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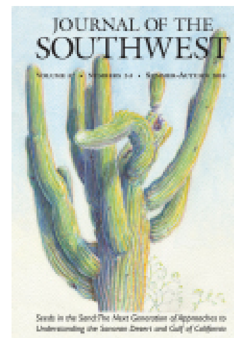

Journal of the Southwest, Volume 57, Numbers 2 and 3, Summer-Autumn 2015, pp. 337-390 (Article)

Published by The Southwest Center, University of Arizona
DOI: 10.1353/jsw.2015.0003

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This paper is dedicated to the memory of Miguel Fernando Lavín (1951–2014), a pioneer of the PANGAS initiative who dedicated his life to advance the field of oceanography in Mexico. He was a visionary who connected oceanographers, marine conservationists, and fisheries managers.

Introduction

Small-scale fisheries contribute about half of global fish catches, or two-thirds when considering catches destined for direct human consumption (FAO 2014). Small-scale fisheries play an important role in food security and nutrition, poverty alleviation, equitable development, and sustainable use of natural resources, providing nutritious food for local, national, and international markets. More than 90% of the world's fishers and fish workers (those who work in pre-harvest, harvest, and post-harvest activities, including trade) are employed by small-scale endeavors that underpin local economies in coastal, lakeshore, and riparian ecosystems. This, in turn, generates multiplier economic effects in other sectors (FAO 2014). These activities may be a recurrent sideline undertaking or become especially important in times of financial difficulty. Small-scale fisheries represent a diverse and dynamic sector, often

Journal of the Southwest 57, 2–3 (Summer–Autumn 2015) : 337–390

characterized by seasonal migration. They are strongly anchored in local communities and reflect historic links to fishery resources and traditions. Many small-scale fishers and fish workers are self-employed and are direct food providers for their household and communities. Most small-scale fisheries lack formal assessment, and the development of the sector over the past four decades has led to overexploitation of resources in several places across the globe. Recent studies estimate unsupervised small-scale fisheries are in substantially worse condition than fisheries where stocks have been assessed (Costello et al. 2012). Furthermore, the health of marine ecosystems and associated biodiversity are a foundation for the livelihoods and well-being of small-scale fishers.

In 2005, the PANGAS project was created with funding from the David and Lucile Packard Foundation as part of the Foundation's initiative to support ecosystem-based management (EBM) for sustainable coastal and marine systems in various parts of the world (mainly the Western Pacific, U.S. West Coast, and the Gulf of California, Mexico). PANGAS is an acronym in Spanish that stands for Pesca Artesanal del Norte del Golfo de California: Ambiente y Sociedad (Small-Scale Fisheries of the Northern Gulf of California: Environment and Society). "Pangas"

Figure 1: Pangas in the Gulf of California. Photo by Adrian Munguía-Vega.

also refers to the small skiffs (6–8 m in length), made of fiberglass, with 55- to 150-horsepower outboard motors. These are versatile boats that can use multiple types of fishing gear, hold two to three fishers, and are the primary vessel used by small-scale fishers in the northern Gulf of California (NGC), México (Cudney-Bueno and Turk-Boyer 1998) (figure 1).

From its inception in 2004 as a "fuzzy"—yet ambitious—idea of ultimately coupling biophysical and human processes for management of small-scale fisheries at a regional scale (the NGC), the idea quickly transitioned to the assembly of individuals who could bring a broad, multidisciplinary perspective for research and management of small-scale fisheries. PANGAS was structured as a multidisciplinary and bi-national initiative with the goal of developing and testing an interdisciplinary framework for ecosystem-based research and management of small-scale fisheries in the NGC ecosystem and increasing capacity for ecosystem-based research in the Gulf of California. PANGAS grew as a consortium of six leading academic institutions and nonprofit organizations with experience in the NGC, with the direct involvement of 50+ researchers, students, fishers, and management practitioners. Partners in the project have included two leading academic institutions from the Southwest United States (University of Arizona's School of Natural Resources and the Environment [UA-SNRE] and University of California Santa Cruz [UCSC]) and one from northwest Mexico (Centro de Investigación Científica y Educación Superior de Ensenada, Baja California [CICESE]). It also included three leading Mexican nonprofit organizations with decades of experience working in the NGC (Comunidad y Biodiversidad, A.C. [COBI], and Pronatura Noroeste A.C. [PNO]) and in both sides of the U.S.-Mexico border (Intercultural Center for the Study of Deserts and Oceans [CEDO, Inc. and CEDO, A.C.]).

While there had been other initiatives aiming to link biophysical and human processes for management of fisheries in the NGC, these were disaggregated from a broader regional context and lacked the scientific focus and financial investment to try to answer complex questions useful for management purposes at regional scales. The bet was that the PANGAS model would allow us to better understand the complex interactions between small-scale fisheries and the biophysical and institutional processes within which they operate. More importantly, it would help direct policy toward a more holistic and sustainable management of the region's marine resources.

This paper documents the story of the PANGAS initiative in the past

10 years, from its inception to its development phases, with achievements and lessons learned. The paper is divided into three main sections: (1) a short description of the different phases of PANGAS; (2) a description of the PANGAS framework and the distinct biophysical and governance components developed within the initiative; and (3) a section describing the development of multidisciplinary tools, capacity building, and lessons learned after a decade of interdisciplinary collaborative research, training, and management.

PANGAS Phases

The PANGAS story has four phases. In the first phase (2005–2008) PANGAS partners developed a framework for ecosystem-based research on small-scale fisheries in the NGC and conducted needed research concentrating on understanding and characterizing the small-scale fisheries in the NGC (biophysical, socioeconomic, and governance elements) by answering some key questions:

1. Which are the main fishery resources?
2. What are the spatial/temporal distributions of fishing activities?
3. What are the social-biophysical linkages affecting this distribution?
4. Which and where are the critical habitats for the maintenance of small-scale fishery resources?
5. What are the life histories of commercial species, especially regarding growth and reproduction?
6. What are the social institutions in which small-scale fisheries operate?
7. What are the levels of connectivity among and between fishery stocks and the underlying oceanographic circulation processes affecting larval retention and dispersal?

During this time period, the project also focused on building an education program for students from Mexico and other parts of Latin America interested in small-scale fisheries as well as training commercial divers from various communities to conduct underwater monitoring of rocky reef ecosystems.

In phase 2 (2008–2011) all the information collected was processed and incorporated as technical opinions for a variety of fisheries management and marine conservation tools such as Mexico's National Fisheries Chart (*Carta Nacional Pesquera*); fisheries management plans and spatially explicit ordinance programs (*programas de ordenamientos*); conservation and management plans for marine protected areas (MPAs); Environmental Impact Assessments (*Manifestaciones de Impacto Ambiental*, MIA); and an ecosystem model, among other things.

In the third phase of PANGAS (2011–2013) the team defined baseline indicators for some of the conservation and management tools that were in place in the NGC and extended PANGAS's monitoring program to work in collaboration with various governmental agencies.

Finally, the goal in the current phase (2014–2016) is to continue sharing the accumulated experiences, data, and science through research, education, and synthesis of information to solve more complex questions within the NGC and in other parts of Mexico, and determine how PANGAS will evolve.

PANGAS Framework

The performance of small-scale fisheries is affected by complex interactions and feedbacks between biophysical and social systems. To understand this complexity requires not only the analysis of various subcomponents of interconnected systems but also a means to integrate these into comprehensive and useful policy outcomes (Cudney-Bueno et al. 2007). One way to achieve such integration is offered by the Institutional Analysis and Development (IAD) framework (*sensu* Ostrom et al. 1994), which PANGAS adopted and used as an overarching methodological approach. The IAD framework is a tool for investigating the use of common-pool resources (CPRs),[1] commons dilemmas, and institutional solutions to those dilemmas (Pomeroy and Beck 1999; NRC 2002). This framework has been used extensively to design policy experiments and empirically test theories and models linking institutions (the human-crafted rules and norms) and the sustainability of CPRs (*sensu* Ostrom et al. 1994; Pomeroy and Beck 1999; Rudd 2004).

Under the IAD approach, data were collected in the "physical world" (i.e., physical oceanography, larvae retention and dispersal, species' life histories), the "cultural world" (i.e., fishing organizations, social norms), and the "set of rules" (i.e., government-crafted fishing rules, local arrangements) that govern the common-pool resources situation (*sensu* Ostrom et al. 1994). We assumed that given a set of external ecological, social, and institutional constraints, fishers consider the costs and benefits of various behaviors, and act according to their perceived incentives (Rudd 2004). The aggregate patterns of interaction (i.e., fishing effort) lead to specific outcomes (landings, degree of use of specific areas) that can be evaluated according to relevant criteria (e.g., Would it be feasible to establish no-take zones under a particular setting? Are harvest levels beyond a socially and ecologically sustainable threshold?). In the following sections we will present a synthesis of the main elements developed within the PANGAS research framework (figure 2).

