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The collection of fisheries data remains a major challenge for fisheries officers in Pacific Island countries, especially in remote outer islands. Noting the rapid increase in Internet availability throughout the region, SPC has addressed the issue of data collection through the development of a new mobile phone and tablet application that will facilitate the collection of data from small-scale fishers, and ease the transfer of this information from outer islands to central fisheries offices (see p. 2). This new app will also reduce the time lag between data collection and data processing, which is critical for proper and timely assessments of fish stocks. It will be interesting to see how quickly fisheries officers adopt this new tool.

In the Pacific Islands region, aquaculture may only become economically viable when natural stocks of certain fish and invertebrates are so depleted that their market value "goes through the ceiling". For sandfish, the highest-valued and largely overexploited tropical sea cucumber (see p. 22), the time for commercially viable aquaculture may have come. Public and private sandfish farming experiments are taking place in several countries, including Kiribati (see p. 13). It is strange to think that successful aquaculture may sometimes be the result of weak fishery management.

The word data is cited more than 100 times in this issue, which is not surprising for a newsletter dedicated to fisheries, but this may be a sign that the attention of *Fisheries Newsletter* contributors – and readers – is increasingly focusing on management concerns.

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Tarawa, Kiribati (image: Michel Blanc)

Prepared by the Pacific Community, Division of Fisheries, Aquaculture and Marine Ecosystems, Information Section

Mobile phone data collection app for artisanal fisheries makes its debut in Funafuti, Tuvalu

The Pacific Community (SPC) has just released an innovative new mobile and tablet application called 'Tails' that revolutionises electronic collection of artisanal tuna catch data. Tails allows coastal fisheries staff to easily collect tuna and bycatch information from small-scale fishers in remote locations and send it instantly back to the main office for analysis, even when Internet connectivity is limited. This new technology eliminates costly and time consuming delays in sending paper-based data from outer islands to the central fisheries office, and enables fisheries officers to monitor and manage artisanal tuna catches with today's data, not last year's data.

Tuna are an important protein source for coastal communities and a significant traditional food source in many Pacific Island communities. The consumption of tuna in coastal communities also helps to relieve pressure on commonly targeted reef fish species, especially those in ecosystems under threat from external factors such as overpopulation, climate change or natural disasters. Many Pacific nations are investigating increased local tuna consumption as part of a strategy of food security and reef fisheries conservation and management, and this reliance on artisanal tuna catches needs to be monitored.

Pacific communities are often dispersed widely over large ocean areas, which typically makes data collection a very slow and expensive process. These data are, however, valuable for monitoring changes to the artisanal tuna catch rates, evaluating the effectiveness of nearshore fish aggregation devices and other food security projects, and ensuring the conservation of valuable coastal marine resources. A better solution was needed to streamline data collection, reduce costs and allow coastal fisheries staff to spend more time collecting and analysing data, and less time dealing with the logistics of paper-based information.

Tails provides a rapid method of sending small-boat catch data from remote locations to central fisheries offices. This ensures that data collection and analysis can occur quickly enough to support fisheries management initiatives and decision-making in Pacific Island countries and territories. The app was developed by Bruno Deprez, Steven Bagshaw and Andrew Hunt from the Data Management Section of SPC's Fisheries, Aquaculture and Marine Ecosystems Division, and it relies on Tufman 2, SPC's standard fisheries data management platform, which is widely used in the region.

Artisanal data collection often occurs in areas with limited Internet connectivity and the Tails app was designed and built to address this challenge. By allowing data collection to be performed completely offline, Tails is then able to send weeks or even a month of collected data in one transfer when even a modest Internet connection is available. Tails also requires very little bandwidth to operate, and can send off around 500 fishing trips' worth of data to the national office with only one megabyte of data.

First field trial of the Tails app, February 2016, Nauru (image: Andrew Hunt).

Field trials of Tails were first conducted in Nauru in February 2016, and the first full deployment was carried out in Funafuti, Tuvalu the following month. Early feedback has been very positive and development and improvement of the application continues.

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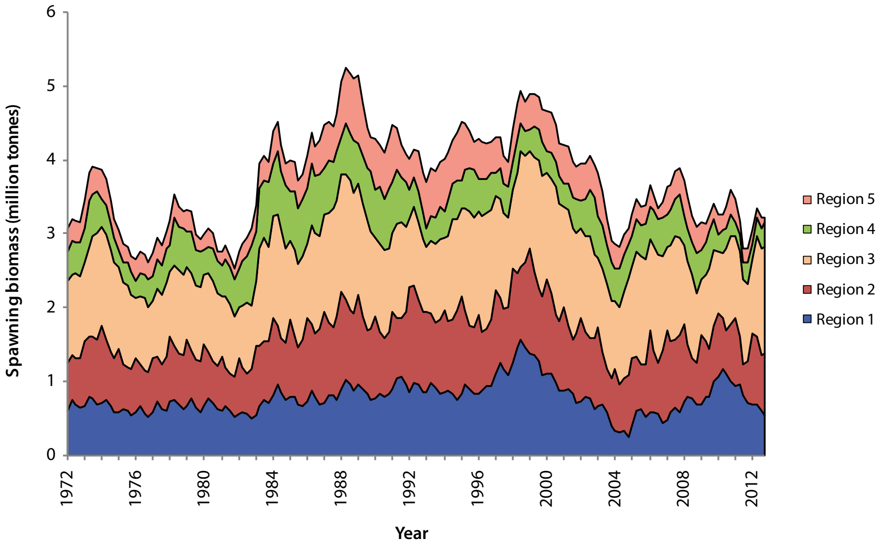
Workshop continues the development and implementation of SPC's key tuna stock assessment software: MULTIFAN-CL

In March 2016, the Stock Assessment and Modelling Section of the Pacific Community's Oceanic Fisheries Programme (OFP) hosted Dr Dave Fournier in Noumea. Dave is a world-renowned fisheries modeller and software developer, and a few years ago was a recipient of the American Fisheries Society's prestigious Ricker Award[1]. He is a pioneer of the field that has come to be known as "integrated fisheries stock assessmentand published the seminal article on the topic in 1982[2].

Dave has worked with SPC, initially as a staff member, and later as a contractor, since the 1980s primarily developing the fisheries stock assessment programme MULTIFAN-CL, which at the time represented the first serious attempt to implement integrated fisheries stock assessment in a general way. During his visit to SPC, Dave worked with Nick Davies (another key MULTIFAN-CL developer) to further enhance MULTIFAN-CL and ensure it remains at the cutting edge of tuna fisheries assessment.

The MULTIFAN-CL assessment software (www.multifan-cl.org) has been used since the 1990s to assess the western and central Pacific Ocean's tuna stocks, in particular, skipjack, yellowfin, bigeye and south Pacific albacore. The results from the model form a key part of OFP's provision of the best possible scientific analyses to underpin our advice to members of the Western and Central Pacific Fisheries Commission and the Pacific Community. The software has been specifically tailored for western and central Pacific Ocean (WCPO) tuna fisheries to make the best use of the specific fishery and biological datasets SPC has, in particular: catch, effort and fish length and individual weight data of tuna from different fisheries in the WCPO; information on fishery catch rates over time; our understanding of key biological characteristics of the tuna; and movement information (as well as other features) from the extensive tagging programmes that have occurred within the WCPO over many years[3].



MULTIFAN-CL estimates of skipjack spawning biomass in the western and central Pacific Ocean, by five model regions.

During their stay in Noumea, Nick and Dave also held a four-day training workshop on using MULTIFAN-CL software and its new features, for scientists from both SPC's Oceanic Fisheries and Coastal Fisheries programmes. The workshop was extremely well received and gave our scientists a considerable step forward in developing stock assessments for skipjack and southwest Pacific blue shark, which that will be presented at the 12th Scientific Committee of the Western and Central Pacific Fisheries Commission this year.

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[1] http://www.admb-project.org/news/dave-fournier-received-the-american-fisheries-society2019s-ricker-award
[2] Fournier D.A. and Archibald C.P. 1982. A general theory for analyzing catch at age data. Canadian Journal of Fisheries and Aquatic Sciences 39:1195–1203.
[3] See, for example : http://www.spc.int/tagging/
http://www.spc.int/DigitalLibrary/Doc/FAME/InfoBull/FishNews/118/FishNews118.pdf
http://www.spc.int/DigitalLibrary/Doc/FAME/InfoBull/FishNews/141/FishNews141_04_Leroy.pdf

The three Vs of tag recovery data processing: validation, validation, validation

A just-tagged yellowfin tuna is measured before going back to the ocean (image: Bruno Leroy, SPC).

The Pacific Community (SPC) has tagged and released tunas in the western and central Pacific Ocean since 1977. These tagging efforts have been carried out through three tagging programmes: the Skipjack Survey and Assessment Programme from 1977 to 1981; the Regional Tuna Tagging Programme, from 1989 to 1992; and, the current Pacific Tuna Tagging Programme (PTTP), since 2006. In total, more than 700,000 tuna have been tagged and released, of which 100,000 have been recovered and reported to SPC. Tagging experiments provide important inputs to analyses that support management of tuna resources in the region, including stock assessment models.

Tagged fish can be detected months after recapture and at a range of stages in the tuna supply chain, for example: on fishing vessels during well transfers or sorting; during the transfer of tuna from fishing to transhipment vessels, and unloading from transhipment vessels; in cold-storage facilities; and in canneries. Previous studies have demonstrated relationships between the reliability of tag recovery information and other variables, such as the time elapsed between tag recovery and tag detection. As such, a critically important component of the tagging programmes is rigorous data quality control by SPC staff, including cross validation of tag recovery data with available information from other datasets. After cross-validation, each recovery is assigned a best estimate of recovery date and position, and reliability indices for the perceived uncertainty in these key data fields (e.g. a recapture date best estimate of 12 March 2015, ± one week). Cross-validation compares tag recovery information from external datasets such as vessel tracks from vessel monitoring system (VMS) data and vessel logbook data, in order to estimate the reliability of information provided by tag finders. For example, VMS data could be used to confirm that the fishing vessel reported to have recovered a tag was likely fishing in the vicinity of the reported recovery position on the reported tag recovery date, based on the location and speed and azimuth profile of the vessel. Additional controls based on the growth rate of the tuna during its time at liberty, the maximum distance travelled or the bathymetry are also used to ensure the quality of the data. The cross-validation process represents a considerable investment of time and resources, particularly when high numbers of tag recoveries are reported shortly after tagging cruises, with up to four staff contributing on a part-time basis.

However, this poses an important question: How accurate are the perceived reliability indices for recovery date and position? And how can we determine this, if we do not know exactly when and where tags are recaptured by fishing vessels? Tag seeding experiments provide the means to investigate these questions. In tag seeding experiments, observers on purse seiners secretly insert conventional tags in tuna. Recovery data from tag seeding experiments receives the same data quality controls as PTTP recoveries. The date and location of seeding can then be compared directly with the best estimates of recovery date and position resulting from the cross-validation process, and the errors in the best estimates compared with the perceived reliability assigned during cross-validation.

