and the often embedded establishment of marine protected areas, are too frequently implemented through top-down processes underpinned by sectoral objectives, such as biological conservation and promotion of offshore energy (Jones et al., 2016; Flannery et al., 2018). Better use of the collaborative and integrative elements, and data on multiple dimensions of the trade-offs being negotiated, would enable marine spatial planning to be a useful part of a process to navigate toward both *inclusive* and *sustainable* development (Bennett, 2018).

On current trajectories, efforts to delineate ocean and coastal space hold strong parallels with other significant conversions of a public or community-held resource into private goods (such as those that took place through colonization) and risks a similar disenfranchisement of the maritime equivalent of peasant farmers (Araghi, 1995; Bernstein, 2010; Linebaugh, 2014). This trend is known among its critics as "ocean grabbing" or "coastal grabbing," and attracts similar concerns for food and nutrition security as those expressed regarding contemporary large-scale land acquisitions (Franco et al., 2014; Bennett et al., 2015; Bavinck et al., 2017; Barbesgaard, 2018). Driven by economic interests relating to newer industrial developments such as aquaculture, mining and tourism, as well as conservation of the coasts (e.g., mangrove conservation for blue carbon), this trend contributes to the growing squeeze that small-scale fishers face (Cormier-Salem and Panfili, 2016; Said et al., 2017; Bavinck et al., 2018; Brent Z.W. et al., 2018).

To optimize wealth creation, spatial allocation is often packaged with market-based instruments (Anon, 2014; Holmes et al., 2014), including fostering links to global markets (Sampson et al., 2015), and institutionalizing licenses and taxes to maximize revenue (Hoegh-Guldberg et al., 2015). A convincing argument for some is that replacing or consolidating SSF into larger industrial operations will streamline management, improve productivity, and increase economic return (Cunningham et al., 2009). These are the fundamental building blocks of what are described as rights-based approaches that prefer transferable quotas or purchasable rights. In sum, these approaches are based on assumed economic incentives that come when community or individual rights of ownership or access to a fisheries resource or fishing ground have been clearly defined (Allison et al., 2012). The view that this is the best approach to manage fisheries is influential in ocean governance policy and dialogue (Barner et al., 2015; Barbesgaard, 2018).

A rights-based approach rolled out using individual transferable quotas fundamentally differs in its underpinnings and implementation from a *human*-rights approach; the latter being advocated by small-scale fishers and their supporters (Allison et al., 2012; World Forum of Fisher Peoples et al., 2016) and which stresses alignment to a broader human-rights based approach to international development, adopted by many international development agencies since the late 1990s (Ratner et al., 2014). For those with an eye on human rights and well-being, the implementation of (fishing) rights-based strategies designed strongly toward an economic rationale raise serious concerns that fisheries benefits will largely be captured and controlled by a relatively few powerful entities (Béné et al., 2010; Cardwell, 2015; Høst, 2015). An additional challenge is that the economic rationale and objectives of powerful actors and well-resourced (economic or environmental, for example) initiatives may not be as transparent as they need to be. Deeper analysis of the different ways in which the terms "Blue Economy" or "rights" are invoked illustrate that fundamental divides remain in ocean governance objectives and the proposed mechanisms through which they will be realized – even where discourses appears, on the surface, to align (Silver et al., 2015; World Forum of Fisher Peoples et al., 2016; Voyer et al., 2018).

Global markets undeniably present opportunities for SSF but pose similar risks as privatization. In servicing global markets, intermediaries who control distribution may capture increasing benefits at the expense of fishers (Purcell et al., 2017), at the same time making fish less accessible to the poor. Breaking the connection between consumers and their local food system introduces new vulnerabilities generated by volatilities in global food markets and distribution channels. There is also strong evidence that gains generated in distant markets, and the income from large scale enterprises and centralized revenue collection rarely trickle down to benefit local producers and those most in need (Wilson and Boncoeur, 2008; Béné et al., 2010, Béné et al., 2016). The governments and funders backing the Blue Economy must weigh fisheries governance models driven by narrow economic rationale, as well as non-fisheries developments, against the risks they bring to local food, nutrition and livelihood systems, and the control that local women and men have within those systems.

BENEFITS OF SMALL-SCALE FISHERIES

Fish are a source of essential micro-nutrients for more than four billion consumers and provide more than one sixth of the global demand for animal protein (Béné et al., 2015). Growing populations and greater prosperity escalate demands for fish globally (Béné et al., 2015). The Blue Economy is concerned with increasing food production from the sea, but there is little evidence of the consideration given to whether this production will benefit those with the most pressing food and nutritional needs.

Aquaculture is the fastest growing food sector globally and the potential to achieve large increases in production sit well with the Blue Economy agenda (European Commission, 2012). Yet, aquaculture developments can compete for geographic space, fisheries resources, and impact environmentally upon fishing grounds of SSF. The potential for aquaculture to generate income, produce food, and even conserve species and habitats is lauded without explicit recognition of these interactions and tradeoffs (e.g., Froehlich et al., 2017). There are concerns that growth in aquaculture responds to market demand for particular types of fish from those most able to pay, or that farmed fish do not meet, or reach, the nutritional needs of the most nutritionally vulnerable children, women and men (Golden et al., 2016; Bogard et al., 2017). However, where aquaculture does lead to greater supplies of fish in domestic markets of developing nations, to realize optimal social benefits, aquaculture can indeed *complement* rather than replace fish supplied by SSF (Toufique and Belton, 2014; Belton et al., 2016).

Despite aquaculture expansion in some regions, capture fisheries still produce about half the world's fish, much of which is consumed locally or by those who catch it. Some 97% of the world's fishers live in developing countries, of which 90% are engaged in the small-scale sector (World Bank et al., 2012). Increases in supply from aquaculture and well-managed industrial fishing will help meet increasing global demand, particularly from relatively affluent consumers or where assumptions about redistribution can be met. Yet, poor and marginalized women and men around the world will continue to rely on SSF for food and livelihoods for decades to come – particularly those living in sub Saharan Africa, the mega-deltas of Asia and the small island states of the Pacific (Golden et al., 2017).

Many SSF operate in regions where infrastructure is limited, government accountability and regulations are weak, and in some cases, where conflict disrupts formal trade and food security. A strength of SSF lies in their ability to persist in many of these contexts and continue to generate and distribute food and income where formal markets and global supply chains function poorly. For example, the relatively isolated and rural populations of the Pacific small island developing states exhibit high rates of participation in SSF which provide a foundation of local economies, a principle animal-source protein in diets (Gillett, 2016) and provide a key coping strategy in the face of shocks (Eriksson et al., 2017). Although some SSF may be considered economically dysfunctional and ecologically unsustainable (Cunningham et al., 2009; Vincent and Harris, 2014), the sector continues to generate income and serve the nutritional needs for millions of families worldwide. In some instances, SSF provide routes out of poverty for both men and women, and act as engines of growth at local and national levels (Bavinck, 2014). Furthermore, SSF also have broader non-monetary values, and play an important role in maintaining the identity, culture and the wellbeing of coastal communities (Jentoft and Eide, 2011; Weeratunge et al., 2014).

Resilient SSF have adapted and modernized, and in many instances are both sophisticated and highly efficient – although not always moving in the direction of improved ecological sustainability. Despite some SSF having long histories and cultural connections, SSF are not necessarily antiquated or outmoded, and cannot be dismissed simplistically as historical relicts of a bygone age. Small-scale fishers in poor countries have been early adopters of technologies such as mobile phones, e-money and global positioning systems (Jensen, 2007), and have responded to demands from new markets, such as the emergence of live reef fish exports from the Philippines to China (Fabinyi et al., 2014). SSF contribute to diversified livelihood systems that enable coastal people to benefit from fluctuating fisheries (e.g., Allison and Ellis, 2001; Cinner and Bodin, 2010), while simultaneously benefitting from opportunities in agriculture, tourism and the urban economies of rapidly changing coastlines (Betcherman and Marschke, 2016; Lowe and Tejada, 2019).

The dynamic nature of SSF has seen them persist despite ever-increasing and diverse pressures. As with every industry that draws on ecosystem services, SSF will need to continue a trajectory of change to sustain ecological, economic and social outcomes. Where seascapes are rapidly transforming, SSF must also adapt to coexist with potentially competing sectors such as tourism, conservation, offshore energy and industrial fishing. Yet, despite their adaptability, there is a limit to how far SSF can be squeezed without substantial loss of the benefits they provide. A physical, economic and political operating space for SSF must be maintained if they are to continue to deliver nutritious food to those in need, to efficiently distribute economic benefits widely, and remain adaptive and flexible.

We do not know if replacing the food and employment provided by SSF would cost more than the potential economic gains that arise from governance reforms to maximize efficiency. Calculations of the aggregate gains that could be made by optimizing global fisheries toward their maximum economic yield (Srinivasan et al., 2010; Costello et al., 2016) are optimistic, in that they rely heavily on the assumption that gains made will trickle down and will be equitably distributed in such a way that, for example, brings benefit to the poor and malnourished. Further, the cost and delayed rewards of such reform may be beyond the capacity of many poor countries (Béné et al., 2010) and may meet with strong political resistance which would increase social and economic costs.

OCEAN FUTURES

Sustainable development policy in the anthropocene must navigate the space between the environmental ceiling or "planetary boundaries" (Steffen et al., 2015) and a "social foundation" (Raworth, 2012). To date oceans and coasts have not been well accounted for in the calculation or conceptualization of planetary boundaries; yet data and approaches to integrate marine systems have been laid out (Nash et al., 2017). Governing within planetary boundaries that account for marine systems will require collaborative approaches that may be guided by quantitative and participatory foresight models and scenario development, within which tradeoffs between different objectives and amongst different sets of actors can be explicitly examined and negotiated (Nash et al., 2017). Lack of data exacerbates the low visibility of SSF in ocean policy. The on-going Illuminating Hidden Harvest initiative (WorldFish et al., 2018) will provide the data required to ensure global reviews and foresight studies properly include SSF. With awareness of power differentials between actors and relative priority given to different objectives, addressing this global environmental governance challenge provides an opportunity to more closely examine transformative ocean governance initiatives, such as those within the Blue Economy.

In efforts to ensure that the rights, interests and voices of SSF are respected in this challenge, the Food and Agriculture Organization facilitated the production of the *Voluntary Guidelines for Securing Sustainable Small-scale Fisheries in the Context of Food Security and Poverty Eradication* (FAO, 2015), incorporating the input of some 4000 fisher, government and community representatives. In 2014 the "SSF Guidelines" were formally adopted by 143 member states. These guidelines propose principles that are sensitive to food security, and human rights, and that promote empowerment and inclusive decision-making. This is a substantial step forward in ensuring SSF perspectives are addressed and it is encouraging to see the guidelines being referred to not only by fisherfolk organizations, but by conservation non-government organizations and governments (Jentoft et al., 2017; Singleton et al., 2017).

The development and mainstreaming of the SSF Guidelines are a major achievement for SSF – representing their economic, social and ecological objectives. These principles provide timely guidance for governments, international institutions, civil society and industry dialogue around the future of the Blue Economy. A just operating space for SSF within the Blue Economy, in accordance with these guidelines, will help ensure that the production and distribution of nutritious, affordable food from the sea – a public good – is not traded off against the pursuit of exclusive conservation or more concentrated wealth. The challenge now is for states and civil society organizations to lead fisheries governance increasingly toward implementation of these principles (Jentoft, 2014). The implementation challenge will be greater where ocean space and resources represent interests for powerful corporate and state actors external to the fisheries and conservation sectors. A recent global meeting of SSF, their supporters and the research community (Too Big To Ignore, 2018) reported progress on the implementation included the preparation of national plans of action, philanthropic and development investment, growing capacity of civil society organizations, and the emergence of new SSF stakeholder platforms (e.g., newly formed fisher civil society platforms in Africa). These initiatives signal a growing social movement amongst a diverse and numerous set of actors, but also demonstrate that there are organized and legitimate representative bodies with which the proponents of the Blue Economy agenda can hold dialogue to bring better alignment with a social justice agenda.

Small-scale fisheries are diverse, dynamic, and complex. Governance scenarios for ocean futures must accommodate this diversity without overly simplified or "blue print" approaches. The future of the ocean will likely include some forms of rights-based approaches, and where these are embedded within a human-rights approach, alignment with the SSF Guidelines is possible (Song and Soliman, 2019). Ocean governance will however, require an expanded set of management approaches (e.g., adaptive co-management), decision supporting tools (e.g., foresight, scenario and trade-offs), engagement strategies (e.g., multi-stakeholder platforms and governance networks) and accountability and monitoring mechanisms. A safe and just space will rely on there being a good fit between the nature of fishery systems and the institutions that govern (Folke et al., 2007). A range of examples demonstrate that inclusive and interactive governance can successfully manage the tensions between national and regional economic growth, local livelihood resilience, and food and nutritional security for those most in need (Jentoft and Chuenpagdee, 2015). There are examples emerging of where SSF have sustained ecological resources even under relatively high pressure, for example, in coastal areas where local governance institutions persist and are suggested to contribute to sustained ecosystems (Cinner et al., 2016). Whilst the social, ecological or economic achievements of such examples must still be subject to ongoing critical evaluation, they illustrate some successful pathways to negotiate among societal actors at multiple scales. Research can continue to contribute by offering an enquiry that is sensitive to equity and power, and by making explicit successes, and trade-offs, in changes to ocean governance.

CONCLUSION

Contemporary ocean governance reforms commonly recognize the potential for economic wealth alongside the risks of ecological sustainability. We argue that it must also account for the potential social impacts that a focused drive toward economic wealth will have. Avoiding these social impacts, and retaining the benefits SSF provide to society, requires improved representation of SSF in international, national and multi-stakeholder policy and investment arenas – this has been a substantial challenge given the sector's dispersed, diverse and dynamic nature. The more recent formations of regional and sub-regional SSF platforms (that engage with and/or nest within existing global groups) now make this a surmountable challenge. More inclusive dialogue may uncover the nature and extent of concerns over the current array of economic reforms and bring forward a broader suite of ocean and fishery governance solutions, including those that maintain traditional systems of communal or common property resource management. Determining and implementing the suite of approaches that consider social objectives alongside wealth generation and conservation, and that are adaptable to the diverse contexts in which SSF operate, will benefit from scrutiny of scenarios through participatory processes. If the Blue Economy is to be a legitimate vision for governing the oceans, then alongside industry and conservationists, the voices, interests and human rights of the largest groups of ocean-users – women and men who service, fish and trade from SSF – must be represented and recognized from the outset of the solution design. These are primary rights holders to whom ocean governance must be accountable.

AUTHOR CONTRIBUTIONS

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Defining Small-Scale Fisheries and Examining the Role of Science in Shaping Perceptions of Who and What Counts: A Systematic Review

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Small-scale fisheries (SSF) have long been overshadowed by the concerns and perceived importance of the industrial sector in fisheries science and policy. Yet in recent decades, attention to SSF is on the rise, marked by a proliferation of scientific publications, the emergence of new global policy tools devoted to the small-scale sector, and concerted efforts to tally the size and impacts of SSF on a global scale. Given the rising tide of interest buoying SSF, it's pertinent to consider how the underlying definition shapes efforts to enumerate and scale up knowledge on the sector—indicating what dimensions of SSF count and consequently what gets counted. Existing studies assess how national fisheries policies define SSF, but to date, no studies systematically and empirically examine how the definition of SSF has been articulated in science, including whether and how definitions have changed over time. We systematically analyzed how SSF were defined in the peer-reviewed scientific literature drawing on a database of 1,723 articles published between 1960 and 2015. We coded a 25% random sample of articles ($n = 434$) from our database and found that nearly one-quarter did not define SSF. Among those that did proffer a definition, harvest technologies such as fishing boats and gear were the most common characteristics used. Comparing definitions over time, we identified two notable trends over the 65-year time period studied: a decreasing proportion of articles that defined SSF and an increasing reliance on technological dimensions like boats relative to sociocultural characteristics. Our results resonate with findings from similar research on the definition of SSF in national fisheries policies that also heavily rely on boat length. We call attention to several salient issues that are obscured by an overreliance on harvest technologies in definitions of SSF, including dynamics along the wider fisheries value chain and social relations such as gender. We discuss our findings considering new policies and emerging tools that could steer scientists and practitioners toward more encompassing, consistent, and relational means of defining SSF that circumvent some of the limitations of longstanding patterns in science and policy that impinge upon sustainable and just fisheries governance.

Keywords: small-scale fisheries, capture fisheries, fisheries governance, fisheries policy and management, fisheries science, systematic review, FAO, small-scale fisheries guidelines

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INTRODUCTION

For many the term "small-scale fishery" (SSF) evokes a mental image of small, traditional fishing craft equipped with low-tech gear requiring labor-intensive fishing methods. Fisher*men* are typically the central subjects of this platonic scene, operating boats individually or in small-crews in the pursuit of fish. Even individual fishing strategies are often presumed to follow one of several archetypical models of behavior, whether inherently ecologically and socially harmonious, and therefore sustainable, or conforming to the economically rational, competitive fisher of fisheries bioeconomic models (St. Martin, 2005). This dominant imaginary of SSF is often spatialized, presumably limited to the tropical seas of the Third World, as opposed to the fully capitalist, industrial fisheries that inhabit the First World (St. Martin, 2005).

This prototypical image of fishermen adrift in a sea of small boats is easily conjured, yet it obscures the broader assemblage of diverse livelihood activities that occur along the SSF value-chain. We consider SSF as encompassing these wide-ranging activities undertaken throughout the value chain by both men and women in inland and marine fisheries, including harvesting from boats and on foot, along with pre- and post-harvest labor that occurs on land (FAO, 2015). However, even the term "value chain" can become a misleading metaphor, suggesting tidy relations organized into discrete and equivalent links. In practice, the meshwork of actors and relationships that comprise the value chain are not so clear-cut or orderly, but are rather diffuse, tangled and contingent—assembling and re-assembling into new alignments along an uneven and shifting terrain (Li, 2007; Anderson and Mcfarlane, 2011). The geographic and temporal extent of SSF value chains defy common assumptions about their smallness. The reach of small-scale value chains is not limited to the global south: SSF are found in inland waterways and seas across the globe, spanning different freshwater and marine ecosystems, development contexts, and political arrangements. Nor are they confined to the past, despite conventional associations between SSF and traditional practices: SSF have persisted as a way of life throughout human history through adaptation to changing social, environmental, and economic conditions.

In this paper we probe the gap between the heterogeneous and dynamic existence of SSF in practice and the one-dimensional caricature typically portrayed and embedded within the dominant imaginary of SSF. We take the definition of SSF as an entry point to explore this enduring paradox and consider how practices of knowledge production have shaped perceptions of what SSF are, and therefore, how they should be valued and governed.

Dividing Capture Fisheries Into Small-Scale and Industrial Categories

Fish resources are one of the last hunted commodities on earth, pursued through a variety of tools and techniques ranging from spears and traps to sonar detection (Campling et al., 2012). Collectively these activities are known as capture fisheries, a motley grouping that includes seemingly disparate fishing enterprises, including families or collectives gleaning on foot in the intertidal zone, hired crews of 3–5 fishers working from wooden or fiberglass boats fashioned with outboard motors, and industrial trawlers the size of a football field with onboard processing facilities (World Bank, 2012). For the purposes of studying and managing these activities, the full spectrum of capture fisheries is often simplified and divided into "small-scale" and "large-scale" or "industrial" fisheries: categories that are presumed at first glance to be distinct and mutually exclusive. Exactly where to draw the line between these categories is contested, but typically the division hinges on assumptions about the role of fishing technologies and the nature of human progress. Rather than depicting SSF and industrial fisheries as coextensive categories, representing "disaggregated and diverse sets of practices unevenly distributed on the economic landscape" (Gibson-Graham, 1997), this binary template is tacitly understood as both a spatial and temporal hierarchy—where industrial fisheries are the dominant category, located in the First World and temporally ahead of SSF along a unilinear path toward progress. Arrayed this way, industrial fisheries appear to succeed SSF in an evolutionary-like model of fisheries development as the naturally dominant and more efficient mode of production (Gibson-Graham, 1997; p. 115). With each category defined by their presumed technological differences, this division circumscribes SSF as the subordinate category—an inefficient mode of fisheries production from the past—while industrial fisheries are depicted as the natural progression and future of fishing. "Against this narrow imagination of an industrial fishing future" (Jadhav, 2018a), SSF are implicitly (and at times explicitly) treated as the subordinate category and conferred a more marginal status and a lower priority on national and global fisheries agendas.

Disregard for SSF is evident in the history of the modern institutions of fisheries science and management, which arose to address the challenges of industrial fisheries and intensifying resource exploitation in the early twentieth century (Cushing, 1988; Smith, 1994; Johnsen et al., 2009). Meeting the demands of the rapidly expanding fishing industry after the turn of the century required new kinds of data and scientific expertise focused on quantitative understandings of individual stocks and their relationship to fishing effort (Cushing, 1988). Scientific techniques of translation were needed in order to transform fish into natural resources—inputs suitable for capitalist production (Luke, 1995; St. Martin, 2005). In addition to new methods of discursive representation and calculation, implementation of scientific management plans required centralized oversight and the creation of new government bodies to administer fisheries (Jentoft et al., 1998). Ideologically this new mode of fisheries management was founded upon an innate optimism and trust in experts' ability to translate unruly fish, fisher folk, and technologies into abstract objects that could be ordered and managed through the application of economic rationality and mathematical models (Mccay and Finlayson, 1995; Johnsen et al., 2009). Attempts to extend these techniques designed for industrial fisheries to SSF have resulted in repeated failures, both in terms of ecological and social outcomes (Berkes, 2001). Meanwhile the existence of longstanding local institutions for fisheries governance and sea tenure in SSF were systematically discounted as non-scientific (Johannes, 1981; Cordell, 1989; Berkes, 2018), archaic practices with no place in the modern reconfiguration of fisheries science and management.

The Imminent Rise of Small-Scale Fisheries

Despite longstanding asymmetries between SSF and industrial fisheries, recent changes indicate that another future is possible. Scientific attention to SSF is on the rise as evidenced by a marked increase in peer-reviewed publications on SSF in the last two decades (Purcell and Pomeroy, 2015; Basurto et al., 2017b) and the development of global partnerships for collaborative SSF research such as the Too Big to Ignore network (Chuenpagdee et al., 2017). The passage of the Food and Agriculture Organization's (FAO) Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries in the Context of Food Security and Poverty Eradication (SSF-Guidelines) in 2014 marked a historical turning point for SSF. As the first globally negotiated policy specifically for the small-scale sector, the SSF-Guidelines differed from other fisheries instruments because they were developed through an inclusive, participatory process and took a human rights-based approach to fisheries governance (Allison et al., 2012; FAO, 2015; Willmann et al., 2017). While the arrival of the SSF-Guidelines marked a profound departure from fisheries policy-as-usual, this shift was regarded as long overdue: fishers, fishworker organizations and related civil society organizations (CSOs) began calling for the development of a specific set of guidelines over a decade earlier (Jaffer and Sunde, 2006; ICSF, 2007; Sharma, 2008, 2011; Pictou, 2017). Discontent among fisher organizations coalesced over the passage of Code of Conduct for Responsible Fisheries in 1995—guidelines which purportedly set standards for global best practices pertaining to all capture fisheries yet only contained four mentions of the specific needs of SSF (Johnson, 2006). It took nearly 20 years to ratify a corollary set of guidelines for SSF at the Committee on Fisheries (COFI). However, in contrast to their longstanding marginal status within global policy, SSF now command their own standing agenda item at the biennial convening of COFI, where 2022 was designated the Year of Artisanal Fisheries and Aquaculture and an expanding cohort of member states have made public commitments to implement the SSF-Guidelines in their national fisheries (FAO, 2018).

As the tides of attention appear to be shifting toward SSF, we believe it is timely to ask: if SSF are on the rise as a subject of interest in science and policy, then what, exactly, counts as small-scale fisheries? On the surface, this appears to be a simple question and matter of straightforward classification: a specific fishing enterprise or wider fishery is better suited either to the small-scale or to the industrial category. Yet upon closer consideration it becomes evident that the definition beneath each category is linked to more fundamental issues about the relationship between nature, technology and society that are not so clear-cut or ethically neutral (Johnson, 2006; Arbo et al., 2018). Defining SSF is not a mere technical matter of where to draw the line between small-scale and industrial fisheries; it is, rather, a value-laden decision with political implications and material consequences both for the environment and for humans who depend on fishing for their livelihoods and food security (Johnson, 2018). Based on our own observations at different international fisheries fora, the issue of the definition often presents a stumbling block for efforts to achieve mutual dialogue and consensus agreements on fisheries governance at national, regional, and global levels. While ostensibly speaking of the same category—SSF—dialogue often unravels when the definition is unpacked in practice, and divergent perspectives arise over which characteristics of SSF are most salient and worthy of inclusion at the expense of others. Scientists play an important role in these debates as an influential community widely regarded as experts in the matters of environment and natural resource management, yet the situatedness of knowledge and the effects they produce often go unscrutinized (Haraway, 1988; Turnhout, 2018). We believe it is pertinent to explore the relationship between scientific knowledge production and the definition of SSF, asking: How have scientists navigated defining SSF as a subject of study? Can we identify any common traits among scientific definitions, and do commonalities vary over time and space? Lastly, what can a closer look at these patterns reveal about the relationship between the definition, presumed priorities and present blind spots in SSF research and policy?

One way to approach these interrelated questions empirically is to analyze the growing body of scholarship on SSF. In doing so, the overarching goal of this paper is to examine how scientific knowledge has shaped the definition and perceptions of who and what counts as SSF through a review of scientific literature on SSF.

The Emerging Global Picture of Small-Scale Fisheries

How SSF are defined is pertinent considering the recent push to scale up knowledge on the sector. Constructing a global picture of SSF requires amassing and aggregating different sources of data, a major challenge for a sector that has long been considered data-poor. Within fisheries, SSF have historically gone uncounted, underestimated, or undifferentiated—overlooked or hidden within national fisheries statistics. The reasons for this data gap are multiple. The diversity and plurality of SSF frustrate efforts to systematically and reliably count them at higher scales, and these challenges are further exasperated by a chronic lack of institutional capacity and meager political will to prioritize SSF, their specific data needs, and unique methodological challenges (Welcomme et al., 2010; Kittinger et al., 2013; Basurto et al., 2017a). However, in recent decades global momentum is building to prioritize counting SSF through innovative methodologies to combat the chronic inaccuracies of existing data and the sector's subsequent invisibility. In 2012, the FAO collaborated with the World Bank and WorldFish researchers to generate better global estimates of SSF independent of self-reported national fisheries statistics. Through use of country-level case studies and assimilation of existing data sources, the resultant "Hidden Harvest" report and the forthcoming "Illuminating Hidden Harvest" unveil previously underestimated contributions of SSF to human well-being, providing new figures on the magnitude and impacts of SSF that avoid some of the limitations of official government statistics (World Bank, 2012; Worldfish, 2018).

The global picture of SSF emerging from these efforts suggests that, despite the name, SSF are by no means "small." On the contrary, SSF are much larger than previously thought and appear to have an outsized impact on human health and nutrition, poverty alleviation, jobs, and the structure of seafood markets (Jentoft et al., 2017). Emerging accounts affirm that SSF likely land nearly half the world's seafood, playing a critical role in food security and nutrition, especially for those living in poverty (Kawarazuka and Béné, 2010; World Bank, 2012; Bennett et al., 2018). The nutritional value of wild-caught fish is manifold, providing a high-quality source of protein, fatty acids and micronutrients vital to combatting malnutrition and disease (Béné et al., 2015; Golden et al., 2016). Access to fish is especially important for the diets and health of pregnant women, infants and lactating mothers (Bogard et al., 2015; Thilsted et al., 2016), for the populations of many small island developing states (SIDS) (Béné et al., 2016), and for sociocultural groups with longstanding ties to the sea or inland waterways (Mccay, 1987; Funge-Smith, 2018). Further, new evidence suggests that the nutritional value of wild-caught fish may exceed that of farmed fish (Belton and Thilsted, 2013; Thilsted et al., 2016; Bogard et al., 2017), underscoring the continued importance of capture fisheries even alongside the rise of aquaculture.

In terms of employment, SSF are by far the oceans' largest employer—greater than industrial fisheries, oil and gas, shipping, and tourism combined (World Bank, 2012; OECD, 2016). Experts suggest that inland SSF likely provide even more jobs than their marine counterparts (56 verses 52 million) and play an especially important role in local nutrition and food security (Welcomme et al., 2010; World Bank, 2012; Bennett et al., 2018; Funge-Smith, 2018). The composition of the SSF workforce is also more diverse than previously thought, with women representing nearly half of SSF workers globally (World Bank, 2012). From the net to the plate, women are found along the entire SSF value chain and dominate the post-harvest sector in many parts of the world (Choo et al., 2008; World Bank, 2012; Kleiber et al., 2015). Once landed, fish are transformed into an array of products and become highly traded commodities—some of the most traded food items in the world (FAO, 2018). While often associated with subsistence use and barter exchange, fish landed by SSF circulate within markets at various scales, including in local fishing communities, through extensive networks of regional markets, and in an increasingly globalized system of international trade (FAO, 2018). Greater granularity is needed to better understand the distributional and nutritional consequences of changing trade relations in SSF and interactions of markets at different scales (Bennett et al., 2018).

Beneath each of these generalized figures rests a definition of SSF that served as the foundation for tallying the size and contributions of the sector. As these facts and figures are borrowed, repeated, and circulate beyond their original context, the underlying definition rarely travels with them. As a formidable yet often invisible force, how does the underlying definition shape efforts to accumulate knowledge on SSF as the sector garners greater attention and an increasingly global status? As we begin to illustrate the true size and scope of SSF, the question remains, what are we counting?

The growing body of scientific knowledge on SSF is an important site to explore how SSF have been defined, because "critical awareness of the categories that guide fisheries governance is extremely important" where ongoing reflection can improve their application (Johnson, 2006). Even as the lines between science, policy and politics in the environmental sphere are increasingly interconnected and blurred, sciences maintain a privileged position in environmental debates, shaping how we conceptualize the environment and the policies we enact to manage and maintain it (Chilvers and Evans, 2009; Turnhout, 2018). Taking the performativity of knowledge as a starting point, this scientific knowledge is not merely reflecting reality "as it is" but constituting and shaping that reality while attempting to represent it (Law, 2009). Therefore, rather than assuming what SSF are, we explore how the category has been constructed from its constituent definitional parts. In this pursuit, we work to uncover interwoven patterns and simultaneous blind spots, potentially illuminating opportunities to "cast the analytic net wider" toward more inclusive approaches (Arbo et al., 2018). For example, fisheries have long been erroneously perceived as a masculine space dominated by male workers (Choo et al., 2008; Williams, 2008). The prevalence of this assumption is evident in both fisheries science and policy, where the mere presence of women has rarely been acknowledged, let alone deeper consideration of the intersections between gendered dimensions of environmental knowledge, identity, power, and occupational health and safety. Only in the last decade is the hegemony of "fishermen" starting to crack as the significant number and manifold contributions of women are repeatedly demonstrated and increasingly accepted (Neis et al., 2005; Choo et al., 2008; Gerrard, 2008; Weeratunge et al., 2010; Harper et al., 2013; Branch and Kleiber, 2017).

Debating the Definition of Small-Scale Fisheries

Debates about the nature of SSF and the role of the definition have unfolded over several decades. Early work by Kesteven (1973, 1976) and Smith (1979) acknowledged that some common attributes could be used to distinguish SSF from more industrially oriented fishing operations, but that attributes should be understood as variants along a continuum rather than as belonging to hard and fast categories. Instead of gravitating toward the ease and symmetry of singular distinctions, these scholars advocated early on for a framework based on combinations of technical and socioeconomic characteristics to define SSF (Smith, 1979). The publication of Thomson's (1980) influential table depicting "two distinct world fisheries" provided the first visual illustration of a clear division between small- and large-scale fisheries. The table's two columns contrasted the size and relative value of "large-scale company owned" and "small-scale artisanal" fisheries, symbolized by different types of boats—the former large and modern-looking and the latter a small sail-powered outrigger craft. Thomson's table helped popularize the term "small-scale fishery" and has been repeatedly borrowed, amended, and expanded by scholars over the decades, including Ruttan et al. (2000), Berkes (2001), Sumaila et al. (2001), Pauly (2006) and Fréon et al. (2014).