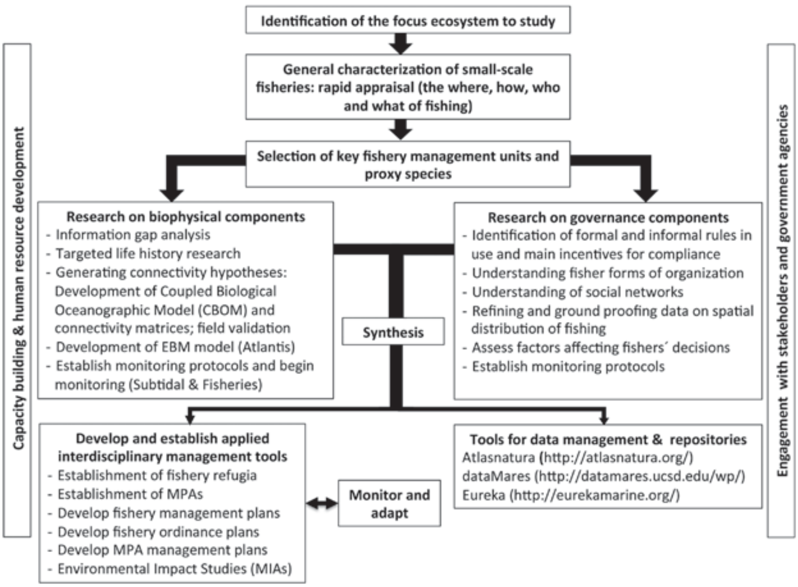

Figure 2: PANGAS ecosystem-based research framework. Arrows show the development of each element over time, while long vertical boxes on the sides show elements that were present during the entire project.

Identification of the Ecosystem and Fishing Activities

The Gulf of California (GC) is a hotspot of marine biodiversity recognized worldwide (Roberts et al. 2002), with almost 6,000 species of macroscopic marine animals (Brusca et al. 2005). It sustains high levels of primary productivity year-round as a result of strong tidal mixing and wind-driven coastal upwelling (Lavín and Marinone 2003). The annual total catch in the GC approaches 500,000 metric tons (MT) (Enriquez-Andrade et al. 2005). Fishing, both large and small scale, is a predominant economic activity throughout the region. It generates over 50,000 jobs involving approximately 26,000 vessels, of which approximately 25,000 are small-scale boats (Cisneros-Mata 2010). The GC produces 77% of the fisheries within Mexico by volume, which represents 51% of the value of the fisheries in the country and concentrates half of the jobs related to fisheries in the nation (IMCO 2013). It is estimated that 85% of the fisheries in the GC are either at their maximum sustainable yield or overexploited (Cisneros-Mata 2010). In Mexico it is estimated that illegal fishing represents about 56% of the national production, which is sold mainly to the United States, central Mexico, and Asia (IMCO 2013).

The GC can be divided into three regions (northern, central, and southern) according to the distribution of marine flora and fauna and unique oceanographic conditions (Walker 1960; Round 1967). For the purposes of the PANGAS project, the NGC is defined as an area of 60,000 km^2 between mainland Mexico and the Baja California peninsula, beginning in the Colorado River delta just south of the international border with the United States and continuing south to the edge of the Midriff Islands region and delimited from San Francisquito (Baja California) to Bahía Kino (Sonora), including San Pedro Mártir Island (figure 3).

The NGC displays about half (47%) of the biodiversity of the Gulf of California, including 2,258 species of marine invertebrates, 367 fish species, 7 marine reptiles, 24 marine mammals, and 146 aquatic birds (Brusca et al. 2005). It also sustains a high number of endemic species, including 128 marine invertebrates, 13 fish species—including the endangered totoaba (*Totoaba macdonaldi*), delta silverside (*Colpichthys hubbsi*), and curvina golfina (*Cynoscion othonopterus*)—and the most endangered marine cetacean in the world, the vaquita porpoise (*Phocoena sinus*), to name a few. Three biosphere reserves are located in the NGC, (1) Alto Golfo de California y Delta del Río Colorado, (2) Bahía de los Ángeles y Canales de Ballenas y de Salsipuedes, and (3) Isla San Pedro Mártir; one national park (Archipiélago de San Lorenzo); a refuge for the critically endangered vaquita porpoise; and four Ramsar sites. The uniqueness of this region is largely the result of the combination of its long geological history, which started with the opening of the Gulf of California and the drift of the Baja California peninsula from mainland Mexico starting ~12 Ma (Dolby et al. this issue), and the presence of distinctive physical and oceanographic features like a complex bathymetry

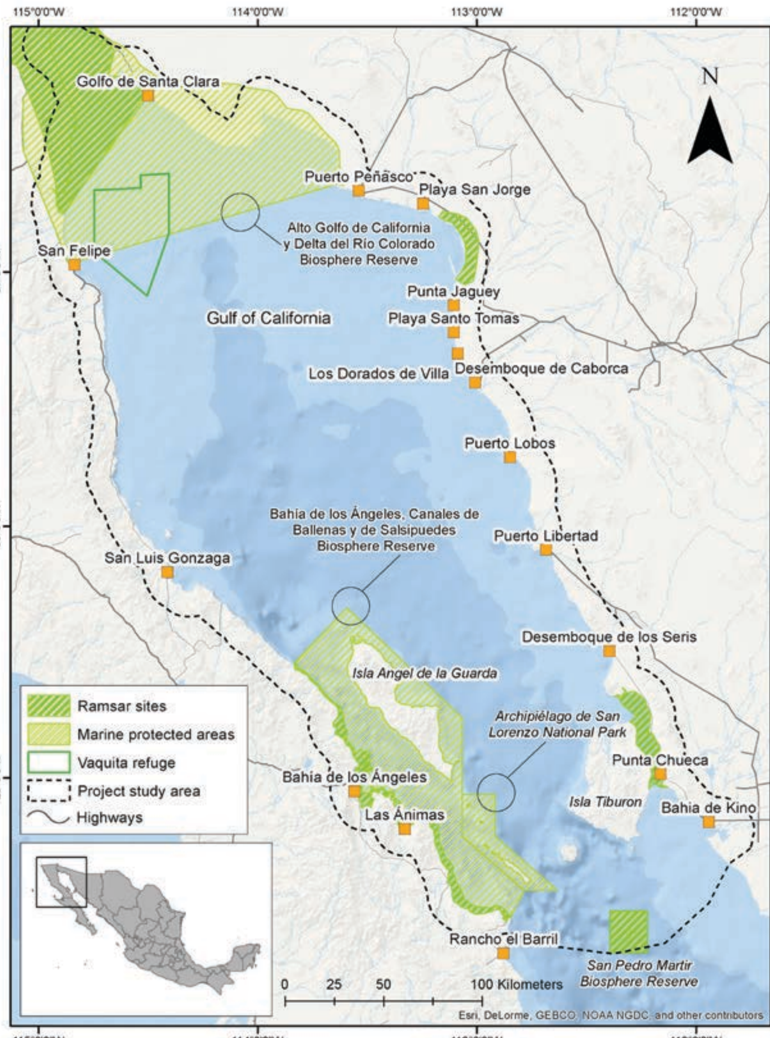

Figure 3: The northern Gulf of California, showing the area studied by PANGAS, marine protected areas, the Vaquita Porpoise Refuge, and Ramsar sites.

with a series of deep basins (e.g., Wagner, Dolphin, Salsipuedes, San Pedro Mártir) and sills, which restrict the circulation between the northern and central GC (Hernandez-Ayon et al. 2013). In its northern part the NGC is relatively shallow (<100 m) while in the south (e.g., Canal de Ballenas) marine canyons reach over 2,000 m deep. The NGC includes 57 islands (including two of the largest in Mexico, Isla Ángel de la Guarda and Isla Tiburón) that are part of a Protected Area for Flora and Fauna in the Gulf of California.

Three oceanographic features are unique to the NGC (Lavín and Marinone 2003). First, the tidal range is the second largest in the world, particularly in the upper GC with a maximum difference between low and high tide of 10 m. Second, it shows an extreme range in seawater temperatures through the year, from a low of 8°C in winter up to 30°C in summer. Third, the entire NGC is characterized by a seasonally cyclonic (counterclockwise) gyre during spring-summer that reverses its direction to an anti-cyclonic (clockwise) gyre during fall-winter (Marinone 2003).

The NGC (between 2001 and 2005) contributed to the Mexican economy with an average annual fish catch of 18,326 MT considering industrial and small-scale fisheries (Erisman et al. 2011). An estimated 80 primary species are targeted (from which ~43 are considered the most important) by more than 3,500 small-scale fishers using over 1,600 pangas, distributed in 17 permanent small-scale fishing communities and other temporary fishing camps (Moreno-Báez et al. 2012). In addition, throughout the region there is an important industrial fishery fleet targeting shrimp and small pelagics like sardine and hake, as well as demersal fisheries of rays, skates, flounder, and angel shark (Lluch-Cota et al. 2007). Shrimp trawling has particularly high rates of bycatch. For example, 26.0% of Mexican trawled shrimp in 2009 was landed in Sonora (10,970 MT), and a recent study in Bahía Kino, Sonora, estimated an average bycatch rate of 85.9% measured by weight (range 54% to 99.2%), including 183 species (97 bony fish, 19 elasmobranchs, 66 invertebrates, and 1 species of marine turtle) (Meltzer et al. 2012).

