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Untapped Potential of Citizen Science in Mexican Small-Scale Fisheries

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Citizen science is a rapidly growing field with well-designed and run citizen science projects providing substantial benefits for conservation and management. Marine citizen science presents a unique set of challenges and lags behind terrestrial citizen science, but also provides significant opportunities to work in data-poor fisheries. This paper analyses case studies of citizen science projects developed in collaboration with small-scale fishing communities in Mexico's Pacific Ocean, Gulf of California and Caribbean Sea. The design and performance of these projects were evaluated against the previously published Ten Principles of Citizen Science, and Scientific Stages of Inquiry. Our results suggest that fisheries monitoring, submarine monitoring of no take zones, oceanographic monitoring, and the use of species identification apps by fishers meet the requirements of the published guidelines and are effective tools for involving the small-scale fishing community in science. Translating effective citizen science projects in to effective fishery management, however, is still at an early stage. Whilst citizen science data have been used locally by communities to adapt fishing practices, calculate recommendations for total allowable catches, establish and evaluate no take zones and detect range extensions of species affected by climate change, challenges remain regarding how to garner official recognition for the data, incorporate these growing sources of data into national policy, and use the data for adaptive management regimes at the national level.

Keywords: citizen science, small-scale fisheries, Mexico, participatory science, traditional ecological knowledge, science-policy interface

INTRODUCTION

Documenting fishers' local and traditional knowledge for the purpose of fisheries science has been commonplace for centuries (Johannes, 1981; Murray et al., 2008); however, fishers have more often been the studied group rather than contributing scientists (Hind, 2014). Despite fishers providing information to document species declines (e.g., Sáenz-Arroyo et al., 2005; Turvey et al., 2010;

Azzurro et al., 2011) or contributing to understanding local ecological processes (Silvano and Valbo-Jørgensen, 2008), fisheries management bodies and researchers have typically omitted fishers as a source of scientific knowledge (Johannes, 2003; Hind, 2014).

In recent decades, citizen science has become a growing field (Follett and Strezov, 2015; Hecker et al., 2018a) that has attracted international attention as a way of generating both large datasets and environmental awareness in target groups. It is increasingly becoming recognized as its own field of investigation (Jordan et al., 2015), with citizen science agencies and associations being launched, both as government departments and non-profit organizations. Bonney et al. (2014) want "*citizen science*" to describe any project that produces reliable data and information that can be used by anyone (scientists, policy-makers, the public) under the same system of peer review that applies to conventional science. This makes citizen science a flexible concept that is often used synonymously with *participatory science.* It considers inclusive, participatory yet structured processes that engage non-scientists in data collection, monitoring and research.

Although the definition and boundaries of citizen science are still debated (Eitzel et al., 2017), there is a general consensus about key components, such as the participation of individuals who do not possess a formal scientific education in different stages of scientific research (Couvet et al., 2008), including study design, data collection, analysis and dissemination of results (Guerrini et al., 2018). Data quality concerns (Freitag et al., 2016) are also being resolved through systemic, organized training and data management systems, with examples from fields such as astronomy (Raddick et al., 2010) and biological sciences such as bird surveys (Sullivan et al., 2009).

Despite the ever-expanding role of the citizen scientist, scientific and policy impacts are likely suboptimal (Follett and Strezov, 2015; Hecker et al., 2018a,b). In a study of 388 projects, only 12% produced peer reviewed articles (Theobald et al., 2015) and there has been a lack of official adoption by government (Hecker et al., 2018b). Marine citizen science projects are particularly underrepresented (Roy et al., 2012; Theobald et al., 2015), reflecting the difficulty and expense of project implementation such as the cost of the equipment required, boat hire, safety and liability, or even unclear access and resource rights (Roy et al., 2012; Cigliano et al., 2015). Successful examples from the marine realm include marine protected area monitoring (Freiwald et al., 2018) reef system monitoring (Pattengill-Semmens and Semmens, 2003), categorization of whale sounds (Shamir et al., 2014), and tracking plastic residue in coastal ecosystems (Hidalgo-Ruz and Thiel, 2013). Citizen science's role as a tool for environmental awareness and education is also well documented (Dickinson et al., 2010; Tulloch et al., 2013; Dean et al., 2018).

A key component of many citizen science projects is community-based monitoring (CBM) (Conrad and Hilchey, 2011). CBM ensures that citizens participate as scientists, rather than solely data collectors (Lakshminarayanan, 2007), and involves local stakeholders monitoring issues of local interest or concern. The United Nations Environment Programe, in partnership with several citizen science agencies, recently established the ambitious goal of engaging 1 billion global citizens in citizen science by 2020 (UNEP, 2017). However, whilst developed countries are leading the way in the establishment of formal citizen science bodies, in Europe (European Citizen Science Association), the United States (Citizen Science Association) and Australia (Australian Citizen Science Association), large-scale national or regional projects in developing nations are still few on the ground. Most marine citizen science studies published to date, for example, are from high-income countries or popular SCUBA diving destinations (Pattengill-Semmens and Semmens, 2003; Goffredo et al., 2004; Ward-Paige et al., 2010). Citizen science has been identified as a priority to help countries track progress toward, and meet, their Sustainable Development Goals (Lu et al., 2015) and Convention of Biological Diversity (CBD) targets. Indeed, mobilizing citizens can be a cost-effective way for countries to meet these needs. For example, the contribution of French volunteers to the CBD targets has been estimated at between €0.67 and €4.42 m per year, effectively providing in-kind support to the government (Levrel et al., 2010). Benefits of CBM are also felt locally. Collaborative action, as part of citizen science projects, has been noted to promote buy-in, adaptive management, and resilience (Aceves-Bueno et al., 2015). Indeed, benefits of collective action on common pool resources are well-documented (Gardner et al., 1990; Ostrom, 1994, 2000) and citizen science by resource users is an extension of this. In developing countries with weak institutions and limited research funding, significant areas of opportunity exist for citizen science to play a role in common pool resource management. With this in mind, data-poor, multispecific fisheries, in areas where national fisheries agencies do not have the resources to adequately monitor resources, would seem ripe for citizen-led project development and data collection through collaborative, scientific processes between fishers, civil society organizations (CSOs) and researchers.