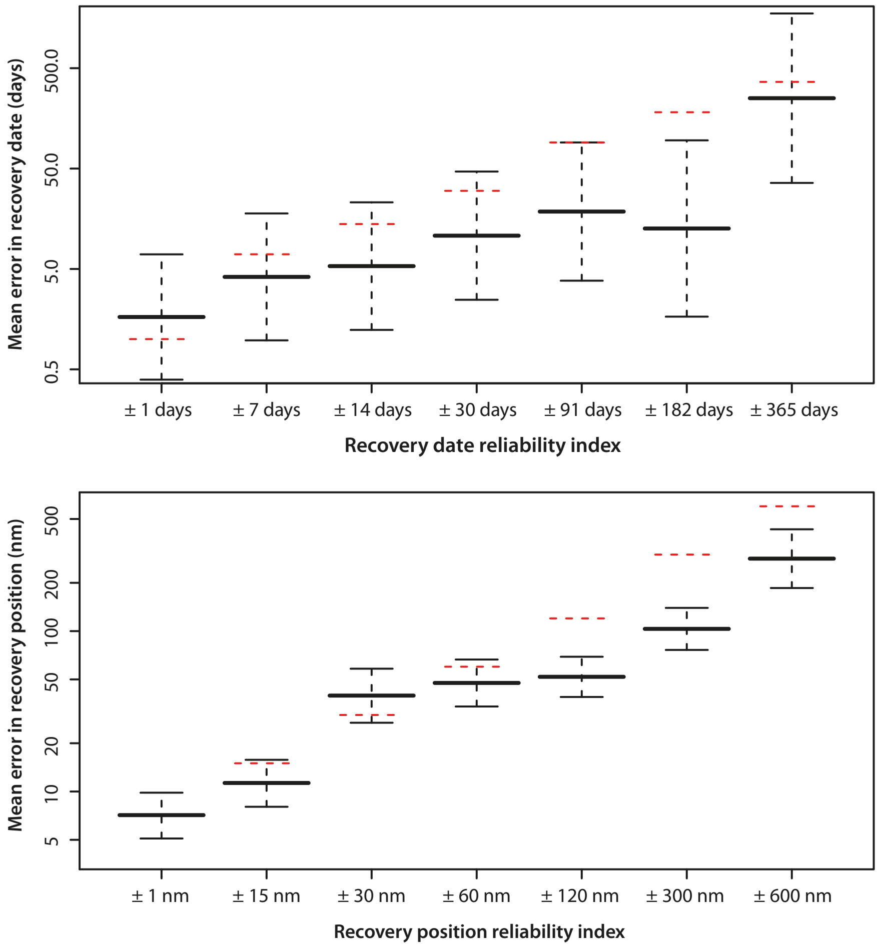

Figure 1. Estimated mean errors in recovery date (top) and position (bottom) against assigned reliability indices. Thick black lines give the best estimate, and thin black lines display uncertainty in the best estimate. Dotted red lines display the perceived accuracy from the cross-validation process.

The errors in recapture date and position for seeded tags increase in proportion to their perceived uncertainty (Fig. 1). This demonstrates that the cross-validation process is capable of accurately determining the relative reliability of tag recovery information. For tag recoveries with high perceived uncertainty in recovery information, the best estimates of recovery date and position are often more reliable than suggested from the cross-validation process. In general, however, the observed errors in recovery position and date are consistent with the perceived uncertainty from the cross-validation process. This suggests that the cross-validation process is also capable of estimating the magnitude of uncertainty in recapture date and position.

Tag seeding information also allows the exploration of factors that influence the accuracy of estimated uncertainty in recovery date and position. For example, the majority of checks and comparisons undertaken during cross-validation rely on accurate identification of the tag recovery fishing vessel. Unsurprisingly, there is clear evidence that errors in recovery date and position are higher when recovery fishing vessels were not correctly identified by tag finders.

The analysis summarised here provides encouraging evidence that the cross-validation process provides accurate estimates of uncertainty in tag recovery information. This allows uncertainty in tag recovery information to be accounted for in analyses of tagging data. Furthermore, tag seeding data provides an opportunity to explore the factors that have the most impact on uncertainty in recovery information. This can inform changes to the tagging programme that can improve confidence in the resulting tagging dataset.

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Sea turtle mitigation in longline fisheries

Six of the seven species of sea turtles found worldwide are considered to be threatened with extinction according to the International Union for Conservation of Nature red list criteria, with interactions with fishing gear posing a serious threat to their populations. The Western and Central Pacific Fisheries Commission (WCPFC) and the Pacific Community (SPC) are coordinating a joint-analysis by their members of sea turtle bycatch mitigation data from Pacific longline fisheries. The study is supported by funding from the Areas Beyond National Jurisdiction Tuna Project, a Global Environment Facility-funded and Food and Agriculture Organization of the United Nations-implemented programme of work designed to encourage and reinforce sustainable tuna fisheries.

*Hooked hawksbill turtle (*Eretmochelys imbricata*) (image: © naturepl.com /Jeff Rotman/WWF).*

The first workshop was held in Honolulu, Hawaii, from 16 to 19 February in conference facilities provided by the Western Pacific Regional Fishery Management Council.[1] There were 31 participants at the workshop, including 15 from SPC member countries (Australia, Cook Islands, Fiji, Federated States of Micronesia, Marshall Islands, Palau, Papua New Guinea, Tonga and United States of America).

The main objective of the first workshop was to characterise current sea turtle interaction and mortality rates under existing fishing operations. A second workshop, to be held in November 2016, will focus on reviewing the potential for various mitigation measures to reduce turtle interactions and mortalities. The dataset compiled for the study consists of observer data from a variety of sources: WCPFC Regional Observer Programme data; national observer programme data held by SPC on behalf of its members; national observer programme data provided by Japan and Chinese Taipei; and observer data for the Reunion longline fishery provided by the Institut de Recherche pour le Développement (IRD). The additional datasets made available to WCPFC and SPC increased the coverage of the combined dataset, including the range of gear configurations sampled by observers, and were critically important to the workshop's success.

An overview of the combined dataset was presented to facilitate discussion on how best to meet the workshop's objectives. This included summaries of information collected by observers in the combined dataset, noting that observer data collection forms and protocols can vary between years. Summary maps of the observer data were also generated to provide a high-level overview of available data For example, maps of interactions per unit of effort were generated to summarise where sea turtles had most frequently interacted with longline gear over the full time-series of the combined dataset (for example, see Fig. 1 for green sea turtle). Workshop participants agreed that three separate analyses of the

[1] The full workshop report is available from: http://www.commonoceans.org/fileadmin/user_upload/common_oceans/docs/Tuna/FirstSeaTurtleWorkshopReport.pdf

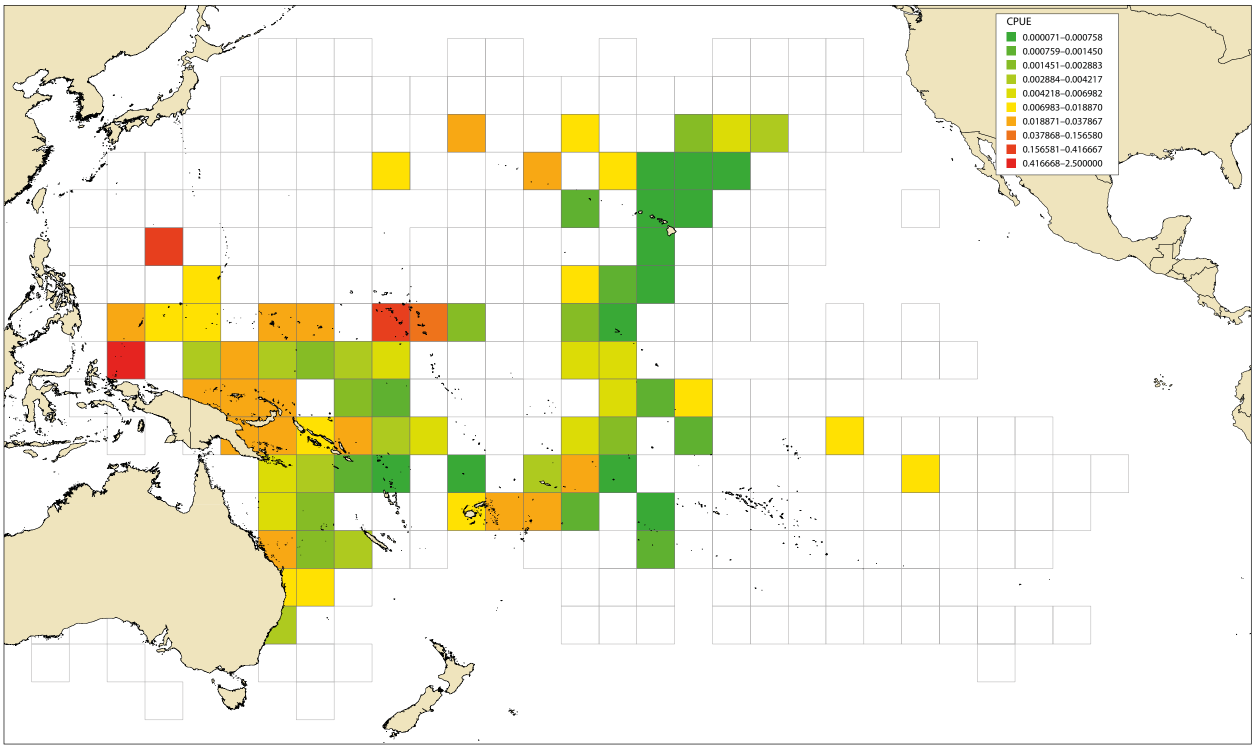

Figure 1. CPUE (number of interactions per 100,000 hooks) for green sea turtle by 5 x 5 degree grid for 1989–2015, based on the combined observer dataset.

combined observer dataset would be required to achieve the workshop's objectives: estimating the effects of various operational variables on interaction rates at the set level; estimating how turtle interaction rates vary by hook position within baskets; and estimating the effects of various operational variables on turtle at-vessel mortality rates. Workshop participants also agreed that the effects of gear configuration and other operational variables on interaction and at-vessel mortality rates were likely to differ between turtle species, and therefore, analyses should take these differences into account to the extent possible with the available data. There were sufficient data to include four species in the analyses: leatherback, loggerhead, green and olive ridley turtles. Post-release mortality rates were not considered due to a lack of available information.

Hook category (shape and size), bait species, hooks per basket, and soak time had the largest effect on set level interaction rates, with significant decreases in interaction rates with the use of large circle hooks and/or finfish bait. Interaction rates of olive ridley, loggerhead and green turtles with deep set longlines were highest for those hooks closest to floats. Interaction rates of leatherback turtles were not influenced by how close the hook is to the float. At-vessel mortality rates were influenced by turtle species, with the lowest mortality rates for leatherback and loggerhead turtles. At-vessel mortality rates also increased with increased fishing depths, as measured by both hooks per basket and float length. Participants concluded that mitigation measures based on hook shape and size, bait species, and removal of the hooks nearest each float in deep longline sets should be priorities for testing at the second workshop.

It will be important to take into account how turtle species are distributed across the Pacific Ocean when exploring the impacts of mitigation measure scenarios on sea turtle populations. For example, the impacts of a fishery adopting a particular mitigation measure will vary among turtle species if there are differences in the underlying densities of the turtle species in the area. Consequently, the workshop generated species-specific maps of relative abundances, using information from the State of the World's Sea Turtles as a starting point[2]. There are gaps in the current knowledge base of sea turtle distribution, and interpretation of existing information can vary among experts so options are currently being explored for expert peer review of the relative abundance surfaces.

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[2] Halpin P.N., Read A.J., Fujioka E., Best B.D., Donnelly B., Hazen L.J., Kot C., Urian K., LaBrecque E., Dimatteo A., Cleary J., Good C., Crowder L.B. and Hyrenbach K.D. 2009. OBIS-SEAMAP: The world data center for marine mammal, sea bird, and sea turtle distributions. Oceanography 22(2):104–115.

The economics of small-scale fishers supplying tuna to an industrial processing plant in Kiribati

Kiribati Fish Ltd (KFL) is a public-private enterprise and is the only export standard tuna processer in Kiribati. KFL operates its own longline vessels and buys fish from small-scale fishers. Over 700 small motorised fishing vessels operate in the Betio and South Tarawa area, and supplying fish to KFL would give local fishers the opportunity to secure better prices for their tuna than they would receive through the local markets. It would also increase the local employment provided by KFL in processing and packing fish.