Over the years, many attributes essential for defining and valuing SSF have been proposed, including the size and type of boat, engine horse power, equipment type, time commitment, catch rates and disposal, environmental knowledge, significance of fishing as a livelihood, and marginality, among others (Kurien, 1996; Berkes, 2001; Kittinger, 2013). Some lists emphasize the importance of technological aspects of SSF (Pitcher et al., 1998), while others address combinations of technological, environmental, social, and political parameters to explore finer variations within SSF and between these two, taken-for-granted categories (Johnson, 2006; De Melo Alves Damasio et al., 2016). Several in depth studies grapple with the specifics and limits of national fisheries definitions, including in India (Jadhav, 2018b), Brazil (De Melo Alves Damasio et al., 2016), Peru (Fréon et al., 2014), Azores islands (Carvalho et al., 2011), and Canada (Gibson and Sumaila, 2017), while others address regional challenges such as in the EU (García-Flórez et al., 2014; Natale et al., 2015; Davies et al., 2018). Other scholars deconstruct common paradigms for understanding fisheries, including supposed divisions between "First World" and "Third World" fisheries (St. Martin, 2005) and the meaning of the term "subsistence fishing" in global fisheries scholarship (Schumann and Macinko, 2007). To date, the only large-scale systematic and empirical study of the definition of SSF on a global scale was conducted by Chuenpagdee et al.'s (2006), who analyzed the definitions of maritime SSF in the national policies of 140 countries. The authors found that only 70% of countries articulated a clear definition of SSF, and where SSF were defined, the most common characteristic used was boat length (65% of definitions). Their analysis illuminates the simultaneous absence of clear definitions of SSF in many parts of the world, and yet an overall degree of consistency in characteristics used, suggesting that sufficient commonalities exist to speak of a generalized approach to defining SSF in policy.

Still others are skeptical of systematic efforts to define SSF, finding the category too elusive and relative to warrant a common definition. From this vantage point, the search for a shared definition is an exercise in futility because SSF are too diverse and locally specific to enable any wider generalizations and useful comparisons (Béné, 2006; Johnson, 2006; Carvalho et al., 2011). However, practically, most researchers and practitioners inevitably need to draw some distinctions and categorize fisheries, whether they use the common divisions of large- and small-scale or other variants, and could benefit from the guidance of shared signposts. Most who discuss the merits and drawbacks of defining SSF strike a balance amidst this debate—acknowledging issues and limits to defining SSF but also finding it possible and useful to cull some common characteristics that bridge different contexts and scales, thus enabling wider conversations on SSF that transcend the particularities of place (Kurien, 1996; Chuenpagdee et al., 2006; Charles, 2011).

It's not clear that any definition of SSF is inherently preferable to no definition, nor that any given definition of SSF will lead to homogenously good or bad outcomes for the diverse workers and environments of SSF at different scales. Scalar specificity matters, and yet the desire to share some common language for defining SSF that transcends scale persists, particularly given the overwhelming mandate to scale-up approaches within environmental governance. Rather than searching for an elusive and ultimately unsatisfactory fixed definition that universally applies, an imprecise definition may be preferable, leaving room to maneuver while signaling some shared traits (Gibson and Sumaila, 2017). Even imprecise definitions could help augment several interrelated issues that stem from the absence of a definition: data deficiencies, paucity of research, political marginalization, and a lingering low-status stigma that often plagues the sector (Chuenpagdee and Pauly, 2008; Carvalho et al., 2011). Meanwhile, the space afforded by an imprecise definition could enable comparisons at the global-level without imposing exclusionary and inflexible boundaries.

Scientific Literature as an Unexplored Site to Study the Definition

Amidst the diverse range of actors with a stake in this debate, scientists continue to play an outsized role in categorizing, ordering and managing natural resources such as fisheries. Environmental policymaking has become thoroughly scientized in the push for more evidence-based interventions, where science is simultaneously posited as the cause, means of detection, and generator of viable solutions to a range of environmental problems (Chilvers and Evans, 2009; Turnhout, 2018). Since the rise of modern fisheries science, the conclusions and recommendations of scientists have been regarded as legitimate, expert knowledge in matters of fisheries classification and governance—in charge of the facts and the problem definitions (Johnson, 2006; Basurto et al., 2017b; Turnhout, 2018). It's now well-recognized that the narrow approach of modern fisheries science alone is insufficient to understand SSF. In response, an increasingly diverse pool of scientific perspectives have joined in the dialogue on the best course for governing SSF, including community ecologists, common-pool resource scholars, political ecologists, and post-structural approaches (Berkes, 2015; Mather et al., 2017).

However, despite the recent expansion of SSF as a topic of scientific interest, no systematic studies have critically examined the workings of scientific knowledge production and the role of the definition of SSF. The goal of this study was to assess how scientists have defined SSF and whether dominant ways of defining SSF have changed over time. More specifically, we endeavored to: (1). Assess the dominant characteristics used to define SSF; (2). Determine whether any patterns present in the definition have changed over time or vary by study geography, aquatic system, or journal outlet; (3). Compare any patterns identified in the scientific literature to results from similar research on the definition of SSF in policy; and (4). Consider the advantages and limits of dominant ways of defining SSF alongside prospects for future improvements.

METHODS

Study Design

The methodological foundation of this study is based on the principle that peer-reviewed publications can serve as indirect measures of knowledge produced on a topic because they are a well-established means through which scientific information is communicated and codified across scholarly communities (Van Raan, 2004). Peer-reviewed journals inevitably provide an incomplete picture of knowledge produced on any topic and are certainly not the only means through which scientific findings are communicated. Nonetheless, scientific journals are longstanding: scientists have used international journals since the seventeenth century (Van Raan, 2004). Further, as opposed to other tacit forms of communication and knowledge exchange, journals are codified and amenable to systematic searches—serving as an accessible and searchable archive of knowledge produced. Scientometric studies have become a popular means to quantitatively assess scientific output on a range of different topics, including fisheries science (Jarić et al., 2012; Natale et al., 2012; Aksnes and Browman, 2015; Syed et al., 2018). Such studies are typically limited to assessing available bibliometric information and quantitative article-level metrics extracted through automated modes of analyses. In contrast to existing bibliometric studies of fisheries science, this study combines qualitative coding with elements of bibliometric analysis to decode common characteristics used to define SSF and to disaggregate these findings based on other article- and journal-level metrics.

Systematic Review Materials and Protocol

To retrieve relevant literature on SSF, we conducted an extensive search using the Web of Science (WOS) database produced by Thomson Reuters and the following the keywords: "small-scale fisher*," "artisanal fisher*," "fisher folk," or "fishing communit*"—asterisks were used to broaden the search to include variations on each word stem. These keywords were chosen to ensure coverage of both common terms in use today (e.g., small-scale fisher, artisanal fisher; Johnson, 2006) and terms popular in earlier decades that preceded the publication of Thomson's (1980) table that helped popularize the term "small-scale fisher." WOS is a widely used and venerated database in systematic literature searches and scientometric studies (Moed, 2006), including reviews of fisheries research (Jarić et al., 2012; Johnson et al., 2013; Aksnes and Browman, 2015; Syed et al., 2018). However, WOS has several limitations, including underrepresentation of certain social sciences and humanities research and a general bias toward English language journals (Moed, 2006). To supplement our primary search, and attain greater coverage of the social sciences, we conducted additional targeted searches to identify relevant social science journals not indexed in WOS with the help of a marine science librarian (see **Supplementary Materials**). Together, our primary and supplementary searches yielded a total of 2,653 articles. Despite our efforts to address the limitations of WOS and to identify all relevant literature for this study, no search database is complete, and our data set likely underestimates the total peer-reviewed publications on SSF and does not include gray literature such as FAO reports or long-standing specialized outlets like *Samudra* or *Yemaya*. Notwithstanding these important contributions, given our explicit focus on the role of scientists and scientific knowledge production, peer-reviewed literature was deemed the most appropriate and accessible form of data for this study.

The full text for each reference was retrieved and evaluated to determine whether it belonged in the study based on the following criteria: sufficient coverage of SSF in the body of the article, accessibility of the full text in digital format, English as language of publication, and the article's peer-reviewed status (see **Supplementary Materials**). After eliminating articles that did not meet one or more of the study criteria, the final data set contained 1,723 articles. Qualitatively assessing the characteristics used to define SSF at the article-level required the coder to read each article until they encountered the section where SSF were defined (or not). Given the time required to locate the definition within each article, a stratified random sample was used to select articles for in-depth coding. Due to the uneven distribution of articles over time, sampling was stratified by decade and different levels of sampling intensity were used. As a rule, we sampled 20% of articles per decade with a minimum of 50 articles per strata. For strata with <50 articles (e.g., the 1960s and 1970s), all articles were read and coded. Across the

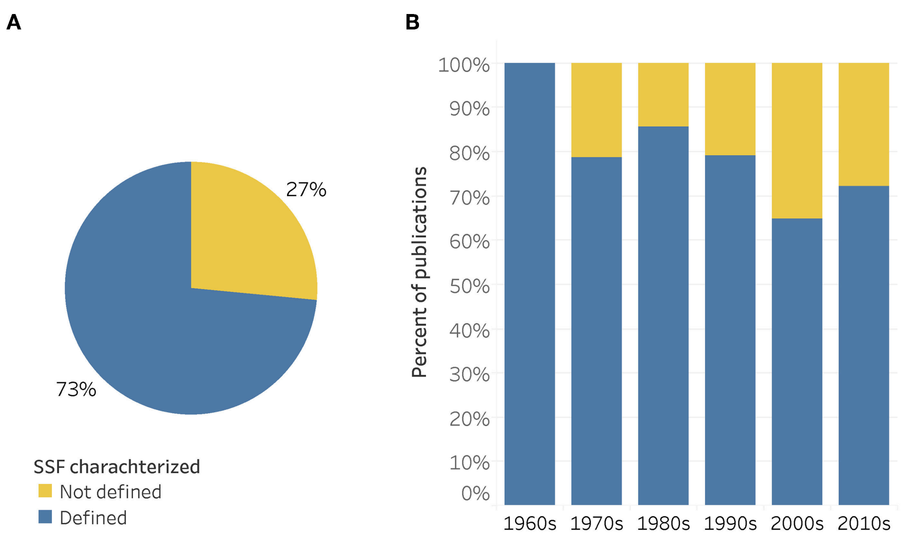

FIGURE 1 | The percentage of articles that provided a definition for small-scale fisheries for the total sample studied **(A)** and by the decade of publication **(B)**.

entire data set, this mixed strategy means that 25% of articles were read and coded ($n = 434$). By oversampling we ensured the study included sufficient literature from earlier decades when SSF publications were sparser. This stratified random sampling approach was deemed the best strategy to compare patterns in the definition over time given the paucity of literature on SSF in the 1960–1980s and the rapid upturn in publications after the late 1990s.

All sampled articles were deductively coded against a set of common characteristics used to define SSF that were derived from the existing literature (Chuenpagdee et al., 2006; Funge-Smith, 2018) and from preliminary research done by the authors (Basurto et al., 2017b) using the qualitative analysis software NVivo 12. We used the following coding structure for each article: whether or not the SSF studied was defined, which characteristics were used to define SSF, the study location, and whether the SSF studied were inland or marine (or both). Each article was also coded for its journal's general audience (natural or social scientists), depending on which citation database indexed that journal (Science Citation Index Expanded or Social Science Citation Index) using the Journal Citation Reports.

The final coded dataset ($n = 434$) was exported into Tableau 12 software for data analysis. Analysis focused on whether the percent of articles defining SSF and the most common characteristics used to define SSF differed by decades and other article-level dimensions (i.e., geography, aquatic system, journal type).

RESULTS

Variability in Definitions of Small-Scale Fisheries Over Time and Space

The majority (73%) of articles provided a definition and or characterization of the SSF studied (**Figure 1A**). The percent of articles that defined SSF varied by decade, with a decrease in articles that defined SSF in the last two decades and an overall downward trend in the proportion over time (**Figure 1B**). The percent of articles that defined SSF for each decade from 1960 to 1990s ranged from 100 to 79%, whereas the proportion of articles that defined SSF were lower for the 2000s (65%), and 2010s (72%). Despite variations between decades, we observed an overall downward trend in the proportion of articles that defined SSF over time.

The percentage of articles that defined SSF varied by the geographic region of study (**Figure 2A**). South Asia (87%), North America (87%), Latin America and the Caribbean (78%), Europe

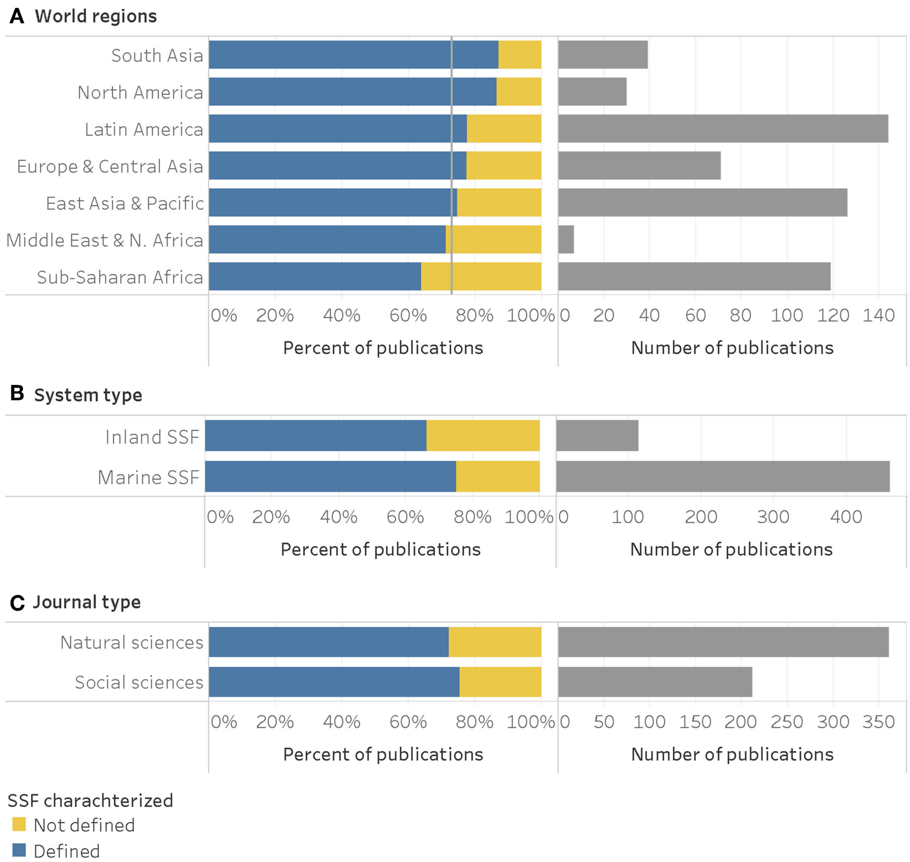

FIGURE 2 | Percentages of articles that defined small-scale fisheries by world regions **(A)**, aquatic system type **(B)**, and journal outlet **(C)**. The gray vertical line indicates the average (73%) for the overall sample.

and Central Asia (77%), and East Asia and the Pacific (75%) were regions where SSF were more often defined. All African regions were below average, with SSF defined in 71% of articles from the Middle East and North Africa and only 68% of SSF studied in Sub-Saharan Africa. Inland SSF were less commonly defined than marine SSFs, with only 66% defined compared to 75% (**Figure 2B**). Lastly, the percentage of articles that defined SSF differed somewhat based on the journal outlet, where SSF were defined in 75% of social science journals and 72% of natural science journals (**Figure 2C**). The number of articles published in social science vs. natural science journals also varied over time in the sample, where social science journals were the most common outlet for SSF publications between 1960 and 1980s, with a marked shift to natural science journals prevailing as the most common outlet from the 1990s to present (**Figure 3**).

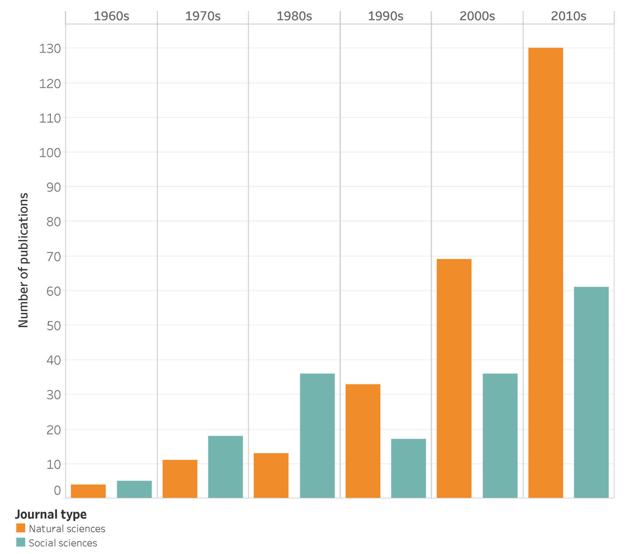

FIGURE 3 | Total number of publications by journal type and decade published in the sample ($n = 434$).

Characteristics Used to Define Small-Scale Fisheries

The most common characteristics used to define SSF (**Figure 4**) were the type of fishing gear (58%), boat (51%; e.g., length, type or material, capacity or tonnage), or sociocultural factors (35%; e.g., ethnic group, religion, caste, class, etc.). Other characteristics used moderately (in 10–20% of articles) included species (19%), motorization (19%; e.g., presence or size of engine), catch disposal (18%), ecology and habitat (16%), distance from shore (13%), and organization of labor and crew (11%). Other characteristics—such as ownership of fishing gear or vessel (6%), trip duration (4%), value chain (4%), time commitment (3%), market integration (<1%), on board storage/refrigeration (zero instances)—were less commonly used to define SSF (i.e., used in <10% of publications).

The relative frequency and relationship among the most common dimensions in definitions varied over time (**Figure 5**). Sociocultural characteristics were the most common dimensions used to define SSF in the 1960–1980s, used in over half of all definitions, but usage declined in the 1990–2010s. Popularity of fishing boats and gear in definitions fluctuated but remained common over the decades, ascending to the top of the list by the 2000–2010s. Motorization was commonly used to define SSF in the 1960–1970s but occurred less frequently in definitions from the 1980s to the present.

Dimensions used to define SSF also varied by world region (**Figure 6A**), where fishing boats appeared most frequently in definitions of SSF in East Asia and Pacific (60%) and Europe and Central Asia (56%), followed by Latin American and the Caribbean (52%) and Sub-Saharan Africa (51%). Boats were less common in definitions of SSF in South Asia (38%) and North America (38%). Motorization was used most frequently in defining SSF in Sub-Saharan Africa (29%) and Latin American and the Caribbean (28%). Fishing gear was most commonly used to define SSF in the Middle East and North Africa (100%), where all other regions had a similar percentage of articles that used this characteristic to define their SSF (between 55 and 65%), except North America where fishing gear was used in only 27% of articles. Sociocultural dimensions were used most frequently to describe SSF in North America (77%) and South Asia (56%), and were less common (e.g., used in a quarter to a third) for all other regions. Comparing the dimensions used to define SSF by the system type (**Figure 6B**) revealed that inland fisheries were more commonly defined by motorization (32%) and sociocultural factors (47%) than were marine SSFs (16 and 32%, respectively). Comparing the dimensions used by the type of journal (**Figure 6C**), publications in natural science journals relied more on technological dimensions (boat, motorization and fishing gear) to characterize SSF, while social science journals, not surprisingly, relied more on sociocultural factors (used in 54% of definitions verse 23% in natural science journals).

Different Features of Fishing Technologies Used in Definitions

Given the importance of technological dimensions in the definitions studied, we also coded for the use of different features of fishing boats, engines, and fishing gear used in definitions of SSF (**Figure 7**). Among articles that used fishing boats to define SSF (**Figure 7A**), the most common features highlighted were boat length (59%), boat type or material (36%), and capacity and tonnage (6%). For motorization, most articles indicated that SSF boats used engines but did not provide further detail on the engine type or horse power. However, 25% defined SSF as boats with outboard engines of 100 hp or less, with few SSF characterized as vessels with inboard motors (**Figure 7B**). SSF defined by fishing gear were most commonly described as labor intensive gear (44%), passive gear (39%), or highly active gear (10%; **Figure 7C**).

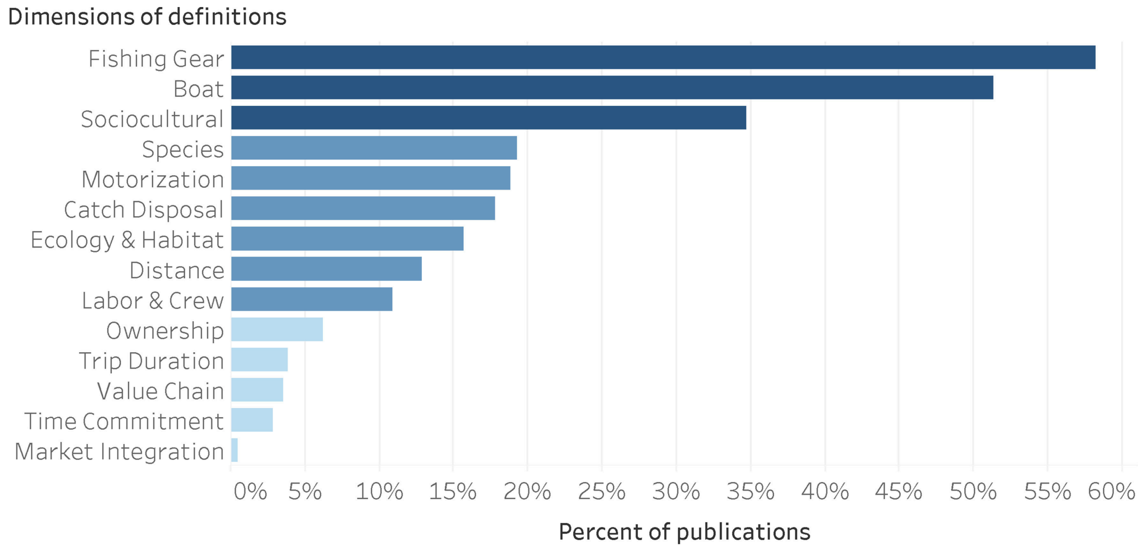

FIGURE 4 | The percentage of publications that used different characteristics to define SSF. The blue shading indicates three natural groupings that emerged from the data based on the frequency of use: commonly used characteristics (35% or more), moderately used characteristics (10–20%), and those infrequently used (occurring in <10% of definitions).

DISCUSSION AND CONCLUSIONS

Deconstructing Dominant Patterns in the Definition

By tracing how different assemblages of potential characteristics are deployed in definitions, our foregoing analysis uncovered several persistent themes and points of divergence in the way scientists have constructed SSF as a subject of study in peer-reviewed literature over the last 65 years. We focus our discussion on the most prominent points of convergence among definitions and consider how they serve to stabilize SSF as a category inscribed by certain essential characteristics, such as fishing boats and fishing gear. We also highlight instances of instability where the definition appears to have shifted over time and space, and finally we consider the implications of these changes and how SSF are understood and governed in practice.

Defining Patterns That Cross-Cut Science and Policy

Overall, we observed that more than a quarter of articles left SSF undefined, which echoes the findings of Chuenpagdee et al.'s (2006) study of national-level definitions of SSF in fisheries policy. Despite using different methodologies, focusing on distinct communities of experts (scientists vs. policymakers), and different types of data (peer-reviewed publications vs. national policies), their study found a similar proportion (70%) of documents that left SSF undefined. The results of these two studies indicate that the absence of a clear definition of SSF is a shared challenge that spans the supposed science-policy divide. Taken together, the findings of these two studies indicate that greater collaboration between scientists and policymakers is needed to clarify what SSF are and exactly whom scientific studies and policies pertain to. The present ambiguity and absence of clear definitions can obscure meaningful variations between different fisheries. Within the same country, and even within the same fishery, resource access and dependency on fisheries' livelihoods among stakeholders varies, making it no longer "sufficient to discuss issues, concerns and challenges in fisheries without being sector- and scale specific" (Chuenpagdee et al., 2006). Presenting scientific findings or policies on SSF without clarifying the intended social and ecological scale, portion of the value chain, and rightful stakeholders muddles national and international debates about the status and best course of action for SSF governance. In the absence of guidelines, room is left to easily repeat past-patterns of excluding pre and post-harvest sector workers, especially women. Presenting scientific findings or policy prescriptions that pertain to and potentially affect SSF without clearly defining the subject of study—a common pattern we observed—can obscure important differences and inequalities between different fisheries and among actors along the value-chain.

For example, in the absence of a clear definition all coastal and inland fisheries in Tanzania are assumed to be "small," which has proven problematic. In Lake Victoria's fisheries, it makes a difference whether you are referring to the endemic *dagaa* (*Rastrineobola argentea*) fishery—where women's small enterprises dominate processing and marketing and fish is traded for local and regional consumption—vs. the export-oriented fishery for the invasive Nile perch, which is controlled by foreign processors and outside money. Left undifferentiated, at present small-scale *dagaa* processors in Tanzania face the same permitting requirements as large-scale processors fileting Nile perch for export. Yet, whereas Nile perch are processed in immaculate facilities certified for export to the EU, *dagaa* processing often occurs along the beach, within individuals' homes, or in small collective compounds. Yet, regulations do not differentiate between the different socioeconomic context,

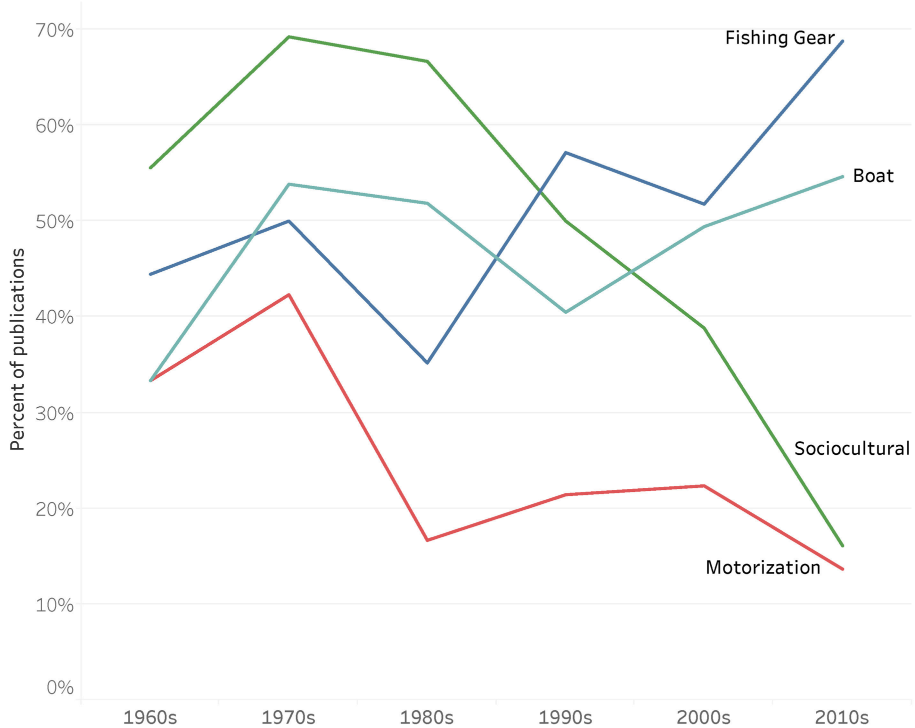

FIGURE 5 | The percentage of articles that defined SSF by different dimensions and decade. Only technological dimensions and sociocultural dimensions were included.

scale and needs of these two fisheries and their post-harvest sector workers. Permitting requirements are set using Nile perch as the standard, creating significant impediments for small-scale processors to gain formal registration, and therefore, to be considered legitimate businesses and rightful participants in fisheries governance. Leaving SSF undefined, and tacitly biased toward the needs of the more profitable Nile perch industry, lumps these drastically different fisheries together despite differences in their relationships to their communities, the economy and the environment. In the absence of a clear definition that distinguishes between these two fisheries, workers in the *dagaa* sector are disadvantaged and overshadowed by more powerful interests.

Secondly, we found that fishing gear and boats were the most common characteristics used to define SSF across our dataset, resonating with Chuenpagdee et al.'s (2006) review of fisheries policies. They found that boat size was the most common factor (65%) in policy definitions, compared to 51% of articles in our study. As a defining metric, boat size was typically formulated as fixed limits on vessel length in both studies. Meanwhile, a host of other possible characteristics proposed in the literature were not frequently observed in SSF definitions, such as organization of labor, relations of ownership, the makeup of the value chain, disposal of catch, and degree of market integration. Defining SSF through fixed technical limits on boat length and gear has implications in the interpretation of scientific research, in policy design and implementation, and in determining who gets to participate in fisheries governance.

Returning to the above example from Lake Victoria, this case further illustrates how fixating on technological limits may fail to address substantial differences among fisheries actors and impacts. Both the Nile perch and *dagaa* fisheries use similarly sized small boats and labor-intensive gear, yet they differ substantially along other dimensions, including capital invested, relations of ownership, and links to markets. Ownership of fishing boats and gear for Nile perch is often highly consolidated, where local and regional businessmen may own up to 100 boats (interview comment, 2/14/18). The fact that both these fisheries are considered "small" by the rubric of boat size and fishing gear underscores that, while the technological means may be similar, the "social organization of production and distribution are very different" (Johnson, 2006). Ecologically these fisheries also differ. Nile perch is an invasive species introduced under colonial rule to dire ecological consequence for the wider lake ecosystem (Pringle, 2005). While the *dagaa* fishery is not immune to sustainability issues, this fishery is focused on endemic cichlid species. Categorizing *dagaa* and Nile perch together within fisheries science and policy conceals substantial differences in the webs of social, economic and ecological relations these two fisheries are embedded within.

Temporal and Geographic Differences

The general downward trend in articles that defined SSF and the simultaneous increase in reliance on certain technologies to characterize them are temporal patterns that emerged from our analysis of peer-reviewed publications over the last 65-years. As

FIGURE 6 | The percentage of publications using different dimensions to define SSF by world region **(A)**, aquatic system type **(B)**, and journal outlet **(C)**.

SSF has expanded as a topic of scientific inquiry, marked by a prolific rise in publications on the topic, scientific knowledge produced on SSF appears to be increasingly detached from a clearly articulated definition of the term. At the same time, scientific knowledge is also more likely to be based upon a narrow conception of SSF, understood in terms of fishing technologies. The spread of technological definitions stands in contrast to the relative decline in the use of sociocultural characteristics, such as ethnicity, religion, caste, class, gender, and history or fishing culture, which were dominant criteria for defining fisheries in earlier decades. While future studies are needed to statistically confirm the significance of the temporal trends we observed, next we consider the import of these patterns in light of existing studies and theory.

While Chuenpagdee et al.'s (2006) study concluded that the patterns they observed in policy definitions were "remarkably stable," they did not explore the potential for historical differences. Our results add nuance to the role of technology in the definition of SSF—indicating that factors such as boat length were not always universal or stand-alone. Indeed, sociocultural dimensions were the most common characteristics used in definitions of SSF in earlier decades (1960–1980s)—observed in more than half of all sampled articles. One possible explanation for this observation is that fisheries scientists focused on industrial fisheries and largely ignored SSF during the rise of modern fisheries science in the 1950–1980s, subscribing to a popular development paradigm that assumed SSF would naturally evolve into or be replaced by an industrial mode of production (Johnson, 2006; Carvalho et al., 2011). While SSF were overlooked by fisheries scientists, who perhaps considered them too trifling to bother with, social scientists dominated the sparse literature on SSF, published their research in social science journals, and focused on understanding the sociocultural dimensions of SSF. Much of this early work applied ethnographic observation to study SSF, offering descriptive, detailed accounts of fishing methods (Craig, 1969; Mccay, 1978; Poggie, 1978; Poggie and Pollnac, 1988), studies of the social structure of fishing households and communities (Davidson and Davidson, 1969; Breton, 1973; Yoshida et al., 1974; Davis, 1986), and of maritime culture (Macdonal.Js, 1973; Bundy, 1977; Byron, 1988). Our results suggest that the expansion of scholarship on SSF in the 1990s was marked by a shift toward publishing in natural science journal outlets and toward a greater reliance on technological dimensions as the defining characteristics of SSF.