Mexico is a top 20 fish producing nation, with catches fluctuating around 1.2 million tons (FAO, 2014), and with one of the longest coastlines in the world (11,000 km), data collection, management and enforcement proves challenging to the overstretched National Commission of Fisheries and Aquaculture (CONAPESCA) and National Institute for Fisheries and Aquaculture (INAPESCA). Small-scale fisheries are of considerable importance (Espinosa-Romero et al., 2017), accounting for 40% of the total catch and involving an estimated 222,165 small-scale fishers (Moreno-Báez et al., 2010). Official reports suggest that 70% of national fisheries are at the maximum sustainable yield and 17% are overexploited (Diario Oficial de la Federación, 2012), however, Cisneros-Montemayor et al. (2013) estimate that illegal, unregulated and unreported (IUU) fishing is considerable, with the actual catch potentially being twice as high as the official statistics. Management reform is necessary to move fisheries toward sustainability (Mangin et al., 2018) but top-down policies have often disenfranchised small-scale fishers (Finkbeiner and Basurto, 2015) or have not taken in to consideration the best available science for effective implementation. The Mexican legal system does not currently have a clear institutional setting for the promotion, implementation and use of citizen science. The fisheries sector is governed by the General Law for Sustainable Fisheries and Aquaculture of 2007 (LGPAS, in Spanish), the main legal instrument that "*ordains, promotes and regulates the integral management and sustainable use of fishery and aquaculture resources*" (LGPAS. art.1). This law stipulates that INAPESCA is the official institution responsible for fisheries research. Layperson participation in research activities and agenda setting is contemplated in two areas: the elaboration of the National Program of Scientific Research in Fisheries and Aquaculture, that INAPESCA must direct and coordinate, taking into account proposals made by research institutions (LGPAS art.29); and the integration of the National Information and Research Network (RNIIPA), where academic and civil society participate in order to present and share their respective research, which INAPESCA may validate and consider as relevant input for further management decisions.

This paper presents 12 citizen science case studies from Mexico's fisheries. We use two published citizen science frameworks to evaluate the participatory nature of the projects and their contributions to fisheries management and conservation. First, we define and describe the marine citizen science projects that are included in the review. We then evaluate the nature of each project against existing citizen science principles and the project stages in which citizens are involved, before discussing the scientific contributions, impacts of collective action, and challenges for wide scale adoption. National reviews of marine citizen science projects are not available in the literature, and citizen science is underrepresented in developing countries. As Mexico, along with neighboring Latin American countries, has yet to develop specific goals, regulations and guidelines for citizen science, we discuss the opportunities for further developing citizen science programs, their contributions to fisheries science and management, and the potential for policy change and scaling to improve fisheries management in data-poor, small-scale fisheries.

MATERIALS AND METHODS

The document co-authors represent civil society and governmental organizations that implement citizen science projects related to Mexican fisheries. During two workshops (August 2018, February 2019) the co-authors developed a list of 12 fishery citizen science projects currently operating in Mexico. These projects were then grouped by theme to form case studies (**Figure 1**). For example, all projects that involved fishers conducting underwater visual censuses were grouped in to one case study, irrespective of the target species or habitat type being surveyed. Other marine citizen science projects were discussed (e.g., turtle surveys, marine mammal surveys) but only those with a fisheries component were included in the review.

Case-Study 1: Fishery Monitoring

Fishery monitoring programs have been established with fishers and community members to collect data on certain species or areas. Small-scale fishers from 14 communities in the Gulf of California, Pacific Ocean and Mexican Caribbean have been trained to collect data on invertebrates (incl. lobster, octopus, clam and penshell) and finfish (incl. corvina, yellowtail, snapper). Community members are trained to use different tools (traditional logbooks, e-logbooks, biometric measuring equipment, genetic sampling techniques etc.) by CSOs in collaboration with local Fisheries Research Centres of the National Institute for Fisheries and Aquaculture (CRIP-INAPESCA). The projects aim to improve the understanding of regional fisheries, fishery dynamics and to collect fishery-dependent and independent data in data-poor regions. We identified four principle types of fisheries monitoring: catch monitoring, spatio-temporal fisheries monitoring, morphometric data collection and stock assessments. Community members are generally not compensated for their participation but receive the necessary training and equipment to conduct the investigation.

Case-Study 2: Underwater Visual Censuses of Marine Resources and No-Take Zones

Over 215 small-scale fishers have been trained to SCUBA dive and evaluate marine resources in the Mexican Pacific, Gulf of California and Mexican Caribbean (Karr et al., 2017; Fulton et al., 2019). These efforts have accompanied the bottom-up creation of 204 km^2 of no-take marine reserves in 25 coastal communities as well as the evaluation of established marine protected areas. The fishers are trained to identify target species and conduct underwater visual censuses of marine resources to evaluate ecosystem recovery using standardized protocols (e.g., Hernández-Velasco et al., 2018). Fishers are paid a stipend during monitoring periods to compensate for missed fishing days.