Characterization of Small-Scale Fisheries: Rapid Appraisal

We implemented three strategies to characterize small-scale fisheries. First, we compiled the literature on the life history of commercially important species for the NGC and developed a database. Second, between December 2005 and July 2006 we visited 17 fishing communities to conduct a rapid assessment (Chambers 1992) of their fisheries, using structured and semi-structured interviews (with a set of closed and open-ended questions). When possible, we participated in fishing activities, engaging in at least one fishing trip representative of each type of fishery (i.e., gillnet fishing, long line, commercial diving, traps). We estimated the number of vessels operating in each site and calculated the required sample size per site (for details see Moreno-Báez et al. 2008, 2010). We then made a random selection of boat captains in each site and conducted a total of 376 semi-structured interviews in all 17 communities. The interview dealt with general social and economic aspects of each fishery and gathered detailed information about the three most important target fisheries for each crew, including a temporal and spatial description of the fishing activities for these species, fishing methods, and spawning sites (Moreno-Báez 2010; Moreno-Báez et al. 2010). A total of 769 species distribution maps were produced during the interviews, and the spatial information was validated in post-survey workshops and integrated into a Geographic Information System (GIS) database (Moreno-Báez et al. 2008, 2010). Third, we implemented a voluntary and confidential logbook program for fishers in 10 communities from January 2006 to December 2007 collecting information about a total of 2,800 fishing trips (PANGAS 2008a). Logbooks for each target species documented the gear used; average capture though the year; fishing costs and profits obtained per kilogram of product; the season; fishing zones; and a general description of the fishery and regulations.

Through the rapid assessment, we identified 73 commonly captured species, from which 43 species were classified as main targets of more than 50% of the communities in the NGC. We found that 40% of these target species are captured primarily during their reproductive season, and 16 species are captured using two or more types of fishing gear (Moreno-Báez et al. 2010, 2012). Fishers used 89% of the 3,000 km of coastline of the NGC and surrounding islands, and 60% of the total area of the region (~60,000 km^2). The method most frequently used to fish the target species was gillnets, followed by diving (with a "hookah" compressor), long lines, and traps. Most communities (13) traveled more than 50 km to reach their fishing grounds, and five communities stood out in their capacity to travel up to 200 km. In addition, we found that 79% of marine protected areas (1,142 km^2) in the region were used to extract 30 main target species. The results also showed a clear seasonal differentiation in species and areas targeted as well as fishing gear and methods used (Moreno-Báez et al. 2012).

From a socioeconomic perspective, the average age of fishers interviewed was 40 years old (range of 17 to 75 years). Forty-three percent of respondents were born in the state of Sinaloa; 68% had between 20 and 40 years of experience fishing in the region; 63% have always been small-scale fishers and 37% have had other occupations prior to becoming fishers (agriculture being the most frequent prior occupation); 67% did not hold other jobs outside of fishing, while 33% had an alternate occupation during some or all of the year; 45% described their job as a "member of a cooperative" and 55% identified themselves as freelance fishers or working for the owner of a fishing permit or for a buyer (PANGAS 2008b).

With regards to fishers' opinions about the main threats to their fisheries, the top five were (in order of importance): (1) bottom trawling for shrimp, (2) overfishing, (3) low market value of their fisheries and high expenses, (4) lack of regulation and enforcement, and (5) the presence of outsider fishers. Their suggestions to solve these problems, also in order of importance, included: (1) regulate fishing permits and active fishing boats, (2) increase enforcement, (3) strengthen or improve commercialization of their products and obtain expert advice to improve fishing cooperatives, (4) adjust and enforce temporal closures for fisheries and regulate fishing gear, and (5) increase their participation in decision making and change fishery legislations (PANGAS 2008b).

Local ecological (LEK) (gathered through additional questions of the survey as well as through longer and focused ethnographic research on three communities) was used to help estimate species abundance trends in the NGC. For example, the data supported a general decline in species abundance across fished and unfished taxa, and showed that older fishers tended to recognize a greater relative decrease in species abundance since 1970 than did younger fishers (Ainsworth 2011). In addition, LEK was useful when estimating the vulnerability of fishing communities to climate change, showing that vulnerability in 12 communities studied in the NGC was lower at sites with relatively lower dependence on fisheries and higher levels of socioeconomic diversification (e.g., Puerto Libertad, Puerto Peñasco, and San Felipe) (Morzaria-Luna et al. 2014).

Selection of Key Fishery Management Units and Proxy Species

Because the small-scale fisheries in the NGC not only use a wide range of fishing gear to target numerous species, but also take place in a variety of habitats (i.e., rocky reefs, sandy bottoms, open waters) and under various institutional settings, a detailed analysis of every fishery was unattainable due to time and budget constraints. In some cases, there was little if any connection between one fishery and another. These realities warranted the need to focus our analyses on identifiable management units. Therefore, in 2007, during the end of the first phase of PANGAS, we developed a strategic plan following the methodology recommended by the Open Standards for the Practice of Conservation[2] methodology. The strategic plan led us to focus on rocky ecosystems and two fishery management units within these: (a) fisheries targeting coastal rocky reefs, and (b) fisheries targeting deep-water rocky reefs.

We decided to focus on these two units for five main reasons:

1. The fisheries that take place on rocky reefs and the species that use and depend on them represent distinct and tangible ecosystems (Cudney-Bueno et al. 2008; Cudney-Bueno and Rowell 2008a,b; Turk-Boyer et al. 2014).
2. Even though rocky reefs cover only a small portion of the GC, numerous studies have recognized the biodiversity value of the rocky reef ecosystems. For example, it is estimated that one-third of all macro invertebrates from the GC can be found at rocky habitats (Brusca and Hendrickx 2010) and many commercially

Table 1. *Conservation targets identified for the NGC small-scale fisheries during PANGAS strategic planning.*

Target	Description
Deep water rocky reefs	Rocky reefs that are deeper than 30 m Physical (including biogenic) structure of the reef
Coastal rocky reefs	Rocky reefs found in subtidal waters up to 30 m deep Physical (including biogenic) structure of the reefs; i.e., *Sargassum* sp. (macroalgae), rhodolith (coralline algae), and black coral beds associated with the reefs
Commercial predatory fish of deep water rocky reefs	Gulf coney (*Epinephelus acanthistius*) Gulf grouper (*Mycteroperca jordani*) Gold-spotted sand bass (*Paralabrax auroguttatus*)
Commercial predatory fish of coastal rocky reefs	Groupers: leopard grouper (*Mycteroperca rosacea*), Gulf grouper (*Mycteroperca jordani*) Snappers: yellow snapper (*Lutjanus argentriventris*), barred pargo (*Hoplopagrus guentheri*)
Commercial benthic invertebrates of coastal rocky reefs	Mollusks: rock scallop (*Spondylus limbatus*), black murex snail (*Hexaplex nigritus*), two-spotted octopus (*Octopus bimaculatus*) Crustaceans: spiny lobster (*Panulirus spp.*) Echinoderms: sea cucumber (*Isostichopus fuscus*)
Coastal estuaries	Mangrove estuaries Non-mangrove estuaries Blue crab (*Callinectes bellicosus*)

important fishes form spawning aggregations at rocky reefs (Sala et al. 2003).

3. Rocky reefs can be used as proxies to address other ecosystem services; for example, snappers targeted by small-scale fishers at rocky reefs use estuaries as nursery habitats (Aburto-Oropeza et al. 2009) and, similarly, groupers recruit to macroalgae beds (*Sargassum sp.*) found also at rocky reefs (Aburto-Oropeza et al. 2007).
4. We had built strong support and ties with fishers targeting rocky reefs, particularly commercial divers.
5. We could provide more meaningful research and management insights given the collective experience of all of PANGAS's collaborators working on these systems.

Once we identified rocky reefs as the main management unit, we selected six specific targets (table 1), and identified threats and opportunities (table 2).