Looking at patterns by study region, we also found an inverse relationship between the use of boats and sociocultural dimensions in definitions of SSF—where, for example, North America was the region where sociocultural factors were the most

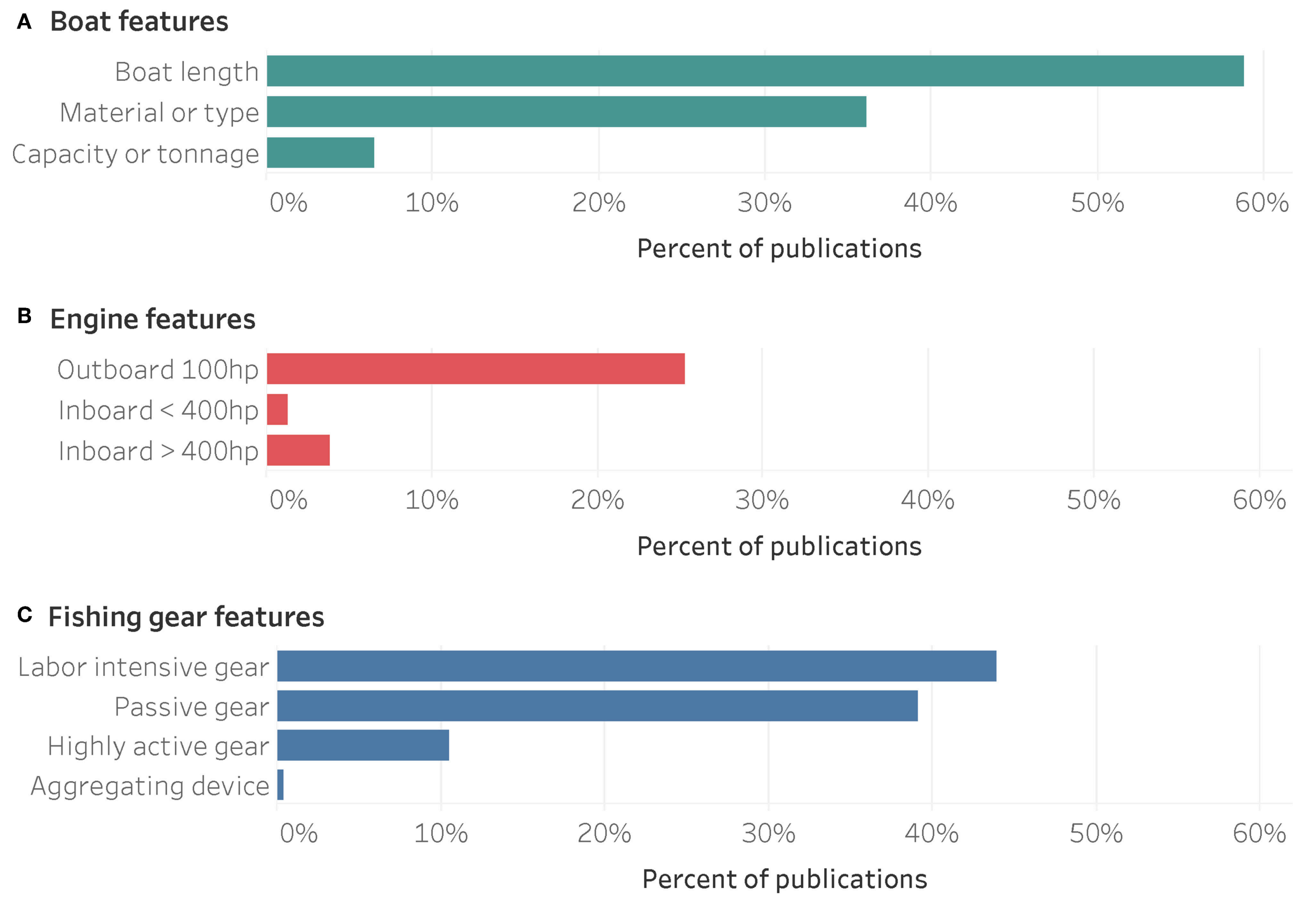

FIGURE 7 | The breakdown of different features used in definitions that relied on fishing boats **(A)**, engines **(B)**, and fishing gear **(C)** to define SSF.

common; it was also the region where boats, fishing gear, and engines were the least prevalent in definitions. Further research is needed to confirm and qualitatively understand this geographic discrepancy we observed in SSF scholarship, including why SSF in regions such as East Asia and the Pacific were more often defined by boat size rather than by sociocultural characteristics. This pattern can be interpreted as stemming from the deep-seated belief that technologies are asocial artifacts that can be isolated from their social domain, a socially constructed duality well-documented by Science and Technology Studies (STS) (Barry and Slater, 2002). Treating fishing technologies as "value-neutral chunks of hardware" (Harding, 2008) denies their existence as deeply social projects, permeated with history and political consequences. For example, in the data set utilization of engines in definitions was popular in the 1960–1970s but declined in use after the 1980s. This peak could be explained by dominant modes of fisheries development that focused on modernizing SSF by introducing motorized engines in many post-independence development packages pushed in the global south in the 1950–1980s (Basurto et al., 2017b). Engines were incorporated into many SSF around the world during those decades, whereas development interventions in the 1990s shifted focus away from technological and infrastructure inputs of previous decades and toward addressing the "problem of property" in fisheries (Campling and Havice, 2014) through interventions such as Individually Transferrable Quotas (ITQs) (Mansfield, 2004; Holm and Nielsen, 2007; Pinkerton and Davis, 2015). However, defining SSF by the presence and mechanics of engines alone (such as horsepower) misses the wider context of development interventions that spread their use throughout many SSFs, and also ignores the more recent shift away from technologically-centered fisheries development in favor of neoliberal governance techniques (Basurto et al., 2017b).

Moving Beyond Technological Determinism

Technological determinism (i.e., defining SSF through a limited focus on certain fishing technologies) is prevalent and possibly on the rise, essentializing SSF as a category inscribed by certain fixed technological characteristics that can be separated from their social context. While dimensions of social life were central to definitions and studies of SSF in earlier decades, the sociality of SSF is presently understudied (Batista et al., 2014), treated as static or inconsequential to the definition of SSF amidst the widening field of scholarly attention. Classifying SSF this way has certain advantages for the outside observer, reducing the less-than-legible characteristics of SSF in favor of traits that are easily identified as "small" (Jadhav, 2018b). This helps stabilize our understanding of the wider field of capture fisheries, translating the unwieldy spectrum of fishing activities into discrete categories that can be ordered and described through a limited reliance on capture technologies.

Here we outline two related issues that stem from technological determinism: First, this mode of defining SSF places undue emphasis on harvesting activities at the expense of the rest of the value chain. Second, centering harvest activities and related technologies embeds a gendered bias in the definition. These two points are discussed in turn, but we see them as mutually implicated.

Linking Value-Chains and Gender Relations to the Definition

Centering capture technologies in the definition equates "fisheries" with "fishing," where SSF are narrowly understood as catching fish at sea, from a vessel, using certain gear types (Harper et al., 2017). Viewed within this narrow technological scope, SSF are reduced and simplified, isolated from the wider web of relations that fish harvesters are embedded within, including their bio-physical environments, management regulations, forms of organization, kinship ties, social norms, and exchange relations (Murray et al., 2006; St. Martin et al., 2007). Relational networks that extend beyond the boundaries of fishing vessels are largely omitted, as SSF are translated into a few observable, measurable traits (boats, gear and engines) that make SSF legible (Scott, 1998). However, as Reed and Christie (2008) put it, fishing enterprises are "not solely undertaken by men and cannot simply be defined in terms of people on boats." Rather, as harvested fish circulate within and between communities, and increasingly regional and global markets, it's clear that the status and future of SSF depends on more than understanding the material technologies and effort of harvesting fish at sea (or on the lake). Rather, just as "every word in conversation is half someone else's, every fish that gets caught is partly that of others" (Pálsson, 2015). Fisheries are made possible by a constellation of livelihood activities and related labor, requisite environmental knowledge, and technologies that traverse land and sea. Moving beyond harvesting to include relationships that span the land-sea divide along the SSF value chain is one way we can expand our understanding of SSF beyond the boat and our imagination of what sustainable governance might look like.

At present, research attention remains focused on technological aspects of the male-dominated harvest sector as the key to addressing the "over-exploitation" problem in fisheries, overlooking value chain dynamics beyond harvesting including post-harvest activities (Bennett, 2005). For example, the *dagaa* and other small pelagic fisheries in Tanzania suffer from high rates of post-harvest loss, estimated to be upwards of 50% (Ibengwe and Kristófersson, 2012). While illegal, unregulated and unreported (IUU) fishing are considered major threats to the sustainability of these fisheries (Agnew et al., 2009; Luomba et al., 2017), little attention has been paid to improving post-harvest processing and storage capacity as an entry point to alleviate resource pressure and to meet growing food demands. Further, post-harvest loss disproportionately affects the livelihoods of small-scale processors who are often women (Bradford and Katikiro, 2019). A single unanticipated rain event can ruin a small business enterprise and jeopardize an entire household's livelihood, leaving many women fishworkers in a state of perpetual precarity. Supporting the social and ecological well-being of this fishery depends on understanding and tackling problems along the value chain like post-harvest loss—not merely manipulating fishing boats and gear. Including actors along the value chain in the dialogue on fisheries sustainability could illuminate new avenues for ecologically and socially just governance interventions.

Given that segments of the value chain beyond harvesting are where women tend to work, it's not surprising that they have been overlooked as fisheries research has historically been gender-blind (Kleiber et al., 2015). However, "gender-blind" does not mean that fisheries research has counted both men and women's efforts equally under one androgynous heading, rather fisheries research has systematically focused on and centered men. This gendered bias is not especially unique to fisheries: androcentricism is evident in the philosophies, methods, and key questions pursued by modern western sciences (Harding, 2016), including the wider fields of environment studies and resource management (Banerjee and Bell, 2007; Reed and Christie, 2008). Despite deep-seated ontological assumptions that masculinity is the default gender (of both scientists and subjects; Harding, 2016), we now know that women constitute a large share of the labor force in SSF globally, but that they work predominantly in shore-side efforts such as gear mending, trip preparation, accounting, financing, fish processing, trading and marketing (Odotei, 1992; Walker, 2002; Shannon, 2006; Weeratunge et al., 2010; Matsue et al., 2014). Women also harvest fish in many parts of the world (Gammage, 2004; Porter and Mbezi, 2010; Hauzer et al., 2013), but men and women often interact with different parts of the ecosystem and may target different species using distinct methods and technologies (Kleiber et al., 2015). Based on a meta-analysis of fisheries research, Kleiber et al. (2015) found that in many cases women's fishing effort exceeds that of men for invertebrates, especially in the intertidal and shallow water zones. But women's fishing effort is often categorized as "collection," "gathering," or "gleaning"—activities that are excluded from what counts as "real" fishing (Pálsson, 1989). Wherever women work in the value chain, their efforts are more likely to be informal and/or unpaid, and consequently either overlooked or considered a "natural" extension of women's reproductive roles and responsibilities rather than "real work" (Harper et al., 2017).

Further research is needed that decenters masculinity as the presumed gender and default identity of fishworkers and the latent subject of scholarly attention. Thoroughly redressing anodrcentricism requires a deeper reconsideration of the underlying epistemologies of fisheries science, rather than merely tacking on gender to existing data collection and analysis strategies. However, broadening perspectives and representation within fisheries science will need to take multiple forms, and we do not advocate that all SSF research needs to explicitly focus on women and gender relations, nor take up a feminist lens (Williams, 2008). Value chains and gender merit greater attention as interlinked issues that can be addressed, at least in part, by approaching SSF beyond a limited focus on the technologies and labor of fishing at sea. Reworking the definition to reflect a more inclusive understanding and representation of SSF is a place to start.

Bright Spots and Prospects for Redefining Small-Scale Fisheries

Despite moments of apparent stability, words are not immobile nor immutable. As words move across space and time and their meanings shift they "inscribe the arcs of our past and present" (Gluck and Tsing, 2009). By tracing these arcs in the meaning of the term SSF our research aims not only to address the limitations of enduring patterns in the underlying definition, but to uncover meaningful fluctuations over time and space. By exposing these shifts and moments of instability, our aim is to deconstruct the apparent naturalness of this dominant mode of ordering and defining SSF, undermining the inevitability of technological determinism in the division of capture fisheries to make space for emergent alternatives. Two promising developments that exemplify the potential for an expanded approach to defining SSF are the implementation of the SSF-Guidelines and the FAO's development of a matrix approach to relationally characterize SSF (Funge-Smith, 2018).

Since the adoption of the SSF-Guidelines, the main challenge ahead is whether and how this voluntary tool will be implemented at the national-level (Jentoft, 2014). The text of the SSF-Guidelines offers the framework for a common definition and shared understanding of SSF as including "all activities along the value chain—pre-harvest, harvest and post-harvest—undertaken by men and women" in both inland and marine systems (FAO, 2015). Building from this broad and inclusive definition, the SSF-Guidelines outline ethical principles that should guide SSF governance without any strict prescriptions for their implementation. Its relatively open stance makes the SSF-Guidelines unique among wider global environmental policy tools; many global conservation agreements rely on universally prescribed targets, narrow definitions of success, and tight monitoring requirements (Campbell et al., 2014a,b). In contrast, the SSF-Guidelines were intentionally designed to be flexible and broad in scope to leave room for their interpretation in place, only mandating wide-ranging stakeholder participation during the national implementation process (Jentoft et al., 2017). Amidst discussions about the promise, possibility and challenges of implementing the SSF-Guidelines, whether and how the definition of SSF might change through this process has received little attention. As countries work toward implementing the guidelines, the various stakeholders involved will be obliged to consider whether their existing definition of SSF suffices, or if it demands reconsideration. Since most national fisheries policies rely on technological dimensions like boat length, and many lack a clear definition to start with (Chuenpagdee et al., 2006), it seems likely that the implementation process will inevitably entail rethinking the definition of SSF as a first step in the governance reform process.

Another FAO tool under development is a relational matrix designed to help characterize SSF at different scales. The "SSF characterization matrix" provides a methodological approach and diagnostic tool designed to "avoid inappropriate classifications that can emerge when relying on a single characteristic or a highly-constrained number of characteristics, such as gear and vessel length" (Funge-Smith, 2018). Developed to augment the problem of simplistic technological definitions, the matrix approach eschews singular metrics and rigid divisions between small and large-scale fisheries. Instead, the matrix is used to score a range of qualitative characteristics on a finer scale, aggregating them to an overall score that can then be used to assess SSF in a particular country or to compare fisheries globally. Decisions about the exact cut off between "large" and "small" can then be made within a given context. In the structure of the matrix different characteristics are taken into consideration and weighted together, which means that engines, fishing gear and vessel length matter, but not more than a host of other characteristics. We see the matrix tool as a positive development in the search for better ways to define and characterize SSF with applications for science and policy, and we believe it provides a practical alternative to the current limited reliance on harvest technologies. The matrix is still being field tested in several countries and adapted accordingly, based on user feedback (Funge-Smith, 2018). As it becomes available to researchers in the future, we see great potential in the SSF characterization matrix as it enables consistent but relational ways of defining SSF that work at multiple scales.

Re-envisioning Small-Scale Fisheries in Tanzania

Lastly, we illustrate the potential for renegotiating the definition of SSF in practice, drawing upon our own research on the implementation of the SSF-Guidelines in Tanzania. Here we briefly examine the central yet contested role the definition plays in fisheries fora, exposing and refracting different sets of underlying values and related politics. Yet, even as the definition rouses controversy, the saliency of the issue is generally not disputed. We highlight the potential difference the definition can make toward alleviating unsustainable and unjust policies in the sector, potentially redressing historical inequities and invisibility long cast upon the sector.

Defining a national plan of action to implement the SSF-Guidelines in Tanzania has required addressing the vexing issue of how to define SSF, outlining which activities will count in relation to policy implementation. At the 2018 national inception workshop toward the implementation of the SSF-Guidelines in Tanzania held in Bagamoyo, a high-ranking government official opened the workshop of over 75 participants from across the country and the sector, posing the question: "Who is a fisher? Someone pulling a net or sitting in an office in Dar es Salaam? With the SFF-Guidelines implementation, we get to identify this in our own context and be one of the first countries in the world to do so" (comment from meeting participant, 2/14/2018). With this opening declaration, the definition was immediately positioned as a fundamental issue that would shape the coming days discussion and any decisive actions toward implementation. Further, the opportunity to implement the guidelines and rework the definition were presented as dual opportunities for Tanzania to be on the leading edge of global fisheries reform.

As the workshop ensued, discussions continued to circle back to the fundamental issue of the definition. Rather than a dry topic of technical classification, discussions were animated, revealing disparities in everyday experience and underlying values placed on the sector broadly labeled as SSF. As we noted in the introduction, the issue of the definition can become a stumbling block to reaching consensus policy agreements. While the text of the SSF-Guidelines mandates that wide-ranging stakeholders participate in implementation, diverse assemblages of actors may not be accustomed to working together to negotiate priorities where policy is usually set in a top-down manner. Further, in Tanzania there are significant differences across inland and marine fisheries, and even within inland fishers, between the development and dominance of Lake Victoria's fisheries compared to other inland water bodies. Actors brought different experiences from their home fisheries and positions within the sector to the table—enlivening conversations. But a lack of familiarity with each other's circumstances also created obstacles to mutual agreement. One fisher from Lake Victoria raised the issue of consolidated ownership of fishing vessels, where he claimed that one man can even own 200 boats yet be classified as "small." In response, another fisher from the coast responded: "We agree that we need to find a *real* definition. The rich people aren't fishers, the real ones go to the water and land fish and work with the fish themselves to get them to market. But some of the problems raised here about Lake Victoria don't apply everywhere, like on the coast. These problems are foreign to me." This interchange reflects the simultaneous potential for identifying common ethical ground, and yet how different geographic and development contexts within one country make articulating a shared definition cumbersome. While both fishers seemed to agree that relations of ownership matter in determining who counts as a real small-scale fisher, how meaningful class differences should be articulated was controversial, where answers to the question of "how much is too much" regarding ownership differed. When actors are unaccustomed to working together, identifying shared values and common language for a nationally representative definition is a substantial hurdle to reaching consensus agreement on policy implementation. The definition can become a thorny subject that simultaneously generates common ground and reveals fault lines.

One issue that generated greater mutual agreement was the need to address the long-standing marginalization of women and post-harvest workers through the implementation of the guidelines. Here, it became clear that altering the definition of SSF beyond a limited focus on harvesting was a necessary component of a multi-pronged strategy to alter historical injustices and treatment of fishworkers, where fisher*men* have long been prioritized. Several ideas emerged and attained consensus as viable strategies to address the interlinked issues of underrepresentation of women and post-harvest workers by making their presence and claims more visible. First, to conduct a national-level mapping study of existing women's organizations in the sector. Second, to use outputs from the mapping study to help build a national platform for women fishworkers. Lastly, to create a Gender Desk at the ministry to help support the platform and existing women's groups and to address gender-specific challenges present in the sector (Bradford and Katikiro, 2019). Whether and how these activities are enacted and affect a shift in the balance of power in SSF remains to be seen.

Yet workshop participants from across the sector and the country mutually agreed that these steps could potentially help ameliorate the cycle of women's invisibility in fisheries research and policy if the identified tasks lead to an alternate definition of SSF that becomes the basis for data collection, decision making, and stakeholder participation in the future. The hope is that these efforts not only lead to revisions of the definition on paper, but a more substantive re-envisioning of the underlying values of SSF in place.

Defining Small-Scale Fisheries for the Future

While scholarship on SSF has been around since at least the 1960s, defining SSF remains an ongoing challenge even as the field of SSF studies expands and diversifies. The diversity of SSF and their illegibility to outsiders has prompted certain techniques of simplification, including the use of reductionist definitions that focus on aspects most easily identified as small-scale, such as boats and fishing gear (Jadhav, 2018b). As perceptual guides, definitions work as metaphorical "maps" that detail which elements are important along the infinite complexity of a given social and ecological terrain. Reading the landscape of SSF through this narrow definition places undue emphasis on male-dominated harvesting at the expense of a more expansive view of the social and ecological relations along the SSF value chain that span land and sea. In the absence of a clear definition, a blank map leaves the reader to fill in the landscape themselves, often inadvertently drawing on simplistic tropes embedded in our mental imaginary of SSF as small-time activities from the past.

Motivated by similar research on the definition of SSF in policy, the results from our systematic review of the scientific literature echo some of the same worrying patterns while also revealing new temporal and geographic trends and disparities that are worthy of deeper consideration. The temporal shifts we observed indicate that, despite dominant practices present in both science and policy, the definition of SSF is not an immutable category fixed in time and space. Rather from a historical perspective, the definition beneath the word "small-scale fisher" is a process-in-motion, where boundaries are contested and mutable over time. In recent decades, these boundaries may be contracting around a tighter and more technologically determined view of SSF in the influential realms of science and policy. Yet, in addition to thinking about what the boundaries of the definition enclose—who and what is included—we can also contemplate the potential for counter hegemonic definitions and knowledge projects that expand our understanding of what constitutes SSF. Particularly as unorthodox actors are invited to the table, such as fishers and post-harvest sector workers themselves, the space for political action and the power to shape knowledge produced on SSF is potentially broadened. Both the SSF-Guidelines and the characterization matrix developed by the FAO offer an alternative conceptual "counter map" of SSF that can be read against the dominant technological definition, offering a more encompassing and dynamic re-reading of the possibilities and place of SSF (Gibson-Graham, 1996; St. Martin, 2009). The application of these tools is also a process-in-motion, one to be followed. Where these tools are applied, alternate definitions could be leveraged that reflect different sets of values or ethical coordinates (Gibson-Graham, 2006)—where SSF are depicted as more than the sum of their harvesting technologies and productivity. How these tools reshape the definition of SSF and unfold in practice, and to what effects, are key areas for future research. Here we have provided some initial insights into this process from our own research in Tanzania.

To understand SSF research priorities for the future, it is important to “review and understand science and research agendas undertaken on SSF in a historical perspective” (Pomeroy, 2016), including how the category of SSF has been constructed and deployed alongside narratives of fisheries problems and solutions (Johnson, 2006). We hope our initial analysis of the historical construction of SSF as a category in science and policy can help shift the discourse on the definition beyond current assumptions that “smallness” is obvious, where “you can know a SSF just by looking at it” (Gibson and Sumaila, 2017). Instead of relying on old tropes that equate SSF with small boats, we beckon scientists and policy makers to take another look—and consider the wider and more lively assemblage of possibilities hidden beneath the surface of the definition.

AUTHOR CONTRIBUTIONS

HS and XB developed the initial concept for the study. XB initially built the database. HS completed data retrieval and organized the database. HS conducted the analysis and interpretation of results with input from XB. HS wrote the first draft of the manuscript and both authors contributed to revisions, read and approved the submitted version.

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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.2019.00236/full#supplementary-material

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Evaluating the Fit of Co-management for Small-Scale Fisheries Governance in Timor-Leste

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Fisheries co-management is an increasingly globalized concept, and a cornerstone of the *Voluntary Guidelines for Securing Sustainable Small-scale Fisheries in the Context of Food Security and Poverty Eradication*, adopted by the United Nations Food and Agriculture Organization member states in 2014. Timor-Leste is a politically young country in the relatively rare position of having underexploited fisheries in some areas that can be leveraged to improve coastal livelihood outcomes and food and nutrition security. The collaborative and decentralized characteristics of co-management appeal to policymakers in Timor-Leste with provisions for co-management and customary laws applied to resource use were incorporated into state law in 2004 and again reinforced in 2012 revisions. The first fisheries co-management pilots have commenced where management arrangements have been codified through *tara bandu*, a process of setting local laws built around ritual practice that prohibits nominated activities under threat of spiritual and material sanctions. To date, however, there has been little critical evaluation of the suitability or potential effectiveness of co-management or *tara bandu* in the Timor-Leste fisheries context. To address this gap, we adapted the interactive governance framework to review the ecological, social and governance characteristics of Timor-Leste's fisheries to explore whether co-management offers a valid and viable resource governance model. We present two co-management case studies and examine how they were established, who was involved, the local institutional structures, and the fisheries governance challenges they sought to address. Despite their relative proximity, the two sites contrasted in local ecology and fishery type; community institutions were starkly different but equally strong; and one site had tangible economic benefits to justify compliance, where the other had marginal and anecdotal fishery gains. In our review of the broader governance landscape in Timor-Leste, we see co-management as a useful mechanism to govern small-scale fisheries, but there is a need to connect legitimized local institutions with hierarchical governance of higher and external influences. Initial successes with implementing *tara bandu* incorporating a small marine closure have stimulated other communities to implement no-take zones – one universally popular but very limited interpretation of co-management. However, we highlight the need for a set of guiding principles to ensure legitimate community engagement, and avoid external appropriation that may reinforce marginalization of certain user groups or customary power hierarchies.

Keywords: customary marine tenure, tradition, community-based resource management, governance, legal pluralism

INTRODUCTION

The *Voluntary Guidelines for Securing Sustainable Small-scale Fisheries in the Context of Food Security and Poverty Eradication* (SSF Guidelines), developed to complement the 1995 FAO Code of Conduct for Responsible Fisheries, were approved by the Committee of Fisheries of the Food and Agriculture Organization of the UN (FAO) in 2014. This commitment provides unprecedented recognition of small-scale fisheries (SSF), which account for almost half of global fish landings utilized for domestic human consumption (FAO, 2018), and employ over 90% of the world's estimated 120 million fish workers (World Bank, 2012). The SSF Guidelines were developed in response to the increasing vulnerability of the economic, food security and nutritional benefits accrued from small-scale fisheries, particularly for many of the world's poorest and most marginalized people. The SSF Guidelines provide a range of high-level, but voluntary, commitments relating to human rights, fisher representation, economic and social development and sustainability. The challenge faced by countries now is the implementation of the SSF Guidelines, by way of aligning, adapting, reconfiguring and strengthening existing small-scale fisheries governance and management arrangements (Jentoft, 2014). This is particularly challenging in low-income countries where small-scale, multispecies fisheries are highly susceptible to governance and management failures (Gutiérrez et al., 2011).

Co-management has captured global attention as the most appropriate mechanism to manage tropical SSF. Fisheries co-management is defined as a relationship between a resource-user group (e.g., local fishers) and another entity (e.g., government agency or non-government organization) in which management responsibilities and authority are shared (Pomeroy and Berkes, 1997; Evans et al., 2011). The philosophy behind co-management is that those who are affected by management (e.g., fishers and other resource users) should be involved in making management decisions (Berkes, 2009), thereby improving the legitimacy of the state involvement in fisheries management through more inclusive and transparent decision-making processes (Evans et al., 2011). Co-management is well aligned to the commitments of participation, representation, collaboration and coordination (Evans et al., 2011; Wamukota et al., 2012) emphasized in the SSF Guidelines (Cohen et al., 2017). But, below these high-level principles are highly contextualized grounded actions to effectively implement co-management in complex SSF systems (Young et al., 2018).

The degree to which responsibility is shared, and the form and function of co-management, varies by setting, depending on the nature of the fisheries, informal and formal governance institutions, and the capacity, influence and authority of nation-states and fishing communities (Sen and Nielsen, 1996). Much has been written about the evolution, role and performance of co-management in varying contexts in the Pacific island countries and territories (e.g., Govan, 2009; Davis and Ruddle, 2012; Jupiter et al., 2014; Klein et al., 2014) and in the Coral Triangle (e.g., Dirhamsyah, 2013; Cohen and Steenbergen, 2015). Whilst Timor-Leste falls within the Coral Triangle Region, its political and cultural history provides a new set of challenges and a valuable platform for learning.

This study represents the first account of co-management for Timor-Leste's SSF and our first objective is to describe the emergence and form that co-management has taken. Our second objective is to provide some critical reflections on the role of diverse actors and institutions in the implementation process, the sustainability of interventions, and the ongoing resourcing of SSF management in a developing country setting. By drawing on the interactive governance framework (*sensu* Chuenpagdee and Jentoft, 2013) we examine how the characteristics of small-scale fisheries (i.e., *system-to-be-governed*), in these two cases and in Timor-Leste more broadly, render them more or less governable using a co-management approach (*governing system*). We aim to unpack some of the particular challenges and opportunities that co-management might offer up as a principle vehicle with which to govern SSF in Timor-Leste and similar contexts.

MATERIALS AND METHODS

The Interactive Governance Framework (Chuenpagdee and Jentoft, 2013) breaks down the analysis of SSF into three main components: (1) System to be Governed, (2) Governing System, and (3) Governance Interactions. To describe the *system-to-be-governed* we briefly review both published and unpublished literature on Timor-Leste's SSF in terms of types and level of participation, the geographic range and focus of fleets, species targeted, and fishing gears employed. Second, to examine the *governing system,* we draw on previous reviews of the formal legal and policy instruments that have enabled, or could potentially enable, state and municipal and village (*Suco*) levels of government to play a role in SSF governance. We also review published reports that explain how customary institutions have been proposed or invoked in community efforts to manage natural resources. Finally, we examine *governance interactions* to summarize the main co-management developments in Timor-Leste over the last two decades. We then delve into two cases where community-based forms of co-management have been implemented with support from external agencies. Data for these cases are drawn from published literature, and also from the first-hand experiences of authors who were facilitators in the co-management establishment processes in 2012 and 2015. These communities were revisited in late 2016 and again in early 2018 to evaluate how these approaches have fared in recent years. These visits used key informant interviews with fishers, traders and local leaders, and gender disaggregated focus group discussions (FGDs) to evaluate the longer-term effectiveness of the co-management regimes.

For each site we report the target fishery species using published analyses from the Timor-Leste national digital catch monitoring system, *PeskAAS* (including non-boat-based fishing landings), and utilize high resolution vessel monitoring data to characterize the distribution of fishing pressure across space between February 2018 and May 2019. Seven vessels in Adara and 15 vessels in Biacou were fitted with solar-powered boat trackers that record location every second. To classify fishing by range and habitat in each of the case study sites, fishing effort heat maps were created by segmenting the geography into a grid of hexagons, parsing individual trips into segments, categorizing these segments by activity (fishing vs. steaming vs. parking etc.) according to activity classification algorithms, and summing the total amount of fishing time (in hours) spent by the fleet in each grid cell.

RESULTS

System to Be Governed

Timor-Leste makes up the eastern half of the island of Timor and has a population of approximately 1.2 million (GOTL, 2015). It was colonized by Portugal in the sixteenth century, and then following 9 days of independence in 1975, was annexed by Indonesia. The Democratic Republic of Timor-Leste was formed in 2002 following independence from Indonesia. The country has an extensive exclusive economic zone of 77,051 km^2 and a coastline of 706 km, which includes the Special Administrative Region of Oecusse-Ambeno (RAEOA), and the two islands of Atauro and Jaco (**Figure 1**). Following independence, the economy grew rapidly due to offshore oil and gas exploitation, the returns of which sit in a sovereign wealth fund and provide ∼80% of the total budget for Government expenditure (World Bank, 2018). However, petroleum production is declining and few people are directly employed in the oil industry. In addition, levels of poverty, food insecurity and chronic malnutrition remain some of the highest in the world (Grebmer et al., 2015). With over 80% of the population involved primarily in subsistence or small-scale agriculture and fisheries, and over 95% living in rural areas (GOTL, 2015), the sustainable enhancement of this sector is recognized as a priority pathway to building a more diverse economy (GOTL, 2011).