Case-Study 3: Oceanographic Monitoring for Climate Change Adaptation

Climate change is affecting Mexican fisheries (Micheli et al., 2012; Lluch-Cota et al., 2017). Forty-four oceanographic sensors have been installed offshore from 25 communities to collect temperature, DO_2, current and sea level data. Twenty-five fishers have been trained to install, maintain and retrieve the sensors, before uploading the data to share with scientists from CSOs and Mexican and international universities. The long-term goal is to understand the impacts of climate change and co-create adaptation strategies for long-term viability of the small-scale fisheries in a changing climate. Sensors are provided by research centers and CSOs. Fishers receive training in the installation and use of the sensors, but are not compensated for their participation.

Case-Study 4: Naturalista

Naturalista[1] is part of the global iNaturalist network and is hosted by Mexico's National Commission for Biodiversity (CONABIO). Launched in 2013 it now hosts 29,292 species, 1,356,030 individual sightings and has 31,760 users. Any member of the general public can upload information from their smartphone or

[1] http://naturalista.mx/

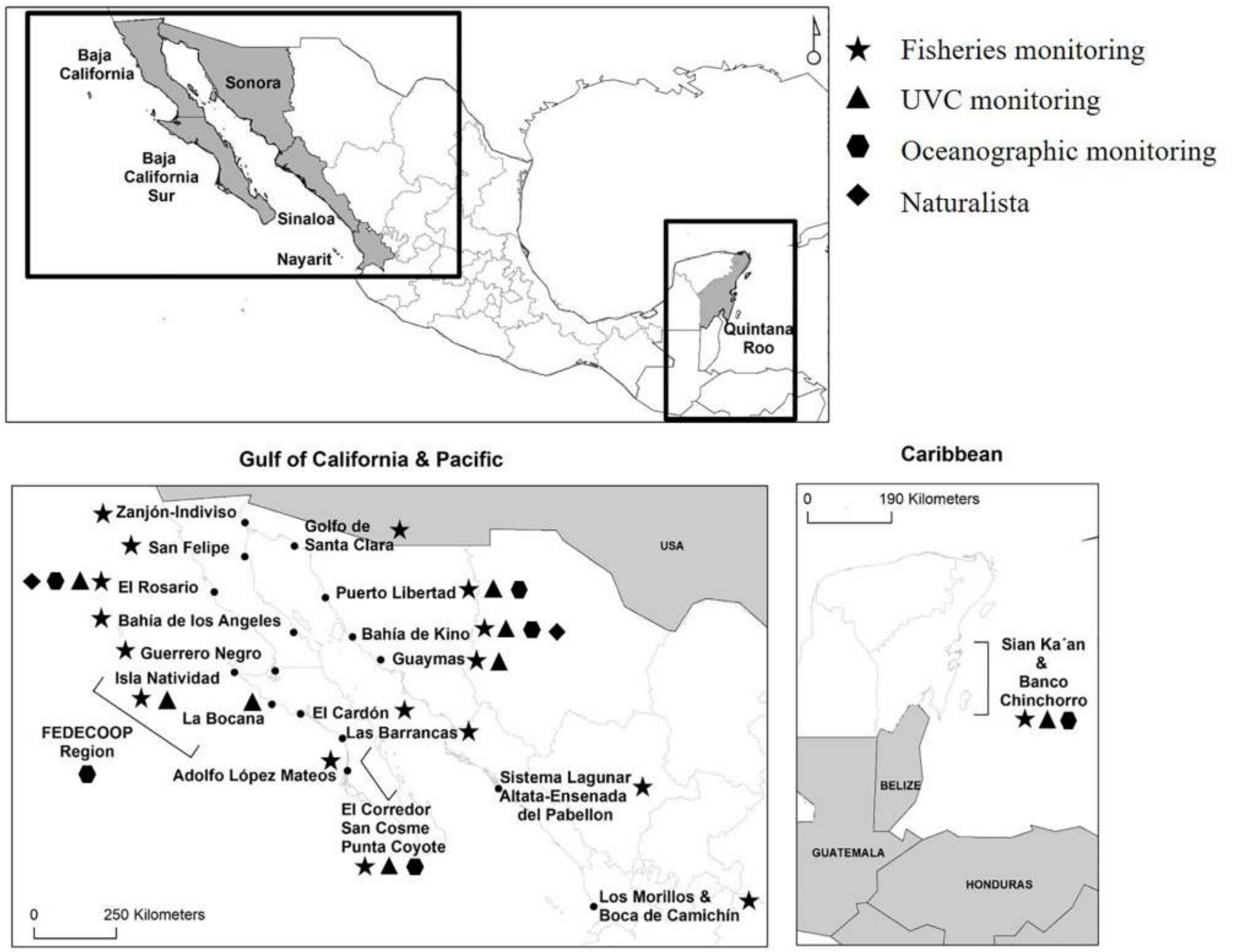

FIGURE 1 | Location of case studies and case study categories.

computer and there are built-in photo-ID and user verification methods to increase data quality. In 2018, CONABIO conducted training courses for fishers in two coastal communities, donating photographic and computational equipment to the communities. In 6 months this resulted in 5,762 total new sightings as well as the identification of 22 species previously unreported in the database.

Evaluation Criteria

Each case study was evaluated using the two frameworks published in the literature and described below. Fisheries monitoring was subdivided in to catch-monitoring and effort and spatial monitoring to reflect the different approaches and methodologies used.

Principles of Citizen Science

In 2015 the European Citizen Science Association published the "Ten Principles of Citizen Science," based on inputs from members of the association (Robinson et al., 2018). Now translated in to 26 languages, they aim to provide a framework against which citizen science initiatives should be assessed. Hecker et al. (2018a) recommended reflecting on and testing these principles. We formulated questions from each principle and used this to evaluate the magnitude as to which each case study met the requirements of the principle.