Table 2. *Identified threats and opportunities for the NGC small-scale fisheries during PANGAS strategic planning for the NGC.*

Target	Threats	Opportunities
Coastal rocky reefs	Overfishing Fishers targeting spawning aggregations Open access or near open access fishing situations Large-scale fish bottom trawling in certain areas Destruction of nursery grounds High fishing effort/fishing effort on the rise	Interest in various communities to establish territorial use rights Current efforts by PANGAS members as well as local stakeholders to establish fully protected marine reserves as well as other types of area-based management schemes Current training and participation of commercial divers in monitoring System boundaries more tangibly defined when compared to pelagic, open water, and even sandy bottom fisheries Most species have high market value and are more prone to market-based management approaches Government interest in the development of regional management plans
Deep water rocky reefs	Overfishing Fishing during reproductive periods Bottom trawling	Small groups of fishers targeting these ecosystems Fishing boundaries more clearly defined between communities without much overlap Species with high export market value

Species selection was based on the following six criteria: (a) collectively they represented a broad spectrum of life histories (i.e., short vs. long pelagic larval duration, PLD); (b) they represented various trophic levels of rocky reef ecosystems; (c) there was strong representation of a particular means of harvest; (d) several distinct communities harvested the species; (e) the targeted species had strong social and economic significance in the region; and (f) reliable information could be obtained for the target species under existing logistical, financial, and time limitations (Cudney-Bueno et al. 2007). Additionally, we included the blue crab (*Callinectes bellicosus*) in the strategic plan even though it was not associated with rocky reef habitat. Although this fishery takes place in sandy habitats, it provided the following opportunities: (1) it was one of the most important fisheries in the region; (2) the fishing boundaries are clearly defined between communities and did not have much overlap, (3) the species was highly valued in the export market; and (4) there was political capital (from the fishing industry and the government) to work toward a potential co-management setting (Cudney-Bueno et al. 2007).

For each of these management units and proxy species/fisheries, we conducted in-depth research on their biophysical and governance components. Following, we present a summary of the approaches used (for details on the overall framework, see Cudney-Bueno et al. 2007).

Biophysical Component

Basic Life History Parameters

We developed a protocol for collecting key parameters of life history (i.e., length of larval stage, growth, size at age, age at maturation, fecundity, periodicity and season of reproduction, and longevity) in several pre-identified important commercial species (table 3). These focus species were chosen for a suite of characteristics, such as their commercial importance (at that time), the intensity with which they were harvested, distinct life history traits, habitat, and region. The information was used to construct fundamental management tools like size limits, seasons, and stock assessments. The life history information also informed state-of-the-art modeling platforms and elaborated on the degree of connectivity between populations as detailed below. Gathering this basic life history information was key in taking the first steps toward developing recommendations for fisheries management and was incorporated into conservation and management legal tools.

Table 3. *Summary of life history information produced by PANGAS through multidisciplinary approaches.*

Species	Topic	Reference
Black murex snail (*Hexaplex nigritus*)	Reproductive ecology, spawning aggregations, age at sexual maturity, growth, longevity, and morphology	Cudney-Bueno et al. 2008; Cudney-Bueno & Rowell, 2008a
Rock scallop (*Spondylus limbatus*)	Age and size estimation, biology, spawning induction, fecundity estimation, larval culture and recruitment	Cudney-Bueno & Rowell 2008b; Soria 2010; Soria et al. 2010
Catarina scallop (*Argopecten ventricosus*) and other bivalves	Larval recruitment	Soria et al. 2013, 2014a
Leopard grouper (*Mycteroperca rosacea*) Gold-spotted sand bass (*Paralabrax auroguttatus*) Gulf coney (*Epinephelus acanthistius*)	Reproductive biology, demographics, and growth from otoliths	Erisman & McGeever 2011; Rowell 2011 (unpublished data)
Gulf corvina (*Cynoscion othonopterus*) Corvina (*Cynoscion parvipinnis*) Chano (*Micropogonias megalops*) Totoaba (*Totoaba macdonaldi*)	Growth, longevity, size at age and age at maturity, otoliths, stable isotopes for habitat reconstruction	Rowell et al. 2005; Rowell et al. 2008a,b, 2010; Rowell 2011; Gherard et al. 2013
Several invertebrates, fishes, seabirds, and marine mammals	Habitat and trophic level through stable isotopes	Aurioles-Gamboa et al. 2013

Connectivity

Most commercial species of marine invertebrates and fish targeted by small scale-fisheries in the NGC display a pelagic larval stage that ranges from a few days to several months (Soria et al. 2014b). During this period, larvae are either transported by prevailing ocean currents to other sites (i.e., connecting sites) or retained near the spawning site where they were produced (i.e., locally retained) (Munguía-Vega et al. 2014). The magnitude of these two processes depends on the pelagic larval duration (PLD), the location and timing of spawning, the oceanographic patterns, and the distribution of suitable habitat (e.g., rocky reefs). These factors in turn affect the recruitment of new cohorts of organisms at a given place and time and the recovery of commercial stocks to pre-harvest conditions. Furthermore, the effectiveness of placed-based management actions, like the implementation of no-take marine reserves, spatial or seasonal closures, and rotational strategies, relies on connectivity patterns as the main biophysical driver. To understand the complexity of marine connectivity, PANGAS developed two scientific tools. First, a coupled biological oceanographic model (CBOM) that re-creates the circulation of the NGC and allows the inclusion of biological traits was developed to predict larval dispersal patterns between sites and local retention processes within sites (Marinone 2003, 2012a; Marinone et al. 2008). Second, connectivity hypotheses from the model output were validated in the field by density counts of recently settled juveniles (Cudney-Bueno et al. 2009), deployment of drifters and acoustic doppler current profilers (ADCPs) to track currents (Cudney-Bueno et al. 2009; Soria et al. 2014b), larval collectors (Soria 2010; Soria et al. 2008, 2010, 2013, 2014a), and population genetics (Soria 2010; Munguía-Vega et al. 2014; Beldade et al. 2014). We employed molecular markers to measure the rates of larval exchange between sites and retention within sites using tissue samples from target species taken in the field for a set of empirical sites that replicate those included in the oceanographic model outputs (Soria et al. 2012; Munguía-Vega et al. 2014).

Oceanographic modeling and *in situ* field observations of oceanographic parameters, including currents via GPS drifters and acoustic profilers and bathymetry via an echo sounder, were conducted in Bahía San Jorge in the upper Gulf of California (upper GC) (Cabrera et al. 2007; Lavín et al. 2007; Ramirez-Mendoza and Alvarez 2008; Cudney-Bueno et al. 2009) and in Isla San Pedro Mártir Biosphere Reserve (Cabrera-Ramos et al. 2010). Oceanographic modeling was used to predict currents and larval transport (Marinone et al. 2009). These oceanographic models were the first to predict that, during the summer spawning season of key commercial species in the NGC, the cyclonic (i.e., counterclockwise) currents transport larvae from the mainland coast of Sonora downstream to Baja California (Marinone et al. 2008; Cudney-Bueno et al. 2009; Sánchez-Velasco et al. 2009; Peguero-Icaza et al. 2011). Overall, the oceanographic models have shown that the seasonally reversing oceanographic gyre that characterizes the predominant ocean circulation is the primary engine that drives marine connectivity in the NGC (Marinone et al. 2011; Marinone 2012a,b).

To conduct population genetics analyses, it was necessary to develop the genetic tools (i.e., molecular markers or microsatellites) used to measure connectivity. This was done in seven commercial species, including five invertebrates, blue crab (Munguía-Vega et al. 2010b), rock scallop (Munguía-Vega et al. 2010a), black murex (Longo et al. 2011), octopus (Dominguez-Contreras et al. 2014), and geoduck clam (Cruz-Hernández et al. 2014), and two fish species, Gulf coney (Abercrombie et al. 2009) and leopard grouper (Jackson et al. 2014).

Despite the relatively small geographic area of the NGC, genetic analyses have corroborated the presence of significant population structure (i.e., measurable differences in allele frequencies) in multiple species. For species in the NGC, larval dispersal is analogous to a river that flows in a single direction half of the year and then reverses direction the rest of the time. Our oceanographic models for the summer months suggest larval dispersal via cyclonic (counterclockwise) currents, from the Midriff Islands region toward southern Sonora and continuing along the coast to northern Sonora and the upper GC. This cyclonic gyre has been validated via gene flow estimates in several species that spawn during summer, including the rock scallop (Soria et al. 2012), the blue crab (Munguía-Vega et al. unpublished), the Gulf coney (Beldade et al. 2014), and the leopard grouper (Munguía-Vega et al. 2014; Jackson et al. 2015). As expected, because the gyre in the NGC reverses its direction twice a year, species reproducing during the winter phase of the gyre (i.e., anticyclonic or clockwise direction) show similar patterns but in completely opposite direction. For example, the direction of larval dispersal in the geoduck clam spawning during winter, as inferred from genetic estimates, goes from San Felipe toward Puerto Peñasco and down the coast to central and southern Sonora (Munguía-Vega et al. 2015).

The presence of asymmetric connectivity in the NGC has several implications for management:

1. Existing guidelines widely used for managing fishery resources in open ocean systems with symmetric connectivity are not directly applicable in the NGC, highlighting the importance of ecosystem-specific approaches.
2. Fishing within a given site depends on management actions taking place upstream, implying that depending on PLD, distant communities separated by dozens of kilometers (short PLD) or even a few hundred kilometers (large PLD) are linked by larval dispersal.
3. The benefits of management actions (e.g., no-take marine reserves, spatial and seasonal closures) are strongly biased in particular directions, such that management of upstream sites could be the most effective strategy for the entire region.