Recent figures suggest there are ∼5000 fishers in Timor-Leste (GOTL, 2015), with over 2000 of these on the island of Atauro (Mills et al., 2017). The fisheries sector in Timor-Leste is almost exclusively small-scale, and in this context, small-scale fishing activities refer to those that take place on average less than 5km from shore, targeting reef fish and small, near-surface, open-water species such as sardines, mackerel scad, needlefish, garfish, and flying fish (López-Angarita et al., 2019). Fishing often serves as part of diverse livelihood strategies that simultaneously include agriculture, foraging, small-scale business and sporadic engagement in paid employment; each of which may become more or less important at different times of the year (Alonso Población, 2013; Mills et al., 2017).

The majority of boat-based fishing in Timor-Leste is done from one and two person non-motorized wooden outrigger canoes (82%). The remaining 18% consists of both slightly larger canoes with "long-tail" outboards (katintin) (63%) and larger wooden or fiberglass boats with outboard engines (35%) (AMSAT International, 2011b; Alonso Población, 2013). Following independence, foreign development assistance funded the distribution of approximately 300 outboard engines and 1,500 gill-nets to coastal fishers (Sanyu Consulting, 2003), conducted in part as a gear swap for beach seine fishing gear, which was banned. Gear types such as hand lines, spear guns, cast nets and monofilament gill nets, deployed from beaches, and across reef and seagrass habitats are simple and low-cost. Gill netting and hand-lining in and around river plumes target seasonally occurring schools of sardines, mackerels and scads. Seaweed farming and sea cucumber harvesting take place on seagrass beds (Park et al., 2012), while gleaning for molluscs, fish, crustaceans and cephalopods is common in the intertidal zone. Gleaning represents an important fishery livelihood undertaken predominantly by women and children for subsistence and/or sale (Sandlund et al., 2001; McWilliam, 2003; AMSAT International, 2011a; Alonso et al., 2012). In terms of landed weight and contribution to income, finfish are the most important group for fisheries livelihoods. However, gleaned catches contribute directly to household food and nutrition security, and to varying extent buffer the seasonal and stochastic nature of fisheries livelihoods (Tilley et al., in review).

Nearshore fish aggregating devices (FADs) are allowed by law and are commonly utilized by coastal fishers to increase access to denser schools of small pelagic fish. Fish around the FADs are targeted using hand lines, gill nets or seine nets known locally as *chinchin* and *lampoon* (Tilley et al., in review). Beach seine nets were banned after independence, but their use continues in areas where habitats are degraded or where fisheries productivity is low. Other highly destructive methods such as blast fishing and poisoning have all but ceased aside from localized use of naturally occurring, organic toxins in gleaning reef fisheries.

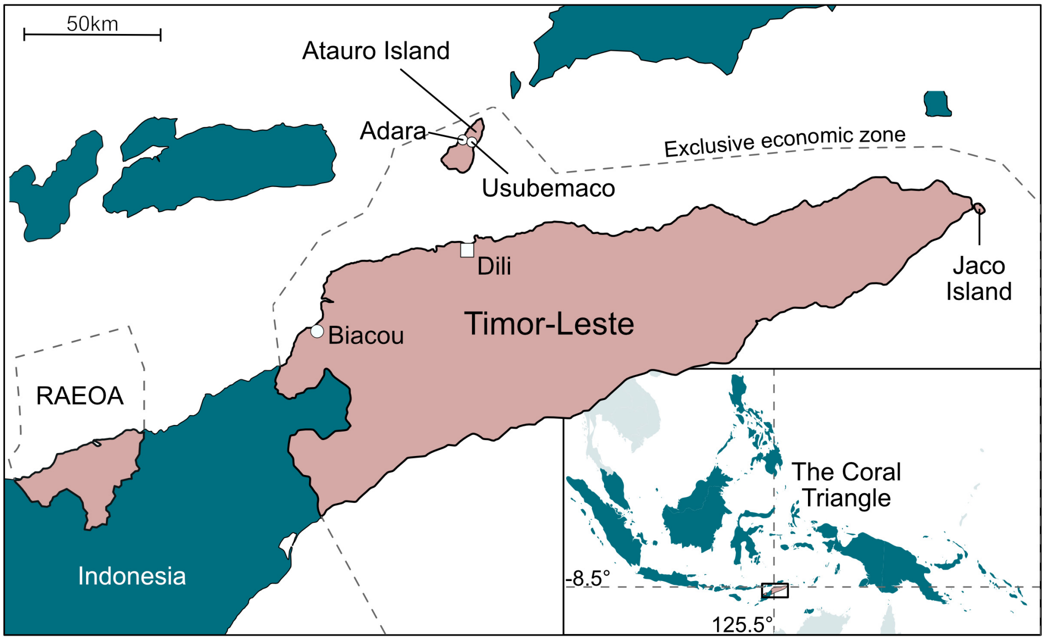

FIGURE 1 | Map illustrating Timor-Leste within the Coral Triangle region (inset). The main map shows the two case study locations where forms of co-management have been established, (a) Biacou community, and (b) Adara community located on the Island of Atauro, in relation to the capital, Dili and the Special Administrative Region of Oecusse-Ambeno (RAEOA). The dotted line represents the EEZ.

Small-scale fisheries play a crucial role in local food and nutrition security and livelihoods, and researchers suggest there is potential to enhance these contributions in Timor-Leste (Mills et al., 2013). Preliminary surveys from coral reef fishing grounds in Timor-Leste, however, suggest that mean fish sizes are small compared to neighboring sites in Indonesia (McCoy et al., 2015). Fisher surveys and focus groups in fishing communities across the north coast of Timor-Leste and Atauro Island also suggest declines in catch volume and fish sizes in reef fisheries, although there are no empirical time series data available to support this. Underwater visual surveys of reef fish biomass across Timor-Leste suggest healthy reef fish populations (López-Angarita et al., 2019). Both the case study sites examined in this paper have narrow fringing reefs, which provide limited fisheries productivity, but the country is in the relatively unique situation of having very lightly exploited stocks of small pelagic fish (Alonso et al., 2012; Mills et al., 2013). This underlines the need for fisheries management and diversification of fisheries to exploit more sustainable pelagic stocks, while simultaneously, addressing common concerns remaining about sustainability of nearshore marine resources for meeting subsistence needs, government-set nutrition goals, and conservation commitments (Alonso et al., 2012; NDFA, 2012; Mills et al., 2013).

Governing System

Fisheries governance in Timor-Leste involves two major governing systems: state-based institutions developed post-Independence, and community-specific customary institutions that have persisted and evolved through several hundred years of Portuguese colonialism and 25 years of Indonesian administrative rule (Feijó, 2015). In view of this paper's scope we refer to state-based institutions (referred to as hierarchical governance by the Interactive Governance Framework) and custom-based governing institutions (referred to as self-governance by the Interactive Governance Framework), and how these two governing systems interact in co-governance or co-management which is, arguably, a newer and emerging governance system for fisheries in Timor-Leste.

State-Based Governance

Independence from Indonesia brought the need for Timor-Leste to develop its own fisheries laws and define sector priorities, providing the opportunity to promote a sustainable model of fisheries management (Alonso et al., 2012; Alonso-Población et al., 2016). Timor-Leste's constitution stipulates that "Everyone has the right to a humane, healthy, and ecologically balanced environment and the duty to protect it and improve it for the benefit of the future generations" (Article 61 n.º1). Whilst this recognizes a shared governing responsibility, the fisheries sector is formally (approved by Law Decree n.º14/2015, of 24 June) the governance responsibility of the Ministry of Agriculture and Fisheries (MAF).

Post-independence, a highly centralized governance system has developed and a mismatch between budget, bureaucratic processes and the requirements of municipalities are common (World Bank, 2012). The principle of decentralized public administration is clearly established in Timor-Leste's constitution (section 5), and over the past 15 years, government administrations have developed and adopted various decentralized governance frameworks, although none have yet been fully implemented (Cummins, 2015). In the most recent iteration, the Government approved Law-Decree n.º3/2016 (of 16 March) outlines a strategy of reform that will ultimately see the creation of a second, locally-elected, tier of government in each of Timor-Leste's 12 Municipalities (the 13th region of RAEOA is already given a degree of budgetary autonomy with Special Administrative status).

In the current structure of MAF, the Fisheries Department has a national office based in the capital Dili, and fisheries officers operate from MAF offices in each municipality. The national fisheries office is responsible for the monitoring of marine resources, collecting data and taxes on exports, administering boat licensing, and all enforcement and compliance including inspections of foreign licensed fishing vessels. There are 96 fisheries staff employed across 13 municipalities, some of whom work as community-based field officers who (depending on local levels of fishing and municipal resources available) typically include field extension activities like recording fish landings, training fisher and trader groups, and managing fish landing centers. These municipality-based fisheries officers play an important coordinating role with village and *suco* level leaders (**Figure 2**), and will be important actors in co-management as the link between the two hierarchies of governance, e.g., in escalating infractions outside the jurisdiction of local authorities or vision of co-management such as encroachment by industrial or foreign fishing vessels. In practice, the activities of both national and municipal fisheries departments and their influence over Timor-Leste's fisheries sector are limited due to low institutional, human resource and financial capacities relative to the scale (number of fishers and fish traders) and scope (geographic expanse) of fisheries activities – particularly small-scale fisheries. For example, in 2017 the fisheries received only 0.07% of the national budget (López-Angarita et al., 2019). As stated by a MAF official, this "is not in proportion to the number of persons employed in rural activities, nor the number of people living with food insecurity in rural areas" (in da Cruz, 2016). Although, the number of staffs employed by MAF has increased substantially since early post-independence (from 350 people in 2002 to 2196 in 2015; da Cruz, 2016), the majority of the expansion has occurred in the agricultural sector.

Community-Based Institutions

The most relevant interpretation of "community" in Timor-Leste would relate to the geographical distribution of people in a *Suco* (village) and *aldeia* (hamlet), whereby several *aldeias* form a *Suco* (consistent with Miyazawa, 2013). While the composition of some *Sucos*, particularly in urban areas, has been altered due to colonial influence and migration, these communities are based on historical and cultural connections, linked to *uma lulik* or *uma lisan* (traditional "house group") relationships established through kinship, marriage and alliance. It is suggested that *lisan* (customary law) is still the main source of law and authority for most Timorese people, particularly in rural areas (Cummins, 2015). It provides community cohesion and conflict resolution mechanisms, informs the allocation of leadership and decision-making power, and guides the use of communal resources (Cummins, 2015). This combination of customary governance

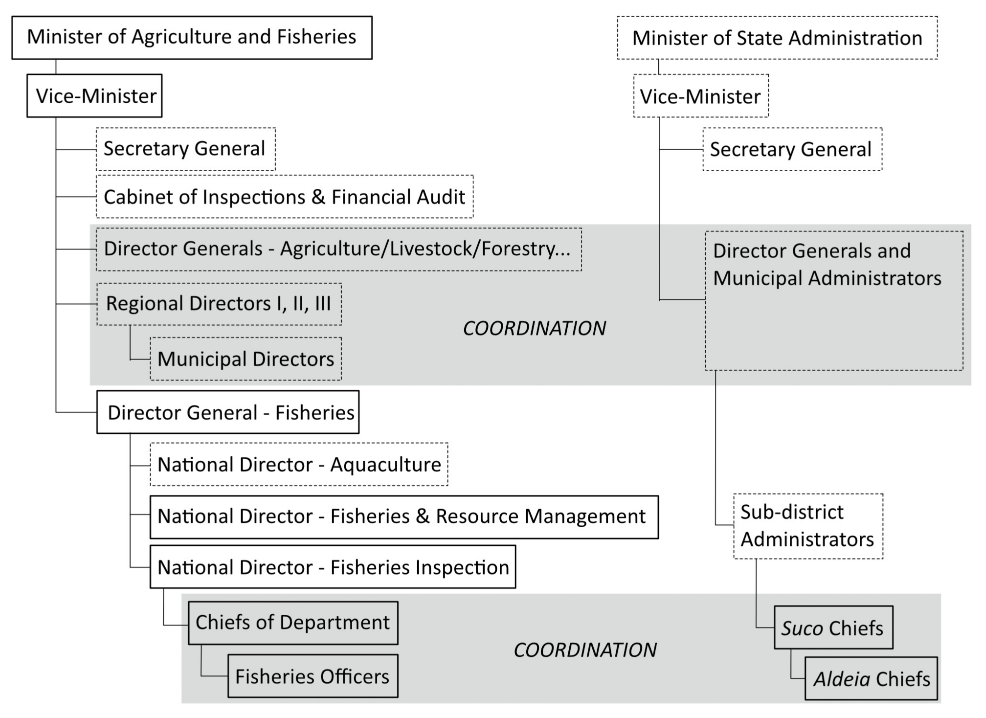

FIGURE 2 | The hierarchical structure of fisheries related departments of Timor-Leste's Ministry of Agriculture and Fisheries, and at what levels these coordinate with municipal, *suco* and village level governance under the Ministry of State Administration.

layered with state-based institutions has resulted in a current governance system described as political hybridity or a form of legal pluralism. It consists of two sets of institutions and laws, from very different worldviews, which community leaders must balance on a daily basis to ensure their decisions are legitimate and effective in their communities (Cummins, 2015).

Suco leadership has played an important role from before Portuguese colonization to the present. In recognition of this, provision for the election of a *Suco* council in each of Timor-Leste's 442 *Sucos* was first established in 2004 (Law nº5/2004, of 14 April), formally incorporating existing customary practices into state-based institutions (Cummins, 2015). In preparation for the creation of a Local Government at the Municipality level, the recently adopted *Suco* Law (Law nº9/2016, of 8 July 2016, pmbl.) refines the composition of the *Suco* council and takes further steps to legally affirm the "authority functions that are traditionally associated to [the *Suco*]." The *Suco* council is composed of community leaders elected by community members, as well as a *lia-na'in* (a customary authority figure who holds ritual and judicial powers) (Cummins, 2015), and encourages greater representation for women and young people through a formalized quota system[1]. As outlined in the law, *Suco* councils and their leaders have a broad range of duties and responsibilities, including dissemination of state-based laws and regulations, and the promotion, adaptation or preservation of custom-based laws. However, actions may not be undertaken at the detriment of the State or Municipality tiers of government (Article 6).

Given their authority and responsibilities, *Suco* councils are critical points of engagement for both government and non-government organizations interested in carrying out community-based activities, including the establishment of new co-management committees or co-management arrangements for natural resources such as fisheries (Costa Pereira et al., 2013). The strength, priorities and perspectives of these local leaders (Suco and Aldeia chiefs) appear to be more important for successful resource management than an active and engaged district MAF fisheries officer.

While it has been suggested that Timorese people have less of a connection to the sea than other island nations (e.g., in the Pacific), local and traditional management and relationships with coastal resources do exist in parts of Timor-Leste. Despite being historically ignored or excluded by the Portuguese and Indonesian regimes, these institutions have persisted to varying degrees (McWilliam, 2003). *Tara bandu* refers broadly to laws or prohibitions (Hicks, 2004) that can be applied by communities to regulate land use or fisheries harvest in a given area for a set period of time (Shepherd, 2013). This may apply to, for example, prohibiting deforestation in terrestrial ecosystems (JICA, 2015), establishing temporal fishing bans in a freshwater lake (Needham et al., 2013), and banning the harvest of certain species or in specified coastal fishing areas (Alonso-Población et al., 2016, 2018). These custom-based laws are closely related to cultural conceptualizations of the relationships between humans and non-human entities, and are complied with in part due to people's belief that if they break the rules, they will be cursed (Miyazawa, 2013). *Tara bandu* is enacted through a mix of diverse rituals leading to a usable regulatory practice of interactions within communities and between humans and their environment (McWilliam et al., 2014).

In the last 10 years, non-government organizations (NGOs) have initiated projects to re-introduce or strengthen *tara bandu* in various parts of Timor-Leste. Whilst it is often framed by NGOs as a longstanding and important tradition, *tara bandu* (as with other similar customary institutions e.g., Cohen and Steenbergen, 2015) has undergone a process of contemporary revitalization and re-imaging since independence (McWilliam et al., 2014; Alonso-Población et al., 2016, 2018). Observers have suggested that the application of *tara bandu* in managing natural resource use is merely appropriation of the institution to achieve externally formulated conservation and sustainability objectives (McWilliam et al., 2014), and its nature and presence in between governing systems reflects the presence of a legal pluralism (Alonso-Población et al., 2018). Nonetheless, *tara bandu* appears to hold legitimacy with communities, NGOs and government alike (see **Table 1**) and its invocation in community-based resource management or co-management seems almost inevitable. *Tara bandu* has played "an inherent part in the development of local ordinances to protect the forest-watershed areas" (MAFF, 2004, p38 in Miyazawa, 2013) and it has been suggested that it should form the basis of community-based fisheries management efforts (Needham et al., 2013). The MAF "has been encouraging the revival of *tara bandu* for both technical and political reasons" which are perceived as "benefiting both governmental authority and customary leaders" (Miyazawa, 2013).

Tara bandu is now also recognized by the state-based Environmental Framework Law (Article 8). This law affirms that *tara bandu* may be established through local common law to conserve the environment and promote the sustainable use of natural resources, and importantly, declares that the State will ensure the regulated area is effectively protected. More generally, the Constitution (Article 2 n.º4) affirms that "The State shall recognize and value the norms and customs of East Timor that are not contrary to the Constitution and to any legislation dealing specifically with customary law."

Co-management Policy Development Since Independence

The notion that state- and community-based management should be harmonized and interacting has had a degree of currency since independence. The various development of policies, regulations and programs in Timor-Leste related to fisheries co-management are summarized as a chronological timeline in **Table 1**.

Case Studies

Here we present two case studies of the development of fisheries management systems in contrasting settings. We have selected

[1]The Council is composed by: the Suco Chief; the *aldeia* Chiefs of the Suco; a female delegate from each Suco's a*ldeias;* a male delegate from each Suco's *aldeias*; a female youth representative from the Suco; a male youth representative from the Suco (Article 10, Law n.º9/2016, of 8 July 2016).

TABLE 1 | A timeline of fisheries co-management developments in Timor-Leste since 2000.

What	Year	Who	Description and co-management development	Comment
"Fish for the Future" – first national fisheries policy	2001	MAF	Focused on nascent state priorities such as staff capacity building, assertion of jurisdiction, and development of legislation (Alonso et al., 2012).	
Co-management or community-based, coastal resource management framework	2001	MAF under the World Bank's second Agriculture Rehabilitation Project	Detailed proposed community-based, coastal resource management scheme (Stockwell, 2001, 2002).	No follow up or implementation (Stockwell, 2002).
Law Decree 6/2004 of 21 April – establishes the general basis of the legal regime for fisheries and aquaculture management and regulation	2004	MAF	Provides for the creation of co-management committees with powers related inter alia to "compliance with conservation and management measures of fishing resources, protection of the marine environment, assistance in controlling illegal fishing and compliance with the fisheries legislation" (Article 114).	Currently under review (2018).
"Fish for Sustainability: Our Strategic Plan for Fisheries, 2006–2011" – a new fisheries strategy	2005 (drafted), 2007 (released)	MAF	To "encourage and facilitate community-based, fisheries management initiatives and aims at establishing a network of local, community-supported marine protected areas and encourage involvement of NGOs" (MAFF, 2005).	Not approved by the Council of Ministers, nor legally endorsed by the government (Alonso et al., 2012).
Development and establishment of Timor-Leste's first marine protected area, Nino Konis Santana National Park (NKSNP)	2006–2009	MAF in partnership with a consortium of Australian agencies	Project included a planning workshop for the NKSNP marine component which endorsed "a community-based approach to planning [. . .] – i.e., Locally Managed Marine Area (LMMA) model – to build local support, stewardship and provide for co-management" (Edyvane et al., 2009).	The adoption and implementation success of management process has not been critically assessed.
	2009–2013	USAID's Coral Triangle Support Partnership, implemented by Conservation International in partnership with MAF and a local NGO	The Indonesian National LMMA Network supported development and planning of LMMAs at Manatuto and Hera including exchange visits, community surveys and participatory planning in 2011–2012. Worked with communities of the NKSNP to identify priority resources and develop management solutions, leading to the development of a multiple-use marine park zoning and regulatory scheme, and community-based management plans (Weeks et al., 2014). As part of this work, a manual was produced on "*Guidelines for Establishing Co-Management of Natural Resources in Timor-Leste"* (Costa Pereira et al., 2013).	
Regional Fisheries Livelihoods Program for South and Southeast Asia (RFLP) – a regional program, implemented in six Asia-Pacific countries	2009–2013	Implemented by the FAO in close collaboration with the Timor-Leste Government, funded by the Kingdom of Spain.	Aimed at "strengthening capacity among participating small-scale fishing communities and their supporting institutions toward improved livelihoods and sustainable fisheries resources management," including the establishment and strengthening of co-management mechanisms (Needham et al., 2013). In Timor-Leste, the RFLP focused on building basic governance systems, such as the development of a National Fisheries Statistics System and a National Census of Fishers and Boats, among other activities. NDFA staff were also engaged to gather information from communities on informal management arrangements and governing mechanisms in coastal areas. Through this exercise the community of Biacou were identified as interested in re-enacting their *tara bandu* for management purposes.	Further details on the Biacou case study are provided below.
Participatory development of the first exclusively marine *tara bandu* in the community of Adara on Atauro Island	2015–2016	Implemented by WorldFish funded by the Australian Center for International Agricultural Research	A highly participatory approach involving all stakeholders in Adara, as well as relevant government agencies. Regulations, boundaries and fine structure were devised by the community, including a closed area with a "reef tax" for diving and snorkel groups wanting to enter.	Further details on the Adara case study are provided below.

(Continued)

TABLE 1 | Continued

What	Year	Who	Description and co-management development	Comment
National Fisheries Strategy	2017–2018	MAF and WorldFish funded by Norway and the Asian Development Bank.	Between 2017 and 2018, the DGP and WorldFish conducted national consultations with fishers in every municipality of Timor-Leste to inform the drafting of the NFS. The two primary strategic actions identified were (1) to update and harmonize the legal and regulatory frameworks of the sector; and (2) to develop an institutional framework conducive to participatory and transparent co-management of marine fisheries.	López-Angarita et al., 2019

these cases because they are the most mature examples of co-management in the country, and authors of this paper have been involved in the development of both cases. The first, Biacou, is on the mainland of Timor-Leste in a pelagic-focused fishery. The second is on Atauro Island, the most fish-dependent region of Timor-Leste (Mills et al., 2011), where reef fisheries are important, and supporting a developing stream of income from eco-tourism was a high priority for the community.

Case Study 1: Biacou Community

The *aldeia* of Biacou is situated in Bobonaro Municipality at the western end of Timor-Leste's north coast (**Figure 1**), some 23 km from the border with West Timor, Indonesia. Road access along the coast to Dili and inland to the Municipal capital,Maliana, is good and brings with it significant trade opportunities. Biacou is a hamlet of 100 households and 579 people (GOTL, 2015) and represents one of the most important fishery landing sites of the country in terms of landed weight per year (NDFA, 2016). Fishing is predominantly motorized with fishing taking place as far as 25 km from Biacou (**Figure 3**). Catch is dominated by small pelagic and semi-pelagic fishes such as moonfish (*Mene maculata*), sardines (*Sardinella* spp. and others) mackerel scad (*Rastrelliger* sp.) and flying fish (*Cypselurus* sp.) (López-Angarita et al., 2019). No stock assessment data exist for this area. Fishing is a major livelihood activity for most households, although livelihood portfolios are mixed and include agriculture, salt production and trade. The mean price for fish was ∼USD $2.80/kg with little variation between species at the time this study was carried out (Tilley et al., in review). In terms of local level authority, Biacou has an *aldeia* chief and is part of *Suco* Aidabaleten. The MAF office for Bobonaro Municipality is located inland, in Maliana, but a fishery officer is also based in Biacou community as a caretaker of the fisheries center (*Lote de peska*).

The community of Biacou recognized that they were facing environmental issues such as ongoing drought, deforestation and destruction of coral reefs for lime production, so they actively sought information and opportunities for outside help to design and declare a *tara bandu*. The Regional Fisheries Livelihoods Program for South and Southeast Asia supported the community in formally recognizing and instituting *tara bandu,* and using it as a means to strengthen marine resource management. This was seen as an invaluable opportunity to gain insights about implementation and longer-term enactment of principles of *tara bandu*. A detailed account of the process of establishing the *tara bandu* in Biacou is given by Alonso-Población et al. (2016), who note:

"This *tara bandu* was not a measure imposed by the state institutions or by development agencies, although community leaders received external support during the process to establish the governance arrangement. Far from being an alien measure imposed anew, it represents an example of the revitalization of a customary practice and a claim for the assertion of land, coastal and marine rights, resource exploitation and management by the local community."

Discussion of the Biacou *tara bandu* began in 2010 and it was enacted in August 2012. Discussions involved the formal (*Suco* chief, *aldeia* chief, National Directorate for Fisheries, and Aquaculture staff) and informal ritual authorities of the relevant origin house groups (*rai na'in kaer bua malus*), along with community members. The *tara bandu* rules and penalties were written in a public document signed by community representatives and witnesses, the places under protection were mapped, and a *tara bandu* map was painted on the wall of a public building. The final enactment of the *tara bandu* involved not only the aforementioned figures but also high-level political figures such as the Secretary of State for Fisheries and Aquaculture, who formally recognized the community's crucial role and authority in governing resources.

The *tara bandu* rules establish restrictions over the use of *lulik* (sacred, taboo) spaces, terrestrial resources (protection of forest resources, banning slash-and-burn agriculture) and marine resources (protecting coral, mangroves, prohibiting bomb and poison fishing, protecting turtles, and their eggs), and address conflict resolution (particularly between youth groups). It involves a three-step graduated penalty system, with second and third offenses giving rise to increasingly harsh penalties. In line with custom-based practice, penalties involve the offender providing food (goat, buffalo, rice), cash and other supplies (alcohol, cigarettes, betel nuts) to the community, which are consumed in a community feast once a reconciliation agreement has been reached. Payment of penalties to the community occurs after the offender admits to breaching the *tara bandu* rules and a stepwise reconciliation process. It is considered in the offender's interest to acknowledge their breach in the *tara bandu*; this rests upon the logic that by not holding the reconciliation ritual that re-establishes the *tara bandu*, offenders are punished by the spirits of the *rai na'in* or the ancestors, who are considered the ones enforcing the ban. Needham et al. (2013) recount the first enactment of the *tara bandu* penalties when a 100 years

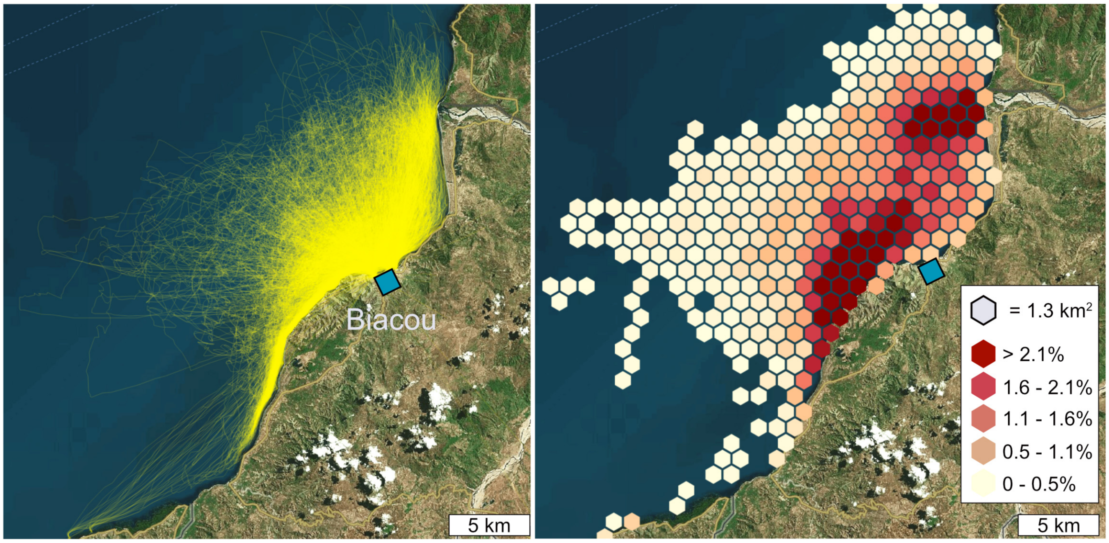

FIGURE 3 | Continuous tracking data and a fishing density heat map for 20 SSF vessels in Biacou from February 2018 to May 2019. The heat map color gradient is continuous and reflects the proportion of total fishing effort in hours for that hexagonal area. © Pelagic Data Systems. Satellite Imagery ESRI-Leaflet 2019.

old tamarind tree burned down. After the offense occurred, a community discussion and a conflict resolution procedure were held – locally called *nahe biti* (unroll the mat) (Babo-Soares, 2004) that involved both ritual and formal authorities, followed by a community feast and ritual to re-establish the ban.

In late 2016, men's and women's FGDs and key informant interviews with Biacou community members provided insights into the status and effectiveness of the *tara bandu*. Both groups stated that the *tara bandu* regulations were still effective and strictly enforced by the *aldeia* chief with the support of the MAF municipal officer at the fish landing center:

"*Both men [the Chief & security guard] are regularly reminding people of the rules*" (Women's FGD).

Others were also active in ensuring there was a broad understanding of the rules:

"Every point listed under the tara bandu has been enforced, and people follow them. The community, the local authorities and the rai na'in *[spiritual ancestors] are making sure the rules are followed*" (Men's FGD).

Both groups noted that "almost all" people in the community were happy with the application of *tara bandu* as it had increased their knowledge of marine resources, and had shown good results. Men and women from the community had integrated the *tara bandu* as a new cultural norm. There had been clear behavioral changes due to the regulations (agricultural practice, fishing locations, mangrove cutting) all of which would be expected to have positive dividends for the sustainability of natural systems. While anecdotal evidence from villagers suggested increases in vegetation on the surrounding hills, diversity of fauna in the mangrove systems and numbers of small fish, there are no empirical baseline data to test these assertions.

Importantly, and in contrast to the Adara case study below, there have been no direct/immediate financial returns from the formal declaration of the *tara bandu*. A key difference between these cases is that there is no tourism in Biacou. However, people's participation in the declaration process, and interview and focus group responses, suggest that they value the formalized institution, and are convinced of its importance in securing the community's natural resource base. Given this, it seems highly likely that the regulations will continue to be active and effective into the foreseeable future. Indeed, there was considerable motivation to extend the *tara bandu* to other resources. Interestingly, on our return visit in 2018, men and women both highlighted that a ban on using gill nets in front of the mangrove area had had the biggest impact on their lives (both in terms of constraints and positive outcomes). This new rule, which was not included in the original *tara bandu* document of the community due to internal controversies between community members, reflects the adaptive nature of the *tara bandu* to accommodate new management measures as the need arises. The important role of the ritual authorities and mostly the *Aldeia* chief in socializing rules and enforcing the *tara bandu* was very clear, and continued success may be dependent on this strong and engaged leadership.

Case Study 2: Adara Community

The aldeia of Adara is located on the west coast of the island of Atauro (**Figure 1**). Adara is a hamlet of 98 households and 452 inhabitants (GOTL, 2015), and is accessible only by sea or by rough walking tracks across the island's central uplands. The steep topography inland of Adara and limited rainfall reduce horticultural activities to small hold farming. These conditions and year-round favorable seas have brought about a high dependence on fisheries livelihoods (Mills et al., 2017) that goes back many generations (Magalhaes, 1918; Barros Duarte, 1984). Yet, even self-identified fishers in Atauro pursue multiple livelihoods, complimenting fishing with limited crop and livestock farming or small businesses (Mills et al., 2017).

Livestock represents an important savings and investment mechanism, whereby any additional money accrued by the households from various livelihoods, will be invested in purchasing animals (AMSAT International, 2011a). The shallow water gill nets and close range spear guns utilized in Adara limit exploitation mainly to reef areas within 5 km range from the landing site (**Figure 4**). Reports from local fishers that catch rates have been declining in recent years are difficult to corroborate. Mean reef fish biomass of 2,207.8 kg/ha was the highest among five sites surveyed using underwater visual surveys in 2017 and 2018 (López-Angarita et al., 2019), which lies well above the range of reef fish biomass estimates from unfished reefs in the Indian Ocean (500–1800 kg/ha) (Graham and McClanahan, 2013) and is more than an order of magnitude higher than biomass seen on heavily fished reefs (MacNeil et al., 2015). Fishing is concentrated in the thin fringing reef areas and on the reef edge, and the catch assemblage is dominated by the small pelagic Carangidae (mackerels and scads) and reef dwelling fusiliers (Caesionidae) and soldierfishes (Holocentridae) (López-Angarita et al., 2019). The mean price for fish was ∼USD $1.81/kg with little variation between species at the time this research was carried out (Tilley et al., in review).