Stages of Scientific Inquiry

Wiggins and Crowston (2011) identified five types of citizen science projects (Action, Conservation, Investigation, Virtual and Education) and eleven stages of scientific inquiry for a citizen science project. The projects in this contribution are *Conservation* and *Investigation* projects and the involvement of the fishers in each case study example was evaluated against the eleven stages of scientific inquiry.

RESULTS

Our review identified that most projects considered the majority of the ten principles of citizen science (**Table 1**) and fishers were

TABLE 1 | Evaluation of case studies using the Ten Principles of Citizen Science (Robinson et al., 2018).

Principle of Citizen Science / **Type of Project**		**Actively involves citizens in scientific endeavor?**	**Produces a genuine science outcome?**	**Professional and citizen scientists benefit from participation?**	**Participation of citizen scientists in multiple project stages?**	**Citizen scientists receive feedback from project?**	**CS is considered a research approach like any other?**	**Project data and meta-data are made publically available?**	**Citizen scientists acknowledged in results and publications?**	**CS program is evaluated on its scientific output, data quality and impact?**	**Project leaders consider legal, ethical and environmental impacts of activities?**
Fisheries monitoring	Catch monitoring	Yes	Yes	Yes	Yes	In most cases	Yes	No	Yes	Yes	Yes
	Effort and spatial monitoring	Yes	Yes	Yes	Yes	Yes	In most cases	In some cases	Yes	Yes	Yes
UVC in marine reserves		Yes	Yes	Yes	Yes	Yes	Yes	In some cases	Yes	Yes	Yes
Oceanographic monitoring		Yes	Yes	Yes	Yes	In some cases	Yes	No	Yes	Yes	Yes
Naturalista		Yes	Yes	Yes	In some cases	Yes	Yes	Yes	In some cases	Yes	Yes

Project meets requirements of principle?
Yes | *In most cases* | *In some cases* | *No.*

involved in many of the stages identified as part of a process of scientific inquiry (**Table 2**).

All projects actively involve fishers, usually at several project stages. Citizens (principally fishers but also community members) have been trained to conduct scientific tasks such as collecting biometric data, installing and removing oceanographic equipment, conducting underwater visual transects, species ID and completing fisheries logbooks for their community's catches. All projects have produced genuine scientific outcomes, whether that be peer-reviewed science (e.g., Torreblanca-Ramírez et al., 2008; Erisman et al., 2012; Gherard et al., 2013; Fulton et al., 2018; López-Rocha et al., 2018), technical reports, science-based fisheries management (e.g., calculating recommendations for total allowable catches for corvina and clam in the Gulf of California), or adjusting fishing seasons due to changes in temperature (for example the sea urchin fishery of Baja California where fishers adjust their behavior based on data from the temperature sensors (A. Hernandez-Velasco, personal communication)). Unexpected scientific discoveries have also been documented, particularly range extensions of tropical species due to warming waters (see citations in **Table 3**).

Fishers benefit from the projects through increased learning experiences, training, better understanding of their ecosystem, and in some cases, increased social standing, for example the "*buzos-monitores*" (survey divers) have become spokespeople for their communities (Fulton et al., 2019). Scientists also benefit, as trust between both sectors increases during the co-design and operation of projects, opening the potential for new investigations with a sector that has traditionally been cautious of outsiders (Mackinson and Wilson, 2014). The incorporation of traditional ecological knowledge in to research design also increases efficiency as fishers guide aspects such as site selection. Additionally, fisher-citizen scientists have begun to organize themselves, with examples of groups of fishers in the Corvina fishery, Bahía de Kino, and Banco Chinchorro forming civil society organizations to allow them to continue the citizen science schemes independently from the original project organizers. In the case of Bahía de Kino, nine fishers created the CSO "*Grupo de Monitoreo Submarino y Análisis de Cambio Climático*" (Submarine and Climate Change Analysis Team) in 2011 and have since been hired by the National Commission of Natural Protected Areas (CONANP) and larger CSOs to conduct monitoring in marine reserves and train other fishers as part of peer-to-peer learning exchanges.

Whilst meta-data is publically available for some of projects (e.g., Mascareñas-Osorio et al., 2017; Comunidad and Biodiversidad, 2018; Palacios-Abrantes et al., 2019) in public repositories, project data are not publically available in open access databases. The exception to this rule is Naturalista, where all information is immediately published online, can be consulted by anybody with internet access, and can be downloaded in full. For most projects, particularly in the fishery and marine reserve case studies, data were available to project participants upon request and were shared privately with participants and management bodies (i.e., CONANP, CONAPESCA and INAPESCA). Interestingly, the principle reason that data are not publically available stems from the fishing community itself and is related to the ethical consideration of the activities. Despite fishing a federal resource (a common good), fishers are cautious about publically sharing specific information about local stock health due to concerns about other fishers ("outsiders") using this information to their detriment. Specific examples of this include fishers requesting that coordinates of fish spawning aggregation sites or abundance data on high-value benthic resources (e.g., abalone) inside marine reserves are not shared. Their caution is understandable, examples of outsiders pilfering no-take zones once they hear about stock recovery are not uncommon (Cudney-Bueno et al., 2009).

Fishers are acknowledged in publications, consistently in the acknowledgments (e.g., Erisman et al., 2012; Fulton et al., 2019), but also as co-authors (e.g., Micheli et al., 2012; Fernández-Rivera Melo et al., 2015b; Rossetto et al., 2015). As with other citizen

TABLE 2 | Fisher involvement in the eleven stages of scientific inquiry (Wiggins and Crowston, 2011) in identified projects.

