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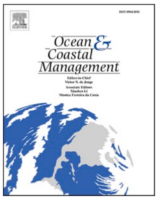

Evaluating ecosystem impacts of data-limited artisanal fisheries through ecosystem modelling and traditional fisher knowledge

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ABSTRACT

Ecosystem approaches to fisheries management (EAF) are increasingly relevant for intergovernmental fisheries policies, national management plans, and seafood certification guidelines. To aid in integration of EAF in tropical artisanal fisheries, this study evaluates the potential ecosystem impacts of four distinct fisheries (kelp forest, sandy shore, pelagic, and reef ecosystems) in Mexico, using quantitative trophic models and a comparable network developed using fishers' traditional knowledge. Notably, the fishers' model was actually more complex than science-based models and could be a highly useful baseline for subsequent collaborative efforts for ecosystembased management. At current fishing levels, these fisheries are not expected to have significant ecosystem impacts, though we identify species that could be potentially impacted if fishing effort were to considerably increase and that should be monitored. Explicitly considering ecological interactions—whether or not this can be fully integrated into reference points—in co-managed fisheries can help prioritize monitoring and management measures, supporting ecologically sustainable fisheries and the social and economic objectives of artisanal fishers.

1. Introduction

An ecosystem approach to fisheries management (EAF) involves explicit consideration of ecological, environmental, and social factors linked to the use of marine resources (Slocombe, 1993; Hilborn, 2011). Despite generally lower management capacity in developing nations or regions, particularly for artisanal fisheries that often catch multiple species and have limited quantitative data, EAF can nonetheless be implemented within adaptive frameworks. This is well-expressed by Murawski (2007), who noted that, despite information gaps, "there usually is information to at least identify qualitatively the likely interactions among species and sectors and the directionality of particular human activities on biota and their social and economic impacts. Adaptive management approaches incorporate new information as it becomes available, and [identify] priorities for science to reduce uncertainty and improve understanding of the effects of policy choices." Here, we identify and evaluate potential ecosystem impacts for data-limited artisanal fisheries, using quantitative trophic models from peer-reviewed literature (built using Ecopath with Ecosim, EwE) and built from fishers' ecological knowledge. This type of analysis would ideally inform structured decision-making approaches and help prioritize targeted research in support of co-management initiatives to achieve sustainable and socially equitable fisheries (Espinosa-Romero et al., 2011).

Artisanal (or, small-scale) fisheries are by far the largest marine industry in terms of employment, with 100–260 million people around the world participating in capturing or processing of seafood (World Bank, 2012; Teh and Sumaila, 2013). In developing nations, over half of total marine fisheries production is landed by the artisanal sector and, importantly, virtually all of this catch is for human consumption (World Bank, 2012), unlike industrial fisheries where a significant portion of high-quality catch is used for reduction and animal feeds (Cashion et al., 2017). Artisanal fisheries are thus vital to social-ecological systems along most of the world's coasts (Allison et al., 2012), including in

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remote areas and in Indigenous communities that have been historically marginalized (Cisneros-Montemayor et al., 2016). Despite their important contributions to global food security, national economies, and local livelihoods, artisanal fisheries are often difficult to manage and face challenges including inequitable power dynamics and access to resources (Finkbeiner et al., 2017), inappropriate legal, management and data collection frameworks (Salas et al., 2007; Allison et al., 2012), and overfishing due to technological change and increased fishing capacity (Selgrath et al., 2018).

It is important to underscore the fact that limited data in artisanal fisheries—often regarded as one of the biggest challenges to their management—is often not the problem *per se*, but rather is a result of underlying weak local and institutional governance. This includes a limited capacity to effectively integrate community needs, objectives, perspectives, and knowledge into management policies, implement those policies, and monitor outcomes (Cisneros-Montemayor, 2018). In these cases, data-limited assessment methods can provide valuable insights into fishery performance and potentially beneficial policies (Carruthers et al., 2011; Kleisner et al., 2013), but underlying factors leading to overfishing and unsustainable practices by artisanal fisheries need to be understood and addressed in place in order to increase benefits and identify priority objectives and focal research areas (Espinoza-Tenorio et al., 2011; Giron-Nava et al., 2018; Cisneros-Montemayor et al., 2018).

In this context, Local Ecological Knowledge (LEK) can be a highly valuable source of nuanced and locally specific information, not only on social contexts that transcend traditional fisheries management (Finkbeiner et al., 2017), but on ecological dynamics and observations that can complement, challenge, and guide scientific research (Beaudreau and Levin, 2014; Singh et al., 2017; Ainsworth, 2011). This is particularly important when there are indications of serious risks to continued artisanal fisheries due to overfishing, climate, or economic changes which require responsive and adaptive co-management that can respond more quickly than normal research timelines (Murray et al., 2009). Most artisanal fisheries in the Gulf of California (as is often the case across the world) take place in remote or isolated sites, where access for management and conservation bodies is limited mainly due to insufficient personnel and resources (Salas et al., 2007; Ainsworth, 2011). In addition, artisanal fisheries are inherently complex and dynamic due to seasonality of local resources (Moreno et al., 2017); consequently, maintaining formal catch records is often a challenging task and LEK can become essential (Salas et al., 2007; Silvano and Valbo-Jørgensen, 2008).