Despite its isolation, Adara is now a relatively popular dive and eco-tourism destination. Tourism efforts began in 1994 when simple beach cabanas were built by an Indonesian company, but only one or two tourists reportedly ever came. In the late 1990s and early 2000s, tourists in search of calmer snorkeling and diving beaches during the wet season started investigating Adara by walking overland from Usubemaco (the main dock of Atauro, where boats from Dili arrive). In 2010 and 2013 simple cabanas were constructed by a private tour operator and community members, respectively. However, tourism did not increase significantly until 2013, following the release of a documentary about Adara (Alonso-Población et al., 2016), and the establishment of direct boat routes from Dili.

Considering the high vulnerability associated with specialized livelihoods, compounded by the perceived declines of reef resources and fisheries, Adara undertook a process to introduce community based resource management (CBRM). In 2013, the international research organization WorldFish began supporting the Adara community to develop fishery management plans and establish a locally managed marine area (LMMA) (Mills and Tilley, 2017); at the community's request, this was based on the *tara bandu* mechanism. Consultative processes were facilitated by the *aldeia* chief and overseen by a committee of men and women appointed by the Chief. As in the Biacou case study, a set of rules were drawn up to govern resource extraction across the entire area considered to be community fishing grounds, and a 0.04 km^2 area of reef directly in front of the community was permanently closed to all extractive activities. Critically, the location of this closed area was discussed in detail and agreed upon in women's focus groups, as women's gleaning activities would be displaced by the closed area. As in the Biacou example, rules were established that *tara bandu* violators would be fined a quantity of food items, with repeat offenders subject to a doubling and tripling of the fine quantities. The Adara community recognized and exploited the growing interest in Adara as an off-the-beaten-track tourist destination, and established a "reef tax" for snorkelers and divers entering the no-fishing zone. However, rules relating to ancestral spirits were not recognized since, in contrast to Biacou, Adara community members predominantly follow Protestant Christian beliefs, and traditional spirituality

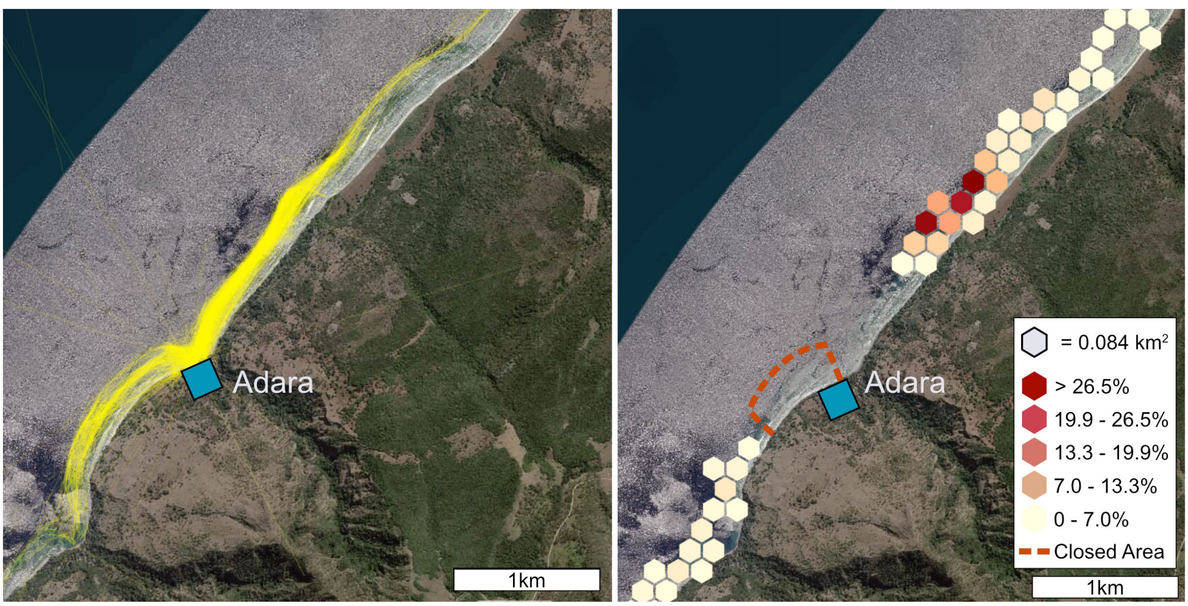

FIGURE 4 | Continuous tracking data and a fishing density heat map for seven SSF vessels in Adara from February 2018 to May 2019. The heat map color gradient is continuous and reflects the proportion of total fishing effort in hours for that hexagonal area. The red dotted line represents the closed area established in April 2016 as part of the *tara bandu* process. © Pelagic Data Systems. Satellite Imagery ESRI-Leaflet 2019.

and associated institutions have all but disappeared. Instead, the agreed rules were approved by the pastor and officially recognized by local government departments, with maritime police and administrative and *Suco* officials present at the opening ceremony in April 2016. Reef taxes contributed by tourists are accumulated and an elected committee of three community members (currently led by a woman) are responsible for their safekeeping until the community elects to publicly open the box, and vote on its usage for communal projects. Projects initiated after the first such ceremony were to develop the community's piped water infrastructure and set up a kindergarten.

When asked directly about what drove compliance to *tara bandu* regulations in Adara, community members stated that it was the church's recognition of the process (through their local pastor), and the tangible monetary benefit of having tourists visit the area. Adara provided the first example of *tara bandu* for marine resources on Atauro Island since before Indonesian occupation, and can arguably claim that their success is responsible for rekindling interest from many communities on the island in establishing LMMAs and a *tara bandu*. It represents a successful case in managing small-scale fisheries that can and has been expanded further afield, as compliance to regulations seems very strong with clear, direct benefits from tourism income.

DISCUSSION AND CONCLUSION

Coastal fisheries systems have seen a surge in investments and policy development toward the establishment of CBRM and LMMA sites, particularly in the Pacific region (Govan, 2009; Jupiter et al., 2014). However, as such systems of governance are increasingly promoted, there is growing recognition that coastal communities may not have the governing power to manage fishery resources against powerful external interests (e.g., Bailey and Zerner, 1992), for vulnerable species or fisheries of high economic value (Hamilton et al., 2019), or against the encroachment of "outsiders" into a particular groups fishing ground (Pomeroy et al., 2015) without government or legal backing. Additionally, while there is a need to uphold the diverse needs, interests and ritual attachments of fishers and fishing communities, mechanisms that support national-level agency to meet development aspirations, management responsibilities and compliance concerns must be considered. A potential solution to reconcile the national with the local interests lies in co-management, where the technical, governance and financial support from governments and or other external agencies are integrated with the knowledge, lived experience and legitimacy of local institutions in fishing communities (McWilliam, 2003).

Our case studies of coastal co-management in Timor-Leste suggest that, despite its relative infancy as a means to regulate marine resource use, co-management appears to be effective at engaging communities in resource management which can then contribute to multiple objectives of national governments, local communities and also those recognized in the SSF Guidelines in terms of accessibility and wellbeing. The way in which the process and ritual of *tara bandu* has led the development of co-management illustrates a meaningful interaction between the customary and contemporary, and between innate and appropriated cultural practices for fisheries management, as has been shown elsewhere (e.g., Johannes, 1981; Foale and Manele, 2004; Cohen et al., 2012; Cohen and Steenbergen, 2015). In both case studies, the importance of strong community institutions is paramount, but their *raison d' être* and drivers of compliance differ significantly. We explore these drivers, and reflect on the suitability and sustainability of co-management for governing coastal fisheries in Timor-Leste.

Drivers of Compliance and Sustainability

The development of local marine management, while supported by external agencies in both case study communities, was driven by endogenous perceptions of need or the desire for change, or a perceived crisis with resource status. Prior to starting down the pathway toward co-management, community leaders had voiced concerns about the unsustainable use of resources. Both communities were guided through participatory processes that did not have pre-determined donor or government objectives linked to "recruiting" communities to a pre-defined management objective or model of management. Nonetheless, both communities ultimately codified a *tara bandu* agreement.

In Biacou, the belief in ancestral spirits as the enforcers of rules drives compliance. In contrast, in Protestant Adara the support of the church, and the very tangible returns from tourism taxes drove compliance. Success in community-based management systems may be attributed to social as well as ecological dimensions such as fostering a sense of stewardship and collective self-confidence (Murphree, 2009; Wamukota et al., 2012). Furthermore, communities may attribute bequest value to stewarding resources for future generations (O'Garra, 2009), as might be inferred from Biacou's desire to reverse perceived environmental declines. It appears that Adara's success and potential sustainability is largely driven by the opportunity to link resource protection to tourism revenue, and obtain financial returns to fund communal projects. This happens in a Protestant community who lived a particular conversion process by which beliefs in the *rai na'in* spirits and ancestors are not part of the contemporary belief system. There is evidence to suggest that ecological successes of co-management are felt by community members, and the recognition of the process by the Pastor is important, but compliance is predominantly driven by the tangible and rapid accrual of money from tourism to the closed area.

The history of attempts to encourage tourism in Adara implies the community was more aware of contemporary opportunities and we understood these communities to be more accustomed to external assistance, predisposing them to try new approaches such as co-management with an explicit goal of encouraging tourism. Certainly, the levying of a "reef tax" in Adara was a primary reason given for creating a co-management committee because this body would be needed to collect and safeguard the revenue. Yet, Adara and the island of Atauro are exceptions in terms of opportunities linked to tourism. In Timor-Leste, tourism is still in its infancy, with international visitor arrivals the lowest among Southeast Asian nations representing only 0.06% of international visitors in 2016 (UNWTO, 2017). The potential for tourism to benefit local livelihoods is not high for most communities in Timor-Leste, especially on the mainland, with low visitation rates and high numbers of saltwater crocodiles (Brackhane et al., 2018) which directly inhibit the potential beach and dive tourism associated with the development of LMMAs. Nonetheless, even remote community sites on the mainland are excited by the economic promise of tourism (WorldFish, unpubl. data), and may mistakenly identify the implementation of *tara bandu* and closed areas as mechanisms to tap into this potential. Any form of tourism has its inherent vulnerability to political instability, global financial drivers (Sonmes, 1998), or as seen recently in Timor-Leste, fickle pricing behavior of airlines. These will also present new challenges and risks as community members become increasingly reliant on tourism to supplement incomes.

In contrast to Adara, the sustainability of Biacou's *tara bandu* is not reinforced by financial returns, but rather by an engaged leadership (both political and ritual), the firm belief that associated ancestral spirits (*rai na'in*) can resolve contemporary problems (i.e., the current presence of a particular cosmological order), and the belief that current problems arise from the longstanding disrespect for ritual practices (i.e., during Indonesian occupation). The social pressures and fear of ancestral spirits (*rai na'in)* appear to be the primary drivers of compliance. Benefits accrued from management in Biacou are far less tangible and slower than in Adara; although in Biacau some fishers anecdotally reported modest improvements to fisheries. In Biacou, rules were adapted to prohibit gill netting near the mangroves since the establishment of the *tara bandu*, which suggests not only that the legitimacy of the institution had not been eroded with time, but rather that regulations could be strengthened despite fewer quantifiable gains. The increasing education and westernization of youth in Timor-Leste may threaten the effectiveness of these spiritual sanctions in controlling behaviors in the longer term. In other cases, a combination of customary, religious and contemporary (through state law of the perception of illegality) institutions have been applied to bolster one with another (Cohen and Steenbergen, 2015). As contemporary pressures increase, and customary or local institutions (potentially) erode, the need for legal or governance bolstering from a relationship with the state (hierarchical governance) may well increase in Timor Leste, as has been observed in other countries.

Governance Mechanisms and Processes

The "Fishing for Sustainability" national strategy document developed for 2006–2011 may have narrowed the view of *tara bandu* by suggesting that "community-based fisheries management initiatives [should aim] at establishing a network of local, community-supported marine protected areas and encourage involvement of NGOs" (MAFF, 2005). Yet, a deeper understanding of *tara bandu* historically (e.g., Miyazawa, 2013; Shepherd, 2013) and in the context of these two cases, reinforces that *tara bandu* must not be deliberately or unintentionally confused as a *no-take zone*, or a method for one. Whilst the *tara bandu* CBRM mechanisms implemented in both our case studies have involved the spatial demarcation of fishing zones, only Adara incorporated a closed area for the specialized purpose of protecting a diving area for reef tourists. *Tara bandu* can, and should, be considered as a form and process of local management plan, in being a set of agreed rules governing the use of resources. Importantly, as illustrated in depth in other studies (e.g., Miyazawa, 2013; Shepherd, 2013), *tara bandu* can act as a framework for appropriate participatory rule-setting around resources and behaviors; core elements of both co-management and implementing the SSF Guidelines. Area closures can form part of management planning where appropriate (i.e., where benefits from closures exceed the costs to fishers in terms of lost fishing grounds and lost opportunity to harvest). However, in most of coastal Timor-Leste, reefs are narrow so not supportive of high biomass, and the small pelagic species targeted by fishers (López-Angarita et al., 2019) are highly mobile, rendering a spatial closure meaningless. Other fisheries management mechanisms will be more appropriate and effective. In such instances, the participatory framework provided by the *tara bandu* mechanism may still be relevant as a tool for achieving co-management, but institutions that link local area management to greater spatial scales such as fisheries extension officers based in *sucos* (**Figure 2**), will be crucial to success.

Tara bandu should not be considered as the *only* appropriate mechanism for achieving successful SSF co-management in Timor-Leste. For example, some sardine fisheries in Timor-Leste are governed by rules implemented by traditional and *suco* level authorities, where they implement gear and size restrictions on other semi-pelagic fisheries in response to an oversupply of unmarketable fish (Hunnam, personal communication). In these instances, *tara bandu* is not invoked. This suggests there is clear potential to build SSF co-management on existing customary and local-level institutions where they exist. However, it should be at the discretion of the communities and actors involved whether such co-management mechanisms are underpinned by *tara bandu* ritual, or are transparent local-level management rules backed by formal authorities.

Both our case studies suggest that communities can effectively manage their local level behaviors and resource exploitation. However, this does not address concerns about the effectiveness of controlling the actions of outsiders who may not believe in the retributive punishment of ancestral spirits, and/or will not gain from associated monetary benefits. This is common to other Asian contexts where local compliance increases with CBRM development, but external or outsider non-compliance remains pervasive (e.g., Maliao et al., 2009; Nuon and Gallardo, 2011). Over time, this may lead to increases in conflicts which can erode the legitimacy of CBRM. To combat this, literature suggests developing CBRM networks at a wider special scale to foster cohesive management actions (Maliao et al., 2009; Gurney et al., 2014). This is an area where government can play *their* part in co-management, by responding to local or municipal level concerns of illegal or non-compliant fishing activities by outsiders as stipulated in Environmental Framework Law, Article 8 (the State will ensure the regulated area is effectively protected). In reality however, this relies on the General Directorate of Fisheries or the maritime authority being sufficiently resourced to do so, which is currently not the case.

The following section deals with the potential for partners in co-management to enhance broader compliance beyond the local community structures. We also discuss if the lack of continued support and follow up from government/NGO partners is actually co-management, or rather CBRM in the absence of decentralized governance.

Management Partners and Motives

Central to developing sustainable co-management systems, is a meaningful interaction between fishers and fishing communities and governing institutions at multiple scales (national, municipal, or *suco* level). In situations of limited fiscal and human resources relative to the scale and scope of SSF in Timor-Leste, external agencies such as the government, NGOs and development partners may find a legitimate role in attracting resources, facilitating management and design of institutions, and brokering new governance connections. However, building such connections within the dynamic and pluralistic governance structures of Timor-Leste will require careful design. Experience from the Pacific suggests that sustained transformations into CBRM are dependent on building the active support of communities (Abernethy et al., 2014; Blythe et al., 2017). Active support can be built by facilitating participatory scoping and awareness activities, tailoring or adapting rules to fit both local customary and contemporary practices, and engaging established governance structures or decision making processes that are already perceived as being legitimate (Abernethy et al., 2014). Deficiencies in the facilitation process used, such as not prioritizing gender considerations, not involving key stakeholders or not allowing adequate flexibility for community processes of consensus building, can drive rule-breaking and may greatly reduce the capacity of the local community to implement management plans or enforce the rules over outsiders as well (Pomeroy et al., 2015). In some instances, CBRM has actually led to increases in resource user conflicts (Clarke and Jupiter, 2010).

In the Solomon Islands, internal disputes and rule-breaking were higher at sites that received higher levels of support from international conservation NGOs, particularly in terms of management plan facilitation and environmental awareness, compared to sites in which communities had implemented fishery management rules with little or no outside NGO support (Abernethy et al., 2014; Pomeroy et al., 2015). Compliance and enforcement rates were reported to be higher at these latter sites. International NGOs have encouraged the equation by communities of taboos with MPAs to increase their local acceptability and likelihood of adoption. However, there are major differences in permanency, size, objectives, legal status, and design considerations between taboos and MPAs, meaning that sites designed as both may either not perform the ecological functions expected of them as MPAs or will not be sufficiently small or flexible to have minimal negative impacts on community life (Govan, 2009; Halpern et al., 2010). There is a risk that international NGOs will not ensure the best fit between local contexts and how co-management is enshrined in national policy or approaches (Rohe et al., 2017, 2019).

Our two case studies are, from our experience, relatively self-mobilized communities, but *tara bandu* processes were facilitated by external non-government actors. In parallel with experience in the Pacific (e.g., Léopold et al., 2013), development and conservation agencies in Timor-Leste have looked for opportunities for more effective interventions by drawing on existing, albeit eroded, traditions such as *tara bandu* (Shepherd, 2009). Such agencies may work to elicit the "right" behaviors derived from a world view often unaligned with local understandings (Shepherd, 2004) and at times in direct opposition to local needs – notably food and nutrition security. A thin veneer of participatory language may hide an approach that in reality is more akin to telling participants exactly how, and in what, they are to participate, and selling the potential gains to full participation. As such, the true extent of political will and self-mobilization can be hard to discern for anyone outside of these processes. *Tara bandu* revival has been actively endorsed and encouraged by NGOs and development partners in Timor-Leste since independence (Miyazawa, 2013), driven on the one hand by the desire to protect marine areas by conservation NGOs, and on the other by the need to build on local strengths given the insufficient financial or human capacity to enforce more formal top–down methods of management. The very small scale of fisheries and communities imply they are predisposed to being cohesive, with elected *suco* leaders, which may enhance their capacity to govern their resources in spite of complex and pluralistic rule structures.

The combination of *suco* level governance and ritual beliefs related to *tara bandu* compliments the responsibilities and duties allocated to the *suco* councils. *Suco* councils are intended to represent the interests of community members. However, given the hybridized nature of governance in Timor-Leste, they may simply reflect customary power hierarchies, and hence may reproduce and reinforce existing inequities. This "elite capture," where control of resources by influential individuals reduces incomes and access rights of poor fishers (Khan et al., 2012), may be at play in Biacou, where ". . .three households belonging to Biacou's founding lineage showed a disproportionately high fishing capacity. The community's customary and administrative leadership at the time of research centered on these same households. While the average household boat ownership in Biacou was one boat per household, each of these households owned at least four boats" (Steenbergen et al., in review). In the same vein, the co-management committees provided for in Timor-Leste's Fisheries Law Decree (6/2004, Article 114), may also merely reflect traditional village hierarchies. Governance decisions must rely on connections formed through the *Suco* council, but at the same time take into account community structure, power inequities and cultural nuances to avoid reinforcing elite capture.

Fishers are often the most vulnerable and marginalized people within a community, stuck in social-ecological traps where fishing is a last resort and high dependence can drive overexploitation (Cinner et al., 2008; Cinner, 2011; Cole et al., 2018). In these cases, the establishment of protected areas can exacerbate marginalization and poverty, especially amongst minorities (Christie, 2004; West et al., 2006;

Charles et al., 2016). Similarly, women's gleaning activities, which are often conducted close to communities when time is available between home duties, are particularly susceptible to exclusion through closed areas. Despite the small size of the closed area in the Adara case study (0.04 km^2), this may still have had significant consequences on certain sectors of the fishery such as women gleaners, had they not been active participants in the design process. The promise of co-management is that by integrating voices from government and civil society (e.g., resource user groups, like fishers) in decision-making processes, the balancing of social and ecological sustainability objectives captured in the SSF Guidelines can be achieved.

The diverse nature of tropical reef fisheries implies they are among the most difficult to manage (Gutiérrez et al., 2011). Timor-Leste's SSF are predominantly non-mechanized and nearshore with limited large pelagic species targeted, making the focus of management very much on nearshore ecosystems. Land tenure, particularly the interaction of customary and contemporary tenure, is a work in progress in Timor-Leste. Customary marine tenure is even more loosely defined; boundaries may extend seaward from acknowledged land boundary markers (McWilliam, 2003) or relate to broad habitat types rather than to specific distances or geographical points. Ostrom (1990) highlighted the importance of clearly defined boundaries as a basis for co-management and this has been observed throughout the Pacific Islands, although such boundaries are often de facto, based on customary practice and not necessarily legally recognized (Govan, 2009). The important point is that resource managers (communities and government) are clear about which resources are being co-managed and therefore who the prime beneficiaries are. In Adara, in the absence of any formal enforcement by the government, the community takes it under their own authority to guard "their" resources against fishing by other communities on reefs and around fish FADs. The sustainability of co-management in these settings may rely on investment by government or external partners in recording traditionally recognized boundaries or locally acceptable marine extensions of the terrestrial *aldeia* and *Suco* boundaries (Alonso et al., 2012). The establishment and initial successes of the Adara LMMA has promoted the grass-roots growth of CBRM among Atauro Island communities. Other communities have since self-mobilized to establish SSF regulations and no-take LMMAs, or have reached out to NGOs for assistance with the co-management process. However, the converse is also occurring where well-resources external actors have used such initial success to aggressively push *tara bandu* as a mechanism to achieve externally derived objectives with insufficient resources or time given for local engagement, consultative gender-aware rule development, and understanding context. This emphasizes the need for knowledge exchange and the establishment of best practice, to strengthen the capacity and resilience of communities and leaders to engage with external agents and retain use rights (that enable stewardship), and strengthen the capacity of government to ensure legitimate process.

Effectively delivering the government contributions to co-management presents logistical challenges which may potentially be offset by decentralized institutional structures in Timor-Leste such as the municipal MAF offices (**Figure 2**). Decentralized approaches can enhance the resilience of the social-ecological system by being flexible and adaptive (Folke et al., 2005; Armitage et al., 2009) and can carry out simple and cost-effective co-management activities that support CBRM, such as identifying problems, facilitating lesson sharing between communities, facilitating agreement of rules, and sustaining community action (Govan et al., 2011; Govan, 2013). However, the capacity of Timor-Leste's government to structure and initiate decentralized environmental legislation is constrained by a lack of financial, technical and human resources, professional training and judiciary and public awareness of environmental laws. Furthermore, imposing an additional level of formalized governance onto the existing local institutional governance adds substantial complexity (Cummins and Leach, 2012), and it should be kept in mind that as governance becomes more decentralized, there is a risk that some people will be further marginalized or disadvantaged, due to potentially reinforcing local power hierarchies with formal governance.

In conclusion, the case-studies and analysis presented here suggest that self-governance persists in Timor-Leste and is implemented and relevant for fisheries management of nearshore coastal resources at limited scales, by building on locally legitimate institutions. Co-management can operate in Timor-Leste, by utilizing or interacting with these customary, legal and religious institutions of self-governance, while at the same time leveraging hierarchical governance mechanisms to manage larger scale fisheries challenges. Currently, the intermediary role of fisheries officers in escalating issues of (e.g.) outside encroachment is undefined, and the capacity for MAF to respond is very limited. *Tara bandu* is clearly a valuable institution for the development of local rules, and for facilitating engagement of resource owners and stakeholders in multi-scale governance, but must be supplemented by contextually-derived approaches and institutional architecture appropriate to managing important mobile fisheries resources (such as small pelagic species) at scales larger than community fishing areas. It is timely, following the example of Pacific countries, to design a set of best practices and principles to ensure legitimate community engagement (considering needs and aspirations, gender, and power inequities). These should be defined with some urgency and upheld by central government. The current reliance on external development partners and NGOs, while necessary, must be supplemented by a structured and well-coordinated program of capacity development that seeks to ensure sustainability of investments in governance and management.

AUTHOR CONTRIBUTIONS

AT, DM, and PC designed the study. AT analyzed the fisheries data. PC, AT, DM, AD, and MG were responsible for designing and implementing the data collection visits to the case-study sites.

AT, DM, MP, PR, KH, EA-P, MR, TA, AD, MG, DS, HG, and PC wrote sections of the manuscript.

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An Experimental Approach to Exploring Market Responses in Small-Scale Fishing Communities

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Small-scale fishing communities are increasingly connected to international seafood trade via exports in a growing global market. Understanding how this connectedness impacts local fishery systems, both socially and ecologically, has become a necessary challenge for fishery governance. Market prices are a potential mechanism by which global market demands are transferred to small-scale fishery actors. In most small-scale fisheries (SSF) this happens through various traders (intermediaries, middlemen/women, or patrons). By financing fishing operations, buying and selling products and transferring market information, traders can actively pass international market signals, such as price, to fishers. How these signals influence fishers' decisions and the consequent fishing efforts, is still poorly understood yet significant for future social-ecological sustainability. This paper uses an economic framed field experiment, in combination with interviews, to shed light on this. It does so in the context of the Philippine patron-client "*suki*" arrangement. Over 250 fishers in Concepcion, Iloilo were asked in an economic experiment, to make decisions about fuel loans in light of changing market prices. Interviews with participants and their patrons gathered additional information on relevant contextual variables potentially influencing borrowing. They included fisher characteristics and socio-economic conditions. Contrary to our hypotheses, fishers showed *no* response in their borrowing behavior to experimental price changes. Instead, gender and the previous experiment round were predictive of their choice of loans in the experiment. We explore possible reasons for this and discuss potential implications for social-ecological sustainability and fishery governance.

Keywords: global seafood trade, behavioral economic experiments, gender roles, patron-client relationship, Philippines, market price, fisher behavior

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INTRODUCTION

Small-scale fisheries (SSF) are increasingly linked to expanding global seafood trade and, as such, are also more affected by various market features at these larger scales, such as fluctuating demands, volatile prices, or eco-certification schemes (Berkes et al., 2006; Crona et al., 2015, 2016). The small-scale nature of these fisheries means their connections to international seafood trade also have implications for human development, local exploitation, and food security (Béné et al., 2016). For example, with trade liberalization, prices received by small-scale fishers are no longer domestically set, but are affected by international markets, and thus much less connected to, or driven by, local supply and overexploitation (Thanh and Flaaten, 2012). The exact ways in which fishers' extractive behavior and subsequent ecological sustainability is affected by market integration remains unclear. One often cited mechanism through which international markets penetrate SSF societies is price. Existing literature on SSF suggests that fishers change their efforts as a result of economic incentives (Andersson and Ngazi, 1998; Gössling, 2003; Kooiman et al., 2005; Johnson, 2010; Máñez and Ferse, 2010; Brewer, 2011), but their specific responses (a behavior) to fluctuating world market prices, and the effect of these responses on resource extraction, remain uncertain. In fact empirical literature documents a wide range of responses by fishers to such price changes (Pollnac and Crawford, 2000; Salas et al., 2004; Miñarro et al., 2016), indicating that our understanding of this complex phenomena is still incomplete.

Studying the effects of price changes on fishing and ecosystem dynamics is complex because market incentives trickle through the social fabric of fishing societies and are generally transferred to fishers via trading agents positioned between the fishers and local, regional, or international market systems. Within SSF, these traders (often referred to as middlemen, patrons or intermediaries) provide a range of both social and financial services. They represent a key link in transferring global market incentives to production, which they do largely though financing and loans, e.g., providing new vessels and gear (Johnson, 2010; Máñez and Ferse, 2010). The reciprocal services provided by traders to fishers, in return for loyalty, supply, favors and other benefits, enable fishing populations around the world to operate in settings where institutional, and social support may be scarce (Carnaje, 2007; Johnson, 2010; Ruddle, 2011). They also buffer variabilities in income and livelihood due to drivers such as seasons, policies or natural disasters (Drury O′Neill et al., 2019). These reciprocal relationships are often termed patron-client relationships. They vary in their degree of formalization or institutionalization and can range from the provision of petty cash advances to fisher acquaintances, to acting as godparents to fishers' children due to inherited family business ties. Research has flagged that patron-client relationships can be both exploitative and beneficial depending on the context (Hardiman, 1996; Johnson, 2010; Ferse et al., 2014; Nurdin and Grydehøj, 2014; Miñarro et al., 2016; Purcell et al., 2017). Yet how they mediate fluctuating price changes and transfer these to fishers, and how this in turn influences extractive patterns is poorly understood. This paper takes a first step in addressing this gap by using methods from behavioral economics to examine the influence of seafood prices on fishing efforts through patron's provision of fuel loans, and how this is filtered by fisher characteristics and the patron-client system. More specifically we ask:

- To what extent does a change in the price, filtered through a patron (under uncertain catch rates) affect fishers' loan taking behavior, and consequently their assumed fishing effort?
- What household and individual level characteristics (e.g., nature of patron-client relationship, economic conditions, gender, gear type, and financial risk preferences) predict fishers' propensity to take fuel loans from patrons?

In this study behavior is conceptualized as an observable output of a decision-making process; a cognitive process involving either analytical thought, conscious or unconscious drivers or feelings as well as recognition-based or by the book decisions e.g., based on social roles (Weber and Lindemann, 2007). We assume that loan-taking decisions are directly translated into action or behavior.

Contrary to theoretical approaches that assume "rational actors," behavioral economic experiments can capture the bounded rationality of decision makers and test the influence of a particular variable (such as price), while accounting for other factors (such as gear type, gender norms, risk attitudes, and household funds or assets owned), which have all been argued as potentially important in determining fishers' financial and extractive decisions (Platteau, 1989; Eggert and Lokina, 2007; Fabinyi, 2007; Croson and Gneezy, 2009; Ruddle, 2011; Charness and Gneezy, 2012; Miñarro et al., 2016; Kininmonth et al., 2017). Yet, despite the promise of behavioral economic experiments to understand complex social-ecological causality, the SSF literature has, to date, been dominated by a "rational actor" model of decision-making (Fulton et al., 2011). Similarly, many fishery market interventions have also been informed by economic theories resting on assumptions of rationality, even though such assumptions of actor behavior are unlikely to hold true in the context of 'small-scale societies' like SSF (Henrich et al., 2001; Jentoft and Eide, 2011). This paper aims to shed new light on the complex causality between international seafood trade and local fishing and loaning behavior by making use of experimental methods. We believe this provides a novel addition to SSF scholars struggling to understand these complex dynamics, but also provides knowledge on fisher and patron responses to market fluctuations, to better inform attempts to develop sustainable fishery governance interventions, as noted by Kininmonth et al. (2017).

The paper first elaborates on our choice of methodology in the Methodological approach section. The Case Study subsection to the Experiment Participants subsection then situates and justifies the experimental design within the context of the Province of Iloilo, the fisheries of the area, the patron-client system (known locally as the *suki* system), and how patrons themselves respond to price fluctuations. Based on our two overarching research questions we develop a set of hypotheses regarding how our focal variables relate to loan taking and the extractive behavior of fishers. We anchor these in existing theories or empirics and describe the experimental design we used to test them. Our results are then elaborated in relation to the context of the field sites and discussed in relation to other studies on SSF and trade. We finish with a short reflection on the limitations in the experimental setting and design.