Typology of volunteer involvement **Type of Project**		**Define question**	**Gather information**	**Develop hypothesis**	**Design study**	**Collect data**	**Analyze samples**	**Analyze data**	**Interpret data**	**Draw conclusions**	**Disseminate results**	**Discuss results and ask new questions**
Fisheries monitoring	Catch monitoring	In most cases	In most cases	In most cases	In most cases	Yes	NA	In some cases	In most cases	In most cases	In most cases	Yes
	Effort and spatial monitoring	In most cases	Yes	No	Yes	Yes	No	No	In some cases	In most cases	In most cases	In most cases
UVC in marine reserves		Yes	Yes	In some cases	Yes	Yes	NA	No	In most cases	Yes	Yes	Yes
Oceanographic monitoring		Yes	In some cases	Yes	Yes	Yes	NA	In some cases	In most cases	Yes	Yes	No
Naturalista		In some cases	No	In some cases	In some cases	Yes	NA	No	Yes	Yes	Yes	Yes

Project involves fishers at this stage?

Yes | *In most cases* | *In some cases* | *No* | *NA*.

TABLE 3 | Direct impacts generated by the case study citizen science projects.

		Changes to fisheries regulations and management	Contribution to management plans and programs (CONANP/CONAPESCA)	Appropriation of project/Changes of perspective	Improved conservation/ sustainable fisheries	Detection of changes	Examples of scientific contributions
Fisheries monitoring	**Catch monitoring**	Data have been used to calculate total allowable catch	Data have contributed to the creation of species specific management plans and MPA conservation objectives	Improved understanding of reproductive cycles, stocks and increased respect for fisheries regulations. Creation of community spokespeople	Increased respect for fisheries regulations and data used to support Fishery Improvement Projects and moves toward sustainability	Detection of shifting fishing seasons and catch composition	Danemann and Peynador, 2002; Torreblanca-Ramírez et al., 2008, Gherard et al., 2013; Erisman et al., 2017; Aburto-Oropeza et al., 2018; Bolser et al., 2018; López-Rocha et al., 2018; Cota-Nieto et al., 2018
	Effort and spatial monitoring	Data have been used to calculate total allowable catch and design strategies to support fishers affected by international embargos	Data have contributed to the creation of species specific management plans and MPA conservation objectives	Increased participation in decision making	Fishers/cooperatives have used information to auto-regulate and adjust effort	Detection of shifting fishing seasons and fishing grounds	Paredes et al., 2010; Erisman et al., 2012; Erisman et al., 2014; Erisman et al., 2015; Johnson et al., 2017; Erisman et al., 2017; Jiménez-Esquivel et al., 2018
UVC in marine reserves		Creation and adaptive management of 204 km^2 of no take zones	Data collected to evaluate eight MPAs and 39 no take zones	Fisher-surveyors become community spokespeople	Increased area of no-take and adaptive management	Monitoring has detected range extensions of seven species, likely due to warming waters	Martínez-Torres et al., 2014; Fernández-Rivera Melo et al., 2015a,b, 2018; Hernández-Velasco et al., 2016; López-Fuerte et al., 2018; Fernández-Rivera Melo et al., 2018; Fulton et al., 2018; Fulton et al., 2019
Oceanographic monitoring		Data used to support local closed season change for sea urchin fishery	Data shared with MPA managers to inform conservation objectives	A network of cooperatives/ communities collaborating and communicating to maintain sensor networks	Improved fisher understanding of oceanographic processes and climate change	Hypoxia events, temperature spikes with resulting impacts on benthic species	Micheli et al., 2012; Woodson et al., 2019
Naturalista		No	Unknown	5,762 sightings in two fishing communities in 6 months	Unknown	Addition of new species to international database. Detection of range extensions	

science projects, the number of academic publications stemming from the collaborative research is likely underestimated (Follett and Strezov, 2015) and recognition could be improved for cases where data are reused or repurposed. Recognition of data for fisheries and conservation management decisions does occur, but often informally. Data collected contribute to the conservation objectives of federal marine protected areas, with CONANP providing funding to community groups to conduct environmental surveys, for example in Isla San Pedro Mártir Biosphere Reserve, or Bahía de Loreto National Park. In fisheries, INAPESCA remains the central authority responsible for fisheries science in Mexico and data collected have contributed toward the calculation of recommendations for total allowable catches and establishment of no-take zones, and although data are not officially recognized as citizen science data, they have been used by INAPESCA to justify management recommendations.

Fishers are involved in most stages of scientific inquiry (**Table 2**; Wiggins and Crowston, 2011), with the exception of sample analysis (which for most cases does not apply, but remains technically difficult, for example, involving fishers in analyzing genetic samples which are conducted away from the community) and data analysis. Most projects are co-created (develop hypothesis and study design), with ideas from fishers and researchers contributing to the study design, methodology and the selection of study sites and target species. These ideas include the need to collect information on important but vulnerable fishery species (e.g., the corvina fishery, Karr et al., 2017), abnormal events (e.g., hypoxia, Micheli et al., 2012), or in newly created no take zones (e.g., Corredor San Cosme-Punta Coyote in Karr et al., 2017 or Fulton et al., 2018). Data collection always involved fishers. When data collection is periodic (e.g., marine reserve monitoring), fishers usually work alongside researchers who also collect data. For long term fisheries monitoring, trained fishers operate independently in their communities with periodic follow up from researchers.

Formal data analysis is almost exclusively conducted by scientists affiliated with national and international universities, fisheries research centers (CRIP-INAPESCA) and CSOs. Most commonly, analyzed data are presented back to fishers during formal events such as community meetings and cooperative assemblies. During this participatory meetings fishers can discuss, draw their own conclusions, and ask new questions.