Notwithstanding the challenges above, there is an increasing number of artisanal fisheries around the world with important advances in governance capacity, including various forms of co-management and strengthened access rights (De la Cruz-González et al., 2018; McCay et al., 2014; Pérez-Ramírez et al., 2012; Basurto et al. 2012). At the international level, the importance of the sector was highlighted through the publication of the FAO Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries (FAO, 2015), that has further bolstered efforts worldwide to assert the importance and rights of local artisanal fisheries and re-align management frameworks with local contexts (Jentoft et al., 2017; Cisneros-Montemayor et al., 2018). For these cases, data and scientific analyses can facilitate an important next step towards achieving and increasing sustainable benefits. An EAF, given its wider ecological and social purview as noted above, is an integral part of this shift to improved management.

In that context, programs such as fishery improvement projects (FIPs) are a relatively recent type of support pathway from private firms (mainly seafood certification bodies and civil society organizations) to fishing communities or firms to adopt the EAF, achieve sustainability and, ultimately, increase economic and social benefits (see Cannon et al., 2018, and references therein). The close link between these types of programs and formal seafood certification standards normally requires that artisanal fishers meet and report on specific benchmarks including evaluating potential ecosystem impacts. A key criticism of such approaches, however, is that progress evaluation of complex themes may be reduced to superficial box-ticking exercises with limited scientific data and advice (Christian et al., 2013). In any case, considering ecosystem impacts from artisanal fisheries—a complex theme—requires an approach that is formal and scientifically sound in order to be meaningful, yet flexible and applicable to fisheries with limited resources and potentially complicated socio-ecological dynamics (Fernandez-Rivera Melo et al., 2018).

This study applies a multi-level framework for evaluating ecosystem-wide impacts from artisanal fisheries. The approach considers general mechanisms of impact (bycatch, trophic relationships, habitat), and focuses on using a flexible approach to fit a range of ecological and fishery types given available data. Ecopath with Ecosim (EwE), the most accessible and widely used marine trophic modelling platform, is used here in the specific context of providing information on potential ecosystem impacts (a task which the platform is indeed designed to perform). When no quantitative data were available, a comparable trophic network was constructed based directly on fisher's empirical knowledge.

An overarching research question, in addition to evaluating potential ecosystem impacts from the case study artisanal fisheries, is whether fisher knowledge can be used to produce quantitative models comparable with scientific ones and therefore represent a first baseline to be used in official management plans. Our case studies include four fisheries with different ecological characteristics (kelp forest, sandy shore, pelagic, and reef ecosystems) and data availabilities in a developing nation, with a focus on providing transparent advice to community and co-management efforts to improve fisheries sustainability.

2. Methods

This study outlines an approach for anticipating and quantitively (using scientific and/or traditional fisher knowledge) evaluating the most likely and potentially significant ecosystem effects of artisanal fisheries within a tropical developing region. This section presents the approach to anticipating impacts and obtaining information to evaluate their potential (*Evaluating direct and indirect impacts*), a method for estimating quantitative impacts when data is available to do so, and the case studies to which these methods were applied. We are keenly aware of the usefulness of fully qualitative fisheries assessment methods (e.g. Fletcher, 2005; Pascoe et al., 2009), yet our aim was to offer a way to assess fisheries using a well-established quantitative platform as well as qualitative empirical knowledge.

2.1. Evaluating direct and indirect impacts

We focus specifically on the four types of impacts (direct and indirect) outlined in Fig. 1. Direct impacts include fishing mortality rate of target and non-target species; these impacts are the most commonly studied and estimable and are indeed the focus of most management actions. Another form of direct impact is through the degradation or modification of habitat, which leads to decreased stock or ecosystem production potential. The main form of indirect impact that we focus on in this study is that occurring through trophic relationships between target and bycatch species and the rest of the ecosystem. This is addressed through the use of ecosystem models as detailed below. A second type of indirect impact is a reduction in foraging efficiency due to fisheries effects; this entails a more complex set of interactions for which generally there is less available data. Therefore, here we include qualitative information derived from observations for the case studies considered.

Evaluating direct and indirect ecosystem impacts (e.g., Fig. 1) from a given fishery depends on the availability of information on catch structure and size, gear types (for direct impacts), and the underlying structure of the ecosystem (for indirect impacts). Understanding the first

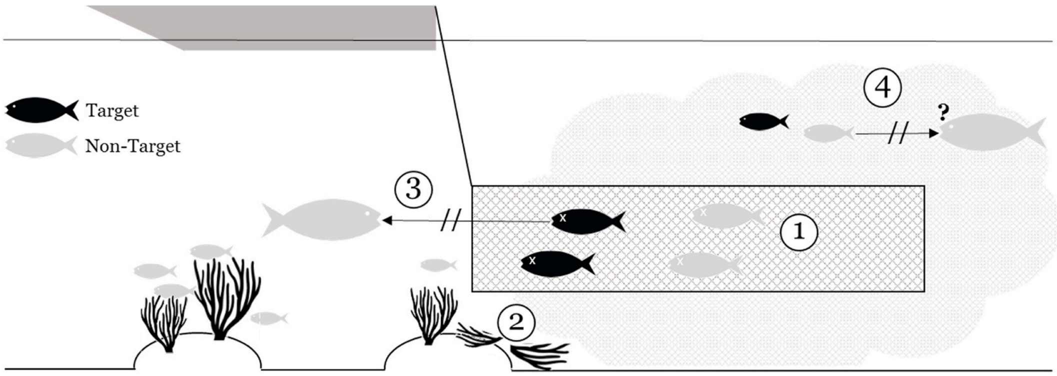

Fig. 1. Typology of ecosystem impacts from targeted fisheries considered in this study. Direct impacts include 1) removal of target and non-target species and 2) habitat alteration leading to decreased productivity. Indirect impacts include 3) reduced prey availability for non-target species through trophic linkages and 4) reduction in foraging efficiency of non-target species through behavioral or habitat-linked effects (for example, increased turbidity, ambient noise, or changes in relative abundances and subsequent behavior that hinder predators' ability to find prey).

set of impacts is relatively straightforward as it depends on knowing what species are caught in the fishery and, if possible, how much. When this information is not available from monitoring programs (as is common in global fisheries; Pauly and Zeller, 2016) it can be obtained from fishers (Fig. 2), particularly as exact catch amounts are not essential in this analysis that focuses on the relative strengths of fishery system interactions.