4. Most of the largest areas where fishing takes place are sustained simultaneously by high levels of local retention, contribution of larvae from upstream sites, and oceanographic patterns that concentrate larval density from all over the region.
5. Within species, populations along the coast show characteristic gradients of decreasing (or increasing) population sizes and genetic diversity in relation to the direction of the predominant ocean flow, which has implications for establishing MPAs, conserving biodiversity, and preserving the adaptive potential in the face of environmental change.

Biological Monitoring

During the PANGAS project, various types of monitoring activities were conducted to evaluate biodiversity and fisheries populations and measure the effectiveness of management actions. Activities included subtidal censuses on offshore islands and other rocky reefs, monitoring of biological parameters of various species, *in situ* density monitoring of benthic mollusk species in various habitats, catch monitoring and the use of onboard logbooks, and sampling of larvae in the pelagic environment.

We adopted and adjusted the PISCO[3] subtidal monitoring protocols for ecosystem monitoring in the NGC (PANGAS 2008c; Rojo et al. 2011), and developed long line and trawl sampling protocols for sand/muddy bottom habitats (Ainsworth 2008). Subtidal monitoring cruises were conducted in June 2007, 2010, and 2011 including dozens of sites throughout the NGC. With these data we have evaluated species richness, abundance, and diversity of the commercial and noncommercial fish and invertebrates of the rocky reefs. Databases for the presence and abundance of fish and invertebrates for each cruise were curated, revised, and homogenized among years, totaling over 200,000 records (Sánchez-Alcantara 2012). With these data we established baseline ecological conditions including community structure, richness, abundance, diversity, equity, trophic level, heterogeneity, key species, and changes in size structure for coastal rocky reefs, reef fishes, and invertebrates (Gonzalez-Cuellar 2012; Gonzalez-Cuellar and Reyes-Bonilla 2012). Baseline data were also established in the Bahía de los Ángeles y Canales de Ballenas y de Salsipuedes Biosphere Reserve and Archipiélago de San Lorenzo National Park Reserve for 2009 (Reyes-Bonilla et al. 2010a) and 2010 (Reyes-Bonilla et al. 2010b), including fish biomass (Reyes-Bonilla et al. 2011).

Various manuals and protocols were developed for monitoring fisheries. The manuals include sampling design and units of measure, methods for monitoring density *in situ* and for measuring biological parameters, data recording methods and proposed protocols for data analysis, and follow-up on obtaining permits for experimental or commercial fishing. We produced monitoring manuals for a number of programs, including onboard (Pérez-Valencia et al. 2013a) and fisher logbook (Pérez-Valencia et al. 2013b) programs being applied in the upper GC and Colorado River Delta Biosphere Reserve; a community catch monitoring program implemented in the Puerto Peñasco-Puerto Lobos corridor, south of the upper GC reserve (Downton-Hoffmann et al. 2013c); and protocols for onboard and beach monitoring programs for finfish (Downton-Hoffmann et al. 2013b) and benthic mollusks (Downton-Hoffmann et al. 2013a) within the reserve and in the Puerto Peñasco-Puerto Lobos corridor. This innovative community logbook program, which documents all of the catch in the corridor, provides a detailed view of the temporal and spatial dimensions of fisheries by community (Downton-Hoffmann et al. 2013c). We developed a set of indicators for measuring richness, diversity, and size of species caught, trophic level of captures, and total biomass for priority fisheries species in the Puerto Peñasco-Puerto Lobos corridor allowing for assessment of fisheries and ecosystem health, offering important baseline data for inter-annual comparisons (Turk-Boyer et al. 2014).

We designed and implemented an ecological monitoring program for the upper GC reserve, including the Vaquita Porpoise Refuge. We conducted a total of five oceanographic cruises, timed to capture the primary fish and shrimp spawning periods (June 2008, 2010, and 2013) and to document seasonal changes (March 2011and September 2012). The cruises sampled 85 stations using protocols developed by PANGAS to produce a detailed description of the physical and chemical seascape of the region (Lavín et al. 2010). For each cruise, we generated conductivity, temperature, and depth (CTD) data and vertical profiles of temperature, salinity, density, dissolved oxygen, and fluorescence (chlorophyll *a*) (Godinez-Sandoval et al. 2010, 2011, 2012) and determined fish larval abundance, distribution, and zooplankton volume (Sánchez-Velasco et al. 2011; Jimenez-Rosenberg et al. 2012a,b, 2013; Sánchez-Uvera 2012) as well as the abundance and distribution of shrimp larvae and post-larvae (Galindo-Bect et al. 2011, 2012; Barron-Barraza 2013). Two main spawning areas were identified in the NGC for coastal demersal and epipelagic fish species, one in the frontal zone of the upper

GC and the other in the frontal zone to the south of the Midriff Islands region (Danell-Jiménez et al. 2009; Sánchez-Velasco et al. 2013). Four distinct regions based on larval fish habitats and hydrography were described (Sánchez-Velasco et al. 2012). The spawning area identified in the upper GC contrasts with the low larval abundance found in the center of NGC (Sánchez-Velasco et al. 2014).

Atlantis Ecosystem-Based Modeling

An Atlantis ecosystem model (Fulton et al. 2011) was developed in collaboration with the Northwest Fisheries Science Center, National Oceanic and Atmospheric Administration (Ainsworth et al. 2011). Atlantis integrates multiple ecological parameters and management scenarios with an explicit representation of food webs and the flow of energy and matter in the NGC. Biological parametrization of life history parameters for the functional groups that make up the model drew heavily on biological monitoring carried out during the PANGAS project, including species distributions, diet composition, and habitat characteristics (Ainsworth et al. 2010). Data on characterization of fisheries and fishing communities collected in phase 1 of the PANGAS project were used to develop the fisheries submodule in the model. The resulting ecosystem model for the NGC has been used to explore various management questions, including exploring trade-offs between fisheries and conservation of the vaquita porpoise (Morzaria-Luna et al. 2012), measuring the indirect effects of conservation policies on the coupled human-natural ecosystem of the NGC (Morzaria-Luna et al. 2013), and corroborating that full compliance with harvest regulations and quotas yields ecological benefits (Ainsworth et al. 2012a,b). The Atlantis model is currently being used to test the effects of climate change scenarios on the food web of the NGC (Morzaria-Luna et al. unpublished).

Governance Component

Rules in Use and Incentives for Compliance

Understanding how institutions affect or shape fisheries performance is a key part of providing practical insights for the development of management strategies that promote sustainable fishing. In the GC there is widespread evidence of declines in fish stocks upon which small-scale fisheries depend, and these declines are largely attributed to policy failures.

We obtained some information on governance issues at the scale of the NGC through the rapid assessment described earlier. For instance, in terms of how fishers organize, fishers in the NGC can work one of a number of ways, including as a cooperative member, as an independent fisher, for a permit holder, or for a buyer (who can also in turn often be a permit holder). Respondents were asked to select the option that best described their work. Nearly half of respondents described their job as "member of a cooperative," followed by independent fishers (21%) and working for permit holders (20%). Only 5% said they worked for a cooperative but were not members. Only 1% of respondents said they were a permit holder, which shows us how difficult it is for independent fishers (who are not associated with any cooperative) to access fishing permits (PANGAS 2008b).

In addition, we investigated formal and informal rules-in-use regulating access and resource use by small-scale fishers in Bahía de los Ángeles and Bahía de Kino, the two most important fishing communities of the Midriff Islands region. Methods included examining legal documents, semi-structured and structured interviews, and participant observation. Results indicate that the percentage of fishers holding fishing rights and actually using them to report and commercialize catch was quite small in both communities (fishing rights are held by a few absentee operators or permit holders locally known as "*permisionarios*") (Cinti 2010; Cinti et al. 2010a,b, 2014). In both communities, insufficient support from the government in provision of secure rights, enforcement and sanctioning, and recognition and incorporation of local arrangements and capacities for management arose as important needs to address. There is a need to formally recognize fishers as fundamental stakeholders and actors in decision-making processes for their local fisheries, and for working cooperatively toward the design of management strategies and regulations that provide better stimulus for resource stewardship and discourage overfishing. We highlight the critical role of higher levels of governance, which when disconnected from local practices, realities, and needs can be a major impediment to achieving sustainability in small-scale fisheries, even in cases where several facilitating conditions are met (Cinti et al. 2014).

We also evaluated the conditions under which small-scale fishers self-organize for managing common-pool resources, field-testing the framework proposed by Elinor Ostrom for analyzing the sustainability of social-ecological systems (Ostrom 2009). By conducting interviews with key informants we found that fisheries in the region have different levels of self-organization. Conducting quantitative analyses on the characteristics of the resource unit, resource system, users, and governance system of four fisheries we found that those with characteristics similar to those proposed in the framework were experiencing higher levels of self-organization than those that did not share those characteristics. We also found that two of the ten variables proposed by Ostrom were particularly relevant for self-organization in the NGC: collective-choice rules and local leadership (Castillo-Lopez 2010).