Whilst project design and data collection followed a consistent process in each of the project types, in some scenarios two parallel pathways emerged after data were collected. As **Table 2** shows, fishers are not commonly involved in data analysis. This step typically involves researchers from CSOs and universities cleaning and processing the data before conducting statistical analyses, which are then interpreted before being disseminated within the fishing communities during formal events. Weeks to months may pass between the fishers collecting the data, seeing processed results and being able to draw conclusions and discuss. However, in some scenarios, such as marine reserve monitoring, a much more rapid feedback loop begins the moment the fisher-citizen scientist leaves the water after a survey (**Figure 2**). As the supervising scientists are leaving the community, the fisher-citizen scientists are already analyzing the data *they saw* using the same traditional ecological knowledge system that they use to make daily decisions on where to fish. The fishers then communicate this interpretation to their community through the traditional channels. This process can be complete in hours to days, much faster than the scientific system employed by the citizen science project managers.

Naturalista allows citizens from any part of Mexico to participate at any time, and currently has over 31,000 users. Marine projects can be created by any user to collect data on specific species or areas. Despite this, marine data are sparse, of the 1,356,030 data points, less than 1.4% are marine fish and invertebrates. In 2018, 21 coastal community members were trained to use the app, to pilot a project to increase marine data in priority areas. In 6 months, this resulted in 5,762 new data points of which 23% were marine fish and invertebrates. Users of the platform can also make their own projects, selecting target species and study areas. Due to the open science nature of the platform it is difficult to verify the impact in terms of scientific publications. It is, however, a powerful tool for documenting Mexican biodiversity through the participation of the general public although, at present, it favors terrestrial ecosystems.

DISCUSSION

The marine citizen science projects in this review present similar advantages and difficulties to those highlighted in other research (e.g., Conrad and Hilchey, 2011; Roy et al., 2012; Theobald et al., 2015). The inherently collaborative nature of citizen science projects compensates for many of these difficulties. When fishers identify with the long term goals, and see what they too have to gain, they are willing to co-invest in the activities (with their time and equipment), helping drive project longevity. It also serves to incorporate traditional ecological knowledge in to mainstream science projects, build synergies, and helps develop and answer questions in a constantly changing environment. Most case studies meet the Ten Principles for Citizen Science and the majority of the eleven stages of scientific inquiry providing validation and legitimacy for the projects. The Ten Principles (Robinson et al., 2018) are an effective framework against which projects can be assessed and should be part of the design of all future citizen science projects in Mexico, not just in fisheries.

As in other reviews (Roy et al., 2012; Aceves-Bueno et al., 2015; Theobald et al., 2015) our marine citizen science case studies require considerable investment on the part of the project leaders (in this case CSOs and researchers) and participants, both in time and equipment. The projects have been successful because project leaders provide constant follow-up and invest heavily in creating capacity in each community. Equipment costs are not insignificant, with the purchase and maintenance of SCUBA gear, boat time and technology needing to be considered for the lifetime of the project. This is an important consideration that has yet to be fully resolved. None of the case study projects are designed to end, and all currently depend wholly or partially on philanthropy. Steps must be taken, in collaboration with the fishers, government agencies, philanthropic organizations and researchers to institutionalize and assure funding for the projects, if the goal is to maintain them indefinitely.

As a "top-down" national-level citizen science project, Naturalista, differs from the others. Its scientific contributions are significant with 19 species discoveries (although none are fish), 29 new sightings for Mexico and 747 reports of

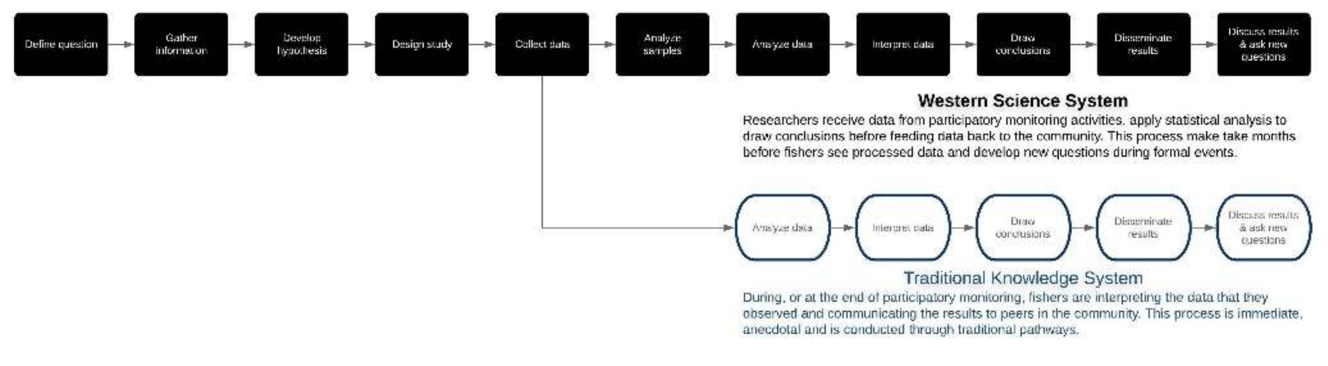

FIGURE 2 | The emergence of parallel pathways by researchers and fishers after data collection.

invasive species (Tello, 2018). Challenges include significantly increasing the number of marine sightings (considering the difficulties discussed by Roy et al., 2012), increasing photo quality, and limited internet connectivity in remote regions (Tello, 2018). The specific training in Naturalista for members of fishing communities has proved effective, significantly increasing the proportion of fish species reported and should be rolled out throughout coastal communities. Many fishers in Mexico have smartphones, using them daily for communication with family members, commercialization and social media (Gastelum et al., 2015). There is considerable potential for scaling this model as it bypasses some of the pitfalls mentioned in the previous paragraph.