In order to increase the amount of tuna supplied by local fishers, the Kiribati Ministry of Fisheries and Marine Resource Development (MFMRD) and SPC deployed a number of nearshore fish aggregating devices (FADs) around Tarawa, provided 89 local fishers with fish handling training in late 2013, and trained fishers in new fishing skills in 2014. Initially, this initiative was successful, with more than eight tonnes of tuna supplied by local fishers to KFL in December 2013. Since this initial positive impact, however, KFL data indicate that there has been a rapid and significant decline in the amount of tuna supplied to them — down to zero in late 2014 and 2015.

SPC's Economist (Fisheries) conducted an analysis of the market barriers that small-scale fishers face, and investigated how these barriers impact fishers' ability and willingness to supply KFL with high quality tuna. This article is a summary of the final report and highlights the report's key findings.

Methodology

A market barrier analysis was conducted to: 1) understand why small-scale fishers on Tarawa were not supplying fish to KFL, and 2) what could be done to encourage them to do so (See Box 1). Twenty-five fishers from three fishers' groups and two independent fishers participated in a mix of group discussions and one-on-one questionnaires. While this sample clearly does not represent all fishers in and around South Tarawa, it does provide insight into the main issues regarding why fishers do not supply fish to KFL.

Market barrier analysis

Finance

One of the barriers to fishers supplying KFL, is that the company requires fishers to follow good fish handling practices, and one of the conditions is that fishers must carry ice on their boats to keep fish fresh until the fishers return to port. Fishers with smaller boats, however, do not carry ice and, therefore, are unable to supply KFL with fish. Larger boat owners on the other hand do not have concerns about carrying ice.

A discussion with small boat owners identified money as a significant barrier to enlarging the size of their boat, which would enable them to carry ice and thus supply KFL with fish.

Fishers' perception was that banks required collateral to secure a loan, and a depreciating asset such as a boat was insufficient collateral. In most cases, the only accepted collateral was land. This is clearly a significant barrier to expanding fishing effort and increasing employment and revenues from the industry, and in the Kiribati economy in general.

The first recommendation is, therefore, that further work should be carried out to confirm the lending conditions within Kiribati's finance markets, and explore other financing possibilities.

Market barrier analysis

In economic jargon, a market barrier negatively affects an economy because it reduces the allocative efficiency of resources and, therefore, results in a societal welfare loss (the welfare of society is lower than it could otherwise be). Understanding market barriers, their root causes and market signalling allow interventions to be made. These interventions are designed to correct the identified barriers, but may introduce other market barriers or adverse incentives into the system, so a careful understanding of the situation is required.

In plain English, a market barrier stops an expected outcome or impact from being achieved. Market barriers may be attitudes, incentives, market functioning, market structures, prices or governance systems. An understanding of market barriers is critical to ensuring project success.

Selling fish at a roadside stall on Tarawa (image: Michel Blanc).

Regulations and documentation

There is no regulation in Kiribati for fishers to carry ice, and fishers are able to sell un-iced fish at local markets because of local demand. As with much of the rest of the Pacific Islands region, there are no 'pull' factors, such as price premiums in local markets for iced fish, or local demand requirements, and no 'push' factors, such as regulations. This weakens the incentive to use ice and good fish handling practices, and decreases the chance of supplying fish to KFL.

The requirement to register with KFL was not seen as a problem and was considered a straightforward process. This indicates that paperwork is not a barrier to fishers supplying KFL with fish.

Off-loading fish catches

The fact that fishers can offload their fish and get cash very quickly when selling to KFL was seen as a significant advantage by fishers. It means that they (or their family) would not have to spend time sitting at the market selling fish and, as a result, could undertake more productive activities. However, KFL's supply conditions decrease the strength of these incentives.

In addition, KFL only accepts bigeye and yellowfin tunas. Previously, KFL accepted reef fish, bottomfish and other types of pelagic fish. From December 2013 to February 2014, three tons of reef fish and bottomfish, and ten tons of tuna were supplied to KFL. This meant that fishers did not incur additional costs and time in visiting both KFL and the local markets in order to offload their fish. KFL has, however, since stopped accepting fish other than bigeye and yellowfin tunas, and also has a 10 kg minimum size per fish. Fishers reported that only 40–50% of their catch had the potential to meet these requirements. The result is that fishers cannot gain benefits from supplying only KFL, but instead face additional financial and time costs when they visit both KFL and the local markets to offload their catch.

Fishers also tend to target smaller fish because they know that they will be able to sell these at the local markets, whereas larger sized tuna are much harder to sell. This means that when larger fish are rejected by KFL, fishers have nowhere else to sell them, This significantly increases their financial risk.

It is, therefore, suggested that KFL conduct a trial whereby it accepts all fish, at market prices, from fishers who supply them with export-grade tuna and sell these at cost where they currently sell tuna byproducts. This should be cost neutral for KFL, which already sells fish byproducts to local buyers.

Fish handling

The need for careful handling and cleaning of fish for KFL was highlighted as a barrier to supplying KFL. While this takes minimal additional time (fishers estimated two to three minutes per fish), all fishers felt that it was too much work for so little gain. Careful handling and cleaning of fish is an important requirement for export quality fish and is a non-negotiable requirement of KFL. Retraining selected fishers may help improve their understanding and practice of techniques. Equally, price differences between KFL and the main market will need to be stronger in order for fishers to invest the time to clean their fish.

Travel distance

Due to KFL's position at the western end of Betio, Bairiki fishers must travel longer distances to offload their catch, which means they incur higher costs in terms of fuel and time. (Bairiki is 3 nm round trip from KFL.) This, therefore, negatively impacts the willingness of fishers to supply KFL, as was discovered from interviews with Bairiki fishers, and fishers from the east side of Betio were less willing to supply KFL.

Setting up collection facilities at other points around South Tarawa could be considered in order to reduce distances travelled by smaller fishers and take advantage of economies of scale of transporting large amounts of fish in one go.

KFL could also consider using the industrial transhipping model on a smaller scale at certain locations (such as near FADs), so the smaller boats can fish and transfer their catch at sea to larger boats better equipped to carry the necessary gear to treat the fish well (e.g. ice). This would reduce fishers' costs, ensure that their boats are within their safety limits, allow fishers to be out fishing for longer, allow them to reload with ice, and reduce handling requirements. All of which better align with fishers incentives, attitudes and current conditions. The exact model used would require further investigation.

Fishing businesses

Fishers indicated that they needed to think of fishing as a business and to manage it as such, but lacked the skills. This lack of knowledge about business management, record keeping and finance means that incentives designed to change fishers' behaviour must be very strong. Essentially, these incentives need to be too attractive to ignore. Current price differentials between KFL and local markets are too narrow to impact fisher behaviour, and the additional requirements that KFL places on fishers further weaken and distort the impact of these price differentials.

It is, therefore, recommended that fishers are provided with assistance to increase their understanding of business management, record keeping and finance.

Cost analysis

A cost analysis was carried out using information supplied by KFL and local fishers. The data used, and therefore the outputs, are confidential and so details cannot

Inside the Kiribati Fish Ltd fish processing facility (image: Michel Blanc).

be published. The analysis, however, demonstrates that the price-based incentive to supply KFL must be sufficient enough to outweigh the extra earnings for being at sea longer and the additional costs incurred by fishers when supplying KFL. The analysis suggests that this was not currently the situation and prices needed to be increased to ensure that the market signals were sufficiently strong. It would be worth undertaking a study to identify exactly what price model would lead to an efficient outcome and increase the supply of tuna and smaller fish to KFL.

Conclusions and recommendations

The data collected for the analysis suggest that the deployment of FADs has increased fishers' access to tuna, and they are achieving good catches of large tuna from them. This analysis used a market barrier approach to investigate the possible reasons why local fishers were not supplying KFL with tuna. Assuming that achieving a supply of tuna from local fishers remains a strategic aim of KFL, a number of recommendations are suggested to improve the supply from local fishers.

Recommendation 1:

KFL should consider accepting other fish from fishers and selling these with the tuna byproducts that they currently sell.

Recommendation 2:

Work with fishers to professionalise their businesses by increasing their understanding of business management, record keeping and finance.

Recommendation 3:

Increase the price differential between the local markets and KFL by increasing the price paid by KFL.

Recommendation 4:

Consider the feasibility of reducing fishers' costs of supplying KFL by using transhipping models.

Recommendation 5:

Identify options for sustainable financing mechanisms (through government, private institutions, or donors) to increase the size of fishers' boats and enable them to carry ice.

Small boat fishers heading out to fishing grounds (image: Michel Blanc).

Acknowledgements

The author would like to thank Kintoba Tearo of KFL for his kind assistance and acknowledge the time given up by members of Betio Fisherman's Association, Betio Fisherman's Cooperative and the Kiriwaru Maritime Cooperative Society Ltd and two independent fishers for taking part in these interviews. The views expressed in this document remain those of the author and not of any organisation associated with this work.

Note

This article will also be published as part of the SPC economic brief series.

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Attachment training in practical analysis of current policy questions

In February 2016, three government analysts — Toaa Tokoia and Tabuki Teoraata from Kiribati and Salome Taufa from Tonga — joined Philip James, Pacific Community's Economic Officer (Fisheries), in Noumea for training in the practical analysis of current policy questions relevant to their individual countries. The two Kiribati analysts were jointly funded by the Ministry of Fisheries and Marine Resource Development in Kiribati and SPC. The economist from Tonga was jointly funded by SPC and New Zealand as part of the capacity development element of the Ministry of Foreign Affairs and Trade's National Institute of Water and Atmospheric Research project supporting the deep water snapper industry in Tonga.

The three analysts spent between two and three weeks at SPC, Noumea, working on a range of issues, including an analysis of the aquarium industry and management plans; analysis of government-supported fish farming businesses; and data collection methodologies for markets.

The analysts were exposed to cost-benefit and other analysis for fisheries and policy decision making. The time in Noumea also allowed the analysts to learn about bio-economic modelling, project monitoring, evaluation and learning from SPC specialists in these areas.

The attachments forged closer links between country and SPC analysts and between different country analysts who are faced with similar issues. It is hoped that these relationships will continue to develop in the future for the benefit of the countries involved.

It is hoped that in the future, economic attachments can become a further element of the very successful young professional and scientific attachment scheme that has been ever present for many years in the Coastal Fisheries Programme at SPC. SPC hopes to attract donor funding to fund additional attachments. Expressions of interest in participating in future attachments should be forwarded to:

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Data from this aquaculture and aquarium holding facility in Tonga were part of the information used to do an analysis of the aquarium industry and management plans (image: Philip James).

Sandfish (*Holothuria scabra*) to boost inshore fisheries opportunities in Kiribati

*The overexploitation of sea cucumber fisheries in Kiribati from the mid-1990s to the mid-2000s has led to the complete and indefinite closure of this export fishery in 2014. Processed beche-de-mer exports peaked at 268.5 tonnes (t) in 2007 with the high-value black teatfish (*Holothuria nobilis*) and white teatfish (*H. fuscogilva*) being the main target species. By 2012, volumes had dropped to just 68 t, which by then were made up largely of the low-value lollyfish (*H. atra*). Efforts at managing the fishery included the hatchery production of sea cucumbers for restocking, which started in 1997 mainly with white teatfish. The project was funded by the Overseas Fishery Cooperation Foundation, and while hatchery production was successful, restocking on its own never became an effective management strategy for the fishery.*

To build on this early work, and in a renewed effort to restore the beche-de-mer sector, the Kiribati Ministry of Fisheries and Marine Resources Development (MFMRD), in collaboration with the Aquaculture Section of the Pacific Community (SPC) Fisheries, Aquaculture and Marine Ecosystems (FAME) Division, have been producing juvenile sea cucumbers sandfish (*H. scabra*) under the Australian Centre for International Agricultural Research-funded project "Improving Community-based Aquaculture in Fiji, Kiribati, Samoa and Vanuatu".

How does this project differ from previous attempts?