Two other studies were conducted to understand the rules and compliance in the NGC. In the first, researchers analyzed the evolution and effectiveness of Puerto Peñasco (Sonora) commercial divers' management efforts to establish, monitor, and enforce a marine reserve network for black murex snail and rock scallop (Cudney-Bueno and Basurto 2009). We found that locally crafted and enforced harvesting rules, including the establishment of community-based no-take marine reserves, led to a rapid increase in resource abundance. Nevertheless, news about this increase spread quickly at a regional scale, resulting in poaching from outsiders and a subsequent rapid negative cascading effect on fishing resources and locally designed rule compliance. Through this study, we showed that cooperation for management of common-pool fisheries, in which marine reserves form a core component of the system, can emerge, evolve rapidly, and be effective at a local scale even in recently organized fisheries. Stakeholder participation in monitoring, where there is a rapid feedback of the system's response, can play a key role in reinforcing cooperation. However, without cross-scale linkages with higher levels of governance, increase of local fishery stocks may attract outsiders who, if not restricted, will overharvest and threaten local governance. Fishers and fishing communities require incentives to maintain their management efforts. Rewarding local effective management with formal cross-scale governance recognition and support can generate these incentives (Cudney-Bueno and Basurto 2009). The second study used the pen-shell fishery as a case study to compare the benefits of using a common property-right regime (in Comcaác territory) vs. individual fishing permits in Bahía de Kino (Basurto et al. 2012). The authors found that the common property-right regime analyzed provided more incentives for creating and locally enforcing access control mechanisms, while fishing permits as granted by the federal government were ineffective in limiting access to resources (open access prevails), having harmful consequences for local fisheries and livelihoods.

Understanding of Existing Social Networks

By identifying communities in a network that are most likely to share information with other communities managers can develop more targeted, effective, and efficient conservation and management actions such as environmental education, outreach, and enforcement efforts, among others. Based on answers in the 376 interviews applied during the rapid assessment, and 175 structured interviews of users in two protected areas, Isla San Pedro Mártir and Bahía de los Ángeles y Canales de Ballenas y de Salsipuedes Biosphere Reserves, we used social network analysis methods to examine the social connectivity of small-scale fishing communities and the network structures associated with collaborative behavior of small-scale fishers in the NGC (Duberstein 2009). There is considerable connectivity between small-scale fishers via kinship ties, within communities, within the region, and with other areas in Mexico. Overall, 82% of the fishers interviewed had other fishers in their families (Duberstein 2009). Fisher kinship relationships are important mechanisms for information transfer. Ninety percent of fishers acknowledged sharing information with members of their families, work partners, or friends (Duberstein 2009). We found the strongest kinship ties (measured by the number of connections between communities) among the communities on the northern Gulf's eastern coast of Sonora (Duberstein 2009).

Communities are also connected by their use of the same fishing zones and MPAs. The results suggest that communities can be grouped for management purposes based on common use of fishing areas and protected areas. This may help fishers and managers develop, implement, and enforce boundary rules and facilitate regional management of small-scale fisheries. There is mixed evidence for the role of social structure in impacting positive outcomes for fishers' ability to collaborate and organize. However, knowing the ways in which information about common-pool resources moves through a network can improve management strategies and actions. Understanding the ways that fishers share and seek out information, combined with effective rules, policies, and outreach efforts, can support the sustainable management of small-scale fisheries in the long term (Duberstein 2009).

Development of Multidisciplinary Conservation and Management Tools

Legal Instruments

A basic premise of PANGAS was to generate multidisciplinary information to directly inform management decisions. We have used a variety of tools for marine conservation and fisheries management already established in the fisheries law (*Ley General de Pesca y Acuacultura Responsable*, LGPAS) and environmental law (*Ley General de Equilibrio Ecológico y la Protección al Ambiente*, LGEEPA). These tools are the best, up-to-date approach to integrate biophysical, socioeconomic, and governance information for small-scale fisheries management in Mexico. The LGPAS was decreed in 2007, and made available new legal tools for management and conservation of fisheries throughout Mexico, including fisheries management plans and spatially explicit ordinance programs. PANGAS took advantage of this opportunity and started developing these instruments collaboratively with the government for the region and species of interest.

Within LGPAS we used five tools: (1) technical fisheries opinions, (2) National Fisheries Chart (*Carta Nacional Pesquera*), (3) fisheries management plans developed by the National Fisheries Institute (Instituto Nacional de Pesca, INAPESCA), (4) spatially explicit fishery ordinance programs (*ordenamientos pesqueros*), and (5) fishing and aquaculture concessions, tools used by the National Commission of Aquaculture and Fisheries (*Comisión Nacional de Acuacultura y Pesca,* CONAPESCA). The environmental instruments that we used to integrate PANGAS data and experience into management actions were the Environmental Impact Assessments (*Manifestaciones de Impacto Ambiental*, MIA) managed by the Ministry of the Environment and Natural Resources (*Secretaría de Medio Ambiente y Recursos Naturales*, SEMARNAT), technical justification studies (*estudios previos justificativos*) for proposed MPAs, and the conservation and management plans for MPAs (*planes de manejo y conservación*) managed by the National Commission of Natural Protected Areas (*Comisión Nacional de* Áreas *Naturales Protegidas*, CONANP). We also incorporated PANGAS results into management effectiveness evaluations for MPAs using biophysical, socioeconomic, and governance indicators (Pomeroy 2004) and an ecological scorecard produced by the Commission on Environmental Cooperation (CEC 2011) (table 4).

Table 4. *Fisheries and conservation legal tools produced through the contributions of the PANGAS project*

Tool	Goal	Target/Site	Reference
Technical fisheries opinion	Biomass evaluation to establish fishing quotas	Pen shell/Bahía de Kino Winged oyster/Desemboque de Caborca	Cisneros-Mata et al. 2011a,b
National Fisheries Chart	Provide information on fishing gear characteristics, biological and socioeconomic data, and management recommendations	Black murex, rock scallop, pen-shell, octopus, blue-swimming crab, Gulf coney, gold-spotted sand bass and groupers (all of NGC)	Rojo & Torre-Cosio 2008; Pérez-Valencia 2009; Downton-Hoffmann et al. 2011; Loaiza-Villanueva et al. 2011a,b; Martinez-Tovar & Turk-Boyer 2011; Pronatura Noroeste 2011
Fishing and aquaculture concessions	Establishment of fishery management concessions in the form of territorial use rights	Clams and winged oyster/Puerto Libertad Pen shell/Bahía de Kino	
Fisheries management plans	Participatory management plan	Swimming crab/Sonora and Sinaloa	DOF 2014; http://plandemanejojaiba.blogspot.mx/
	Bayesian stock assessment	Golden spotted sand bass/Midriff Islands region Swimming crab/Sonora	Alvarez-Flores 2011, 2013
	Draft management plans	Octopus/San Luis Gonzaga/Bahía de los Ángeles area Finfish fisheries/San Luis Gonzaga/Bahía de los Ángeles area Serranids in the NGC	UABC-PNO-ASOCEAN 2012; Ramirez-Rodriguez & Castillo-Lopez 2011
	Ecosystem-based management	Multispecies/Puerto Libertad	Espinosa-Romero & Torre 2013
	Establish a participative monitoring program	Puerto Peñasco-Puerto Lobos corridor	
	Conduct monitoring and population viability analyses (PVA) models	Finfish in Bahía de los Ángeles	UABC-PNO-ASOCEAN 2012
CONAPESCA ordinance plans	Record number of cooperatives, fishers, and pangas	Sonora and Baja California, 99 localities, registered 4,394 boats (pangas) and 5,669 fishers	Espinosa-Romero et al. 2013
SEMARNAT Environmental Impact Assessment	Establish comprehensive monitoring, education, training, and mitigation actions	Multispecies/upper Gulf of California and Colorado River Delta Biosphere Reserve and Vaquita Refuge	Pérez-Valencia et al. 2012; Turk-Boyer & Barrera 2013
Conservation and management plan	Include PANGAS EBM information and recommendations in management	Bahía de los Ángeles and Canales de Ballenas y de Salsipuedes Biosphere Reserve San Lorenzo Archipelago National Park San Pedro Mártir Biosphere Reserve	DOF 2013 DOF 2015 DOF 2011
Justification study for the establishment of a new marine protected area	Establish the technical basis for the protection of critical habitat	Las Encantadas Islands	Sánchez-Ibarra et al. 2013
Scorecards and effectiveness management evaluations	Include PANGAS EBM information in management evaluation	Bahía de los Ángeles and Canales de Ballenas y de Salsipuedes Biosphere Reserve San Lorenzo Archipelago National Park San Pedro Mártir Biosphere Reserve Upper Gulf of California and Colorado River Delta Biosphere Reserve and Vaquita Refuge	Foubert & Sáenz 2013 Torre-Cosio et al. 2011 Turk-Boyer & Barrera 2013