Whilst the goal of this paper is not a review of the quality of the data produced by citizen science, the body of peer-reviewed scientific literature produced from the projects (see **Table 3**) and periodic evaluations (Fulton et al., 2019) show that scientists from leading research institutions are willing to use the information, putting these projects in the 12% of biodiversity citizen science projects that contribute to the scientific literature (Theobald et al., 2015) and meet the targets of the principles. Involving fishers in citizen science also encourages interactions between stakeholders and has produced concrete conservation successes. Data from underwater visual census and landings, have been used to justify the creation of 39 no take zones (either as legally recognized "fish refuges" or voluntary marine reserves, see Karr et al., 2017 for an example) and evaluate eight federal marine protected areas. Fisheries data have contributed to fisheries management in several high-value and important fisheries such as corvina, yellowtail, lobster, octopus and clam. Some of these fisheries are currently in Fishery Improvement Projects on route to eco-certifications and continued data collection is a necessity. Trained fishers are able to act as early warning systems. Fishers have provided information to detect shifting fishing seasons and catch compositions, allowing science-based management decisions to be put in place quickly. These actions are often informal as changes to fisheries regulations can take considerable time. Two examples of this are fishers from Baja California using information from oceanographic sensors to informally shift their sea urchin fishing season to cooler periods when urchin gonads are undeveloped, and fishers in the northern Gulf of California identifying changes in catch composition and fishing grounds due to shifting seasons, and adapting their activities accordingly. Finally, participation in scientific processes and the creation of trust between fishers and researchers means that fishers report unusual events. Seven papers have been published on range extensions or first sightings due to information provided by fishers (Martínez-Torres et al., 2014; Fernández-Rivera Melo et al., 2015a,b, 2018; Hernández-Velasco et al., 2016; Hernández et al., 2018; López-Fuerte et al., 2018) and fishers were the first to detect hypoxia events in the Pacific Ocean due to shifts in the California Current (Micheli et al., 2012; Boch et al., 2018).

Fishers are not regularly involved in data analysis, but have found ways to overcome the time lag that traditionally occurs between data collection and feedback (Robinson et al., 2018). The analysis in each of our case studies is conducted by researchers affiliated with universities or CSOs. This may take months and can cause disillusion amongst the fishers as they are used to working on short time frames with immediate results, and have become accustomed to researchers collecting data on their fishery and then never returning to feedback the information. The traditional networks that fishers use to transmit information about their daily catch, fishing grounds and seasonal patterns of productivity are appropriated to share information about the citizen science projects. Project leaders must adapt to this situation as it can have positive and negative consequences. If a fisher who conducts a visual census sees a positive change in a species in the marine reserve they can quickly become an effective proponent of reserves in their community. Conversely, fishers often expect to see rapid changes in the marine environment following a management or conservation action and this can sometimes lead to disillusion or frustration which then permeates through the community.

Despite the success of these case studies, the potential of citizen science in Mexico remains untapped. By 2030, Mexico's 150 coastal municipalities (Diario Oficial de la Federación, 2018) will have a predicted population of 60 million (Fuentes et al., 2017), many of whom will depend heavily on coastal resources. Mexico's small-scale multi-specific fisheries are data-poor and significant management reform is considered necessary (Mangin et al., 2018). Current Mexican fisheries laws do not provide many formal opportunities for citizen science, and fisheries investigation remains the domain of INAPESCA. However, significant efforts have been made to broaden the national fisheries agenda, introducing cross-cutting issues related to the socioeconomic aspects of fisheries and an ecosystem approach to fisheries management (INAPESCA, 2018). The Mexican legal framework regarding social participation remains limited. Under LGPAS, participation is mainly contemplated through RNIIPA and the law does not contemplate the formal inclusion of CSOs (beyond those registered as research organizations). In practice, social participation in research has occurred. INAPESCA regularly considers citizen-produced data during field studies, resource evaluations or for producing technical reports, and fishers often participate in investigations alongside INAPESCA researchers. However, the omission of citizen science from the national legislation does not credit the users who provide data, nor the institutions that use the data for resource management.

At a time when the ivory tower of scientists is threatened by an increasing distrust in experts (Fairbrother, 2017; Lamberts, 2017), and crucial environmental topics such as climate change pass from the scientific to the political realm, citizen involvement in scientific research becomes ever more important. The stakeholders covered in this paper have made adaptive management decisions at the local level, as suggested by Aceves-Bueno et al. (2015), as fisheries science, generated in data-poor fishers, at the local scale and on topics of interest for the fishers, is trusted by the fishers. Scaling to cover regional fisheries, or include in the national agenda, however, remains a challenge: as Ostrom et al. (1999) documented, having higher numbers of participants increases complexity and potential for conflict between interlinked CPRs (for example, multispecific fisheries), both of which are affected by the uncertainty of climate change. CSOs have played a key role in facilitating this change in Mexico, acting as intermediators between fishing communities and fishery and conservation managers (Espinosa-Romero et al., 2014), whilst producing considerable scientific output (Lopez-Olmedo et al., 2019), but adoption of citizen science by Mexico-based researchers has been slow. The limited participation of Mexican academics in citizen science is a topic that needs to be further explored. Many of the publications generated by our case studies are published by researchers affiliated with CSOs or foreign research institutions. The vertical nature of research in Mexico likely plays a role, as does distrust in citizen science data, the reward system of the National Council of Science and Technology (CONACYT) which critics say discourages collaboration (Altbach, 2015), and established fisheries research priorities (Espinoza-Tenorio and Espejel, 2012). For example, when 202 fisheries research projects financed by CONACYT between 2000 and 2009 were analyzed, most projects were found to focus on ecosystem and commercial species, without taking into account social aspects of fisheries, and there were no transdisciplinary projects that incorporated traditional ecological knowledge and fisher participation (Espinoza-Tenorio and Espejel, 2012), or that developed research using a citizen science approach.