Fishers, especially divers, may be highly knowledgeable about their surrounding ecosystems, including aspects of food web (prey-predators) and habitat interactions they may observe while diving or fishing, or from bycatch or stomach contents of their target species. However, other trophic relationships may be less apparent or of less general interest to fishers, so considering indirect impacts may likely need additional information from scientific research to fully represent the trophic structure of an ecosystem. Data on ongoing effects of fishing on target, non-target species and on habitat is paramount and requires continuous monitoring programs. Studies on the trophic and non-trophic relationships within the ecosystem are also required to assess the direct and indirect effects of fishing; these studies do not necessarily have to be continuous, but must be carried out periodically to update and refine assumptions on ecosystem dynamics. Fig. 2 shows a common decision tree that may be followed for a quantitative evaluation of ecosystem interactions of a fishery.

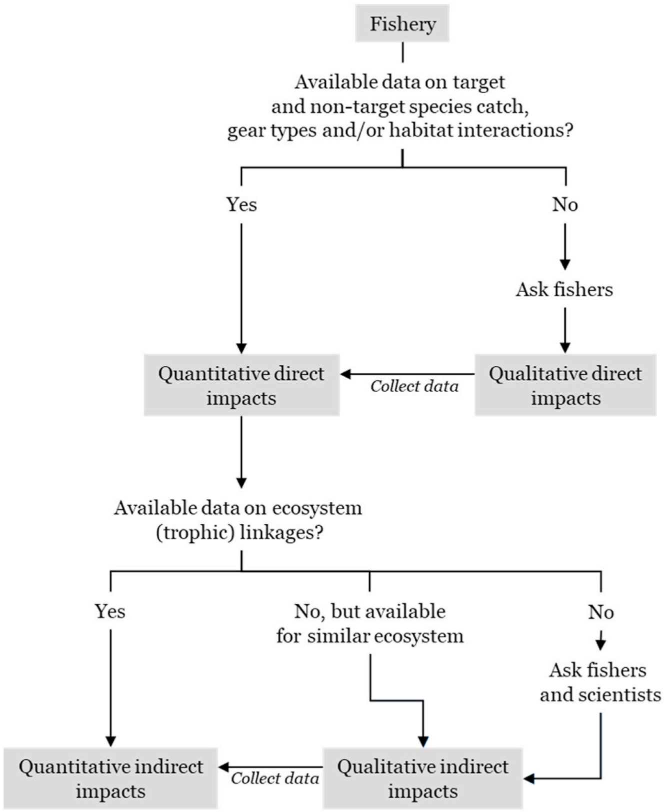

Fig. 2. Decision tree for evaluating potential direct and indirect ecosystem impacts from artisanal fisheries.

In this study we use available peer-reviewed trophic models built using the Ecopath with Ecosim (*EwE*) platform (www.ecopath.org), which represents an ecosystem within a predetermined area based on trophic interactions among functional groups (single species or groups of species with similar ecosystem function). The inputs and outputs of each group are balanced, meaning their production is equal to losses by predation or other sources of natural or fishing mortality, migration or biomass accumulation (Christensen and Walters, 2004). Functional groups are linked through their diets, where each group (except for primary producers) must feed on other groups. The initial (static) representation of the model is specified in the Ecopath component, while any dynamic simulations and scenario analyses are conducted in the Ecosim component. A third component, Ecospace, could be used to represent spatial dynamics, but we did not apply these in this study. EwE is the most widely used ecosystem modelling platform because of its relatively straightforward development compared with other types of ecological modelling approaches (Plagányi, 2007), and the fact that it is open-access and has extensive documentation, a global network of users, and a large and growing repository of existing models (Colléter et al., 2015).

When an EwE model is not available, qualitative knowledge, particularly that of fishers, can be used to identify species within the local ecosystem. Interspecies trophic relationships can then be mapped out to the best of local knowledge, complemented if possible with other types of scientific information (see Case studies subsection below). This approach, which encourages fisher participation and makes them more aware of how their knowledge is used within models for subsequent management advice, has been used to complement scientific data in ecosystem models of Scottish fisheries (Bentley et al., 2018), but to the best of our knowledge not for a tropical artisanal fishery. The output of this exercise is a relational matrix between functional groups (e.g. species) that is the input data for creating a network diagram model (Kamada and Kawai, 1989) similar to the trophic networks produced by EwE. This network model can be analyzed to identify trophic dependencies and direct and indirect fishing effects on species. To address one of our research questions, the complexity of scientific-only and local knowledge-based networks can be quantitatively compared using a clustering coefficient, and inferences drawn regarding potential fishing impacts based on species associations.

2.2. Simulation of fishing effects

In order to project potential ecosystem effects on the food web due to artisanal fisheries (case studies described below), we simulate different fishing mortality rates on the exploited species (functional group). For each case we simulated a gradually increasing time series of annual harvest rate (HR_t) for the functional groups of interest (i.e., target species). The HR_t for exploited groups in the model is expressed as (Ricker, 1975):

$$HR = \frac{F}{M+F}\left[1 - e^{-(M+F)}\right] \qquad (1)$$

where M and F are natural and fishing annual mortality rates. Here, we run an EwE simulation gradually increasing HR from 0 to 1 for a period of 50 years (a 0.02 year^{-1} increase in HR). For each year, F_t was estimated solving equation (1). M was obtained from the Ecopath base model and remained constant over time.