Sandfish juveniles have been produced in Kiribati since August 2015 as part of the first phase of the project. In the second phase, which started in 2016, MFMRD and SPC teams have actively engaged with village communities in North Tarawa and Abaiang where juvenile sandfish are to be released. Community involvement in and their ownership of the project, and of the batches of juveniles that are transferred to them, is critical to the long-term viability of the project as community members become sandfish farmers and eventually harvest a saleable product. The project will integrate findings and a methodology from another SPC project on community-based fisheries management to create synergies between the two concurrent activities and incorporate aquaculture commodities such as sandfish in the suite of options available for coastal communities to derive food and income from. In particular, the project will use sandfish farming as an incentive for the application of measures such as protected areas and rotational closures for the management of other coastal resources.

Sandfish are not present in Kiribati and had to be introduced as part of the project. The introduction of exotic species is rare these days, due mostly to the risk — real or perceived — of introducing pests. The importation of live sandfish broodstock from Fiji was conducted following a thorough import risk analysis by the FAME-Aquaculture team to assess the potential disease and ecological risks and develop strict sanitary transfer measures.

Figure 1. Juvenile sandfish ready to be released in Tabuki, North Tarawa (image: Michel Bermudes).

The choice on sandfish instead of a local sea cucumber species is, like community engagement, a way to maximise the project's impact and its long-term viability. Sandfish is, among all tropical sea cucumbers, the species for which most research related to culture and propagation has been done. The well-established culture technology was readily transferrable to Kiribati with minimal research effort and capacity required. Sandfish is also one

Figure 2. Pen culture at Tabuki, North Tarawa (image: Michel Bermudes).

of a few sea cucumber species that have the main traits for aquaculture on isolated atolls: 1) easy to breed and fast growing; 2) easy to process and store; 3) has a high value; and 4) there is a strong market demand for it.

Progress to date

Since August 2015, MFMRD staff, with the assistance of SPC, has carried out repeated sandfish spawning at the Tanaea hatchery to produce juveniles destined for community-based farming trials in North Tarawa and Abaiang. Practice makes perfect, and with each spawning run and the training provided onsite and overseas at the Southeast Asian Fisheries Development Center in Bangkok, Thailand, local fisheries staff have grown in confidence by honing their skills in all aspects of hatchery production: from spawn induction techniques to the rearing of larvae or juvenile sandfish in a land-based facility. From a couple of hundred juveniles produced at the first attempt, MFMRD staff are now producing several thousand juveniles at each spawn. Hatchery production of sandfish in Kiribati is now conducted with a great degree of confidence and protocols have been refined to optimise local resources. Developing strategies to maximise juvenile production will be one of the outputs of the project.

Moving to the next step and releasing the juveniles they had nurtured in the hatchery, was very exciting for MFMRD staff because they could see the progression of the production cycle. The first seeding in lagoon and pond settings was carried out in February 2016. Around 100 juveniles (Fig. 1) were placed in a 50 m^2 circular pen at Tabuki village, North Tarawa and another 70 juveniles were released in a 35 m^2 circular pen in one of the ponds at EcoFarm, South Tarawa. The circular pens were made from fine 1.2 mm black mesh and were held with wooden stakes to form an enclosure to keep the sandfish juveniles from escaping (Fig. 2).

Six weeks post-release, observations indicated a high survival rate (>85%) and good growth for the juvenile sandfish released in a lagoon pen at Tabuki, North Tarawa (Fig. 3). Observing the cryptic sandfish in the EcoFarm pond has been difficult, possibly because the site is shallower than at Tabuki. Predators in the ponds (mostly crabs) have also been harder to control. Crab traps will be used to minimise predation. Comparing different sites will enable MFMRD staff to determine optimal growing conditions and rearing techniques in the future.

Alongside the transfer of technical hatchery and grow-out culture techniques, community engagement and participation has been the key to a successful first release of sandfish in Kiribati, with regular snorkel surveys to inspect the pen and remove predators proving very effective in this environment.

To boost private sector development, the SPC/ACIAR community-based project is also engaging Atoll Beauties with the propagation of sandfish. Atoll Beauties is a privately-owned aquaculture company that mainly cultures giant clams, in collaboration with communities, for the aquarium market. Atoll Beauties is actively collaborating with MFMRD through a memorandum of understanding, and is providing support to project activities. Their current role involves raising surplus larvae from the Tanaea hatchery to serve as back-up in case of high mortalities at the Tanaea hatchery. Atoll Beauties is also involved with grow-out at Tabuki in North Tarawa, which is proving to be a very good site for juvenile growth and will be tested as a broodstock reserve for future breeding programmes.

The project is an exercise in supply chain capacity building from seed production to harvest. Further improvements will be required both in the hatchery and lagoon nursery to farm sandfish on a larger scale. Project plans for 2016 are to: 1) improve on late nursery culture in the hatchery to increase production of sandfish juveniles; 2) grow some sandfish to adult size so they can be used for the breeding programme instead of relying on the importation of broodstock; and 3) establish community farms in other parts of North Tarawa and in Abaiang.

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Figure 3. Healthy juvenile sandfish in Tabuki, North Tarawa, just weeks after release (image: Michel Bermudes).

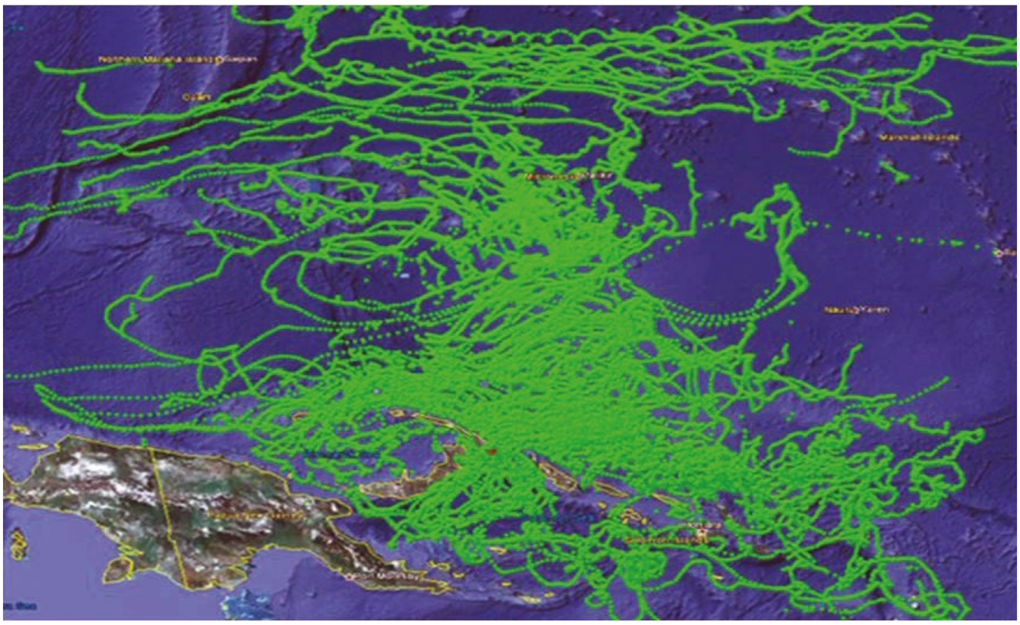
FAO expert consultation on marking fishing gear

Unless it is properly marked and can be located by day and at night, fishing gear can be a serious hazard for other inhabitants and users of the ocean, especially for the safe navigation of vessels. Proper marking of gear can help to differentiate between legitimate fishers and those engaged in illegal, unreported and unregulated fishing activities. The adverse impacts of fishing gear on non-target species of marine wildlife are also well known, and abandoned, lost or discarded fishing gear (ALDFG) presents a major hazard to marine wildlife and is becoming increasingly well recognised. For example, in the United Nations Environment Programme's Global Marine Litter Campaign and the Global Ghost Gear Initiative, a cross-sectoral alliance that is developing sustainable solutions to the global problem of ghost fishing gear (www.ghostgear.org).

An important factor in reducing the hazards of fishing gear and dealing with ALDFG is identifying the owners of the gear and/or the vessel that deployed it. In early April 2016, the Food and Agriculture Organization (FAO) of the United Nations convened an 18-member Expert Consultation on the marking of fishing gear at their headquarters in Rome. Lindsay Chapman, from the Pacific Community (SPC), and Mike Donoghue from the Secretariat of the Pacific Regional Environment Programme (SPREP) were invited to attend in order to bring a Pacific perspective.

This is not a new issue for FAO – the conclusions of a 1991 Expert Consultation on marking fishing gear were presented to FAO's Committee on Fisheries in 1993, but a consensus could not be obtained at that time. During the intervening years, while fishing technologies have evolved, the basic problem has remained the same although a number of new international agreements and legal frameworks have been introduced.

Perhaps the most significant of these is Annex V of MARPOL[1], which prohibits the disposal at sea of fishing gear made of synthetic material. Guidelines for the application of Annex V call for fisheries managers to utilise fishing gear identification systems, and encourages governments to consider the development of technology for more effective fishing gear identification. Both SPC and SPREP have serious concerns about the amount of synthetic material that continues to be carelessly discarded in our region, with consequent potential impacts on navigation and marine wildlife. Many maritime users are probably unaware of their obligations under international law to retain plastics and other non-degradable items on board their vessels for safe disposal on shore.



Tracks over six months for FADs deployed by three purse-seine vessels (source: Maurice Brownjohn, Parties to the Nauru Agreement Office)

[1] MARPOL: International Convention for the Prevention of Pollution from Ships

Both Lindsay and Mike were vocal during the Expert Group discussions on FADs. The Parties to the Nauru Agreement (PNA) estimate that there may be as many as 80,000 FADs drifting in our region annually, and although they are a means of attracting, rather than capturing fish, they are potentially a significant source of marine debris, resulting in unintentional entanglement of marine wildlife and fouling of reefs.

Existing technologies enable FADs to be uniquely identified and tracked remotely by satellites. Although the great majority of FADs that are deployed are tracked, as they drift hundreds or thousands of kilometres from where they were deployed, they are still available for vessels to set their gear around. Although most FADs are not picked up by the vessel that releases them, the question of whether they constitute ALDFG is a moot point. In reality, the cost of fuel sees most FADs disowned once they are beyond the economic range to retrieve them.

The draft guidelines will be presented to FAO's Committee on Fisheries at its annual meeting in July 2016, and it is hoped that after a 23-year hiatus, they will be successfully adopted this time around, making our oceans a little safer for us all.