METHODOLOGICAL APPROACH

We applied a mixed methods approach, systematically testing fishers' responses to price changes (filtered through a patron) in behavioral economic experiments while contextualizing the observed behavior with interviews and observational data. We used a price increase as a proxy for a new connection to a global market. We focused on fishers' decisions to take different size fuel loans (which implies different fishing efforts) from their patrons for fishing (the most frequent loan-type in the study area) in response to uncertain catch rates and changing prices. This was done as a means to isolate the trickle down of market prices through the patron-client link, and how this translates into fishing effort. Our choice of this design is further motivated below, in relation to the real-world context of the Iloilo region. **Figure 1** presents an overarching conceptual framework for the paper which reflects our understanding of the system and the transfer of price to patrons, fishers, the potential contextual influences, and consequent fisher decisions.

Interviews or questionnaires can be inadequate at addressing fishers' behavior and decision-making (one part of human behavior) in relation to market drivers as a result of hypothetical biases associated with data collection (Schulze et al., 1981), and our own extensive empirical work has repeatedly shown this. Behavioral economic experiments instead allow the construction of counterfactual narratives (Harrison and List, 2004), eliminating the hypothetical nature of interview techniques and, through the use of real money, makes the monetary consequences of participant's decisions more real (Kagel and Roth, 2016). Our approach rests on combining interviews, observations and discussions (to provide the background context for both validating the experimental design, and later anchoring the interpretation of results), with so called economic "framed field experiments" (Harrison and List, 2004). We do this in the Philippines where the *suki* system is well-documented as an institutionalized patron-client relationship, prevalent in markets across the country (Davis, 1973; Pomeroy, 1992; Hendriks, 1994; Carnaje, 2007; Ferolin and Dunaway, 2013).

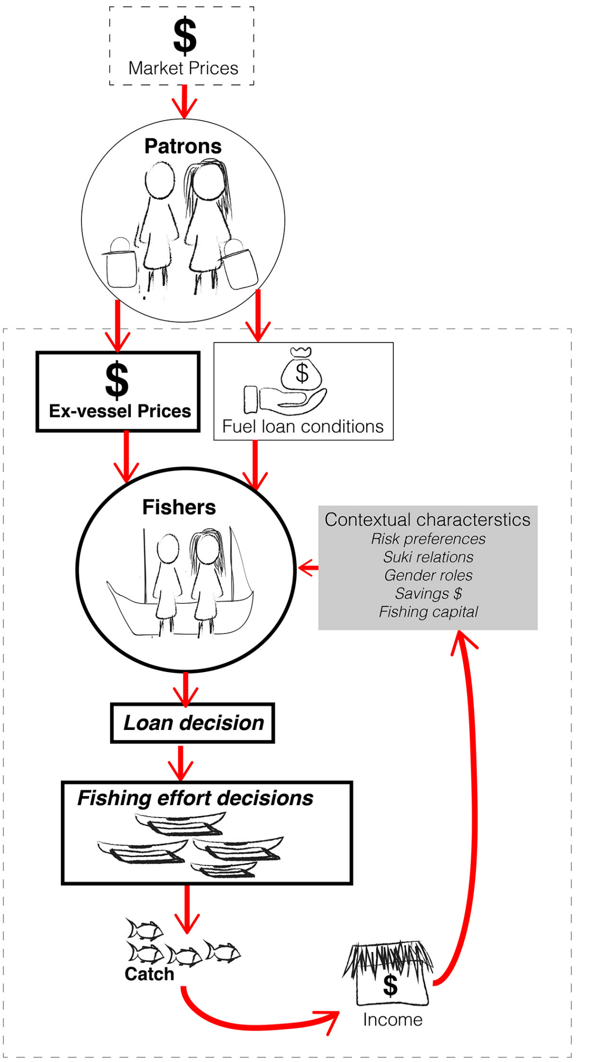

FIGURE 1 | Conceptual diagram of the study system and certain behaviors in focus. The diagram depicts the market prices being received by patrons, who based on this provide an ex-vessel price plus fuel loan conditions (i.e., size, pay back options) to fishers. Fishers then in turn make decisions about the loan and their fishing activities which translates into effort. This results in a catch and then an income, feeding back to their next trip, and related decisions. We highlight in the gray box the contextual characteristics that we hypothesize feed into fishers' decisions.

Case Study Area

The field work took place in the municipality of Concepcion located in the northern part of Iloilo Province (**Figure 2**), which borders the Visayan Sea, home to one of the top three fishing grounds of the Philippines as well as the world's center of marine biodiversity (Ferrer, 2009, 2016; NEDA, 2011). A large part of Concepcion's population of 43,159 as of 2015 (Iloilo Provincial Annual Profile, 2015) lives offshore across 12 island *barangays* (the smallest administrative unit in the Philippines) and is supported largely by fishing, with limited farming due to poor terrain. The fisheries are dominated by small-scale fishers (using boats $\leq$3 GT, locally termed municipal) who sell almost all their catch and leave negligible amounts for household consumption. The Visayan Sea area, in general, is one of the top seafood exporters in the Philippines, thus highly connected to national and international market systems (Hernando, 2005; NEDA, 2011).

Four main fishing styles or types (71% of participants) were identified through structured interviews (post-experiment) amongst the fishers in our sample, summarized in **Table 1** below, which are representative of the fleets around Concepcion.

We selected 11 island *sitios* (settlements) as field sites according to their relative distance to the main fish port and market (so as to capture a range of distances) and representativeness of diversity in the fishing gears, vessels and styles found in Concepcion. Fishers in each *sitio* were recruited to the experiment through the *Barangay* Captain- the official gatekeeper, elected by the *barangay* residents to politically represent the *barangay* at the municipal level.

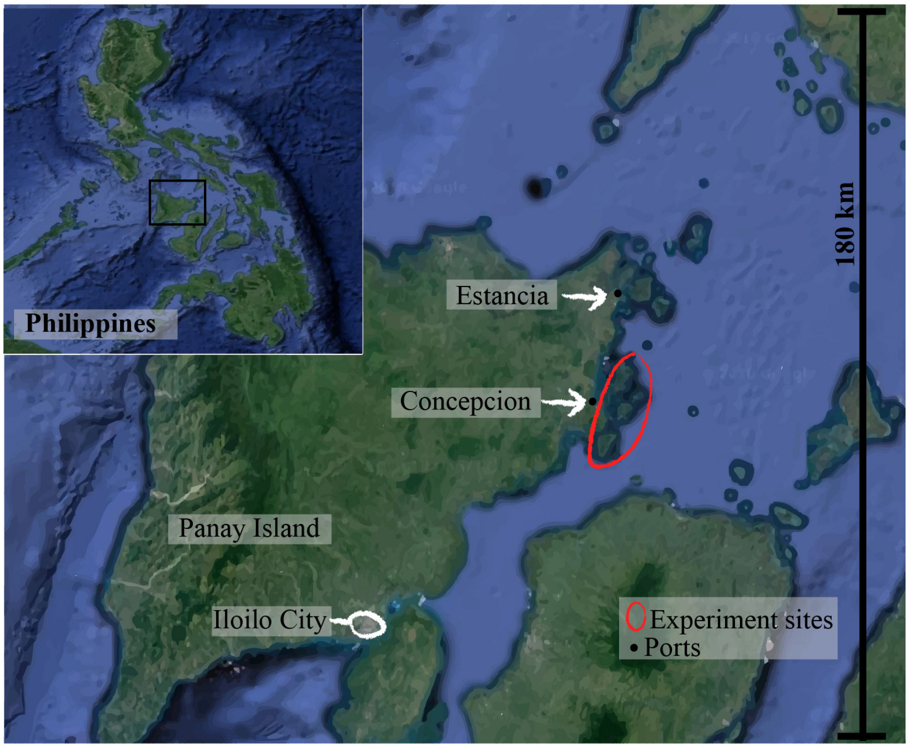

FIGURE 2 | Panay island location in Philippines (inset). The Capital of the main province on Panay Island, Iloilo, can be seen circled in white to the south- Iloilo City. Concepcion is located on the North Eastern seaboard as is Estancia- the other major, and larger fishing port and town to the North of it. The area where the experimental sites are is circled in red.

TABLE 1 | Key features of the four main fishing styles in the study area and proportion of fishers in our sample (and proportion of total women and total men) engaged in each.

Main fishing styles of sampled fishers				
Gear (*Hiligaynon,* English)	***Palubog* bottom set gillnets**	***Taga* hook & line**	***Trol* baby trawl**	***Bubu* fish trap**
Main target spp. (*Hiligaynon*/English/*scientific name)*	*Guma-a*/short bodied mackerel/*Rastrelliger* spp. *Latab*/silver biddy/*Gerres* spp.	*Lagaw*/threadfin bream/*Nemipterus* spp.	*Lokus*/squid/*Photololigo* spp.	*Opusan*/monocle bream/*Scolopsis* spp.
Average vessel length (m)	6–7	6–8	8–9	5.5–7
% Total fishers *(women/men)*	21 *(12/23)*	19 *(17/25)*	17 *(11/35)*	14 *(14/14)*

Seafood products are typically landed in island *barangays* or at the fish ports of Concepcion, Estancia or San Dionisio. There are two main types of patrons in this study – buyers and brokers. In *barangays*, "buyers" (fish traders based from their homes) largely purchase the product. At ports "brokers" are the main trader type. Buyers will sell to brokers or to retailers and wholesalers on the mainland either every day or every week, depending on if they dry the products in their homes. The brokers sell the fresh products most frequently to bigger brokers in Iloilo City, Manila, Manapla, Cadiz, and other cities. Wholesalers largely deal in dry produce and supply national markets, supermarkets and also export. Processing companies in Iloilo Province buy directly from fishers and *barangays* buyers, targeting largely squid and small pelagic fish for international export to Taiwan and China. **Figure 3** depicts the value chain and the sales paths involved, which are further described by Drury O'Neill et al. (2018). This study specifically focuses on the relationship between the fisher and his/her immediate trader (patron- red in **Figure 3**).

Situating the Experiments in the Conception Trade System – Elaboration of the Patron-Client Relationship and Price Change

This section describes the patron-client system and loan dynamics in Concepcion based on complimentary data collection (described under the section "Formulating Hypotheses to Test With the Experiment") to situate the experiment and support assumptions of the experimental design, e.g., that patrons

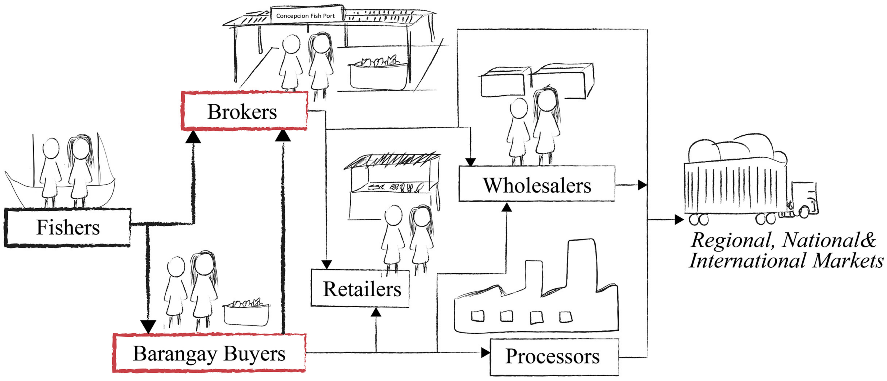

FIGURE 3 | Conceptualization of the market system in the Concepcion Municipality, Philippines. Arrows represent the sales paths of the product being sold. The larger more bolded lines and arrows represent the actors in this paper and study – the fishers, *barangay* buyers, and brokers. The red indicates the patrons.

transmit prices to fishers. Complimentary data was acquired through various interview-types and discussions.

The value chain includes various forms of informal financing arrangements from traders (patrons) to fishers, which form part of the patron-client *suki* system. For details on the *suki* system in other fisheries in the Philippines (see Pomeroy, 1990, 1992). Our field experiments focus on individual fishers' decision-making in relation to the loans and ex-vessel prices offered through this institutionalized *suki* system. While the word *suki* can refer to both a regular customer, as well as the relationship itself (Hendriks, 1994). S*uki* in this paper refers to the relationship. In the Visayas this relationship is characterized by interest-free loans, regularity, trust, personal connectedness and selectivity, where only certain patrons are finally selected as partners (Carnaje, 2007). After loans are repaid, clients (fishers in this case) are typically free to take another lone or switch to a different patron, although a debt of gratitude or "*utang na loob*" may keep them tied (Davis, 1973; Carnaje, 2007).

Loan sizes and frequencies are decided according to fishers' catch rates, fishers' needs and requests, the patron's available capital, and the fisher's loyalty to patrons (i.e., their commitment to land their product only to that patron). Financing includes most commonly, on a daily or weekly basis, the provision of fuel loans (80% of fisher participants) and gear and equipment (once or a few times a year) as well as family-related loans (typically weekly) (53–55% of fishers). Thus, our experiment focused on loans for fuel because of their high level of familiarity to most participants. Similarly, their agency over loan size was anchored in the common practices of the area. Pay back of *suki* loans typically happen upon landing – but if landings are very low then patrons will waive repayments or reduce them until catch rates increase. Patron brokers usually use sales prices of their own customers to calculate gross value of the landed product and take a percentage from this value for their services- so market prices are directly passed to fishers and *barangay* buyers.

Experiment Participants

We ran the experiment with 251 fishers in over 25 experimental sessions in 11 *sitios* within four *barangays*. Demographic characteristics of participants are summarized in **Supplementary Table S1**. Most participants were full time fishers and a quarter had secondary income sources from *sari sari* stores (local shops), carpentry, processing seafood and a range of other activities including farming and state employment. Although women partake in these fishery value chains, fishing remains male dominated in terms of numbers (no official statistics on the number of fishermen and women). We believe our sample with 22.7% women reflects gender ratios in fishing in the area.

Formulating Hypotheses to Test With the Experiment

In this section we operationalize our research questions by outlining six hypotheses based on previous literature and/or previous fieldwork in the area, which are to be tested by the experiment. The latter includes interviews with fishers, traders, governmental-agents and NGOs on trade relations, and market dynamics (Drury O′Neill et al., 2018). **Table 2** describes these hypotheses and how they were operationalized with variables to be tested.

- Price: *Fishers will be more likely to choose a bigger fuel loan from their patrons following a price increase and less likely following a price drop.* We assumed choosing a bigger fuel loan for fishing translates into an increase in effort (time spent at sea or distance traveled) with the intention of landing more (expensive) fish. This increased landing potential is included in the experiment if fishers take the bigger loan. Literature shows fishers responding to prices and high demand by focusing effort on high-value species (Miñarro et al., 2016). Platteau (1989) also finds that when demand is high, especially as fisheries open up to the global market, loan-based selling arrangements with patrons increase.

In addition to price effects, contextual fishing, household and individual characteristics were hypothesized to influence loan-taking behavior:

- Financial risk preference: *Risk-seeking fishers are more likely to take the bigger loan, independent of the price increase. Risk*

TABLE 2 | Main variables (used in the statistical analyses) of interest according to literature, previous field observations, and hypotheses and the aggregate distribution of the variables across the participants in our sample.

Factor hypothesized or observed to have relationship with loan taking	Hypothesized relationship and direction	Variable to measure	Proportions of participants %	
Price	Price increase = increase in bigger loan taking Price decrease = decrease in bigger loan taking	Number of times bigger loans were taken by individual fishers- continuous variable	Control	30
			Treatment 1 (price increase)	34
			Treatment 2 (price increase & decrease)	33
Suki relationship strength	Stronger tie = increased bigger loan taking	Categorical survey responses scored and summed	Rank 0 = no relationship	9
			Rank 1 = flexible relation, easy to change to patron	9
			Rank 2 = medium flexibility, somewhat likely they could change	18
			Rank 3 =not flexible, they are not likely to change patron according to prices, better loans etc	65
Financial risk preference	Risk seeking & neutral = increased bigger loan taking	Gamble choice in post-experiment risk assessment- categorical variable	0 = risk Averse	59
			1 = risk neutral	21
			2 = risk seeking	20
Gender	Men = increased bigger loan taking	Binary variable- men or women	Women	23 (women)
Household savings	Above average savings = increased bigger loan taking	Savings last month in PHP- continuous variable	Above average	38
			Below average	61
Gear type	Category 1 = decreased bigger loan taking Category 2–4 = increased bigger loan taking	4 types of gear categories	1-Lines/spears	26
			2-Traps	15
			3-Large active nets	26
			4-Set/drift/drive in gill nets	33

TABLE 3 | Summary of loan size, catches and incomes (payoffs) for each loan size option, with the base price, and the increased price in the experiment.

Summary of choices and payoffs								
Loan type	Fuel loan size (PHP)	Catch range	Base price 2 PHP			High price 4 PHP		
			Gross income range (PHP)	Net income range (PHP)	Mean net income (PHP)	Gross income range (PHP)	Net income range (PHP)	Mean net profit (PHP)
Big	20	0–20	0–40	–20 to +20	0	0–80	40 to +60	20
Small	5	0–10	0–20	–5 to +15	5	Same as base price		
None	0	0	0	0	0	Same as base price		

PHP, Philippine pesos.

neutral fishers are more likely to take the bigger loan when the price increases (c.f. Eggert and Martinsson, 2004; Eggert and Lokina, 2007). This hypothesis follows from our experimental design and an expected utility framework, in which, risk-loving fishers prefer more risky alternatives. Taking a bigger loan is associated with a high risk of indebtedness with no price increase (see **Table 3**). When the price increases it becomes the best option for expected returns.

- *Suki* relationship strength: *Fishers with stronger relationships to their patron (i.e., more inflexible) are more likely to take bigger fuel loans*. In real life, larger loans indicate a willingness to stay in a *suki* relationship, because they imply deepening the indebted relationship with the patron (field observations, Concepcion, Iloilo, and Philippines). Fishers wishing to switch patron (weaker *suki* relations) are less likely to go for big loans in real life as they want to avoid further indebtedness as to untie themselves. Although loans are paid back each round in the experiment we hypothesized a tendency toward the smaller or larger size loan as result of real-life tendencies. Although the literature does not point to the size of loan fishers would take as a result of their relationship there is evidence of patrons and clients desiring continued and persistent loan-taking, avoiding full repayments to ensure a continued relationship (Merlijn, 1989; Platteau, 1989).
- Gender: *Men are more likely to take bigger fuel loans than women as they are more financially risk seeking. They are also more likely to take a bigger loan to increase their chances to land more catch due to cultural norms associated with gender in fishing in the Philippines.* The literature review by Croson and Gneezy (2009) shows that men are more financially risk seeking than women in risk tasks like gambling and lotteries, although with WEIRD [Western Educated Industrialized Rich Democratic (Henrich et al., 2001)] participants. Charness and Gneezy (2012) find the same gender-influenced risk tendencies in a compilation of results from 10 experiments based on investment behavior.

Literature specific to the Philippines and fishing communities states that masculinity is directly enacted through fishing where the ability to catch fish, especially more fish, is an expression of male success (Dumont, 1992; Russell, 1997; Fabinyi, 2007).

- Household savings: *Household savings are expected to play a role in predicting bigger loan taking, however, the direction is unclear as evidence and observations are ambiguous.* Fishers with more savings could be more willing to take a bigger fuel loan because they have more capacity to pay back and are less risk averse. Literature provides evidence that the income-poor are more financially risk averse. For example, Haushofer and Fehr (2014) using datasets from multiple countries conclude that income poverty leads to risk-averse decision-making. Yesuf and Bluffstone (2009) find high risk aversion in rural Ethiopian farming communities with low-incomes and in a similar agricultural setting in Nigeria Adubi (1996) finds the higher the income the higher the capacity of the farmer to assume risk in their farming. On the other hand, fishers with more savings in the month before the experiment could be less likely to take a big loan as they are less in need of cash to run their vessels (field observations, Concepcion, Iloilo, and Philippines).
- Fishing capital- gear/vessel: *Fishers with labor intensive/larger vessel type fishing activities (active nets, drag/drift/set nets,* and *trap) are more likely to take bigger loans because they are used to borrowing more to finance their fishing operations. Line fishers and smaller vessel users are less likely to take big loans as they need relatively little finance.* This variable might have a relationship with risk preferences- Eggert and Lokina (2007) find that more capitalized Tanzanian fishers i.e., those with more expensive gears and outboard motors are more risk seeking. They compare this with similar results amongst Swedish fishers using trawls, whom are less risk averse than gill net or trap users (Eggert and Martinsson, 2004).

EXPERIMENTAL AND COMPLIMENTARY METHODS

The following sections "Experimental and Complimentary Methods" and "Data Treatment and Analysis," which include the experimental design, methods of data collection, treatment and statistical analysis, are based on and follow the convention of economic experiments (for examples in a SSF context see: Carpenter and Seki, 2011; Noussair et al., 2015; Lindahl and Jarungrattanapong, 2018).

Experimental Design

In this experiment, fishers made individual decisions repeatedly over 12 rounds to take a big or small fuel loan from a patron or refrain from fishing. Fishers made profit based on fuel costs and catches which were randomly drawn each round. Higher catches were possible for fishers taking a big loan (**Table 3**). Participants were divided into three treatment groups who experienced (1) no price change throughout the experiment (control), (2) a price increase (treatment 1 in round 4) for those fishers taking a big loan, and (3) a price increase and then decrease (treatment 2, increase in round 4 and decrease in round 8) during the experiment. **Supplementary Text S2** describes the experimental procedure in detail.

The experiment was framed to resemble the real-world context, while isolating individual fishers' decisions. This individualized approach overlooked some system complexity such as interactions between fishers, or discussions within households, but helped us to understand individual fisher decision-making in relation to loan taking and ensured a sample size that allowed statistical analysis. **Figure 4** conceptualizes the experimental decisions and variables that fishers faced in all treatment groups over all rounds.

To keep the framing anchored in their own fishing experience fishers were given a general introduction (all done orally in a group setting) that informed them a patron offers them a small fuel loan or a bigger fuel loan that will enable them to make larger catches (see **Supplementary Text S3** for the actual instructions used, translated from Hiligaynon to English). In each round (12 rounds in total), each fisher was informed of the fish prices and asked to decide whether to take a big or small loan, or not take a loan and not go fishing for that round. Catches were drawn randomly from a distribution depending on loan size with larger catches possible for bigger loans (**Table 3**). The no loan choice mainly served as an exit option. Loans were paid back in full at the end of each round from the sale of the catch and net as well as cumulative income were recorded for the individual fisher to see. Each round was separate and incomes from previous rounds could not be used in following ones. To ensure that everyone understood the experiment, examples of these calculations were done as a group on whiteboards twice before sessions started.

Before deployment in the field, the experiments were piloted on four occasions, twice with students at a Swedish university, once with Filipino students and once in the field with fishers.

Catches were reported in a unitless scale of 0–20 where 0 was nothing and 20 was a "bumper" catch (which was only possible to land with a big loan). Fishers were asked to relate the catch scale to the range of catches experienced in their current real-life fishing (this interpretation was collected in kilograms in the post-experiment interview described in the section "Complimentary Data Collection"). We did this so as to better interpret their experimental decisions in relation to their real-life fishing trips and assess their understanding of the experiment.

Catches for big and small loans in each round were drawn from discrete uniform distributions; [0,10] for the small loan and [0,20] for the big loan. There was an equal likelihood of all catch rates in each round. In order to facilitate 10 participants per session and to minimize noise from individual randomly variable catches (and increase the statistical power to detect treatment effects), the big and small loan catches for each round were drawn in advance and were the same across all participants, see **Figure 5**. Catches for each round were revealed to participants after they had made their decisions.

In rounds with a higher price (i.e., rounds 4–12 in treatment 1, rounds 4–7 in treatment 2) the ex-vessel price was doubled,

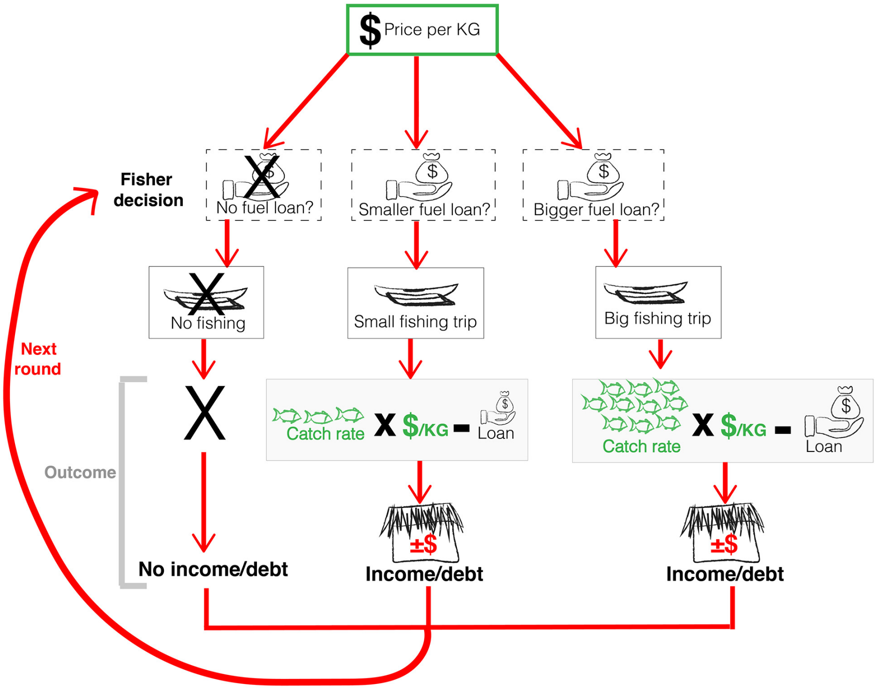

FIGURE 4 | Shows the experimental situation – the decisions and variables within the experiment. Fishers receive a price per kg from patrons. With this price they also get offered a fuel loan. They need to decide whether they take a loan at all or take a smaller or bigger loan (the dashed lines show the decision the fishers must take in the experiment). Depending on that choice they can fish on a smaller trip, a bigger trip or not at all. Those that fish have the chance of a smaller or bigger catch rate depending on the fuel. The catch they end up with is multiplied by the given price per kg and the fuel loan debt is removed. Fishers thus end up with an income or debt or nothing (if they did not fish). They see the outcome and then make the same decisions for the next round. The green represents the experimental variables that are changed in the experiment- the catch rate is random (selected before the experiment) and the price is increased or decreased by the experimenters.

but only if fishers took a bigger loan (reflecting being able to target the more valuable/demanded species). Participants in all treatments were given the same introduction and told that the prices may change; they did not know which direction. At the start of the session and between each round participants were presented with paper decision cards along with catches and incomes from the last round, current prices for the next round and current cumulative income. Fishers indicated their individual decision by ticking a box for big/small/no loan on their paper decision cards. Fishers were not allowed to communicate with each other and contact between participants was minimized throughout the experiment.

Participants were assigned to the sessions according to their availability. Each session was accorded a treatment. We switched treatment after every session to avoid discussion or strategizing amongst past and future participants. Sessions were run individually during the morning and afternoon and participants were not aware which treatment group they belonged to.

Price treatments were introduced at the relevant round with the same information. The control group experienced no change in price throughout the experiment. In the first phase (rounds 1–4) prices were constant across all treatments. In rounds 4–7, prices doubled for treatment 1 and 2 but only the big fuel loan trip (i.e., fishers would have to take a big loan to capture the higher price). In rounds 8–12 prices remained high for treatment 1 and reverted to the original level for treatment 2.

Financial Risk Preference Elicitation

Financial risk preferences of individual fishers were captured at the end of each session using a simple probability decision task before fishers completed the post-experiment interview (see **Supplementary Text S4**, **Supplementary Figure S4**, and **Supplementary Table S4** for details on the decisions tasks). This probability weighting method is standard for measuring financial, and other risk preferences in economics and psychology (Wakker, 2010; Cardenas and Carpenter, 2013; Kahneman and Tversky, 2013). The decision task was explained orally like the experiment itself using written examples on a whiteboard. Fishers were told that one of them would be chosen at random to win the actual money associated with the task (1 in 10 chance), which would be added to their earnings from the experiment. Fishers wrote down their choice on their decision cards before the draw was carried out. Two framings were used, one based on a decision task represented by lottery balls similar to (Cardenas and Carpenter, 2013) and the second framed as a fishing trip (Eggert and Lokina, 2007) but using the same numerical options. These different framings were used to test if fishers preferred and/or better understood the more abstract decision task with the lottery balls or the more realistically framed task with fishing trip incomes. Each treatment was equally divided between risk framings and participants in the same session experienced the same risk framing.

Complimentary Data Collection

Complimentary data was collected through interviews, focus group discussions and observations to allow us to anchor both our experimental design and the discussion of results in relation to the *suki* system, financing and various socio-economic factors of interest (see **Supplementary Table S5** for details on the different methods employed).

Seven focus group discussions were done during field visits the month before experiments with the general fishing community which informed the interpretation of experiment results through subjects such as gender roles, scenarios around the *suki* system and global market demands (See **Supplementary Table S5**). Furthermore, short structured interviews were carried out with all participants after each experimental session (see **Supplementary Material S6** for the post-experiment survey/interview instrument) to collect attributes needed to test our hypotheses. See **Table 2** for variables used and their hypothesized importance for loan taking behavior. Additionally, fishers' own interpretations of the catch rates, trip types and associated incomes during the experiment were elicited to assess how, and if, they could translate the experiment to their real-life contexts. This is a common practice to validate the experimental design (Garzon et al., 2016; Lindahl and Jarungrattanapong, 2018). Every third session was followed by either a focus group discussion (**Supplementary Material S7**) or a semi-structured interview (**Supplementary Material S8**), so as to ensure one was carried out at each sitio but not every session. The post-experiment group discussions gave instant feedback on the salience of the experiment for participants, as well as a general sense of how fishing communities deal with changes in prices, and the ecosystem. The semi-structured interviews complimented the focus groups with individual level details on the same topics. Interview respondents were selected with the help of local "gatekeepers" (i.e., the *barangay* officials) to represent key informants, with a greater knowledge of the general system and those who also interested and articulate in sharing this knowledge.

Before we ran the experiments we also held in-depth interviews with patrons (brokers and buyers in the local *barangays*) to capture the dynamics surrounding their business structures (**Supplementary Material S9**). Understanding how financers make decisions about fuel loans and how they have responded when prices have changed dramatically in the past was important in verifying the experimental design.

DATA TREATMENT AND ANALYSIS

All post-experiment interview and experimental data were collated in a spreadsheet while qualitative interviews and focus group data were translated and transcribed from voice recordings and notes taken during sessions. Demographics including age, gender, education, number of household income activities, savings and number of dependents was tested with Kruskal-Wallis, Wilcoxon, Pearson chi-squared, and Fisher's exact (when less than five observations were made) tests in R (Ripley, 2001) to check for potential structural differences between treatments. Effects of the risk preference task framings on measured risk preference were tested between framings across all treatments with a Pearson chi-squared test. The hypothesized relationship between risk preferences with fishing capital, gender, and savings were also investigated with the appropriate tests to understand if there were associations as hypothesized.

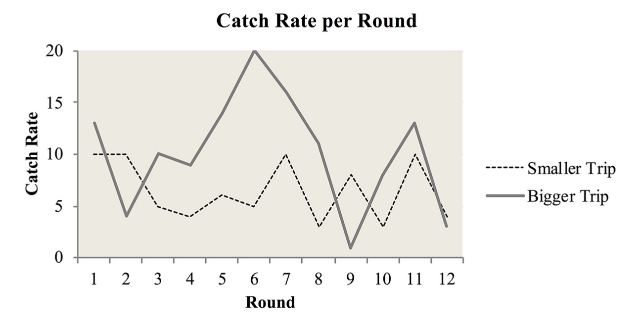

FIGURE 5 | Catch rate per round for the trip with the smaller loan and the big loan. The catch ratings for each type of trip where drawn at random from a lottery before the experimental sessions took place and remained the same throughout all experiments.

We initially tested for differences of average treatment effects (price changes) on decisions before analyzing and testing for other predictors using regression analysis. We tested whether decisions (the number of times small, big, and no loan choice were chosen in each phase) differed between treatments. Each loan choice made by a participant (12 in total) was treated as a single observation and frequencies of no/small/big loan choices were tested against treatments for each phase. Next, we compared the frequency that individual fishers took small, big and no loans, throughout the experiment across treatments. Finally, we tested the frequency of big loan choices per phase between treatments according to the main price hypothesis.