Assuming the Ecopath base model represents a baseline, the first step was to set the initial year of simulation with no fishing mortality, that is $P/B = M$. In this case, the catches of the exploited group are summed to the original biomass for setting $F_0 = 0$. After simulating the HR time series using *EwE*, for each year we extracted the ecosystem indicators to evaluate the effect of the increasing exploitation on the ecosystem. In this study, we used four ecosystem indicators (scaled from 0 to 1), one related to catch (total catch), one reflecting biological community diversity (Shannon's Diversity Index, *SDI*) and two reflecting ecosystem functioning (mean transfer efficiency between trophic levels, *MTE*, and the ascendency/capacity ratio, *AC*, which is an index of ecosystem organization). This allowed us to identify the maximum fishing mortality that can be sustained by the ecosystem and to compare this limit reference point with the current fishing mortality. Additionally, in order to evaluate the impact of fishing on the ecosystem community of species, we analyze the trophic level (*TL*) of the community indicator (*TLco*) (Coll and Steenbeek, 2017). This index is the average of the *TLs* of the community (weighted by the biomass of each functional group) and varies when fishing removes biomass of the food web components affecting the ecosystem structure.

2.3. Case studies

We apply the framework as described above to fisheries in four ecosystem types—kelp forest, sandy bottom, coastal pelagic, coral reef—within Mexico (Fig. 3). These include fishing done by cooperatives on the western coast of the Baja California Peninsula (Bahía El Rosario), the eastern coast of the Gulf of California (Puerto Libertad and Bahía Kino), the Caribbean coast of the Yucatán Peninsula (Sian Ka'an), and a wider fishing area in the central Gulf of California. All of these fishing cooperatives are associations of artisanal fishers, which in Mexico are generally recognized as using open-deck fiberglass boats (7–10 m length) with an outboard engine, operated by 2–3 fishers. These fisheries usually change their gear and main target species throughout the year depending on seasonal availability, market demand, and weather conditions. Here we focus on fisheries directing effort to target species (Table 1). Ecopath with Ecosim (EwE) models were available for each of the case studies (specific references in Table 1), except for the clam dive fishery in Puerto Libertad.

In the case of Puerto Libertad, for which there was no existing ecosystem model, we used a fisher-developed trophic model. A workshop was held in which 41 fishermen participated (20% of the total fishers in the community); participants were between 25 and 50 years old and all had at least 10 years of experience fishing (Espinosa-Romero et al., 2014). The workshop included both fishers using lines and nets (finfish, squid, rays and shark) and divers (penshell, octopus, sea snail, sea cucumber and clam) to have a vision of the entire ecosystem. During the workshop the fishers divided into groups of 5 people and were asked to describe predator-prey relationships between local species to the best of their knowledge. The results of each group were presented in a plenary session. Three main habitats were indicated by fishers (rocky, sandy bottom and pelagic), and birds and mammals were also identified as components of the ecosystem. All information was compared with previous interviews by PANGAS,[1] official logbooks and a set of ecosystem models built for the Gulf of California (Díaz-Uribe et al., 2012; Morales-Zárate et al., 2004; Cisneros-Montemayor et al., 2012; Riofrío-Lazo et al., 2013; Salcido-Guevara, 2006) to highlight any key inconsistencies and allow for further discussion and iteration.

3. Results

Based on existing quantitative and qualitative models and the framework in Fig. 2, we identified direct and indirect (trophic) impacts (Fig. 1) from the artisanal fishery case studies on their corresponding marine ecosystems. Importantly for data-limited management contexts, qualitative models built using expert fisher knowledge need not have fewer groups or interconnections compared to quantitative ones. In fact, the clustering coefficient of the network, which measures model complexity through the probability that the adjacent nodes of a node are connected, were estimated at 0.75 for the lobster fishery and 0.56 for the clam fishery (Fig. 4). Network diagrams for the other cases are available in the corresponding references (see Table 1).

Fig. 5 shows the trends of four ecosystem indicators related with changes in harvest rate of the selected fisheries where quantitative analysis was possible (Table 1). We found that maximum catch in most cases was around a 0.25 harvest rate with the exception of the Humboldt squid fishery, with a harvest rate of 0.38. Shannon's diversity index (H′) decreases with increasing harvest rate, as expected given the implied reduction in target species that are prey for other species in the ecosystem (Fig. 5). In the case of squid, however, H′ increases as squid mortality increases because squid have a relatively high trophic level and high consumption rates, so that declines in their abundance result in increased abundance of prey species.

In the case of the mean transfer efficiency between trophic levels (MTE), all cases showed decreases directly related to increasing harvest rate, with MTE starting to be decrease monotonically when reaching the harvest rate that yields the maximum catch. For most fisheries, the ascendency/capacity (A/C) decreases with increasing harvest rate, with the exception of the ocean whitefish fishery where an opposite trend was found. Note that this result must be taken with caution because a gain in ecosystem order implies a decrease in resilience as a consequence of reducing overhead (Ulanowicz et al., 2009; Heymans et al., 2011).

As expected, increasing harvest rate affects the trophic level of the community (*TLco*) (Fig. 5) but the trends are very different among case studies. We did not find that the trophic level of the exploited group could explain the trend in *TLco*. For example, ocean whitefish and amberjack yellowtail have a *TL* of 2.72 and 3.47, respectively, and *TLco* decreases as harvest rate increases. Conversely, the Humboldt squid and spiny lobster have *TLs* of 3.77 and 2.98, respectively, and increasing harvest rate resulted in an opposite trend.