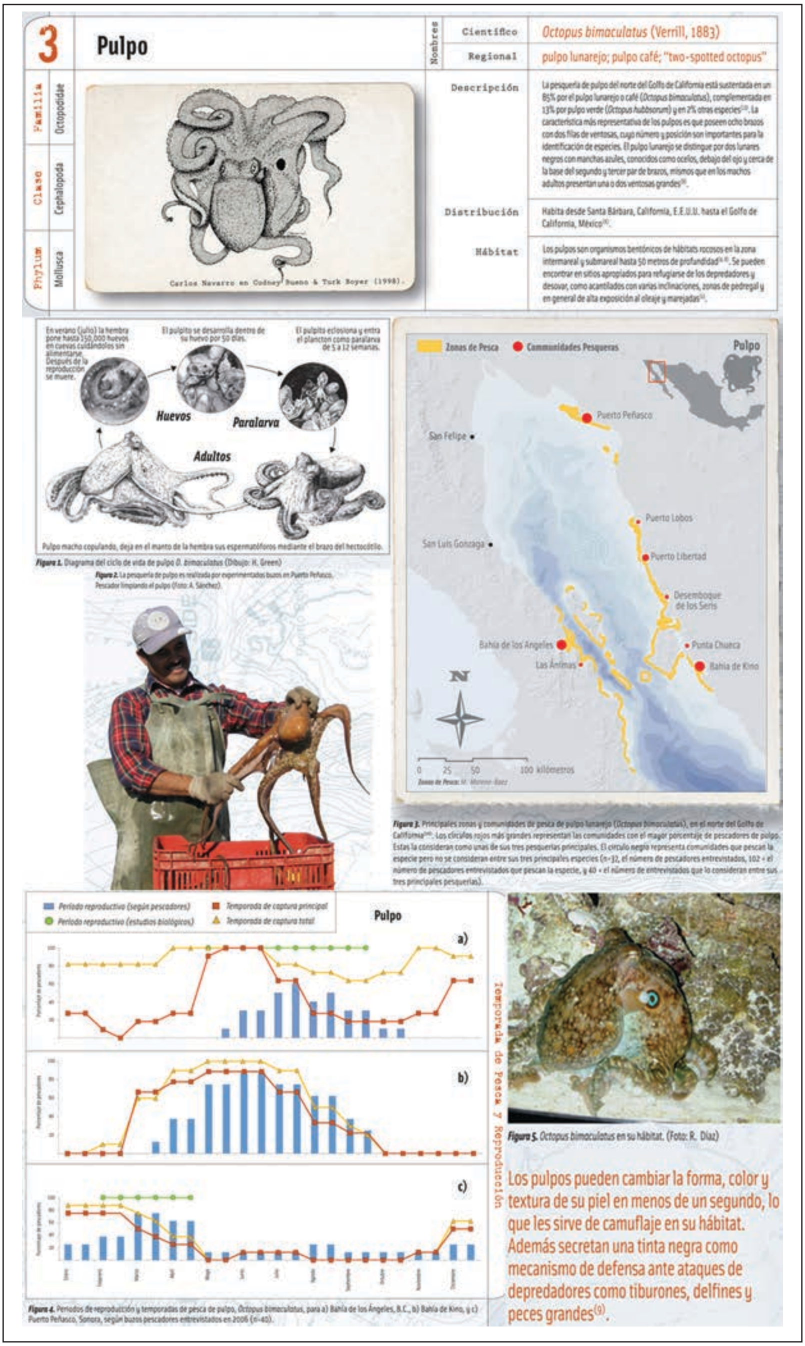

Figure 4: Example of the information included in an octopus fishery card produced by PANGAS.

As part of the process to integrate PANGAS information and experience into the selected fisheries and environmental legal tools, PANGAS supported (1) meetings and forums with multiple stakeholders; (2) identification, collection, analysis, and communication of information, including funding for generating data; (3) crafting and follow-up of rules and agreements, and (4) ensuring representation of stakeholders and empowering and building their capacity, among other activities (e.g., Espinosa-Romero et al. 2014).

In addition, PANGAS summarized ecosystem-based management (EBM) information about five target species in the format of fisheries cards (see figure 4 for an example) produced in collaboration with CONAPESCA and CONANP on rock scallop (*Spondylus limbatus*), black murex snail (*Hexaplex nigritus*), blue crab (*Callinectes bellicosus*), octopus (*Octopus bimaculatus*), and Gulf coney (*Hyporthodus acanthistius*) (PANGAS 2012a–e). These cards were distributed among key fishery leaders, cooperatives, and management officials.

Tools for Data Management and Repositories

Through the development of PANGAS, we accumulated an enormous amount of data that needed to be in secure storage for sharing and use by stakeholders, including students, researchers, NGOs, fishers, and decision makers. Three initiatives using Internet platforms with national and worldwide reach were created to fulfill these needs: Eureka, Atlasnatura, and Conectividad-Dispersion (table 5). In addition, PANGAS is a key contributor to other data repository platforms and initiatives, such as DataMARES, a data-sharing platform developed by researchers at Scripps Institution of Oceanography (table 5).

Capacity Building and Human Resource Development

One of the most striking accomplishments of PANGAS was the capacity developed among small-scale fishers (ca. 50), students (2 undergraduate, 7 master's, 12 Ph.D., 2 postdoc), NGOs (20 people), and multiple academic institutions and government agencies (INAPESCA, CONAPESCA and CONANP) on various fronts, which has been ongoing throughout the entire project. This increased capacity covered various disciplines and activities, ranging from conducting fishery independent

Table 5. *Data management and repositories tools*

Platform	Characteristics
www.atlasnatura.org/2013	Atlasnatura gives users, through an interactive GIS, the opportunity to learn, navigate, and extract useful information on MPAs and areas of high ecological value. This platform will contain the status of several indicators for target species such as fish size structure, total catch, density, diversity, etc. It also contains a database with the results of fisheries monitoring programs.
http://datamares.ucsd.edu	DataMARES is an open access online website created by the Gulf of California marine program of the Center for Marine Biodiversity and Conservation (CMBC) at Scripps Institution of Oceanography. DataMARES includes analysis tools for data integration, metadata, and visualization tools for making informed decisions and serves as a baseline tool for historical information, one-time data collection, and long-term monitoring data of coastal and marine ecosystems in the Gulf of California and around the world. DataMARES is the foundation of new innovative science that allows open, persistent, robust, and secure integration and access of scientific information. PANGAS is a collaborator with DataMARES.
www.eurekamarine.org	Eureka is an open source software tool used to enter and compare SCUBA subtidal monitoring data to assess effectiveness of MPAs.
http://conectividad-dispersion.cicese.mx/	Internet-based tool to show connectivity among distinct regions of the GC based on the HAMSOM oceanographic model for each month of the year and for varying PLDs.

(e.g., subtidal biodiversity transects, larval counts) and dependent (e.g., analyses of fish catches) monitoring to the increased ability of nongovernmental actors and institutions to interact, talk, and work with the government on the production of management outcomes. The latter has allowed PANGAS to apply its diverse tools in management and has resulted in the production of management programs for fisheries and MPAs in collaboration with managers. Individuals who worked within the framework of the PANGAS interdisciplinary applied science programs have now moved into positions of management influence within the NGOs, stakeholders, and academic and government sectors.

It is also important to highlight that as part of our monitoring efforts, we have trained and equipped a team of commercial divers in SCUBA and subtidal ecological monitoring techniques. As an example, with significant PANGAS support the "Grupo de Buzos Monitores de Bahía de Kino," a group of commercial fishers from Bahía Kino, has been monitoring the rocky reefs in the northern Gulf of California since 2007 and MPAs, including the extremes of Mexico, Guadalupe Island in the Pacific Ocean, and Banco Chinchorro (Quintana Roo) in the Caribbean. They are the first fishing cooperative in Mexico to provide professional monitoring services to anyone, obtaining between 10% to 20% of their annual income from these activities. In 2011 these divers became one of 50 winners of Iniciativa México.[4]

Lessons Learned

After 10 years of work and approximately 2.5 million dollars of investment, what started as a project idea evolved into a virtual consortium of six institutions (at its "peak" with the active participation of 50+ researchers, students, fishers, and management practitioners) that produced more than 100 scientific publications (peer-reviewed articles, technical reports, theses, dissertations, and protocols), influenced important policy outcomes, and inspired improved marine conservation and fisheries management policies in Mexico. PANGAS accomplished, amidst all its trials and tribulations, the integration of biophysical, social, and governance considerations into public policies for management of small-scale fisheries at a large, regional scale. Yet, just as there have been important successful outcomes, the PANGAS story is also riddled with challenges, mistakes, opportunities missed, and important lessons, particularly in terms of how to manage the growth and expectations of a large consortium tackling complex research and management questions and how to adapt as the consortium evolved.

In table 6, we summarize seven elements of the evolution of PANGAS that we think should be considered or evaluated, not only for our story but for any project of a similar nature: (1) number of people and institutions involved, (2) diversity of cultures, (3) international scientific research, (4) funding, (5) relationship with diverse government entities, (6) interdisciplinary complexity, and (7) participatory management. Each element was evaluated for the positive and undesired aspects that emerged.