We then built binomial regression models [glm() function in R] with the decision of a big over a small loan as the dependent variable and independent variables according to our hypotheses. We removed the small number of fishers who took no loan because it was not the main variable of interest, and few people choose this option (n = 19 in round 1, n = 23 in round 4). We assessed model prediction power and fit using McFadden pseudo r squared statistics [pR2()] and log likelihood ratio tests [lr.test()]. All contextual variables (see **Table 2**) were investigated for collinearity using the VIF (variance inflation factor), function vif(). None of the resulting VIF values were over 1.5 suggesting no or inconsequential collinearity (Mela and Kopalle, 2002).

The first regression model tested effects of individual and household characteristics on the odds of choosing a big loan in round 1, before any different payoffs had been experienced.

Because the same randomized sequence of catch rates was used in all experiments, and because the big and small loan catches were different (**Figure 5**), each participant experienced payoffs that did not vary randomly between individuals but depended deterministically on the sequence of choices they made in each round. Thus, throughout the experiment, choices in each round may have been influenced by these non-random payoff experiences from earlier rounds. The possible different sequences of choices increased by a power of three with each subsequent round. As a result, we focused analysis on rounds 1 to 4, before the number of possible combinations of previous decisions became too many to control for.

Although we worked through examples with the participants before beginning, as a precaution against the start-of-experiment effect, we repeated Model 1 with round 2 choices (Model 2). In this model we controlled for the effects of the participants first choice by adding this round 1 choice as an independent variable.

In the next steps (Models 3–5) we tested for effects of the price increase on the likelihood of choosing a big loan. The dependent variable for Models 3–5 was whether a big loan was chosen in round 4, the first round when prices increased. Model 3 tested the effect of the price rise (i.e., treatment 1 and 2) while Models 4 and 5 additionally controlled for the choices made and experiences of rounds 1–3, by including the choice sequence from these rounds as nominal dummy variables. Although there were $3^3 = 27$ possible sequences of choices for rounds 1–3, the six most common combinations of choices captured a large proportion (91%) of the participants (see **Supplementary Table S10** for the top six options). Thus, we added these six sequences as dummy variables, and excluded fishers that chose other sequences in rounds 1–3 from Models 4 and 5. This maintained the largest possible sample size while minimizing the degrees of freedom needed to incorporate previous choices in rounds 1–3. To interpret the effect of these choice sequences, we looked at the payoff fishers received each round and cumulatively, which indicated if they had a good (above average pay off) or bad (below average payoff) experience of the experiment. Model 5 additionally controlled for the effect of contextual variables we hypothesized as predictive of loan taking.

In the following section we present the models in relation to how they answer the hypotheses stated in section "Situating the Experiments in the Conception Trade System – Elaboration of the Patron-Client Relationship and Price Change" (i.e., not in numerical order).

RESULTS

We first introduce the results of the risk elicitation task, because this is subsequently used as an explanatory variable in the regression models. We then respond to each of the six hypotheses, first the main treatment- fish price, which is accounted for in Models 3–5, followed by the contextual fishing, household and individual characteristics, used to build Models 1, 2, and 5.

Financial Risk Preferences in the Sample

Among the 251 fishers, 59.3% were financially risk averse, 20.7% risk neutral and 19.9% risk seeking (**Table 2**). Financial risk aversion amongst men and women was similar (p-value: 0.40). Monthly savings and gear type also did not have a relationship with financial risk aversion, as hypothesized (p-values: 0.39–0.59). There was no difference in financial risk preference between the two different framings used (p-value: 0.64). In the focus group discussions, fishers who completed either framing generally agreed they were easy to understand and that both were similar to gambling, which is a common activity in many *sitios*. No strong preference for either framing emerged from any of these discussions, thus both an abstract and real-life framing appeared suitable in assessing financial risk in the certain field context. For these reasons, we do not subsequently distinguish between the two framings in our regressions including risk aversion.

Predicting Loan Taking

The Main Hypothesis- Price (Treatment) Effect

Throughout the experiment participants, on average, chose the big loan 32% (SD 27%) of the 12 rounds, the small loan 59% (SD 28%) of the time and opted out with no loan 8% (SD 15%) of the time. There was no statistical difference between treatments in these choices (**Supplementary Table S11**, p-values: 0.69–0.84), nor was there a difference in the frequency of big loan choices between treatments for the different phases (**Supplementary Table S11**, p-values: 0.22–0.64). From this crude first step no treatment effect of the price increase or decrease was evident, but we revisit the potential influence on prices in the subsequent regression analyses where we control for potential confounding variables.

Models 3–5 all included the price variable, and none showed any treatment effects from the price changes. In fact, a price increase did not predict fishers taking a big loan in round 4 (Models 3–5 **Table 4** – all model outputs can be found in **Supplementary Tables S12, S13**) even when contextualized variables and choices in the previous rounds (1–3) were considered (**Table 4**). On the basis of these findings we reject the first hypothesis that price change appears to have had no effect on fishers' loan taking behavior.

Hypotheses Based on Contextual Variables and Their Influence on Loans and Fishing

The strength of the risk type, *suki* relationship, gender, savings, and gear type (thus operation style), were not significantly predictive of fishers' initial choices in round 1 (Model 1, **Table 4**). Moreover, the likelihood ratio test suggested that we could not reject a hypothesis of no association for Model 1 (9.1610, $p = 0.5169$).

In Model 2 gender and gear type were weakly significant showing that women were less likely to choose the big loan over the small loan and fishers using traps were more likely to take big

TABLE 4 | Summary of model results showing the variables used in the regressions and which ones came out as predictive of bigger loan choices in round 1, 2, or 4.

	Round	Previous choice	Price	Gender	Gear	Suki strength	Risk type	Savings
Model 1 *n* = 233	1			NS	NS	NS	NS	NS
Model 2 *n* = 233	2	Big loan***(2.644)		Women*(–1.70)	Traps*(1.79)	NS	NS	NS
Model 3 *n* = 229	4		NS					
Model 4 *n* = 170	4	Big-big-big***(0.64) Small-small-big***(3.20) Small-big-big** (2.46)	NS					
Model 5 *n* = 170 ❖	4	Big-big-big***(3.88) Small-small-big***(2.59)	NS	Women***(–2.96)	NS	NS	NS	NS

*Model 1 tests fisher's initial tendencies toward the bigger loan at the very start of the experiment. Model 2 incorporates the first decision and tests loan choices in round 2. Model 3 tests for a price effect in big or small loan choices when the price rises and model 4 builds on model 3 by controlling for the previous 3 rounds. Model 5 then adds to model 4 by controlling for the hypothesized contextual variables. *, 10%; **, 5%; ***, 1% significance levels; NS, not significant. ❖ We ran model 5 both with and without risk to understand if gender remained significant without controlling for risk, thus that it explained the variance. The regression coefficients are shown beside significant variables.*

loans. The log likelihood ratio test showed we could reject a null model (of no association) in Model 2 (24.786, $p = 0.01587$).

Model 5 indicated at the 1% significance level that, after controlling for choices in rounds 1–3, women were much less likely to go for a big loan in the fourth round, supporting our hypothesis 4 that gender is a predictor of loan-taking decisions. We investigated this gendered result further and saw a clear pattern – that men much more frequently went for the big loan throughout the experiment, although, no gender difference could be detected in the first loan decisions (Model 1). Over half of the sampled women took the small loan for the first three rounds consecutively and in round 4, 94% made this choice again. Women chose small loans significantly more frequently (78%) than men (54%) across all 12 rounds and large loans significantly less frequently (20%) than men (36%) (for all tests $p < 0.01$).

Although we did find the that average years in a financing relation increased alongside the inflexibility of the arrangement (significant differences between the relationship lengths according to the *suki* ranks 0–3, $p < 0.001$) we could not accept a hypothesis that fishers in inflexible *suki* relationships were more likely to take a bigger loan over a smaller loan when offered higher prices (Models 2 and 5). Additionally, risk type by itself was not a predictor for taking a big loan. All risk types went for the bigger loan between 30 and 39% of the time (p-value: 0.27).

We therefore reject the hypotheses that the contextual variables of financial risk type, *suki* relationship "strength," household savings, and gear type had little or any effect on loan taking behavior.

We cannot reject hypothesis 4 however, as gender does have an effect on loan taking, and in our experiment, men are more likely to take a bigger loan.

Previous Experimental Choices by Fishers as an Additional Predictor of Behavior

In Model 2 we took account of the decision in the first round and saw that the previous choices significantly predicted fishers' decisions. Taking a big loan in the first period predicted the likelihood of taking a big loan in the second round (even though the actual return of the big loan in the first period was rather low at 6 PHP).

In Models 4 and 5 choices in the first three rounds were predictive of the choice in round 4 whether or not contextual variables were accounted for. Small-small-big, small-big-big and big-big-big strongly predicted the big loan decision in round 4 (Model 4). Big-big-big and small-small-big loan choices remained strongly significant, especially the big-only combination, in Model 5 where gear, gender, *suki* relationship, risk and savings were controlled for.

These three choices (small-small-big; small-big-big; and big-big-big) were made largely by men (56 men six women). Cumulative payoffs for these three choices were 30 PHP, 3 PHP, and −6 PHP, respectively, thus they represented quite different experiences in terms of realized catches and revenues (see **Supplementary Table S10** for the expected and realized catches, the payoffs per round and the cumulative payoffs). As noted, the most predictive sequence for taking a big loan in round 4 was to take a big loan for all three first rounds (with a cumulative payoffs of −6 PHP) – showing a subset of participants (17 men and two women) who persistently chose the big loan despite a negative cumulative payoff. Thus, fishers were more likely to take big loans if they took them in previous rounds (Model 2, 4, and 5), even though outcomes of taking them were variable.

In summary, taking a large loan was not affected by a price increase. Instead it was strongly predicted by the previous choices and by gender, with men taking more big loans. The gender effect supports our hypothesis, but this is not explained by higher financial risk seeking preferences amongst men.

DISCUSSION

Are Prices a Short-Term Incentive for Small-Scale Fishers?

We expected fishers to take a larger fuel loan (and thus increase their potential ability to catch more fish) in response to increasing economic incentives, operationalized here through the price of fish. But this is not what we found in the experiment.

Our results reflect some previous literature examining fishers' short-term behavior in relation to a range of factors, including their fishing activities and market incentives. Salas et al. (2004) also had unexpected results in their study of Mexican small-scale fisher's target species choices (for export markets). They too expected the price to significantly affect fisher's relocation of effort and although fishers did respond to changing prices, economic incentives were not the only driving force. Factors such as skill and personal background i.e., being a displaced person, played a role. In the Turks and Caicos spiny lobster and conch fisheries supplying US markets, economic rationality also did not entirely explain the observed behavior (Béné and Tewfik, 2001). They found that rather than intraseasonal price fluctuations seasonal fishing effort allocation decisions were complicated by various individual and collective characteristics, like peer pressure and diving abilities, as well as by the general socio-historical-cultural context of the fishery (Béné and Tewfik, 2001). Abernethy et al. (2007) add to this counterfactual with a case from Anguilla SSF showing that not all fishers sought to maximize profit. Similar to these studies our case, indicates that contextual characteristics of individual fishers play a stronger role in determining loaning and effort than price and economic incentives.

Financing (and the patron-client relations that ensue) has been argued to be a major influence on fishers' short-term extractive strategies in low-income tropical fisheries (Platteau, 1995; Carnaje, 2007; Johnson, 2010). However, we found no effect of the strength of real *suki* relationships on loan taking behavior. One possible reason is a lack of variation in our data. Most participants in our experiment were in an inflexible *suki* relationship (**Table 3**) and fishers in these types of agreements are likely to have been in them for a longer period of time. Long-term patron-client relations are those where both parties wish for them to continue over time (c.f. Merlijn, 1989). However, this seems to also create rigidity in the system as a whole. The complimentary data collected leads us to speculate that indebtedness and the flexibility of local financial arrangements may shape or constrain fisher's market related behavior. The fact that 60% of our respondents said they could not change patrons to follow better prices – seems to indicate that they are not used to responding to price dynamics. Longer, and thus more indebted and inflexible, fishing arrangements, as well as the preference of fishers for the *suki* system in general (77% of fishers open-endedly preferred this source of finance over others e.g., banks, micro-credit) may promote path dependency in the fisheries constraining options to respond to future market or credit options.

Today's environmental governance strategies are increasingly moving their focus from extractive operations to seafood trade as a means to transition fisheries toward more sustainable trajectories. As such, increasing effort is put into market-based tools like certifications schemes, eco-labeling (Fabinyi et al., 2018), and fishery improvement projects (Cannon et al., 2018). However, the rational economic justification for these systems (arguably more relevant to WEIRD contexts) often assumes away the importance of social relations like the *suki* system undermining actor's agency to coordinate and implement changes (Bailey et al., 2016). While it can be useful to conceptually reduce markets to operational variables like price, catch and demand, as we did within the experimental design, it has the potential effect of dislocating the market concept from the social relations that shape resource governance (Bennett, 2005).

Why Did Men Go "Big Big Big"?

One might expect the results we see – where women are much less likely to go for the bigger loan option – to be due to gender differences in financial risk-taking. However, according to our financial risk elicitation task, women were not less financially risk-seeking than men in our sample. In fact, no major gendered differences in individual, fishing or household related characteristics were found. Women and men in the sample used similar engine sizes, boat lengths, and are equally spread across gear types. The only significant gender difference amongst the collected complimentary data was the interpretation of the experimental variables. When asked how many liters of fuel a big or smaller trip in the experiment would need there is a significant difference between men and women ($p < 0.001$). Women interpreted on average half the number of liters as men for both the bigger and smaller trip. Likewise, for catch rates women estimated significantly lower catch rates representing the experimental values of 5, 10, and 20 ($p < 0.001$). For a catch rate of 20, men on average thought of landing three times the amount of fish (KG) than women.

So why do we see these gender difference in our results if it is not financial risk aversion? One possible explanation is the fact that we captured only one type of risk in the elicitation task – yet there are other types of risk domains where men and women may differ, such as physical or health risks (Courtenay, 2000; Deleire and Levy, 2001). As such, respondents' degree of risk taking may be highly domain specific; that is, financial risk aversion may not correlate with preferences associated with physical risk (Courtenay, 2000; Deleire and Levy, 2001; Weber et al., 2002). This might explain our observations. Women may be less willing to take a bigger or longer trip (associated with a big loan) due to the increased physical risk this type of trip involves. Thus, they imagine landing less fish and needing less fuel. Women's interpretations of trip durations, distances, and fishing grounds were almost identical to men, but they might be more averse to spending the average 10 h a day at sea ($\pm$5 h SD) the typical fisher in our sample takes with a bigger fuel loan. Additionally, we carried out the experiments during *habagat,* which brings wet and stormy weather, increasing the physical risk of fishing.

Fisherwomen might be more physically risk averse but there might be a further and/or corresponding explanation to our observed gender differences. The goals of peoples' decisions in particular situations vary as a function of the personality and culture of the decision maker (Weber and Lindemann, 2007). Thus, we believe it is likely we are seeing the effect of cultural role-based decision modes, where participants took the social roles associated with gender in this area of the Philippines into the experiment and, as a result, the associated obligations (ibid). In focus group discussions when fishers, buyers and dryers (both men and women) were asked about gender differences in their work, six out of seven *sitios* all repeated that there is a difference in fishing but not in trade.

The words "heavy," "strength," and "hard" were continuously repeated is these *sitios* in association with fishermen's' work and the word "lighter" for fisherwomen. Three *sitios* concurred that women cannot go out as often or as long as men. *"Men are braver to go to sea than women"* (Focus group participant, Malangabang, 2017). Other studies from fishing communities in the Philippines show that men are conceived of as the financial supporter and bearer of heavy workloads while women deal with child rearing and the household work (Siason, 2000). This may limit the time they have available to go on the bigger fishing trips. The social construct of masculinity potentially pushes men to go big during the experiment – in Palawan, Luzon and the Central Visayas (all in the Philippines) previous studies discuss the displays of masculine identity through the physical rigors of the sea-going occupation and lifestyle of fishing – *"fishing is a gamble and an opportunity for male fishermen to demonstrate their masculinity, economic prowess, and value"* pg. 519 (Dumont, 1992; Russell, 1997; Fabinyi, 2007).

Post-experiment Hindsight: The Roles of Risk, Price, and Finance in Fishing

In hindsight, we realize we limited our analysis of the full dataset due to the experimental design. By reusing the same catch-rate sequence for each session, with a different sequence for bigger and smaller fuel loans, we deterministically linked catch rate experience to the decision made (thus catch was not independent of choice). This created a non-random diversity in experiment experiences, which became exponentially more diverse throughout the experiment. We could only properly control for this effect up to round 4 of the experiment, which is why we could not make use of the whole time series of the experiment in the regression analyses. Note however, that we could still use the full data set when we analyzed the average treatment effects of price changes [see section "The Main Hypothesis- Price (Treatment) Effect"].

Although we tried different risk framings in the experiment, to account for the possibility that the abstract risk frame potentially did not capture risk preferences for fishing, our results showed no differences. Further research could involve investigating the best methods to capture different risk domains and areas of risk important in an SSF context. As noted above, fishing activities are not just affected by financial risk but involve high physical risk and sometimes social risk. For example- masculinity, failing to prove your maleness through fishing may hinder your social status amongst community members. A better understanding of gender-related results could be captured through assessing various domains. The concept of risk propensity still sees no academic consensus on its definition nor measurement.

Our experimental results could not identify an effect of price changes in fisher behavior. We believe this is in part due to the short-term nature of the time frame employed (which was trip based) – though in other literature fishers' behavior is not explained by prices even at seasonal scales (Béné and Tewfik, 2001). Complimentary data collection did not detect any fishing behavior responses to price changes, though price fluctuations and uncertainty, even on a daily basis, were well registered amongst fishers. No *sitios* mentioned fishing in certain habitats, and locations based on price. The only response to price changes fishers mentioned in interviews related to switching patrons to those who offered higher prices – but only if their loans were paid off.

Our results may be proof that short-term price increases (as incorporated in our experiment) may not induce tactical behavioral changes in marine resource extraction. If this is the case, the simulated impact of the global market on fishers' behavior may not be observable in the short-term. In French Guyana, Béné (1996) identified a global market response in fishing effort only over a 13 years period, while seasonal strategies were still maintained in each fishing season. Fishers can be relatively constrained by their traditions and/or tendencies in response to short-term opportunities despite potential gains (Béné and Tewfik, 2001).

The literature review around this discussion suggests that while our study provided novel information on the impact of patron-client relationships on fisher's tactical decisions, it remains unclear how market integration affects extractive behavior over time, and in turn what the sustainability implications of this are in SSF. The role of patrons and the financing they provide remain key variables of interest for understanding this, but our work shows the need to find ways to incorporate longer time-scales into our examination of behavior. We invite reflections and discussion on how to capture such longer-term structural or strategic decisions in relation to changing markets, experimentally or using other methods.

CONCLUSION

In general, we believe the lack of price response supports the narrative that in the short-term fishers are constrained in their capacity to respond to market incentives. They develop and use fishing strategies in response to the market or regulatory constraints they encounter within their particular social, cultural, and economic contexts. They appear to bring these constraints in the form of gender roles into the experiment. In cash poor environments it can be difficult to adjust strategies even if there is potential gains from such a change – but also, fishers with the technical and capital capacity to change often do not in the short-term (e.g., Béné and Tewfik, 2001). Developing theoretical and empirical knowledge on the connections between seafood trade and SSF dynamics is increasingly important amid insatiable global markets, as there is evidence that many fisheries have crossed ecological thresholds to meet demands and high price incentives (Kooiman et al., 2005; Béné et al., 2010). Outcomes of global markets are filtered by context specific conditions at the local fishery scale (Crona et al., 2016). However, conventional fishery management often simplifies or ignores this, especially the complex power relations intertwined with fishing capital access, local fish trading agreements, and market pressures that impact fisher's extraction (Kininmonth et al., 2017). Our somewhat unexpected findings are important as they highlight gaps in our understanding of human behavior in the fishery context, and illustrates that "conventional truths" of fishers' responses perpetuated in scholarly fields may need to be challenged in order to achieve truly sustainable governance strategies.

With regards to governance insights, the results suggest a path dependency in credit, and loan relations due to longstanding relations. Policies that aim to introduce new micro-credit or – finance schemes to coastal communities could help families pay back existing loans as part of the program. This would limit the continued influence of informal options and debt cycles, creating room for new choices and options within the fishing community. However, we also highlight that capacities to act can be influenced by social relations. These relational influences are likely to affect fishers' decision-making and should be accounted for when implementing policies, as they represent potential leverage points to intervene in the system (see also Drury O'Neill et al. (2019) for a deeper discussion on this topic). The fact that gender appears to influence fisher responses highlights the deeply cultural responses people in a fishery may have to interventions. Finding ways to account for such cultural perceptions in interventions may lead to fruitful governance experimentations, such as engaging with masculinity ideals to influence male fishers into patrolling or reporting harmful illegal activities.

ETHICS STATEMENT

This study was carried out in accordance with the recommendations of the ethics committee at the Stockholm Resilience Centre with written and/or oral informed consent from all subjects. Before any interviews or experiments took place all subjects were informed of the purpose and intent of the research and all subjects gave either written or oral informed consent in accordance with the Declaration of Helsinki. The protocol and plain language statement was approved by the ethics committee at the Stockholm Resilience Centre.

AUTHOR CONTRIBUTIONS

All authors conceived and designed the research, and wrote the manuscript. ED, TL, TD, and BC designed the experiments and analyzed the data. ED, BC, and AF collected the data.

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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.2019.00491/full#supplementary-material

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Navigating Complexities: Agent-Based Modeling to Support Research, Governance, and Management in Small-Scale Fisheries

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The sustainable governance and management of small-scale fisheries (SSF) is challenging, largely due to their dynamic and complex nature. Agent-based modeling (ABM) is a computational modeling approach that can account for the dynamism and complexity in SSF by modeling entities as individual agents with different characteristics and behavior, and simulate how their interactions can give rise to emergent phenomena, such as over-fishing and social inequalities. The structurally realistic design of agent-based models allow stakeholders, experts, and scientists across disciplines and sectors to reconcile different knowledge bases, assumptions, and goals. ABMs can also be designed using any combination of theory, quantitative data, or qualitative data. In this publication we elaborate on the untapped potential of ABM to tackle governance and management challenges in SSF, discuss the limitations of ABM, and review its application in published SSF models. Our review shows that, although few models exist to date, ABM has been used for diverse purposes, including as a research tool for understanding cooperation and over-harvesting, and as a decision-support tool, or participatory tool, in case-specific fisheries. Even though the development of ABMs is often time- and resource intensive, it is the only dynamic modeling approach that can represent entities of different types, their heterogeneity, actions, and interactions, thus doing justice to the complex and dynamic nature of SSF which, if ignored can lead to unintended policy outcomes and less sustainable SSF.

Keywords: interdisciplinary methods, interactions, data paucity, integrated systems, complex adaptive systems, social–ecological systems

INTRODUCTION

The sustainable governance and management of small-scale fisheries (SSFs) has proven to be a tremendous challenge, exacerbated by their complex nature (Mahon et al., 2008; McClanahan et al., 2009; The World Bank, 2012; FAO, 2014). At the heart of this complexity lies the high diversity of the social, institutional, and ecological entities in SSF, the interactions within and among these entities, and the range of outcomes that arise from these interactions (Degnbol and McCay, 2007; Ostrom, 2007; Smith and Basurto, 2019). The wider context that SSF are embedded in adds to this complexity, e.g., international trade relationships, fishers' migration, technological change, and increased tourism (Kittinger et al., 2013; Crona et al., 2015; Eriksson et al., 2015). Apart from this complexity, the frequent lack of fine resolution cultural, socio-economic, and ecological data complicates the development, implementation, and evaluation of policies and management strategies that are sensitive to the local context (Jentoft, 2017; Johnson et al., 2017; Agapito et al., 2019). The combination of complexity and lack of information limits our understanding of how a policy will be received, and often lie at the heart of unintended policy outcomes (Degnbol and McCay, 2007; Lewison et al., 2019). Important advances have been made by meta-studies highlighting common factors that can be linked to sustainable outcomes, such as leadership, social cohesion, and co-management (Gutierrez et al., 2011; Ovando et al., 2013; Crona et al., 2015; Cinner et al., 2016). However, less attention has been paid to why and how these factors and processes occur in the first place, how they interact to produce (un)intended results, or how they can be promoted through policies.

Agent-based modeling (ABM) is a computational modeling approach that may help embrace complexity and overcome information paucity-related problems. Different from other modeling approaches, ABM allows for the assessment of why and how interactions between different actors and their environment result in a particular outcome, while accounting for the impacts of different external drivers (Bousquet and Le Page, 2004). In a fisheries context, ABM allows exploration of how agents (e.g., fishers, traders, fleets) change their behavior in response to changes in their environment. This is different from standard fisheries models, which typically aim at predicting future states of a fishery by modeling variables at the macro-level (e.g., fleet behavior, fishing effort, market demand) as characteristic of the whole fleet (Quinn, 2003; van Putten et al., 2012; Nielsen et al., 2018). Even though standard fishery models are powerful, they are often not adequately flexible or sensitive to the micro-level complexities of SSF (Weber et al., 2019), nor able to fully represent the social dimension in fisheries (Fulton et al., 2011; van Putten et al., 2012; Burgess et al., 2018).

There are a number of advantages to using ABMs over traditional fisheries models. They enable qualitative and quantitative data to be combined to understand the underlying processes of empirical phenomena (An et al., 2005; Edmonds, 2017; Magliocca et al., 2018). Similarly, ABMs can be interactive and collaborative and have the potential to bring together different stakeholder groups, thus reconciling different knowledge bases, assumptions, and goals (Poteete et al., 2010; Étienne, 2013; Taylor et al., 2016). Finally, they allow the integration of diverse knowledge to ask questions about how particular behaviors at the individual level could give rise to patterns at larger scales and what interactions and processes may have produced a given outcome or pattern (An et al., 2005; Heckbert et al., 2010; Conte and Paolucci, 2014).

This paper aims to elaborate on the untapped potential of ABM to tackle complex governance and management challenges in SSFs. We first outline what ABM is and how the development process of an agent-based model may take place. We present a short review of SSF publications that use ABMs, detail three challenges for SSF management and governance, and use examples from our review to illustrate how ABMs have been used to help address them. We end with a discussion on the potential usefulness of ABM to address contemporary SSF challenges and discuss what is needed to unlock this potential. The intended audience of this paper are those interested in having more tools available to address SSF management and governance issues and questions that relate to complexity, those curious about using ABM, and those who design, manage, or participate in ABM projects.

AGENT-BASED MODELING IN A NUTSHELL

What Is Agent-Based Modeling?

Agent-based modeling[1] is a dynamic, computational approach that represents the actions and interactions of agents and their environment, and simulates how these result in emergent patterns and relationships (Sterman, 2001). In ABMs it is possible to represent agents of different types, their heterogeneity, and the interactions between agents and their environment over time (**Box 1**). These interactions can be conditional on agents' own characteristics, the behavior of other agents, and the state of their social–ecological environment. These micro-level interactions result in macro-level (or system-level) outcomes that, in turn, feedback to affect the interactions occurring at the micro-level (**Figure 1**). This capacity to study micro–macro dynamics and adaptive behavior of agents makes ABM better able to represent complex adaptive system dynamics than other (aggregate) modeling approaches (Levin et al., 2012).

Developing an Agent-Based Model

There are several phases in the development of ABMs: *design*, *implement/build*, *test*, *experiment* and *analyze*, and *communicate*. The exact shape these different development phases take is linked to the purpose and the context of which the model is developed within. The purpose of an ABM can range from basic theoretical understanding of a phenomenon or problem to assessing a case specific policy or management intervention (Edmonds, 2017). Models can be developed as part of individual research projects

[1] Also sometimes referred to as individual-based models (IBMs). Although they are methodologically the same as ABMs, their label is predominantly used in ecology where agents are often ecological entities, e.g., deer, fish, or trees (Grimm, 1999).

BOX 1 | The main elements of agent-based models and their characteristics.

Agents

- Diversity of agent types: Agents can reflect different types of entities. "Social" types such as a fisher, trader, household, company, and market, or "ecological" types such as a species or population of species.
- Heterogeneity within agent types: Within types, agents can have different individual characteristics (e.g., gender, social class, skills, or size classes of fish) and/or different preferences (e.g., fishers being more or less risk averse).
- Agent behavior and intelligence: Agents can be *reactive* by perceiving their environment and responding to change. Agents can also be *proactive* by taking decisions to reach a goal. Agent behavior can be modeled using behavioral theories such as rational, bounded rational, habitual, or modeled based on empirical data (Smajgl and Barreteau, 2017). The "intelligence" of agents can range from simple decision rules to the use of complex mental models (Lindkvist and Norberg, 2014; Schlüter et al., 2017).
- Agent interactions: Agent decisions, behaviors, and states can be affected by interaction with other agents (e.g., human agents can learn, share knowledge, sell and buy commodities, biological agents can prey, feed, or compete for territory), or with their environment (e.g., making decisions based on their catches).

Environment

- Environment representation: Agents are situated in an environment that can be spatially and/or socially structured (e.g., situated in a land- or seascape, or in a social network).
- Ontological correspondence: The model world and its elements often have clear links to their real-world counterpart, including agent type, behavior, rules and norms, and space.

Dynamics and Interactions

- Time-dynamic: The model moves the simulated world through time by letting the agents act/interact, often reflected in discrete steps (e.g., daily or annual time steps).
- Emergence: Overall (system-level) behaviors and patterns arising from individual agents' (micro-level) behavior and interactions is called emergence. These patterns can in turn affect the agents (labeled immergence, 2nd order emergence, or downward causation). An agent-based model is by nature multi-level and represents how different scales co-evolve (e.g., how a fishery system changes over time as fishers and fish stocks adapt to each other over time).

Also see, e.g., Conte and Paolucci (2014); Gilbert and Troitzsch (2005), or Railsback and Grimm (2011).

or multi-stakeholder collaboration processes, which will also influence the purpose and characteristics of the models.

In the design phase the agents and processes relevant to the problem are detailed, and a conceptual model of the ABM is developed. This includes the context in which agents are embedded, assumptions about agent behavior and interactions. The level of complexity of, and focus on, the social and ecological components are also decided upon. The design phase builds on any combination of literature, expert knowledge, and data (e.g., from interviews, surveys, network analysis, laboratory experiments, or participatory processes), and is often a collaborative process between modelers and/or other stakeholders (e.g., researchers, fishery actors, decision makers).

In the implementation phase a programmer translates the conceptual model into code. It often entails even further specification of model details. The type of data and level of detail depend on the focus and purpose of the project. A decision management tool developed for a specific case requires a strong base of case-specific data, whereas an exploration of general phenomena can be based on representative approximations of theoretically derived dynamics. In the testing phase the built model is verified and validated according to the model's purpose, for instance verifying the model behavior and outputs according to model specifications and validating them according to empirical observations (Balci, 2010; David et al., 2017).

The experiment and analysis phase involves using the model as a virtual laboratory to ask the model questions by developing virtual experiments. Some settings are changed in the model and outcomes are observed. As in the model design phase, the experimentation and analysis is often performed in collaboration with project members and/or other stakeholders. Stakeholders and project members (indirectly or directly) use the model to understand various issues, such as the implications of different assumptions or policies, trade-offs, distributional patterns, and emergent phenomena. The last phase, model communication, should, besides regular science communication, be done through publishing the model in an open source library accompanied standardized model documentation, such as the ODD + D (Overview, Design Concepts, and Details + Decision; Müller et al., 2013) and/or TRACE (TRAnsparent and Comprehensive Ecological modeling documentation; Grimm et al., 2014). For further readings on model development see Gilbert and Troitzsch (2005) or Railsback and Grimm (2011).

HOW HAS AGENT-BASED MODELING ADDRESSED SMALL-SCALE FISHERIES CHALLENGES THUS FAR?