For each fishery, species-specific impacts through direct and indirect effects can also be calculated (or inferred, in the case of the qualitative

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[1] PANGAS is an interdisciplinary collaboration that takes an ecosystem-based approach to work with communities in the northern Gulf of California to improve artisanal fishing conditions and ecosystem health. In addition to fishing communities and cooperatives, participants include civil society organizations and universities such as Centro Intercultural de Estudios de Desiertos y Océanos (CEDO), Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE), COBI, Pronatura-Noroeste, University of California Santa Cruz (UCSC), and the University of Arizona.

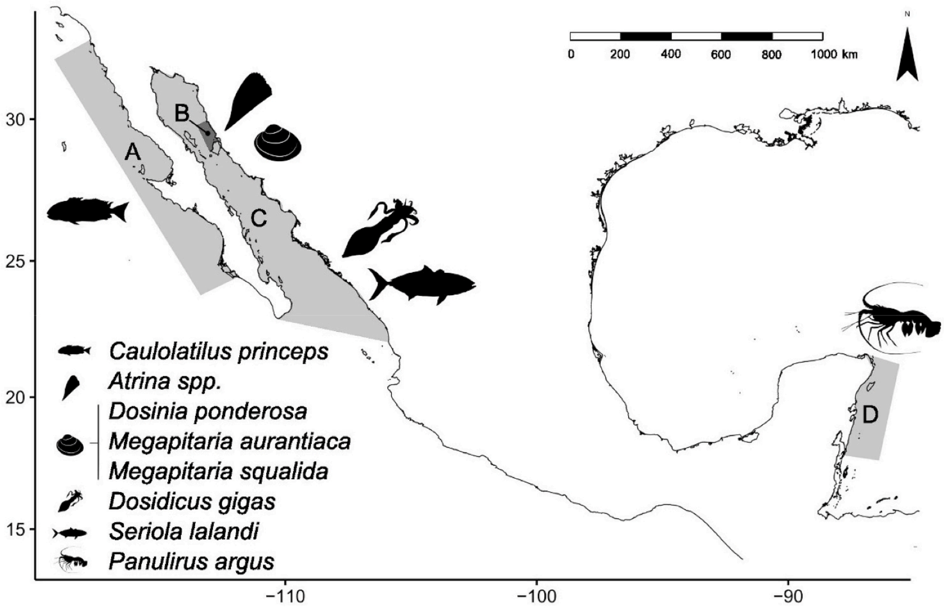

Fig. 3. Case study areas where ecosystem impacts from directed artisanal fisheries where evaluated. Ecosystem types include A) kelp forest, B) coastal pelagic, C) sandy bottom, and D) coral reef.

Table 1
Species and dynamics of ecological impacts identified for each fishery. The evaluation methods follow from available data as outlined in Fig. 2.

Area	Ecotype	Target Species	Fishing gear	Bycatch species	Model available
Bahia El Rosario, Baja California	Kelp forest	Ocean whitefish (*Caulolatilus princeps*)	Hand lines, traps	Traps Barred sand bass, California sheepshead, vieja de fondo (*Semicossyphus pulcher*), cabrilla sargasera (*Paralabrax clathratus*), verdillo (*P. nebulifer*),	Quantitative (Vilalta-Navas, 2017)
Gulf of California	Pelagic	Yellowtail amberjack (*Seriola lalandi*) Humboldt squid (*Dosidicus gigas*)	Handline Squid jigs	Occasionally skipjack (*Katsuwonus pelamis*), but limited due to different seasonality None	Quantitative (Rosas-Luis et al., 2008)
Puerto Libertad-Bahia Kino, Sonora	Sandy bottom	Squalidad callistaSqualid callista (*Megapitaria squalida*) Golden callista (*Megapitaria aurantiaca*) Golden callista [roja] (*Megapitaria aurantiaca*) Ponderous dosinia Ponderosusu dosinia (*Dosinia ponderosa*) Penshell (*Atrina spp.*)	Hand collection in hooka diving	None, though snails and sea cucumbers may be collected if encountered	Qualitative (COBI, 2012 and this study)
Sian Ka'an, Quintana Roo	Coral and rocky reef	Lobster (*Panulirus argus*)	Hand collection from "casitas," artificial lobster shelters built and managed by fishers	Occasional fish spearing for home consumption, no other bycatch	Quantitative (Vidal and Basurto, 2003)

model) based on the trophic relationships between functional groups. There were no significant impacts on ecosystems or particular species at current fishing levels, but it can be nonetheless helpful to consider any potential effects. Key species with trophic linkages to target species were, for the spiny lobster fishery, marine birds and sharks; for the ocean whitefish fishery, marine mammals (such as sea lions), groupers and sharks; for the Humboldt squid fishery, sea birds, whales, sharks, and small pelagic fishes; for the amberjack yellowtail fishery, pelagic sharks; and for the clam fishery, fishes such as triggerfish, groupers, snappers, small sharks, flounders and rays, and benthic invertebrates such as crabs.

4. Discussion

The aim of this study was to apply a straightforward methodology to use scientific and local knowledge to evaluate potential ecosystem impacts from directed artisanal fisheries to inform ecosystem-based fisheries management. Results for our case studies (Fig. 3, Table 1) show that, based on trophic models for these ecosystems, current fishing levels, and the high selectivity of these artisanal fisheries' gears, expected effects on ecosystems from these artisanal fisheries are most likely minimal. Nevertheless, there could indeed be potential changes to ecosystems if fishing mortality were to substantially increase (Fig. 5), so managers and fishers should be aware of key species that could be impacted.