Incorporating citizen science in to policy is a further challenge. Environmental agencies and other government institutions can be hesitant about using citizen science data as it is deemed to be of lower quality than their traditional data sources (Bonney et al., 2014; Owen and Parker, 2018). Hyder et al. (2015) identified several factors that have affected uptake in marine ecosystems, many of which are reflected in this study. Citizen science is not recognized by Mexican fisheries legislation as an official data source, and INAPESCA retains the sole responsibility for scientific decision making in fisheries. However, as we can see from many of the case studies, information from citizen science *is* used to inform management decisions (e.g., stock assessments, total allowable catches and no-take zones), it is just not formally recognized. Mexico should take note of the European Environment Agency (2011) and United Nations Environment Programe (UNEP, 2017) who have both identified the contribution of citizen science data as key components in the drive toward sustainability. It would also be economically beneficial - the contribution of French volunteers to the CBD targets has been estimated at between €0.67 and €4.42 m per year, effectively presenting a saving to the government (Levrel et al., 2010). Mexico's small contributions to fisheries research have been documented elsewhere (Espinoza-Tenorio et al., 2011) and as such an increased focus on participatory research could provide significant opportunities and savings. Delayed fisheries reform has been predicted to cause significant losses in Mexican fisheries (Mangin et al., 2018) and the inclusion of citizen science in management reforms aimed at improving fisheries sustainability could have considerable net benefits to the nation from a purely economic standpoint, without even considering the social benefits of participatory research.

The need to potentialize and formalize citizen science in Latin America as a whole is also apparent. The creation of the Citizen Science Global Partnership in 2017 supports this hypothesis. The Partnership[2] aims to be a "network-of-networks" for citizen science at the global level. The steering committee consists of the United States, European and Australian Citizen Science Associations, with invited observers from the African Citizen Science Association and CitizenScience.Asia. Latin America is notable by its absence. Chandler et al. (2017) found the citizen science contributions to international biodiversity monitoring were mostly located in Europe, North America, South Africa, India and Australia. Only four of the 211 projects in North America take part in, or partially in, Mexico (Chandler et al., 2017). Whilst Latin America has the highest number of "mega-diverse" countries of any region, and thus great potential for biodiversity citizen science, only Chile[3] appears to have a formalized and active citizen science association. This situation may be slowly improving; representatives from >40 organizations conducting citizen science in Latin America met in Mexico City in September 2018 and identified the need for a regional network of practitioners (Tello, 2018). This should continue and be supported by national governments. The legal frameworks adopted in the U.S., with the

[2]http://citizenscienceglobal.org
[3]http://cienciaciudadana.cl

Crowdsourcing and Citizen Science Act of 2016, created in order to "*to encourage and increase the use of crowdsourcing and citizen science methods within the Federal Government to advance and accelerate scientific research, literacy, and diplomacy, and for other purposes*" (Crowdsource and Citizen Science Act of 2016), could provide a benchmark. As a result of this legal framework, the U.S government has developed three key components to promote citizen science and crowdsourcing; a catalog of federally supported projects, a toolkit to assist federal practitioners in citizen science projects, and online communities.

Open Science is a key part of citizen science and public participation in research (Hecker et al., 2018b). In 2014 Mexico's president signed amendments to the Science and Technology Act, the General Education Act, and the Organic Law of the National Council for Science and Technology giving all Mexicans free access to scientific and academic production, which have been partially or fully financed by public funds. More recently, in 2017, an open science policy was published, formalizing these amendments. We consider these to be important steps that will potentialize both public access to data and encourage citizen participation in science in Mexico.

The combination of successful examples of citizen science, such as those discussed in this article, as well as the institutional and legal frameworks being put in place in Mexico, suggest that citizen science will play an ever-growing role in Mexican fisheries. Considerable barriers are still to be overcome to ensure that scaling and replication are made possible and that the participation of the fishers, along with the data generated, serve to improve fisheries sustainability, education, co-responsibility for resources and to protect livelihoods in coastal communities. Citizen science will continue to be a growing field and current and future projects should look to follow current examples, and evaluate themselves against existing frameworks such as the "Ten Principles of Citizen Science" (Robinson et al., 2018) and the Stages of Scientific Inquiry (Wiggins and Crowston, 2011) to ensure that they remain true to the goals of citizen science.

CONCLUSION

Structured citizen science programs in Mexico's small-scale fisheries provide a wealth of data and opportunities, for fishers, researchers and managers. Data generated have been used to evaluate stocks and habitat, detect the impacts of climate change and increase our knowledge on fisheries. It has also empowered a network of local leaders, who are now transmitting a message of environmental stewardship in their communities. Challenges, however, remain, particularly regarding how to incorporate these growing sources of data in to national policy, garner official recognition, and use the data for adaptive management. The institutionalization and adoption of citizen science by the government agencies responsible for managing fisheries and by researchers based at Mexico's universities could help these models scale in to national data collection networks supported by the resource users.

DATA AVAILABILITY

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

AUTHOR CONTRIBUTIONS

SF conceived the idea. SF, CL-S, AW, FF-C, CG, FF-RM, SY, MO-V, DF, and ET-B analyzed the data, discussed the results, and wrote and edited the manuscript. All authors provided valuable contributions.

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