Review of Agent-Based Models in Small-Scale Fisheries

We reviewed the literature on the application of ABMs in SSF. A keyword search of Web of Science [("small-scale fisher*") OR ("artisanal fisher*") OR ("subsistence fisher*) OR ("coastal fisher*")] AND (Agent-based OR multi-agent OR ABM) resulted in six relevant publications based on the criteria that the models should include both social and ecological components, and be linked to governance, management, or policy issues. Through an extended search for papers on fish trade and references within the first set of papers, six additional publications were found. For further details on the review procedure, see the **Supplementary Material**.

The published models were used to understand a number of different phenomena, such as increased harvests emerging from cooperative forms of management (Gutierrez et al., 2017); factors facilitating the emergence of self-governance (Wilson et al., 2007); increased harvests in relation to the placement of marine protected areas (Rudd et al., 2003); the emergence of either fishing cooperatives or patron–client relationships as the

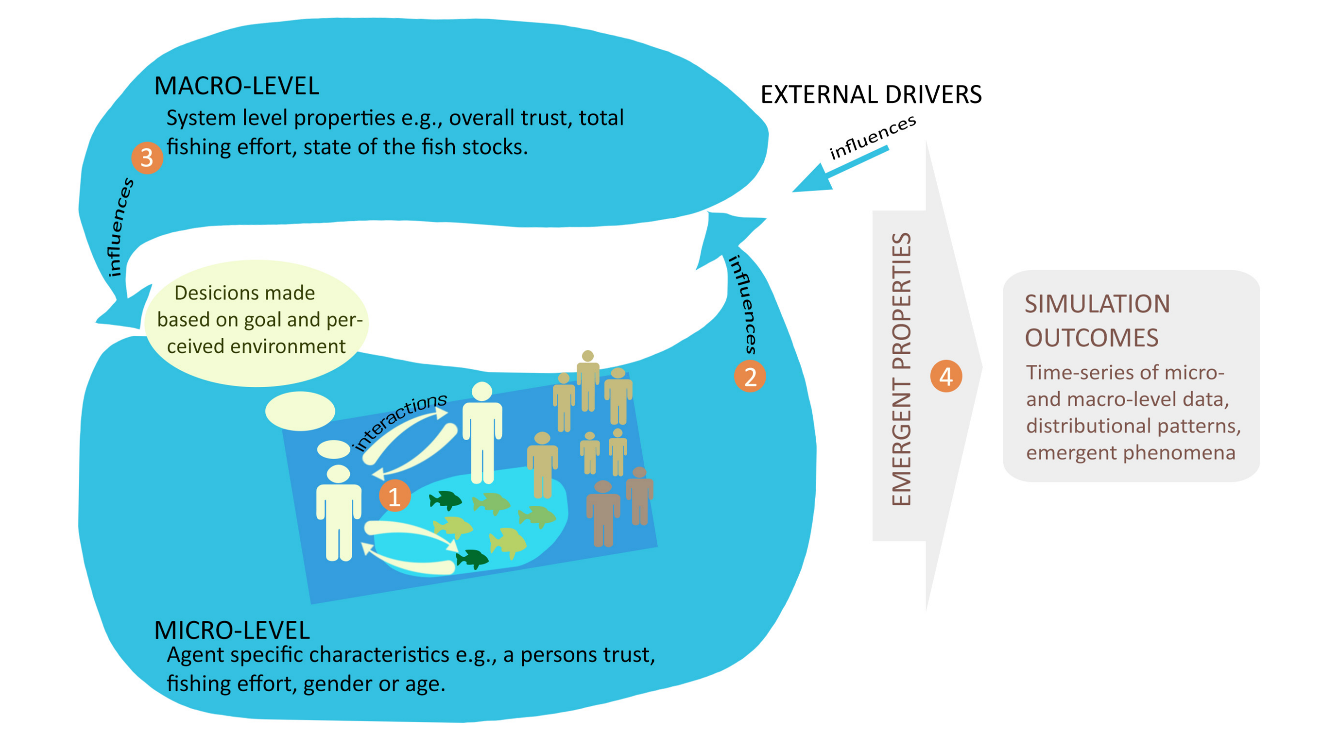

FIGURE 1 | Conceptual description of an ABM. In a co-evolving process, actions at the micro-level change the aggregated variables at the macro-level, which in turn influences actions and interactions at the micro-level. This co-evolutionary process continues until the end of the simulation. (1) Agents perceive their environment, including other agents, and act according to their goal. (2) The micro-level dynamics influences the macro-level, possibly influenced by exogenous drivers. (3) The state of the macro-level variables in turn influences the behavior of the agents at the micro-level. (4) During and after the simulation distributional patterns within micro-level variables may be observed and measured, and emergent properties at the macro-level.

dominant form of self-governance (Lindkvist et al., 2017); the emergence of balanced harvesting (Plank et al., 2017); long-term effects of tourism and urbanization on coral reef health and fisheries (Perez et al., 2009; Melbourne-Thomas et al., 2011); and causes of overfishing and environmental (reef) degradation (Bousquet et al., 1993, 1994a,b; Worrapimphong et al., 2010; Forrester et al., 2014). In all papers, a single fishery or fishing community was modeled, with a notable exception of Perez et al. (2009) and Melbourne-Thomas et al. (2011) who move beyond a single community to study four geographical areas of economic development that depended on one shared coral reef and several shared fisheries.

We identified three different purposes of the ABMs uncovered in our review: (1) to *understand* how some SSF phenomena emerge, and to explain the mechanisms (i.e., factors and processes) that were effective (Wilson et al., 2007; Lindkvist et al., 2017; Plank et al., 2017); (2) as *policy assessment tools* to identify and explain the mechanisms behind why some policy, or way of organizing the fishery, may be better than another (Rudd et al., 2003; Melbourne-Thomas et al., 2011; Gutierrez et al., 2017); and (3) as *a participatory tool* to co-produce knowledge about a fishery with stakeholders, as pioneered by the Companion Modeling team[2] (Bousquet et al., 1993, 1994a,b; Worrapimphong et al., 2010). Perez et al. (2009) and Forrester et al. (2014) also developed their ABM through participatory approaches but did not use role playing games.

The flexibility of ABM creates a diversity of possible ABM applications on how to solve some of the most pressing challenges of studying and managing SSF. **Figure 2** draws out some of the key diversities along four axes and situates the reviewed publications. We find that half of the studies aimed to understand a phenomenon or problem and half to evaluating a policy or management plan (**Figure 2A**). Models more often had an ecological, or social–ecological focus than a purely social focus (**Figure 2B**). The models tended to build on detailed empirical data rather than on theories (**Figure 2C**). Finally, models more commonly had a participatory focus than a purely academic focus (**Figure 2D**). Specific features of the models' agents, agent behaviors and interactions, linkages to globalized drivers, and how the models deal with data input and output, are further described in the **Supplementary Material**. Next, we draw on the strengths of ABM and its applicability to SSF challenges.

Agent-Based Modeling for Addressing Small-Scale Fisheries Challenges

Small-scale fisheries management is exposed to many challenges that are rooted in their complexity and data scarcity characteristics, as evidenced by the models from our review. We outline three challenges for SSF management that ABM

[2]https://www.commod.org

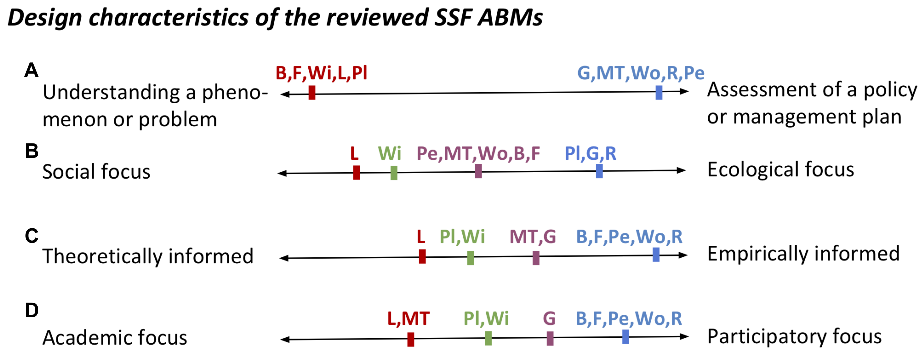

FIGURE 2 | Key differences in ABM purpose and development issues for different SSF models. The colored labels represent the SSF models, which are subjectively placed along four gradients based on the results from the review. The gradients represent: **(A)** a stronger model purpose of understanding (participatory or not) versus assessment; **(B)** model design has a more social focus versus ecological focus (midpoint indicates equal social and ecological focus); **(C)** the model is more strongly based on theories versus data; and **(D)** the development process of the model involves mostly researchers versus a strong participatory focus. B, Bousquet et al. (1993; 1994a; 1994b); F, Forrester et al. (2014); G, Gutierrez et al. (2017); L, Lindkvist et al. (2017); MT, Melbourne-Thomas et al. (2011); Pl, Plank et al. (2017); Pe, Perez et al. (2009); R, Rudd et al. (2003); Wi, Wilson et al. (2007); and Wo, Worrapimphong et al. (2010).

could help to address: (1) improve the way collective action and heterogeneity in human behavior is incorporated in research and management; (2) develop policies that are sensitive to local contexts while also accounting for regional and global contexts; (3) tackle data paucity and uncertainty. We reflect on how ABM could contribute to solving these three challenges and illustrate this with the SSF models from our review.

Challenge 1: Collective Action and Human Behavior

A key challenge for the sustainable governance and management of SSF revolves around collective action, cooperation, and human behavior (Townsend et al., 2008; Gutierrez et al., 2011; Basurto et al., 2013; Ovando et al., 2013). Locally this can occur through self-governance and co-management initiatives, but at broader scales by linking to other organizations at regional, national, and global levels, as well as by connecting to neighboring fishing communities to gain support for locally managed resources (Marín et al., 2012; Finkbeiner and Basurto, 2015; Oliver et al., 2015). Such initiatives require social cohesion and trust between actors (Ostrom, 1990; Gutierrez et al., 2011; Basurto et al., 2013; Ovando et al., 2013; Kosamu, 2015; Oliver et al., 2015).

Agent-based modeling can represent collective action by: (1) simulating how self-organization can emerge; (2) simulating how trust or loyalty increases or decreases within a group; (3) simulating how fishers harvest a resource based on their self-organization and the levels of trust; (4) accounting for the spatial distribution of resources and fishers movements; and (5) modeling interactions such as information exchange between fishing organizations.

The model by Lindkvist et al. (2017) was developed to investigate under which conditions cooperative and non-cooperative forms of self-governance may establish and persist in a hypothetical fishing community in Northwest Mexico. Their ABM was based on in-depth fieldwork, surveys with fishers, interviews with fish buyers, and a fish buyers' logbook, to capture key hypotheses of fishers' day-to-day fishing and trading. Model results indicated that high diversity in fishers' reliability, and low initial trust between members of the cooperative, makes the establishment of cooperatives difficult. Their results also showed that once cooperatives establish, they cope better with seasonal variability in fish resources and provide long-term security for fishers compared to non-cooperative forms of self-governance.

Wilson et al. (2007) designed an ABM to understand the emergence of self-governance in the lobster gangs of Maine, United States. Results show that in the Maine lobster fishery biological and technological circumstances combined with individual self-interest created conditions favorable for collective action. The model describes the way collective action emerges from the adaptive behavior of competing fishers. The model simulates the dynamic adaptation (learning) of fishers interacting in a complex, changing (social) environment, and provides an example of analyzing micro-level processes that emerged into social–ecological fishery patterns at the macro-level.

Gutierrez et al. (2017) developed a spatially explicit ABM for the sea urchin fishery off San Diego, CA, United States. They assessed the benefits of cooperative harvesting by incorporating spatial and temporal variation in fishery yields. They found that the marketability of sea urchin roe depended on gonad (reproductive organs) yield and quality, which in turn depended on the spatial and temporal conditions of associated kelp beds. However, competition among divers within a non-cooperative system created a "race for shellfish" preventing higher gonad yield per unit of effort. Model results showed that, for the most cooperative scenario where information sharing among divers was greatest and harvest was coordinated, sea urchin catches were at least 10% higher and gonad yield 35% higher than in the non-cooperative scenario. As such, information sharing and organized harvesting typical of well-functioning cooperatives led to the more sustainable use of local resources.

Plank et al. (2017) investigated the consequences of allowing a fixed number of fishers in a SSF to choose the size of the fish they aim to catch. They examine this from a game-theoretic perspective and test their predictions using an agent-based model for fishers' decisions coupled with a size-spectrum model for the dynamics of a single fish species. They show that small-scale gillnet fishers, operating without size-based regulations, end up catching small and large fish in proportion to their productivity, in other words balanced harvesting. This is significant because it shows that, far from being unachievable, balanced harvesting can emerge without external intervention under some circumstances. Controls are needed to prevent overfishing, but minimum size regulations alone are not sufficient to achieve this. Instead, size regulations can reduce sustainable yields by confining fishing to a relatively unproductive part of the size-spectrum.

The reviewed papers thus have been used to study the emergence of collective action and the establishment and persistence of cooperative groups by Wilson et al. (2007) and Lindkvist et al. (2017), respectively; Gutierrez et al. (2017) demonstrated the benefits of cooperative harvesting strategies while Plank et al. (2017) model self-interested non-cooperative agents that obtain the goal of balanced harvesting. All models from these publications were based on individual fishers and their decision-making. However, none of the models studied the different levels and scales that SSF are a part of, such as the implications of connecting horizontally across communities or connecting vertically up to other organizations at regional, national, or international level.

Challenge 2: Developing Policies That Are Sensitive to Local Contexts While Accounting for Regional and Global Dynamics

Fisheries policies come in different forms, each with different benefits and constraints, and it is unlikely there is a one-size fits-all solution (Degnbol and McCay, 2007; Ostrom, 2007; Berkes, 2012; Chaigneau and Brown, 2016). On the one hand, an effective policy has to account for the local context of a fishing community and for the heterogeneity in fisher characteristics, perceptions, and behavior (Mwaipopo et al., 2010; Bennett and Dearden, 2014; Gelcich and O'Keeffe, 2016; Singh et al., 2018; Wosu, 2019). At the same time, SSF are embedded within, and interact with, larger scales such as regional and national institutions, and global markets (Crona et al., 2015; Pace and Gephart, 2017; Bennett and Basurto, 2018). An effective policy should address a specific governance problem while considering the complexity and interactions within the broader fishery system. For instance, to obtain sustainable social–ecological outcomes across geographical scales for one fishery, a policy needs to account for any interdependencies with other fisheries, both in terms of potential food web interactions, and in terms of displacements of fishing effort when fishers enter or exit a fishery area (Gaines et al., 2010; Berkes, 2012).

Agent-based models can be used to represent and thus study the role of context and scales over time because they can reflect heterogeneous agents; history, culture, and individual differences between fishers (such as fishers' perceptions and typical behaviors). ABMs are, however, also able to represent interactions beyond a local SSF with other distal interactions such as global market dynamics or climate change. This may be helpful in the process of integrating knowledge from different stakeholders, experts, and researchers (Weber et al., 2019).

Several ABMs we reviewed were aimed at assisting in the design process of policy development and a governance plan while accounting for the cross-scale and embedded nature of the socio-ecological system (Bousquet et al., 1993, 1994a,b; Perez et al., 2009; Worrapimphong et al., 2010; Melbourne-Thomas et al., 2011; Forrester et al., 2014). The model developed by Perez et al. (2009) is an exemplary ABM that combines knowledge from different stakeholders and researchers. The focus of their study was on the interactions between tourism, urbanization, fishing, and coral reef health in four fishing communities that shared the same reefs and fisheries in the Quintana Roo region, Mexico. Model results revealed an interesting causality of increasing tourism and urbanization leading to degraded reefs, concomitantly causing a decrease in tourism, which in turn forced tourism workers to turn to (illegal) fishing, causing a sequential collapse of three fisheries. The model was able to re-produce time series and projected future scenarios. However, the authors claimed that the strength of the model lay in its capacity to integrate social, economic, and ecological components into a coherent framework that can inform multi-level governance issues and public policy. Melbourne-Thomas et al. (2011) extended Perez et al.'s (2009) model by coupling it with a biophysical model of the Quintana Roo region. A preliminary evaluation of the coupled model system gave reasonable predictions for fisheries and ecological variables and indicated that the model could be used to examine scenarios for future social–ecological change in Quintana Roo.

The study in the upper gulf of Thailand by Worrapimphong et al. (2010) addressed the relationships between increasing tourism in the coastal wetlands and the increasing pressure on locally important razor clam populations. The purpose of this modeling study was to develop a management plan and to engage the different stakeholders in collective discussions. This was achieved through combining an ABM with role-playing games. The games promoted alternative clam management plans, such as establishment and rotation of zones closed for harvesting, and quota systems. These plans were more deeply investigated with the ABM to simulate different scenarios (reserve, quota, and combinations of reserve and quota), which enabled better-informed discussions between different stakeholders. As a result of the work, stakeholders were able to present a sustainable management plan to regional policy-makers.

Forrester et al. (2014) depart from the assumption that complex social–ecological systems are not amenable to simple mathematical modeling and posit that solving sustainability challenges calls for an integrated approach. Based on empirical knowledge of local stakeholders and experts, they mapped conceptions of beach management units in Kenya. Two models were developed: one local-level ABM; and one overarching multiple-entity conceptual model of the system which provided a general landscape within which the structurally realistic ABM could exist and be understood. The two representations together contributed to understanding the links between the local system and other levels of decision-making. The authors stated that this model combination helped develop easily accessible tools for stakeholders, by representing the system both in a bottom-up the (the ABM) and top-down (the conceptual model) manner and by capturing and conceptualizing ecosystem dynamics and processes, and the broader system it is embedded within.

These models represent the interdisciplinary, multi-sector, and multi-scale approach called for by many SSF researchers (McClanahan et al., 2009; Kittinger et al., 2013; Bennett and Dearden, 2014; Crona et al., 2015; Purcell and Pomeroy, 2015; Chaigneau and Brown, 2016; Gelcich and O'Keeffe, 2016; Basurto et al., 2017). Whether these modeling projects have been successful in improving governance and management in SSFs is yet to be determined.

Challenge 3: Dealing With Data Paucity and Uncertainty

In most SSFs data on catches, stock status and environmental, economic, and social attributes are often unavailable (Kalikoski and Franz, 2014; Jentoft and Chuenpagdee, 2015; Johnson et al., 2017; Giron-Nava et al., 2018; Agapito et al., 2019). Furthermore, the data that are available are often misreported or patchy (The World Bank, 2012; Cisneros-Montemayor et al., 2013). This generates a gap in the possibilities to understand how specific policies and changes in fisher behavior might affect a fishery from an ecological, social, or economic perspective (Fulton et al., 2011). In light of this information paucity it is difficult to know what empirical data are most useful to inform management (FAO, 2017; Jentoft, 2017). This challenge becomes even larger given the need to tailor policies to the local context and to account for external drivers. As such, information on other system variables such as how fishers respond to particular policies or incentives, how fishers are organized, levels of trust in a fishery and market dynamics may be more important for the design and implementation of policies (Basurto et al., 2013; Crona et al., 2015; Finkbeiner et al., 2017; Battista et al., 2018).

The challenge of data paucity in design and analysis concerns every modeling approach including ABM. Data enable models to be grounded in reality, but *post hoc* data also provide a means for testing the link between model results and the real world. A lack or absence of data can in some cases prevent model development in the first place. However, even in data-poor situations ABM can make use of qualitative data from experts or anthropological studies (Ghorbani et al., 2015), thus contributing toward understanding complex issues by testing and comparing different theories, explanations, and important variables in a "virtual" model-based laboratory. ABM can also inform priorities for future data collection (Worrapimphong et al., 2010; Cooper and Jarre, 2017; Lindkvist et al., 2017; Burgess et al., 2018). For example, testing how sustainable resource use, profits, and satisfaction are affected by different assumptions for fishers' behavior can give insight into priorities for data collection (Burgess et al., 2018). In the case of the aforementioned razor clam fishery in the gulf of Thailand (Worrapimphong et al., 2010) there was a lack of data for the population parameters (natural mortality rate, carrying capacity, and number of recruits per female), which led to uncertainties in the outcomes of different management options. This knowledge gap indicated which parameters needed to be further studied, but also that some management options, such as quota schemes, could better account for this uncertainty and still result in sustainable harvests. Similarly, in the absence of location choice data, simulating fisher movements as a response to different drivers such as price, increased catches, or crowding could help to understand the dynamics of fisheries exploitation (e.g., Carpenter and Brock, 2004; Soulié and Thébaud, 2006; Barbier and Watson, 2016).

The complex adaptive systems' nature of SSFs means that incorporating additional data cannot always reduce uncertainty. While more data will certainly enhance understanding, key structural uncertainties about processes and interactions in SSF and fisher responses to different policies are likely to remain. Policy-making thus needs to manage this uncertainty through the design of adaptive and reflexive processes (Dunn et al., 2016). ABM can help assess the possible range of expected outcomes, given uncertainty about human behavior (Fulton et al., 2011), and to test how robust management strategies are based on key uncertainties (van Putten et al., 2012).

OPPORTUNITIES AND LIMITATIONS

Agent-based modeling is a tool that can deal with the complexity of SSFs by assessing consequences of interactions and assumptions on how these interactions occur. Ironically this also creates complex challenges for the model development process by requiring decisions on what parameters and processes to include in the model and which to leave out. In the analysis phase, questions may arise around what exact variables are driving the results, and more general questions such as: "will the model output change if we increase the number of agents?," or "if we simulate a longer time period will results change?." Consequently, time, resources, and active collaboration between those involved in designing, developing, and interpreting an ABM are key to successful outcomes of the modeling project.

The complexity, and the extent to which SSF are embedded into a larger-scale contexts, mean that a thorough investigation of policy solutions to a place-based problem will not be simple. The cultural, socio-economic, and ecological characteristics of a local SSF fishery or fishing community, and their wider context must be considered. While an agent-based model can be developed to incorporate these dimensions, the type of nuanced understanding that an ABM can provide may not be the policy-maker's priority because they may need concrete results with minimal uncertainty, and solutions that fit within the current policy schemes (Taylor et al., 2016; Allison et al., 2018). In these situations, models can instead be used to test interdependencies, investigate trade-offs among policies, while simultaneously including important heterogeneity among fisheries actors.

Like any modeling approach, ABM suffers from misconceptions and critique, such as being costly or opaque. However, in most cases there are two sides of the argument. ABM can be costly in terms of time and expertise, the cost may be higher if the purpose is predict outcomes of a policy intervention in a case-specific situation, but can be lower if the purpose is to understand a general phenomenon. Cost can also be higher if prior models do not exist, or if models need to be built from scratch for different scales or situations. This cost could be reduced if based on existing models, however, as our review showed, few models exist thus it may be difficult to find a model to build from. Although The Network for Computational Modeling in Social and Ecological Sciences[3] provides a library of ABMs of social–ecological systems that are open source and reusable, few fisheries models have been published there. At the code hosting platform GitHub[4] the agent-based model POSEIDON is freely available for fisheries research (Bailey et al., 2019), other examples include the DISPLACE model for spatial fishing planning and effort displacement (Bastardie et al., 2013), and more case-specific models (e.g., Yu et al., 2009; Cenek and Franklin, 2017). However, using such extant models still requires coding and there is no standard software or module library for fisheries ABMs to date. In the future, the availability of comprehensive libraries of (re)useable models could help to make ABM available to a broader user community in SSF.

Rigorous conventions for documenting ABMs (e.g., ODD by Grimm et al., 2010; and ODD + D by Müller et al., 2013) have been adopted by large parts of the ABM community which helps increase the accessibility and transparency of ABMs thus facilitating sharing and adaptation of parts of existing models. Ultimately, further experimentation with ABM in SSF, if supported by rigorous documentation and open-source sharing according to standardized protocols, may coalesce into an accessible resource that would facilitate adaptation and adoption of existing code, or even a common ABM framework for addressing typical, regularly encountered SSF questions. Inspiration could be taken from other modeling frameworks such as Ecopath with Ecosim (Villasante et al., 2016), where a common software, model, data sharing framework, and active community of practice and training networks have facilitated applications in diverse fisheries contexts around the world. ABM could also be integrated with such fisheries modeling approaches to move toward integrating more social dynamics and agent-based features into ecologically based models, which could also assist in reducing the cost and broadening the use of ABMs.

In social–ecological systems research ABMs are becoming more common and are generally regarded as a useful scientific tool, but they still suffer from critique for inconsistent documentation and testing, as well as lack of transparency in communicating results (Schulze et al., 2017). Skepticism toward ABM may partly be driven by academic expertise and to a certain extent territorialism, but there is rightful criticism that ABM requires better documentation, testing, and communication to support understanding (Waldherr and Wijermans, 2013). ABMs will only be useful for improving SSF governance and management if they are developed following good modeling practice. This entails a better understanding among fisheries scientists and managers about why, when, and how to use ABM in SSF (see **Box 2** for a summary).

[3]https://www.comses.net/

[4]https://github.com/

BOX 2 | Summary points.

ABMs can improve research, management, and governance of SSF in a globalized context while taking account of the complex nature of individual entities and data paucity because:

- One can model interactions, processes, and mechanisms at the micro-level to understand and explain emergent outcomes at the macro-level.
- They do not always rely on quantitative data. Depending on the purpose of the model it may be desirable to substantiate model design and validate model outcomes with expert knowledge and qualitative assessments and/or theories.
- It is possible to integrate different types of data, knowledge, and theories in a realistic setting which makes it easier to integrate knowledge from stakeholders, experts, and scientists across sectors and disciplines.
- The development phase can reveal which agents and interactions are important to understand the dynamics of a system. They can also point to which variables and processes require further investigation, especially with regards to individual decision-making, and give rise to new questions that can be explored empirically or through modeling.
- They allow the exploration of how changes can affect actors or the environment. For example, changes in micro-level distributional patterns such as income or catch, or in macro-level variables such as the biomass of fish, or biophysical conditions.

What is ABM less useful for?

- Problems that are simple enough that an ABM becomes redundant.
- Phenomena where the agents, their decisions, and situations do not differ, i.e., heterogeneity is not key in emergent behavior, in which case computationally cheaper models should be considered.

What are points of caution?

- Depending on the purpose of the study, the model development process may be too time consuming and costly.
- Balancing the complexity of building the model with the interpretability of the outcomes is difficult.
- Extensive documentation of agents, interactions and mechanisms through relevant protocols need to be utilized in order to avoid making the model opaque to others.

NB. Some of the summary points raised here may also apply to other modeling approaches.

FRONTIERS FOR AGENT-BASED MODELING IN SMALL-SCALE FISHERIES

Models are models and can never replace empirical studies, because the questions that models can answer are often different from those that empirical studies address (Levin et al., 2012; Schlüter et al., 2012). However, often multi-method approaches that combine modeling and empirical work can reveal insights and understanding that cannot be gained by a single method. With this complementarity in mind, we elaborate on the empirically defined research questions and areas of research where the features of ABMs could be pertinent in the context of SSF.

All standard fisheries models recognize the importance of aggregate fishing effort, but ABMs offer the potential to understand the micro-level processes that generate this effort. An understanding of total fishing effort as an emergent outcome from individual fishers' characteristics and decisions offers more realistic policy levers to influence effort; not by unenforceable attempts to command and control fishing effort, but by influencing the context and outcome of individual interactions that ultimately determine the total effort. An ABM focuses on decision-making processes of fisheries actors and their embeddedness in social and ecological contexts. Therefore, new empirical questions related to the behavior of fishers can emerge in the modeling development phase (Cooper and Jarre, 2017; Lindkvist et al., 2017; Schlüter et al., 2019). In a similar way, ABM is also well suited to explore how individuals may react differently to new interventions (Epstein, 2008). An illustrative example of how this can be done is suggested by Battista et al. (2018), who present a step-wise approach of how new interventions at the individual level can be introduced in a fishery, but do not recognize the utility of ABM in their approach. In this case, ABM offers an additional step of virtual experimentation, before the proposed step of experimentally testing interventions in laboratory or field experiments. ABM thus can help assess, understand, and explain SSF outcomes in a way that accounts for heterogeneity in behavior, the characteristics of fisheries actors, and the diversity of the ecosystem, to do justice to the complex nature of SSF. This is something that no other modeling approach can do.

Small-scale fisheries are inherently multi-level with important interactions across geographic or organizational scales such as trade or climate change impacts. ABMs are a suitable method for the study of cross-scale interactions, which are difficult to represent using simpler mathematical models. However, none of the models we reviewed addressed interactions beyond the local or regional level such as global market dynamics. The potential for ABM to explore interactions with regional or global processes thus remains an important frontier for future exploration. In fact, none of the ABMs include trade dynamics at any scale yet it is one of the most challenging issues faced by SSF (Béné et al., 2010; Crona et al., 2015; Pace and Gephart, 2017). Classical ABMs on trade by Epstein and Axtell (1996), Kirman and Vriend (2001), and Tesfatsion (1997) provide insights into heterogeneous trading actors and factors that mediate trade relationships such as loyalty, that influence trade patterns and price dynamics. A possible frontier is to couple or reuse parts of these trade models in fisheries contexts to help understand how trade at one or multiple scales affects SSF.

Another topical domain where ABM has a large potential is the mobility and migration of fishers, which is a well recognized adaptation strategy in SSF around the world (FAO, 2017). Movements of fishers can be connected to international markets through teleconnections, which is a known driver of sequential overexploitation in some fisheries (Berkes et al., 2006; Eriksson et al., 2015). However, the conditions that trigger or constrain fishers' movements has to date been neglected (Swartz et al., 2010; Anderson et al., 2011). ABMs are a viable choice to analyze exploitation patterns and the diverse mechanisms driving these from the bottom-up, even in situations in which there is a lack of quantitative data on the movement patterns of fishers. Instead, expert knowledge or data about what drives fishers to move can be modeled to understand the emergent movement patterns of individual fishers. Here, the ontological realism of ABMs is an advantage because it is easier to relate characteristics and behaviors of agents to real world experiences than determining a mathematical functional form of a variable relationship. Carpenter and Brock (2004) have studied fisher mobility between lakes, while Soulié and Thébaud (2006) modeled mobility in a theoretical, highly regulated fishery; however, our review has not identified any studies on mobility or migration in coastal SSF.

Finally, the challenge of dealing with data scarcity and uncertainty opens up a novel pathway for using ABMs in SSF. As Cooper and Jarre (2017) highlight, ABMs may provide novel grounds for identifying and understanding what social and economic data are useful to quantitatively collect over time or to further investigate qualitatively.

We conclude that the ability of ABM's to address SSF as complex adaptive systems, taking account of diversity and heterogeneity of actors and interactions within and across scales, can improve our understanding of SSF dynamics, and inform policy and management actions. ABMs can serve as boundary objects and virtual laboratories to integrate different knowledge sources or problem perceptions and test assumptions and possible explanations of phenomena in a collaborative or participatory process, with the aim of exploring their consequences for system outcomes or unraveling complex underlying causes. The need to better understand complex causation and causal mechanisms in the governance of social–ecological systems has recently been highlighted (Biesbroek et al., 2017; Ferraro et al., 2019; Schlüter et al., 2019). While policy assessment in virtual ABM laboratories can help assess the uncertainty associated with a policy or management intervention, using ABM to scrutinize possible explanations of SSF phenomena can help build understanding and theory for enhanced governance (Schlüter et al., 2019). In summary, ABM is a promising approach to develop complexity-based analyses and understand the governance of the dynamics of SSF, particularly when applied in larger processes involving multiple stakeholders. While such processes can be time intensive, they can do justice to the complex and dynamic nature of SSF, which, if ignored can lead to unintended policy outcomes.

AUTHOR CONTRIBUTIONS

AJ, EL, and BG-M provided the original idea. EL, AJ, BG-M, XB, TD, NW, MS, AG-N, and IP designed the manuscript outline and content, and reviewed the manuscript. EL performed the review and wrote the original manuscript. EL, NW, TD, and BG-M prepared the conceptual design of the visualizations. EL, NW, BG-M, IP, TD, MS, and AG-N edited parts of the manuscript.

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