The best approaches and indicators for evaluating fishing effects at the ecosystem level have been discussed for decades (Gislason and Sinclair, 2000; Cury and Christensen, 2005; Heymans et al., 2016). Most methods for considering fishing impacts at some point account for trophic interrelations among species, and here we use indicators representing four ecosystem levels, the target species (total catch), the surrounding biological community (Shannon's index), the ecosystem organization (A/C ratio) and ecosystem dynamics (transfer efficiency between trophic levels). All of them are relatively easy to estimate from

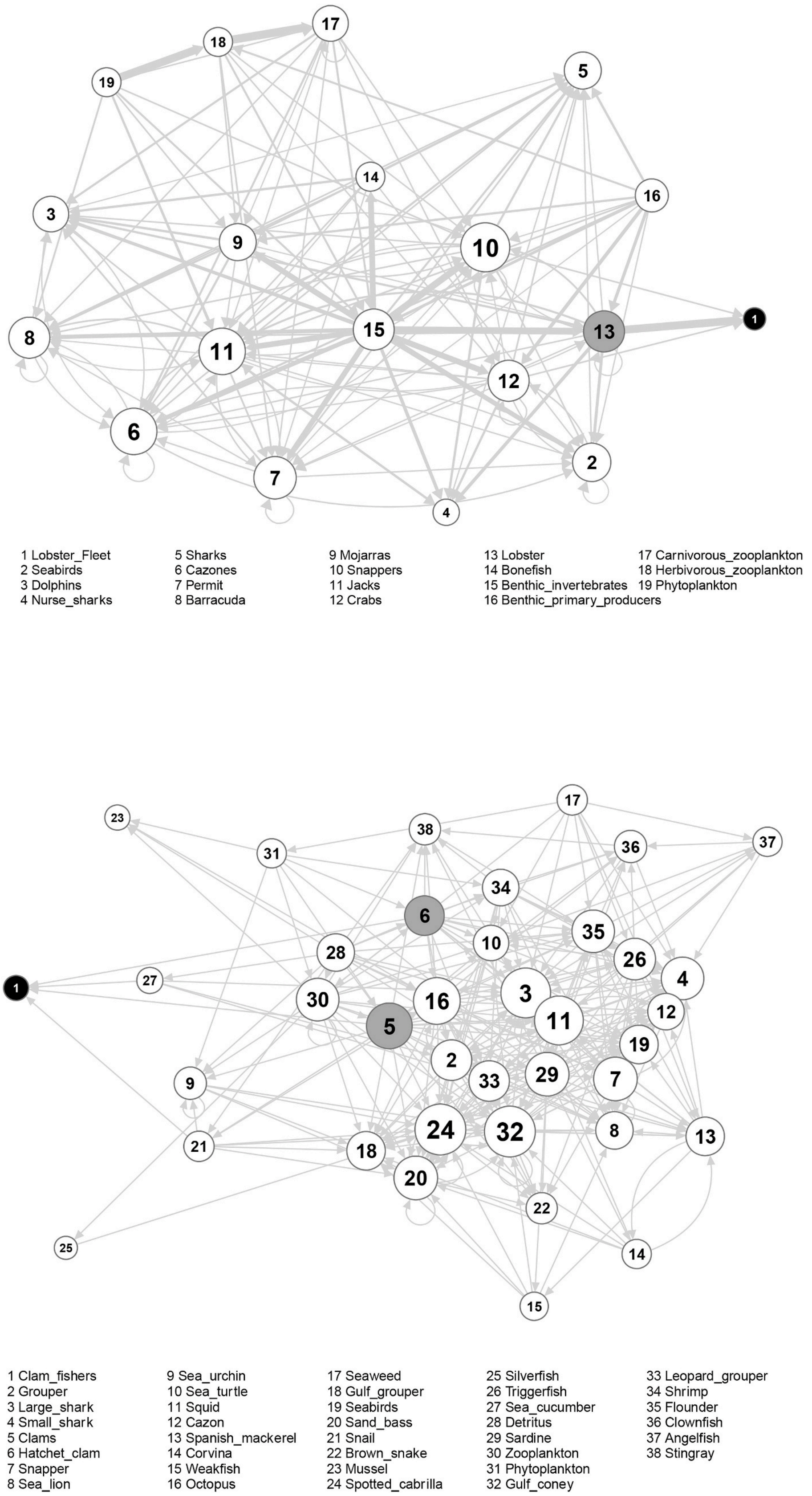

Fig. 4. Network diagram from quantitative Ecopath with Ecosim model for the artisanal lobster fishery in Sian Ka'an (top) and the qualitative ecosystem model developed by fishers in the artisanal clam fishery, Puerto Libertad (bottom). Trophic links (light grey), target species = grey nodes, non-target species = white nodes, fishery = black nodes. In the case of lobster fishery model, the line widths are relative to the magnitude of trophic relationships.