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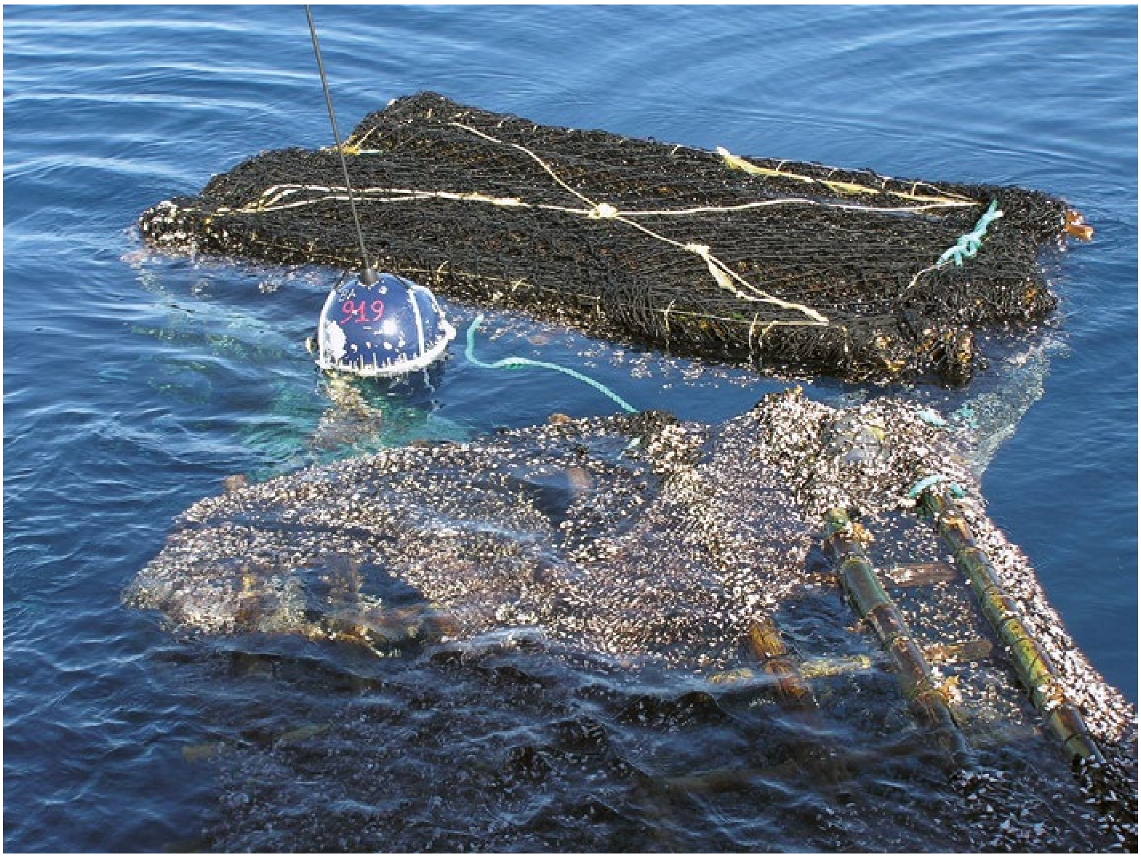


A drifting FAD equipped with a radio beacon (image: Marc Taquet, FADIO/IRD-Ifremer).

The 2016 version of the Benefish study

In 2002 and 2008, the Asian Development Bank undertook studies to quantify benefits from the fisheries sectors of Pacific Island countries. Reports were issued from those studies and the information in them has been frequently cited. These reports are known in the Pacific Islands region as the "Benefish" reports.

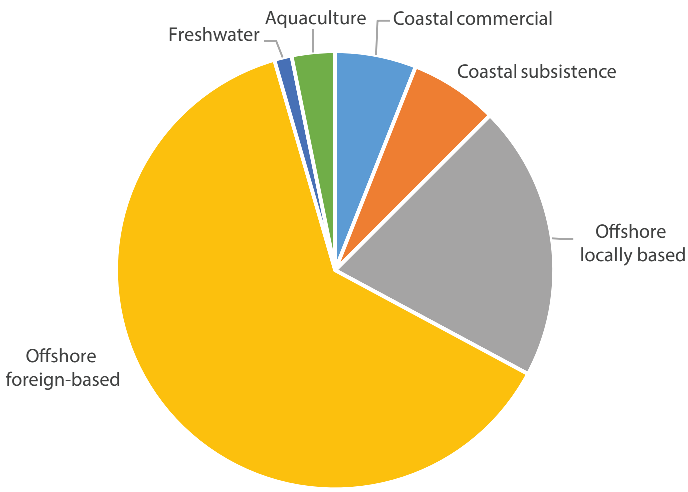
In early 2014, discussions between the Pacific Community (SPC) and the Australian Department of Foreign Affairs and Trade resulted in an agreement to sponsor an update of the earlier publications. A consultant was recruited, and fieldwork to collect information began in early August 2014 and was completed in early November. Country-specific information was assembled, analysed, and written up in from mid-November to late January, and the main text of the report was produced in February 2016.

Information on the benefits from fisheries is provided in the new Benefish report for each of the 22 Pacific Island countries and territories. The country sections contain the most recent and available data in the following areas:

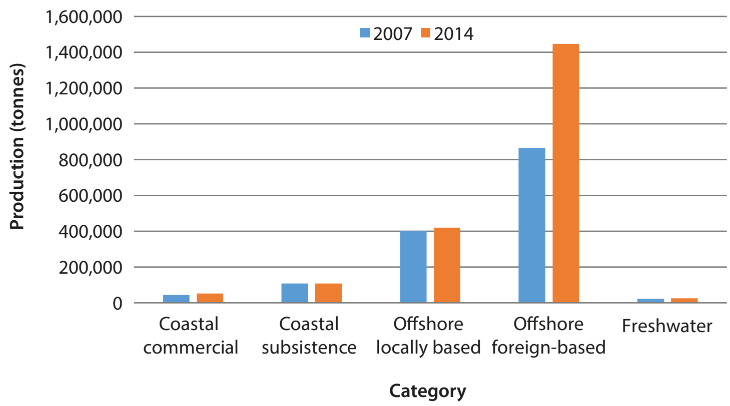
- Recent annual fishery harvests: values and volumes covering the six fishery production categories: 1) coastal commercial fishing, 2) coastal subsistence fishing, 3) locally based offshore fishing, 4) foreign-based offshore fishing, 5) freshwater fishing, and 6) aquaculture.
- Fishing contribution to gross domestic product: fishing's current contribution, how the contribution was calculated, and re-calculation based on annual harvest levels obtained during the study.
- Fishery exports: amounts, types, and the ratio to all exports.
- Government revenue from the fisheries sector: access fees and other revenue.
- Fisheries employment
- Fisheries contribution to nutrition

In addition, the new Benefish book has a discussion of important topics to each country and territory (e.g. the regional significance of access and exports of fishery products), some important features of the benefits from fisheries that have emerged from this study, and recommendations on improving the measurement of fisheries benefits and assuring the continuity of those benefits. Background information on estimating gross domestic product is provided, along with guidelines on estimating the fishing contribution to the gross domestic product of each country or territory.

The new book[1] is currently being edited and translated at SPC, and is currently scheduled for release in July. Presently, much of the information in the book is provisional although some of the more generalised results of the new Benefish study are given in the two graphs below.



Relative value of fisheries production across all countries and territories.



Fishery production by category for the years 2007 and 2014 and across all countries and territories

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[1] http://www.spc.int/fame/en/component/content/article/237-benefish-study-2016

Stakeholders of the Kiribati Community Based Fisheries Management Project gather to discuss lessons learned and way forward

***by Tarateiti Uriam*[1]**

United we stand, divided we suffer

Materiki Toromon, Butaritari community representative

The Community-Based Fisheries Management (CBFM) project in Kiribati is implemented by five partners: the Kiribati Ministry of Fisheries and Marine Resources Development (MFMRD), the Australian Centre for International Agricultural Research, the Pacific Community, the University of Wollongong, and WorldFish.

Initially implemented in May 2014 on two pilot islands of the Northern Gilbert islands — Butaritari and North Tarawa — the project has taken root in five communities on these two islands (Kuma, Tanimaiaki and Bikati in Butaritari, and Buariki and Tabonibara in North Tarawa).

At the onset, the CBFM project was introduced to Island Councils of Butaritari and North Tarawa to seek approval for implementing the project in the pilot communities. The selection of pilot communities was made by the mayor and councillors. The CBFM team subsequently visited these communities to give an overview of the project, get community perception on fisheries and other related issues, and most importantly, to maximise community buy-in to the project. Community-based management plans, which were developed in 2015, include communities' concerns regarding their fisheries. Not surprisingly, some of the recommended measures were common to all five community management plans, such as the banning of destructive fishing gear and fishing practices, including:

- using small mesh sized nets and excessively long gill nets;
- splashing water with metal bars to scare fish and drive them towards nets (*te ororo*);
- encircling corals with gill nets (*borakai*);
- destroying corals to reach fish or octopus;
- fishing on spawning aggregations; and
- catching juvenile fish before they have had a chance to reproduce.

Community members were aware that these fishing practices were harmful but banning them had to be decided on collectively. The CBFM project allowed communities to do so and gave them the tools to enforce these measures by themselves.

Establishing marine reserves was another action that was recommended in all management plans. Bikati was the first community to establish a community-driven marine protected area and was supported by the Island Council and elders' association in Butaritari.

The management plans also enabled communities to extend their vision to other issues that indirectly affect fisheries, such as poor village governance, waste and sanitation, agriculture, education and alternative sources of income.

The long-term success of the CBFM project depends on a coordinated and collaborative approach among communities, island councils, various government ministries, and non-governmental organisations (NGOs). In April, a second stakeholder meeting was held with approximately 45 participants from different groups[2] who gathered to discuss lessons learned, best practices and ways forward to ensure better collaboration between communities and other stakeholders. The mayors of Makin and TUC were invited because of their proximity to both of the pilot islands, which means that they share the same areas of the lagoon for fishing.

The meeting was opened by the Director of Coastal Fisheries, Karibanang Tamuera. Mr Tamuera emphasised the valuable roles that communities have in managing and

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[2] MFMRD, the Ministry of Environment, Lands and Agriculture Development, the Ministry of Internal Affairs (MIA), the Ministry of Women, Youth and Social Affairs, the Office of the Attorney General, the Curriculum Development Unit of the Ministry of Education, mayors from Makin, Butaritari, and North Tarawa and the Tarawa Urban Council (TUC) as well as representatives from pilot communities.

Figure 1. Leaders discussing way forward.
From left to right: Tebura Tanaua (Mayor of Makin), Kareke Itinibeia (Mayor of Butaritari), Tetaake Tenaua (Chairman of the Makin Unimwane Association), Mwaiango Teimwarane (Senior Fisheries Assistant), and Ruoikabuti Tion (Mayor of the Tarawa Urban Council).

sustaining their marine resources. He also mentioned that many of the issues that emerged during CBFM consultations needed to be addressed immediately, and therefore MFMRD was seeking assistance and support from other government bodies and NGOs to ensure that these villages could fulfil what they had envisioned in their management plans. Mr Tamuera stressed the need for stronger collaboration among different government ministries, Island Councils, communities and NGOs for successful outcomes. Mr Tamuera ended his speech by remarking, "We are not owners of these resources, we are only caretakers for the next generation."

The meeting lasted two days and was facilitated by Materiki Toromon (community representative), Ben Namakin and Tarateiti Uriam (CBFM officers). Although the meeting physically took place in a conference room (Fig. 1), it was conducted to recreate the "*maneaba* way", as meetings are traditionally run in Kiribati, in the meeting house called the *maneaba* (Fig. 2). The rules of the *maneaba*, where everyone is equal and free to express his or her own opinion, were applied to the meeting. This is different from other meetings between government representatives and communities where community representatives often feel they are in a position of "inferiority" and "invited" to listen to the expertise of government staff. This helped break down the barrier between community and government representatives, thereby allowing community representatives to speak freely and confidently.

Community representatives were given the opportunity to read aloud their management plans, which impressed participants from the ministries. Declining fisheries was the common issue identified in all of the plans, and villagers were looking for ways to ban the use of destructive fishing practices. Community members feared that even if these bans were respected in their own respective villages, other people from outside could break these rules. These villagers saw the need for bylaws that would enforce their management plan. In response, MIA urged these communities, along with their Island Council, to initiate awareness raising measures in neighbouring villages in order to gain their neighbours' support with the management plan.

Once support for a community management plan was established, the community and its Island Council could then work with MIA to create a bylaw that would recognise the plan of the said community at the island level. The representative from the Office of the Attorney General, Monoo Mweretaka, introduced another option to address this issue: the Attorney General's office recognises the bylaws of NGOs registered with the Ministry of Women, Youth and Social Affairs, if these by-laws complement a government Act. Therefore, if a community registers as NGO under MWYSA, its bylaws will easily be endorsed by the Attorney General's office, and these bylaws will only be enforced in that community.

Because community members see fisheries as a complex and dynamic system, they have identified in their management plans other issues that indirectly affect fisheries. Some of these areas include climate change, waste management, coastal development and erosion, income generation, education, population growth, and governance. Community members spoke about the effect of coastal development, especially the work done on the causeway that is believed to have altered currents and affected the spawning runs of some fish. They also believe that more alternative sources of income will reduce the pressure on fisheries and more support for children's education will allow these children to find jobs and to support themselves financially without always having to depend on fisheries resources.