PANGAS is a virtual entity of six core institutions that produced novel intellectual synergies, but also experienced tensions due to the fact that each institution has its own mission, values, and priorities, as well as its own "brand" and strong individual personalities. A full-time PANGAS coordinator was key to maintaining an effective communication among partners and synchronizing activities to reach collective goals, including a large administrative load. Tolerance and empathy among partners were

Table 6. *Institutional- and implementation-related lessons of PANGAS*

Element	Positive	Undesired
Multiple people and institutions	Creativity and diversity of thoughts Fosters productivity and peer feedback	Slow decision making Difficulty managing large budgets Communication becomes challenging Emergence of interpersonal misunderstandings Strained relationships can emerge
Multiple nationalities	Rich cultural environment and synergies	Translation is time consuming Ideas lost in translation Differences in views on the ways to manage and implement a large project
Bi-national scientific research	Access to state-of-the-art facilities and knowledge Aligned EBM thinking Institutional complementation Cross-cultural exchange of ideas	Difficulties and stalling with paperwork for samples, equipment, border sample crossings, work visas Periods of low commitment from all parts due to differences in priorities between institutions
Funding	Access to substantial funding as a group leading to fast initial growth pace	Large administrative load Difficulty maintaining long-term funding Internal competition for funding
Government relationship	Varying openness to validate and use PANGAS data	Spatial and temporal scales of government did not always align with PANGAS's recommendations Replacement of people in government often meant restarting certain aspects of the project Difficulty in adopting EBM approaches due to institutional/bureaucratic constraints
Multiple disciplines	Development of human resources with an interdisciplinary vision and multiple skills Development of novel tools to accommodate interdisciplinary needs	Interdisciplinary communication is time consuming People pushed outside their comfort zone True interdisciplinary results can take a long time to materialize
Participatory research and management	Decisions built bottom-up in collaboration with users Social capital built	Process is time consuming Process not necessarily accepted by the government

necessary for a successful project, and especially one with the many dimensions of PANGAS. The cultural diversity at the institutional (bi-national) and individual (multinational, including individuals from Argentina, Mexico, Peru, Portugal, and the United States) level provided a rich working environment and perspectives. The different institutions generally worked well together to carry out research activities, but unanticipated bureaucratic delays and misunderstandings produced periods of paralysis. Overall, a successful balance was achieved between research/academic institutions producing science and civil society organizations incorporating the results into conservation and management tools. Here PANGAS has filled the niche of a boundary organization (*sensu* Guston 2001) in the GC, linking scientific knowledge to action.

The need of continued and long-term funding was a cornerstone for the creation of PANGAS. None of the partner institutions involved would have been able to obtain the financial support needed to develop the PANGAS vision working individually, but together the consortium was successful. When the funding diminished, internal disagreements and competition emerged. Paradoxically, however, at the same time new collaborations and more complex research ideas are still evolving using PANGAS data and experience as a base, and projects are beginning to capitalize on the participatory approach taken by PANGAS that requires long times and trust with users. For example, two initiatives to design networks of fully protected marine reserves are in progress in the Midriff Islands region and the Puerto Lobos-Puerto Peñasco corridor, using accumulated PANGAS information. Improvements continue to be made in the Atlantis ecosystem model, as well as the coupled use of oceanographic models and population genetics to understand marine connectivity. These efforts are state of the art at both the national and international levels.

One of the most challenging elements of PANGAS was the relationship with the government. Communication with government entities was generally effective but sometimes messages diluted down the scale within governmental organizations and occasionally collaborations completely had to restart from zero when key people were replaced. In addition, PANGAS spatial and time scales did not always match governmental management scales and priorities, and many times we found ourselves light-years ahead of the government working schedules. There was also strong competition among government fisheries and environmental agencies, which created constant tensions in integrating the produced data, analyses, and recommendations. Today, after 10 years and two different political administrations, the governmental agencies are openly recognizing the knowledge produced by PANGAS and are supporting collaboration of government agencies with PANGAS.

Currently we are in phase 4 of PANGAS, which has us deciding what our next steps will be. Funding is limited and many core people have graduated or moved on to other endeavors. However, after a decade, the PANGAS "brand" is recognized. New partners want to collaborate using PANGAS scientific tools and many opportunities exist to use PANGAS's data, framework, and approach in various parts of Mexico and to share experiences. At the end, this sharing of experiences might be one of PANGAS's main contributions, helping to inform applied research in the NGC, in other parts of Mexico, or elsewhere in the world. An expansion of the geographic focus of PANGAS from the NGC to the entire Gulf of California is a natural and needed next step toward a comprehensive perspective of ecosystem processes. Our studies demonstrating that simple ecosystem trends (such as the direction and strength of the currents at different times of the year) can have strong effects on the distribution of larvae, fishing activities, genetic diversity, and biodiversity could in and of itself change the view of how fisheries and communities are interconnected to each other and foster a shared future based on collective decisions at the regional level.

The interplay between coupled human and natural systems demands management that is agile, and adaptive in nature. As researchers learn more about the dynamics of the social, political, and ecological landscape, our management tools need the capacity to use this information effectively and efficiently. Scientific tools such as those developed for the PANGAS toolbox (e.g., ocean circulation and ecosystem models combined with genetic monitoring of key species) are transferable to other communities and ecosystems. We expect that these tools will continue to evolve, becoming stronger for new generations of marine scientists to understand the complexity of climate and anthropogenic change in ocean ecosystems and to monitor ecosystem changes and the impacts of activities like fishing, mariculture, and management strategies on MPA networks. PANGAS helped establish a diverse socioecological baseline of how fishing takes place in the NGC that could help track future changes related to, for example, climate variability in the near future.

At the time of inception of PANGAS, management of many of the small-scale fisheries lacked basic biological and social information. PANGAS was like a reboot for the community at large to produce quality scientific information inspired by the needs of the users of the fishery resources, and it engaged users in the production of knowledge and also played the role of boundary organization with academia, government, and stakeholders. The data generated, the expertise, the reputation as a trusted source of scientific information, and the relationships built by PANGAS are highly valued assets for the present and future adoption of science-based fishery and marine conservation policies in the Gulf of California.

Perhaps more importantly, PANGAS created the human capacities that "speak" and think in several languages/channels of knowledge. For example, when a PANGAS partner sees a fish, he or she considers it from multiple angles:

1. Who, when, how, and where is it being fished?
2. What is the status of the stock and its ecosystem?
3. How are its populations connected via larval dispersal?
4. Who is (and where are they) selling it?
5. How is the fishery currently regulated?

This thought process represents a fundamental change in how fisheries resources are conceived and managed in the Gulf of California. ✣

Notes

1. Common-pool resources are ones for which exclusion from the resource is costly and one person's use subtracts from what is available to others (NRC 2002).

2. http://www.conservationmeasures.org/wp-content/uploads/2013/05/CMP-OS-V3-0-Final.pdf.

3. Partnership for Interdisciplinary Studies of Coastal Oceans (www.piscoweb.org).

4. A competition launched by the two major television chains from Mexico to recognize projects positively impacting society. The winners got a cash prize and publicity that helped to consolidate the project.

Acknowledgments

The PANGAS initiative has been supported by the David and Lucile Packard Foundation, CONANP, CONAPESCA, CONACyT, Fondo Mexicano para la Conservación de la Naturaleza, INAPESCA, CICESE, the University of Arizona, the Marisla Foundation, the Sandler Family Supporting Foundation, the Tinker Foundation, the Walton Family Foundation, and the Wallace Research Foundation. We would like to express our eternal gratitude to the fishers, license holders, fishing communities members, and governmental officials who kindly participated in this research. Finally we are thankful to all the students and collaborators who have worked with PANGAS throughout the years, including Giacomo Bernardi, Ricardo Beldade, Alejandro Pares-Sierra, Hector Reyes-Bonilla, Cameron Ainsworth, Isaac Kaplan, Carlos Alvarez-Flores, David Aurioles-Gamboa, Xavier Basurto, Amy Hudson Weaver, Alexis Jackson, Esteban Torreblanca-Ramírez, Miguel Angel Cisneros, Pedro Cruz-Hernández, Osvel Hinojosa-Huerta, Jose Francisco Dominguez-Contreras, Caroline Downton-Hoffmann, Rene Loaiza-Villanueva, Sergio Pérez-Valencia, Ivan Martínez-Tovar, Brad Erisman, Octavio Aburto-Oropeza, María Jose Espinosa-Romero, Zeida Foubert, Manuel Galindo-Bect, Víctor Godínez-Sandoval, Carlos Cabrera-Ramos, Ollin Gonzalez-Cuellar, Patricia Jiménez-Rosenberg, Arturo Rubén Sánchez-Uvera, Arturo Ocampo-Torres, Gary Longo, Angeles Yazmín Sánchez-Cruz, Cesar Moreno, Nabor Encinas-Cazares, Alfredo Girón-Nava, Martha Peguero-Icaza, Verónica Castañeda Fernández de Lara, Rafael Ramírez-Mendoza, Luis G. Álvarez, Israel Sánchez-Alcántara, Eduardo Santamaría del Angel, Melanie Culver, and Raphael Sagarin.

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