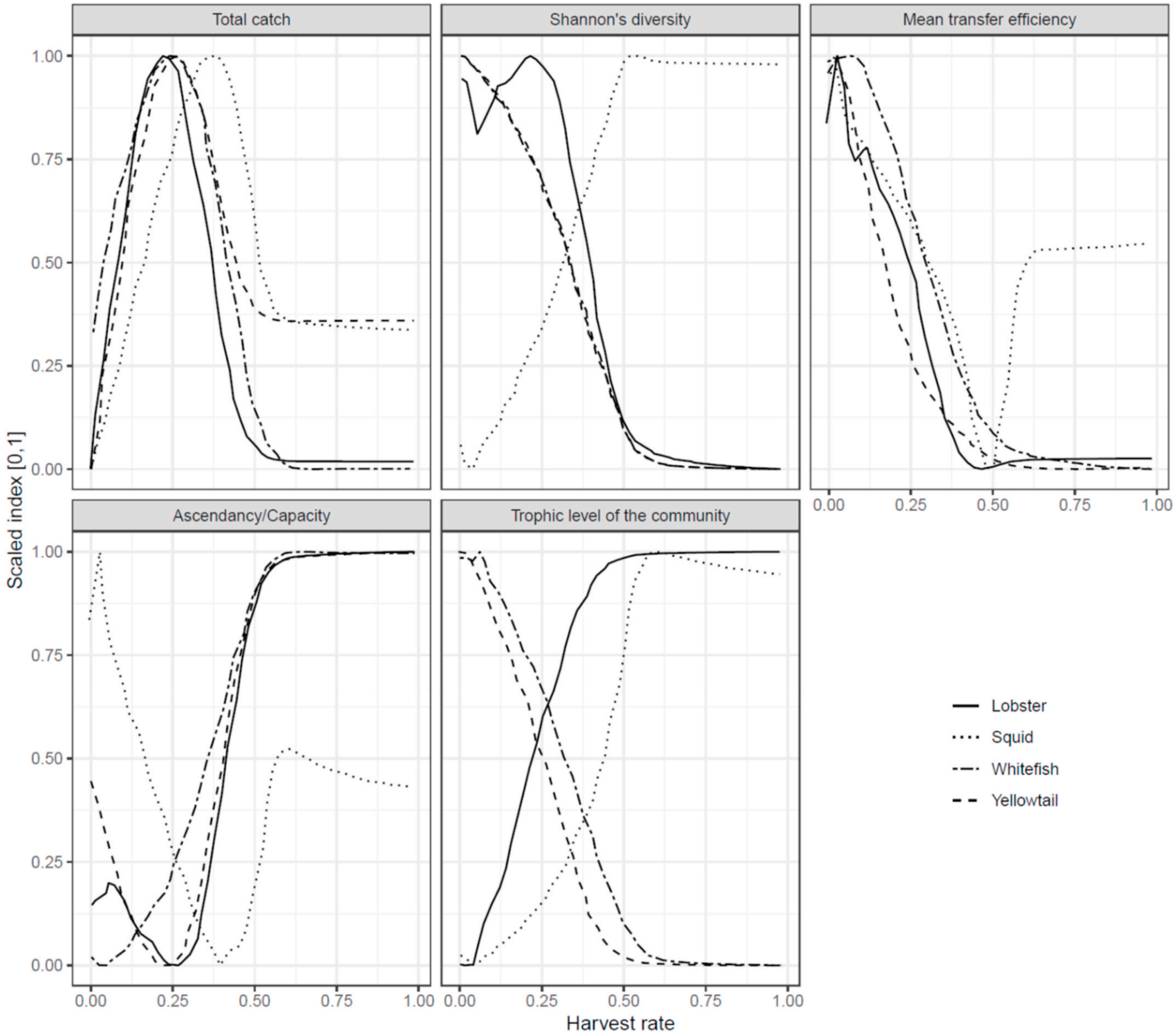

Fig. 5. Indicators resulting from changing in harvest rate of selected fisheries. AC = Ascendency/Capacity.

trophic models, well-accepted in the scientific community, and straightforward to interpret among stakeholders in order to empower them in the decision-making process when exploring ecosystem-based approaches to fishing scenarios.

Co-management is increasingly recognized as an integral part of sustainable artisanal fisheries (Plummer, 2013) and fisher associations have a much more direct role in management strategies. However, they most often must continue to operate within structured decision-making frameworks that are informed by science and match intergovernmental policy guidelines such as ecosystem-based fisheries management (EBFM) (Espinosa-Romero et al., 2011). Notably, EBFM tends to be more pertinent for artisanal fisheries than single-species management because of the inherent multi-species nature of this sector. In practice, however, what is intended to be an overarching approach is also linked with specific benchmarks and data requirements established by, for example, government regulations, seafood certification bodies, or project proposals (e.g., for FIPs). As this study shows, it is indeed possible to formally incorporate or recognize ecosystem dynamics in management even in relatively data-limited situations, at the very least to consider interdependencies between target species and the surrounding environment and potentially other fishing activities.

The effects of exploitation beyond target species is rarely evaluated in artisanal fisheries (Fernández-Rivera Melo et al., 2018) yet it is a key element that needs to be considered by international sustainability criteria which require that fisheries do not seriously damage key elements of the ecosystem (structure and function). Our case studies did not show notable expected ecosystem impacts at current fishery levels due to low bycatch as a consequence of the relatively high selectivity of the gears used, including squid jigs or hand collection (Table 1). Furthermore, none of the fishery targets are keystone or wasp-waist species as could be the case, for example of sea urchin or forage fish fisheries that are usually highly selective but could result in indirect ecosystem impacts (respectively, through kelp forest modification, or decreased prey availability) (Libralato et al., 2005; Cury, 2000).

Other artisanal fisheries however, including for ocean whitefish and jacks in our cases, use gillnets, traps, or handlines that are not necessarily selective and could involve high rates of bycatch. There is, indeed, much evidence that artisanal fisheries can significantly impact marine ecosystems through overfishing and habitat damage, and this must be considered in appropriate management regulations (Selgrath et al., 2018). EwE models have been used to identify these potential issues (Arreguín-Sánchez, 2004; Albouy et al., 2010), though we did not detect significant ecosystem impacts in our case studies. The most likely reason is that these cases are relatively small fisheries with some form of limited access, sometimes simply due to the remoteness of the communities. Local knowledge on seasonal fish aggregation and movement patterns can also reduce bycatch (Teh et al., 2015), as reflected in our case studies (references in Table 1). Results should be considered with caution due to potential uncertainties in assumptions on catches, some of which may not be formally recorded, but it is clear that ecosystem models—ideally with input from and collaboration with artisanal fishers—are an effective tool to evaluate potential ecosystem effects of fishing. Most importantly, the potential impacts of any fishing activity must be considered—quantitatively or qualitatively—regardless of its apparent scale.