This meeting provided communities the opportunity to discuss with government officials from different government ministries on how to go about addressing these issues. Community members felt empowered and motivated by the positive responses from government officials. In the same way, staff from the different ministries were overwhelmed by the efforts that these communities showcased, and they learned a lot from their presentations.

Another important achievement of the meeting was the decision, initiated by government officers, to establish a steering committee. This committee will be made up of staff from the different ministries and chaired by CBFM project officers. Due to their geographic repartition, the involvement of communities is being worked out. It will strengthen the collaboration between the different ministries and communities, and will reduce overlap of activities. All participants were impressed with the meeting's operation, and the TUC mayor, in particular, said: "I have been to a lot of meetings and this is the first meeting where we discuss freely what we want for our people." The mayor from Makin envied Butaritari and North Tarawa pioneering the CBFM project, and urged the CBFM team to visit his island.

The outcomes of the meeting were outstanding and all participants were satisfied, especially the communities knowing that their concerns were taken into account and were heard by government representatives. The meeting also proved that communities are on the same page as government, as highlighted by Tuake Teema, Senior Fisheries Officer, who said, "These communities are now speaking our language, the work they do complements the Fisheries Regulations." Biita Rameka from MELAD in the Agriculture Division encouraged and motivated the communities to lead by example for the whole of Kiribati.

One of the main lessons learned from this process is that close collaboration among different government institutions, island councils, NGOs and communities may be the key to fostering changes in the management of marine resources.

Figure 2. The maneaba*, a traditional meeting house.*

Population genetics of sandfish (*Holothuria scabra*) in Fiji: Implications for resource management and aquaculture development

Roveena Vandana Chand[1*], Paul C. Southgate[2] and Tamara Osborne[3]

Tropical sea cucumbers are mostly exported to Asian markets, where they are considered a delicacy and have the reputation of providing medicinal and nutritional benefits. Intense harvesting of high- and medium-value sea cucumber species has had a great impact on wild stocks. Putting in place and enforcing effective management measures for sea cucumber fisheries has become an urgent necessity.

In Fiji, sandfish (*Holothuria scabra*) is the highest value species among the 28 reported commercial species found. But, overharvesting led authorities to declare an export ban for this species in 1988, a ban that is still in place. However, between leniency in the regulations and seasonal openings, the species continues to be exported with ease at a price of USD 115–1,668 per kilogram for dried and processed product (beche-de-mer).

Research project

In conservation science, maintaining biological diversity at a level of genes, individuals, populations and species through viable breeding populations or metapopulations is a challenge. An important feature of the metapopulation theory is that although connected by gene flow, demes are dominated by local adaptation, extinction and colonisation dynamics. In the sea, populations are assumed to be genetically open systems with high levels of gene flow and limited potential for local adaptation. In marine invertebrates, species with a high larval dispersal potential, the association between gene flow and ocean currents is particularly important for species conservation and management issues.

Habitat discontinuities in Fiji, such as deep water trenches and isolated islands and ecosystems, are ideal for testing theories of biodiversity and conservation.

Sandfish, one of the highest value tropical sea cucumber species (image: Roveena Chand).

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Three different colour morphs of sandfish specimens collected in Fiji waters (image: Roveen Chand).

Distances between islands, the presence or absence of reefs and lagoons, and urban development often restrict the movements of terrestrial and marine organisms, which may result in reduced gene flow among individual populations. Through conservation genetics, our research project attempts to determine if geographically isolated demes of *H. scabra* from various islands in Fiji are genetically different, because of a limited gene flow, and whether populations share a common genetic structure imprinted in the early years of their life cycle supporting a metapopulation dynamics model throughout its geographic range.

Method

The research funded by the Australian Centre for International Agricultural Research is currently being conducted at the University of the South Pacific, Faculty of Science Technology and Environment (FSTE), School of Marine Studies. For the study, 10 individuals of *H. scabra* will be collected at eight different sites in Fiji. The samples will be transported to the FSTE laboratory for DNA extractions. Using standard DNA extraction protocols and polymerase chain reaction (PCR) amplification, samples will be prepared accordingly and sent abroad to a commercial laboratory for DNA sequencing. Sequences received will be analysed using genetic based software programs such as Arlequin and Geneclass.

Expected outcome

The major outcome of the current research will be to evaluate whether ocean currents and distances between islands in Fiji affect *H. scabra*'s gene flow, and its population genetic diversity, structure and effective size. The study will report on whether captive breeding of individual sandfish from two selected sites for the purpose of restocking depleted stocks in the wild is safe genetically at a species level. The results will identify genetic diversity of *H. scabra* in Fiji and assess the probable consequences of overharvesting in terms of *H. scabra* vulnerability to allele effects.

The need for conservation of dwindling populations of *H. scabra* was highlighted in Fiji by the 1998 fishing ban, which is still in place but only partially enforced. The current study may provide the supporting evidence, at a genetic level, that strict and well-enforced conservation measures are urgently needed not only for the *H. scabra* fishery, but also for the survival of the species itself in Fijian waters. It will also be the first time in Fiji that genetics are used to support the management of a marine species.

Application of a harvest strategy to resource-limited deepwater snapper fisheries

Nicholas Hill[1], Tuikolongahau Halafihi[2], Ashley Williams[3], Tom Peatman[1], Simon Nicol[4] and Neville Smith[1]

Deepwater snapper fisheries represent an important resource for many Pacific Island countries and territories (PICTs). Artisanal and commercial fishers target deepwater finfish species for local consumption and export. Many of these fisheries were developed in the 1970s in attempts to relieve pressure from shallow-water demersal stocks. However, since the early 2000s, participation has declined, with some fisheries no longer active. With PICTs looking to improve food security, efforts have been made in recent years to re-invigorate deepwater fisheries.

Effective management of fish stocks requires an accurate estimate of stock status. This is achieved by monitoring and assessing stock levels over time and subsequently controlling harvest rates of the fishery. In PICTs, however, many fisheries remain unassessed due to a lack of data and resources (Costello et al. 2012). This leaves fisheries managers unable to appropriately monitor stocks, thus increasing the risk of overexploitation.

Over the last decade, there has been substantial development of tools for assessing data-poor fisheries (Edwards et al. 2012). These tools have been developed to allow managers to assess fisheries with minimal data or restricted analytical capacity. These methods use a range of data inputs such as catch, effort, length, age and biological data to assess stock status. Data-poor assessment techniques have proven successful, with previously unassessed or overexploited fisheries now sustainably managed (Smith et al. 2014). These improvements, however, have been predominately limited to developed nations.

Implementation of these tools within a harvest strategy management framework represents an exciting opportunity. Harvest strategies involve a series of pre-agreed on decisions that outline how a fishery is to be managed (Dowling et al. 2007). Harvest strategies outline monitoring programmes, stock assessment techniques and management actions that take place based on stock assessment outcomes. By outlining these decisions at the beginning, it becomes a very transparent approach that improves stakeholder engagement. Implementation of harvest strategies has proven successful for many fisheries although it has proven challenging to implement them within a resource-poor context.

With PICTs looking to increase food security, improved utilisation of the full range of available fisheries resources is important. For deepwater snappers, this can be achieved by returning overexploited fisheries to sustainable levels, which will increase their harvest potential, or by developing new fisheries under a sustainable management framework. To achieve this, we applied three data-poor assessments techniques to Tonga's deepwater snapper fishery and outlined how they could be implemented within a harvest strategy framework. We provide appropriate monitoring programmes, assessment techniques and examples of possible harvest control rules. This will not only help improve the management capacity of Tonga's deepwater snapper fishery, but also outline the process for other resource-poor fisheries.

Tongan deepwater snapper fishery

The Tongan deepwater snapper fishery began in the 1970s after a short developmental phase. Official data collection and monitoring of the fishery began in 1986, which aligned with a vessel building project that supplied 40 vessels to the fishery. After its official commencement in 1986, the fishery quickly expanded with reports of high catch rates. The number of vessels in the fishery peaked at 44 in 1988, which corresponded with a peak in harvest and catch rates (TDFMP 2014). Catch rates and harvests declined soon after. A second peak in harvests occurred in 2000–2002, reaching a maximum of ~230 tonnes (Fig. 1), likely driven by improved fishing technology. After this peak, catch rates declined and the number of vessels participating in the fishery concurrently decreased, with less than 14 vessels currently active in the fishery. Spatial expansion of effort and

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changes in species composition suggests that the fishery may be depleted (Fig. 2).

This fishery uses drop lines, primarily in depths of 100–400 m, to target demersal snappers (Lutjanidae), groupers (Epinephelidae) and emperors (Lethrinidae). Many of these deepwater species are slow-growing, long lived, and are late to mature. As a consequence, they are susceptible to overexploitation. Numerous assessments have been commissioned throughout the lifetime of this fishery. External organisations have undertaken biomass dynamic models to estimate maximum sustainable yield (MSY) for this fishery. However, these estimates have ranged widely from ~60–400 tonnes, with large uncertainty limiting their usefulness. Furthermore, a lack of data collection at the commencement of the fishery and the discontinuous collection of data throughout the duration of the fishery reduces the capacity to reliably estimate the current status of this fishery. With concerns of overexploitation, an improved understanding of the status of this fishery is required.

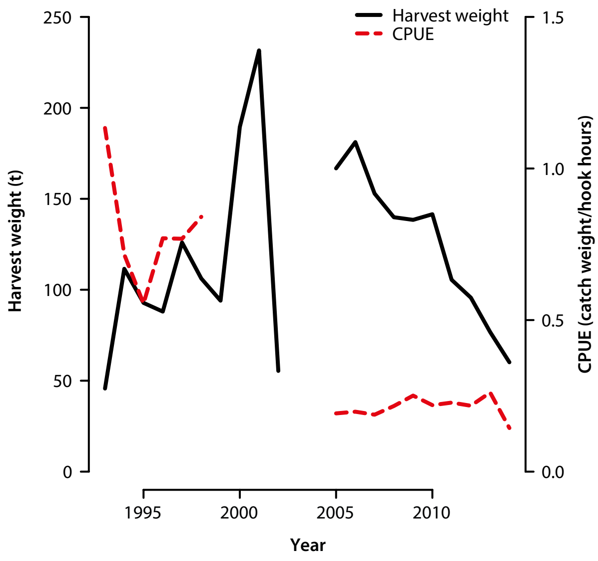

Figure 1. Total harvest weight (t) of deepwater snapper in Tonga, and the corresponding catch per unit effort from 1993–2014.

1. Biomass dynamic model for flametail snapper (*Etelis coruscans*)

Biomass dynamic models use catch and effort data to gain an estimate of MSY – the theoretical maximum amount of catch that can be taken from the stock per year, on average, in the long-term without causing the stock to decline. By harvesting at the rate of MSY, the stock is kept at the point of maximum productivity. To undertake this assessment, an index of population abundance is required, which is used to reflect shifts in stock abundance over time; we used catch rate or catch per unit of effort (CPUE). This requires a monitoring programme that records harvest and effort of all vessels within the fishery and also any factors that influence catchability – factors that will improve fishers' ability to

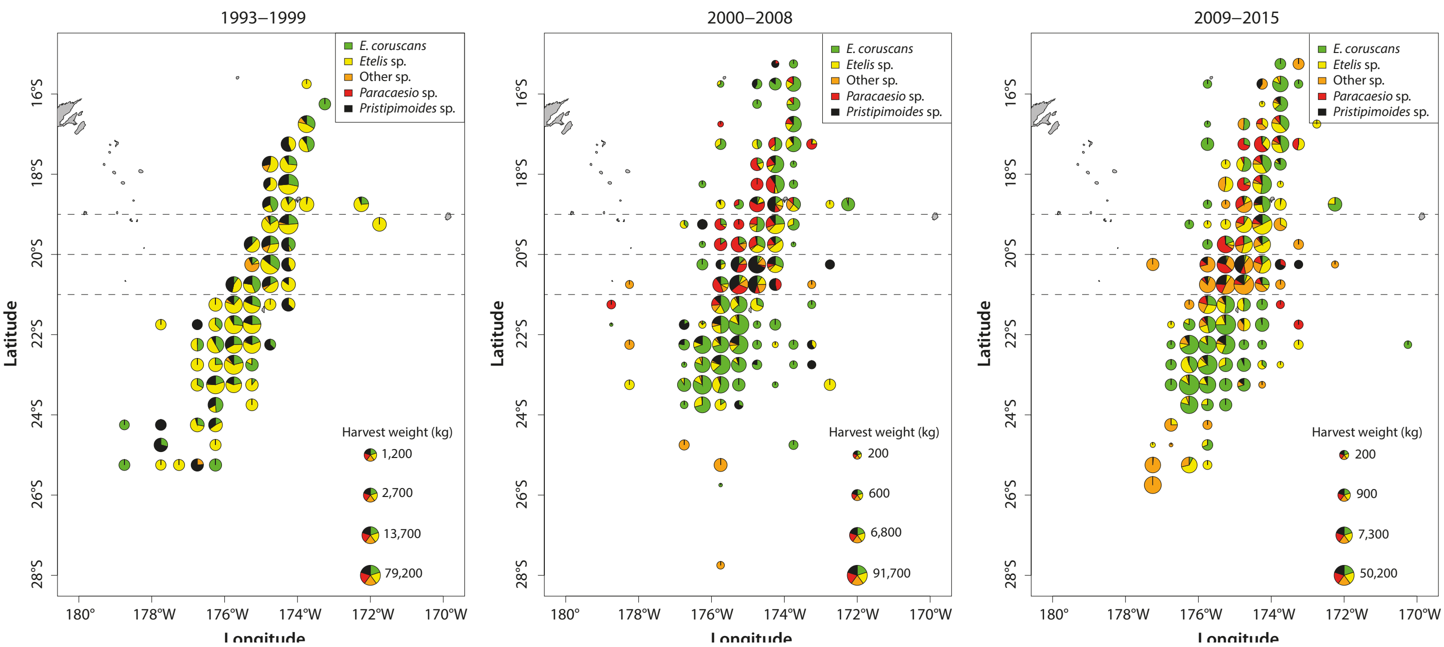

Figure 2. Shifts in species composition and spatial expansion of effort in the Tongan deepwater snapper fishery at 0.5o resolution. Pie radius size determined by total harvest weight (kg) removed from each grid cell across three time periods (1993–1999, 2000–2008, 2009–2015). Species composition is represented by five clusters designated using k-means clustering analysis.

harvest fish. To assess the accuracy of CPUE estimates we modelled three different scenarios (Fig. 3):

1. Base model – that included: year, month, depth fished, vessel, region and species composition.
2. Active vessels – base model but only including vessels that completed >15 trips per year.
3. Core area – base model for grid cells (0.5°) that recorded >1 fishing trip every 5 years.

The results of this assessment suggest that the Tongan deepwater snapper fishery is overfished (Fig. 4). Biomass of flametail snapper dropped below where MSY can be achieved ($B_{MSY} = 0.5\ B0$) in 2000 and has remained below that level since then. Flametail snapper stock is currently at 26–36% of 1993 levels (Table 1). Fishing pressure has declined in recent years, leading to increases in biomass from 25–30%, suggesting that flametail snapper is recovering. It must be noted that these results are relative to the stock size in 1993, not a virgin biomass, due to a lack of data collection at the start of the fishery. A lack of data at the commencement of the fishery and discontinuous data collection throughout the lifetime of this fishery limits the accuracy of this assessment. If it is to be used in the future, the monitoring programme must improve in consistency and coverage.

2. Length-based indicators

This technique investigates length composition of catch over time to infer stock status (Froese 2004). It looks at trends in the proportion of mature individuals, those within the optimal harvest range (L_{opt}), and large individuals (megaspawners), which are assumed to provide a disproportionately large number of recruits to assess stock status (Fig. 5). The aim is to minimise the proportion of juveniles and megaspawners captured and maximise the number of those found within the L_{opt} size range. These goals will minimise the likelihood of overexploitation occurring by ensuring a viable number of adults survive to spawn. To undertake this assessment, a simple monitoring programme that records length frequency of a subsample of catch for a number of indicator species and an estimate of length at maturity for these species is all that is required. The length-frequency distributions of flametail snapper and crimson jobfish (*Pristipimoides filamentosus*) were analysed from 1993–2014. Length data were collected for a large number of

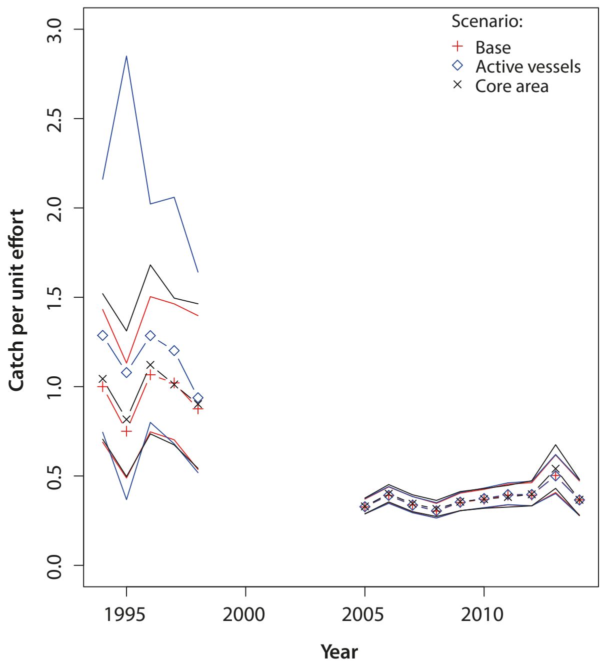

Figure 3. Estimates of standardised catch per unit effort of flametail snapper calculated using harvest weight for three different scenarios.

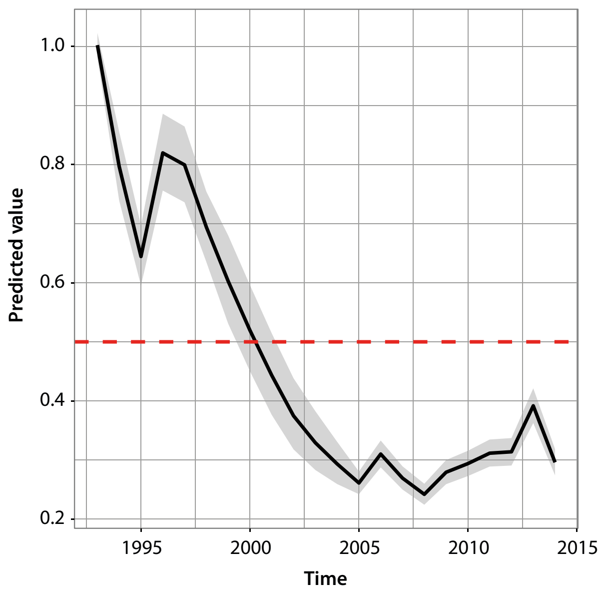

*Figure 4. Predicted stock levels of flametail snapper (*E. coruscans*) from 1993–2014 estimated from the base biomass dynamic model. Dashed red line denotes B_{MSY} for flametail snapper.*

Table 1. Biomass dynamic model outputs for all three scenarios of the Tongan deepwater snapper fishery.

Scenario	MSY (t)	Biomass at MSY (t)	Harvest rate at MSY	Current (2014) biomass (t)	Current (2014) depletion	Current (2014) harvest rate
Base	80.3	2436.2	0.032	1438.8	0.29	0.021
Active vessels	74.0	2151.1	0.034	1518.8	0.36	0.019
Core area	86.6	2905.8	0.030	1527.1	0.26	0.029

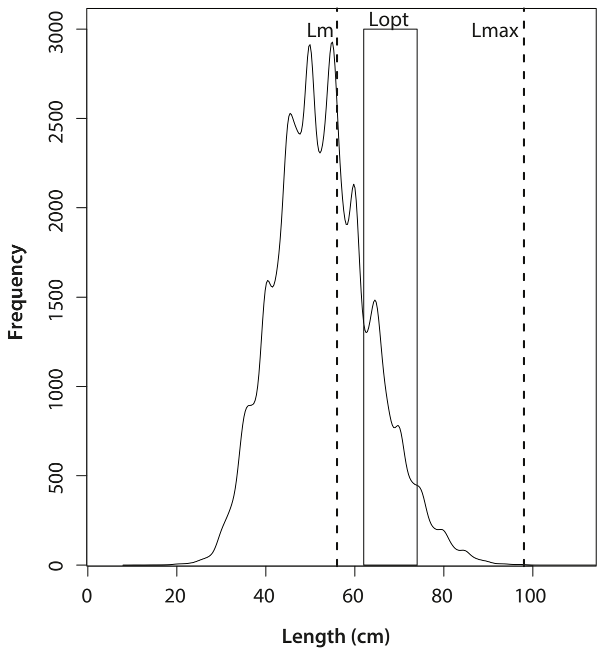

Figure 5. Length-frequency distribution plot outlining the position of length-based indicators defined by Froese (2004) in a theoretical population.

species although only adequate samples were gathered for these two species.

The length-frequency distribution of flametail snapper and crimson jobfish from 1993 to 2014 shifted over time. For flametail snapper, a decline in population health from 1993–2002 was apparent where data are available (Fig. 6A). The proportion of mature individuals in catches declined from 60% to 22%. From 2003 onwards, the number of mature individuals has increased gradually from 22% to 38% in 2014. The proportion of megaspawners has remained low since their initial decline from 15% to ~5% from 1993–1996. These results suggest that the depletion of the stock occurred from 1993 to 2002, with a recent recovery from 2005 to 2014. Crimson jobfish seems to have a more stable population with the proportion of mature individuals captured fluctuating at ~80% from 1993 to 2014 (Fig. 6B). This is likely due to a small length at maturity and individuals recruiting to the fishery at larger sizes. This means that crimson jobfish are more resilient to fishing pressure. Despite this, there is evidence of declines in the proportion of megaspawners encountered, declining from 20% to ~5%. Similar to the biomass dynamic model, a lack of data collection at the commencement of the fishery and discontinuous data hinders this assessment. If continued, fisheries should aim to incorporate a number of different indicator species to help capture trends in the fishery.