Results of this study clearly hinge on the representation of ecosystems in existing ecological models. It was fortunate that models were available for most of the specific areas (Table 1) of our case studies and included the species in question, yet there are still possible issues. For example, ecosystem models and single-species stock assessments face similar challenges regarding the baseline abundances for functional groups. This is particularly important given the common practice of using ecosystem parameters that may have been estimated at other points in time or with different research questions, which may lead to ecosystem representations that may not be entirely consistent with current conditions (Essington and Plaganyi, 2014). Similarly, current fishing mortality assumed in the ecosystem model may depend on whether catch is reported by managers, researchers or fishers and can be uncertain in any case (Garibaldi, 2012); alternative assumptions on current fishing mortality may change scenario projections (e.g., Fig. 5). Some of these limitations could be addressed by complementing or updating ecosystem models with information from single-species assessments designed specifically for data-limited fisheries (for example, the Data-Limited Methods Toolkit; Carruthers and Hordyk, 2018). Most importantly, uncertainties should always be clearly stated, and research questions prioritized to address key questions. Ultimately, it is widely accepted that ecosystem models are highly useful for understanding and communicating general trends, aside from a precise estimation of reference points.

In the context of co-managed artisanal fisheries that are very often data-limited, many of the issues above could be resolved through cooperation and earned trust between fishers, managers, civil society organizations and researchers. For example, in the absence of an existing ecological model on which to base the evaluation of presumed ecosystem impacts from clam fisheries (Table 1), fishers were readily able to construct a qualitative model based on their ecological knowledge. This model was actually more complex (fishers, specially divers, included all species and interactions they have observed) than peer-reviewed ecological models in terms of species groups included (Fig. 4) but, because we obviously did not have an independent (scientific data-based) model for the same area, we cannot assess whether such models are more or less accurate according to scientific standards; this would be a very interesting question for future research. Despite the question of accuracy, the inclusion of LEK alongside science to inform conservation and fisheries programs and strategies requires an acknowledgement of LEK as a credible source of knowledge (Beaudreau and Levin, 2014). These inclusive knowledge systems open up the possibility of contradictory or competing information, and one way to reconcile these possible disagreements is to take a precautionary approach and to err on the side of complexity. Similarly to our results, previous studies which have utilized LEK have found that it can generate more complex understandings of social-ecological dynamics than scientific models (though not always), can provide important historical perspective in understanding resource dynamics, and may be able to signal resource declines more rapidly than management informed through science alone (Chalmers and Fabricius, 2007; Ban et al., 2017; Singh et al., 2017).

It is important that increased respect for and integration of traditional knowledge does not diminish our perception of the crucial value of scientific monitoring and research. Despite the obvious extensive experience of fishers, scientific research can fill in gaps in food web information for smaller or less abundant species that are nonetheless vital for ecosystem functioning. Out of a total of 296 trophic linkages in the qualitative model, 78% were informed by scientific information, 8% by fishers, and 13% by both. Similar efforts in Scottish fisheries involved multiple rounds of workshops, stakeholder engagement, and follow-up research to answer emerging questions both on ecosystem structure and fishing trends (Bentley et al., 2018, 2019). It would be very interesting to further develop this approach and other relatively simple indicators as tools for data-limited EBFM in developing regions.

5. Concluding remarks

In Mexico, as in other regions both developing and developed, it is increasingly clear that implementing traditional top-bottom fisheries regulations is highly difficult and likely inappropriate for meeting either ecological or social goals. Facing widespread overfishing, global climate changes, and complex globalized seafood markets, fishers are part of increasingly specific, complicated issues which require an overwhelming amount of data and assessments even as management bodies are becoming relatively weaker (Salas et al., 2007; Silvano and Begossi, 2012; Farr et al., 2018). The inclusion of fishers' knowledge will therefore continue to gain importance and will most likely become crucial for management. Generalized integration of LEK, in addition to traditional monitoring and assessments, will increase the likelihood of improving fish resources, bridging scientific knowledge gaps, and overcoming the common disconnects between fisheries researchers, managers and fishing communities (Moreno-Báez et al., 2010; Basurto et al. 2012). A key challenge will be to co-create a process for continuous inclusion of LEK in formal management plans and to implement and adapt these as needed, particularly in a changing natural and economic environment. Several fisheries management plans have been developed, most of them in collaboration with an array of stakeholders including industry, government, and non-governmental organizations. In Mexico and elsewhere, national governments will need to recognize and increase capacities to consider distinct regional priorities, moving past centralized decision-making systems to increase investment in local fisheries research and community priorities (Espinoza-Tenorio et al. 2011, 2015).

As reflected in this study, a key benefit of ecosystem-based approaches is that they explicitly place fisheries within a broader social-ecological system that recognizes important economic and social dynamics in addition to trophic linkages between target and non-target species (Espinoza-Tenorio et al., 2014; Finkbeiner et al., 2017). Incorporating ecological interactions into management models—ideally using both scientific and traditional knowledge—then becomes a tool not only for achieving ecologically sustainable fisheries, but for supporting the social and economic goals of artisanal fishers.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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