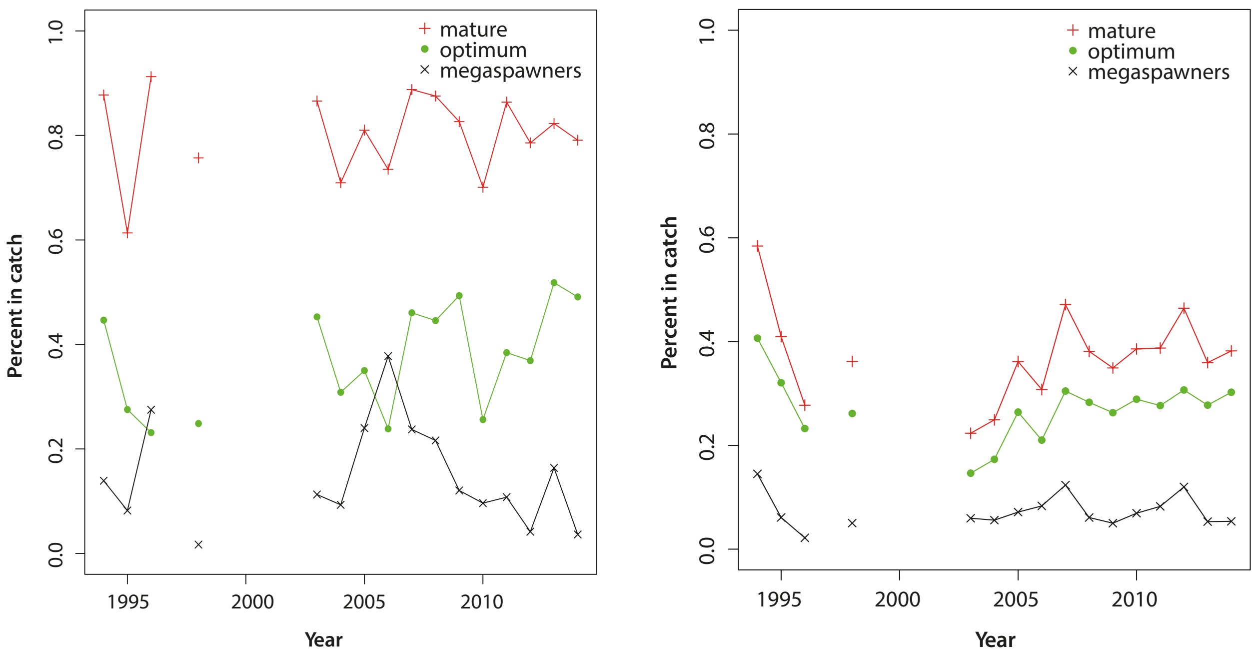

Figure 6. Length-based population indicators for indicator species from 1994 to 2014. A) E. coruscans. *B)* P. filamentosus. *No data for 1997 or from 1999 to 2002.*

3. Catch-curve analysis (age-based indicators)

Catch-curve analysis assesses stock status using age-based indicators over time to estimate fishing mortality. In essence, the more heavily exploited the stock, the fewer old individuals will be present in the population. Similar to the length-based assessment, this technique requires a representative sample of catch to assess its age composition. This was undertaken for flametail snapper in 2012 and 2013.

In 2012, estimates of fishing mortality indicated that flametail snapper were being harvested sustainably. An increase in fishing mortality occurred from 2012 to 2013 suggesting that fishing pressure on flametail snapper may be increasing (Table 2). However, a longer time series of data is required to make robust conclusions. If an increasing trend in fishing mortality was to continue into the future, this would be indicative of increased fishing pressure.

Management options

Results across each assessment were consistent, providing confidence in the outcomes. Trends for the biomass dynamic model and length-based assessment show that stocks declined from 1993 to 2005. From 2005 onwards, there are signs of recovery, likely due to decreased fishery participation. Although lacking an adequate time scale, estimates of fishing mortality from the catch-curve analysis were similar to those from the biomass dynamic model, providing confidence in its accuracy. Therefore, the Tongan deepwater snapper fishery is likely overfished and not operating at optimal levels. However, current levels of effort seem sustainable and are allowing the fishery to recover.

From these results, harvest control rules (HCR) can be assigned based on the outcomes of each assessment technique to initiate management action (Table 3). These are aimed at maintaining the fishery at a level that

Table 2. Estimates of total (Z) and fishing (F) mortality for sexed E. coruscans *in 2012–2013. Estimate of natural mortality (Hoenig 1983) was 0.109 for females and 0.122 for males.*

	Sample size	Total mortality (Z)	Fishing mortality (F)
Males (2012)	215	0.14	0.016
Females (2012)	274	0.13	0.021
Males (2013)	196	0.15	0.025
Females (2013)	282	0.17	0.058

Table 3. Example of decision rule table based on outcomes of each assessment technique. F = fishing mortality, which is an output from catch-curve analysis.

Assessment outcome	Decision rule
1. $Harvest < Harvest_{target}$ 2. $\%mature > \%mature_{target}$ 3. $F < F_{target}$	Maintain or increase quota/effort.
1. $Harvest_{target} < Harvest < Harvest_{threshold}$ 2. $\%mature_{target} > \%mature > \%mature_{threshold}$ 3. $F_{target} < F < F_{threshold}$	Quota/effort should remain constant. Potential for increased data collection/analysis.
1. $Harvest_{threshold} < Harvest < Harvest_{limit}$ 2. $\%mature_{threshold} > \%mature > \%mature_{limit}$ 3. $F_{threshold} < F < F_{limit}$	Decrease quota/effort, e.g.: 0–50%.
1. $Harvest > Harvest_{limit}$ 2. $\%mature < \%mature_{limit}$ 3. $F > F_{limit}$	Decrease quota/effort substantially, e.g.: 50–100%.

best achieves the management objectives. Commonly, a three-level system is used whereby target, threshold and limit reference levels are set for each assessment technique to enact HCRs. The goal is to maintain the fishery at the target reference level that will best achieve management objectives. If the threshold level is reached, it suggests that the fishery is under pressure and often triggers an HCR, which requires further assessment or decreased exploitation. If the limit reference level is reached, the fishery is overexploited and action must be taken to return it to more sustainable levels. These levels are designated based on assessment techniques chosen and management objectives of the fishery. For resource-poor fisheries, a precautionary buffer should also be implemented to account for uncertainty within assessment outcomes due to errors associated with these simple methods. As confidence in assessments and fishery responses to management actions improve, this buffer can be reduced.

Based on assessment outcomes, Tonga's fisheries managers should aim to maintain exploitation rates at or below current levels, which would allow stocks to continue their recovery to levels where greater harvests can be sustainably achieved. This will help to achieve management objectives of stock sustainability and ensure food security and maximisation of jobs for Tonga. This could be achieved through actions such as controlling harvest or effort quotas, or restricting the number of fishers entering the fishery.

Discussion

The ability for PICTs to autonomously manage fisheries resources is paramount to food security and sustainability. This research has outlined several data-poor assessment techniques and how they can be implemented within a harvest strategy framework based on country-specific management objectives. Feedback from Tonga's fishery managers and stakeholders has been positive, with a review currently underway into the management of Tonga's deepwater snapper fishery with cooperation from fishers based on these results. Continued development of harvest strategies applicable to resource-poor fisheries managers must be fostered.

Explicitly outlining monitoring programmes, assessment techniques and subsequent HCRs will aid resource-poor nations in autonomously managing fisheries. By clearly outlining harvest strategies, fisheries can allocate the resources required. The three assessments undertaken represent a subsample of available data-poor techniques that are available. Each requires different data inputs and analysis, provides a variety of options. Length and age-based monitoring programmes can be undertaken simultaneously, streamlining resource use. Furthermore, recent analysis has shown that simple otolith morphometrics can be used to age key deepwater fishery species, eliminating the need for resource-intense laboratory analysis (Williams et al. 2015). These two techniques represent simple assessment techniques that require few resources for monitoring or analysis. In contrast, biomass dynamic model monitoring programmes and subsequent statistical analyses are resource-intensive. As a solution, this assessment may only be undertaken when there are concerns that the fishery is in decline.

Recommendations

From this exercise we have established several key recommendations for Tonga's deepwater snapper fishery and resource-poor fisheries, which aim to improve management capabilities. Firstly, resources must be clearly identified and allocated. This provides managers with a clear understanding of what options are viable. This includes factors such as funding, number of staff, equipment and analytical expertise. In many cases, only a limited number of individuals will be charged with managing a fishery, limiting sampling and analytical capacity. Second, a clear understanding of the fishery must be obtained. This will help determine which monitoring programmes are feasible, where to focus them and what assessments are most appropriate. For example, for many PICTs there is no centralised port to process catches. This makes it difficult to monitor catch and effort, making catch-based assessment techniques unviable. Logbooks represent a potential solution to this problem. Third, key indicator species should be designated to allow concentration of monitoring resources. Comparison of assessment outcomes across species will provide a better snapshot of the status of the fishery. A range of species should be selected that are commonly caught in the fishery and represent divergent life histories. Data collection and analysis of numerous indicator species would strengthen the accuracy of assessment outcomes for Tonga's deepwater snapper fishery. Fourth, the limitations and uncertainties of assessments and monitoring programs must be addressed and accounted for. This can be achieved by setting reference levels conservatively to reduce the likelihood of overfishing occurring. Lastly, stakeholder engagement is very important. Compliance monitoring is likely to be minimal and fisheries must rely on fishers to abide by management controls. Therefore, consultation is important to maximise compliance and engagement, which will aid in achieving management objectives.

These recommendations provide fishery managers with several key considerations that will aid in managing resource-limited fisheries. Implementation of newly developed data-poor assessment techniques within a harvest strategy represents an exciting opportunity for improved management of many PICT fisheries. However, continued research and development of data-poor assessment techniques and management strategies will play a key role in achieving these goals in future. This article was based on a recent fact sheet published by the SPC that can be found online (Hill et al. 2016).

Acknowledgements

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Using SEAPODYM to better understand the influence of El Niño Southern Oscillation on Pacific tuna fisheries

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Introduction

In 2015–2016, El Niño was a strong event, among the three strongest since 1950 (together with 1982–1983 and 1997–1998). In the Pacific Ocean, El Niño Southern Oscillation (ENSO) influences the dynamics of the world's largest tuna fisheries (Lehodey et al. 2011) and ecosystem structure, leading to regime shifts in ocean productivity (Barber et al. 1996; Chavez et al. 1999). The different phases of ENSO move the longitudinal location of the convergence zone of the equatorial Pacific's two distinct and abutting ecosystems: the "western Pacific warm pool", which is characterised by low primary production and high sea surface temperatures, compared with the "eastern Pacific cold tongue" (characterised by cold up-welled nutrient-enriched waters and low sea surface temperature). During the El Niño phase of ENSO, when the tradewinds weaken, the westward flowing currents that drive the westward extent of the cold-tongue weaken, and the warm pool stretches from its origin in the western equatorial Pacific to the eastern Pacific. Conversely, during ENSO's La Niña phase, these currents strengthen under enhanced tradewinds and the westward extent of the cold tongue strengthens and the warm pool is pushed to the far western equatorial Pacific (Picaut et al. 1996). The shifting geographic distribution of these two ecosystems has potentially important implications for understanding the movement of biota, such as tuna, across the Pacific Ocean. The convergence zone between the warm pool and cold tongue is hypothesised to be an ecotone that provides abundant tuna forage, resulting in the core of the skipjack tuna (*Katsuwonus pelamis*) distribution being centered on it (Lehodey et al. 1997). In contrast, bigeye tuna (*Thunnus obesus*), although widely distributed across the equatorial Pacific is hypothesised to be in higher densities in the cold tongue. A relevant question arising from these hypotheses of tuna distribution is whether these two tuna species track the movement of their preferred ecosystems across the Pacific as ENSO shifts the longitudinal boundary of the convergence zone. Moreover, the distribution of skipjack and bigeye is largely inferred from fisheries catch data. It may be that both species are distributed more or less homogeneously across these two ecosystems and the variation in the catch data reflects different vulnerabilities to capture in the two ecosystems.

Analyses have shown that purse-seine fishing vessels with licensing capabilities to fish across the equatorial Pacific Ocean follow the eastward movement of the warm pool with the onset of El Niño (Lehodey et al. 1997, 2011; Williams and Terawasi 2014). The notion that this fleet behaviour is in response to tuna movement is supported by the high catches of tuna that have been reported from the exclusive economic zone of Kiribati during El Niño phases and from Papua New Guinea during La Niña (Lu et al. 2001; Williams and Terawasi 2011, 2012; Zainuddin 2004). However, the strength of this relationship weakens with the duration of El Niño, with some vessels returning to the western Pacific before the westward migration of the warm pool at the cessation of El Niño (Lehodey 2001). Similarly, during El Niño phases, although the tuna catches in Papua New Guinea are lower than those during La Niña, they remain regionally high (Williams and Terawasi 2011). This suggests that tuna movement may be more complex than simply following the position of the convergence zone or the cold tongue.

We use the spatial ecosystem and population dynamics model (SEAPODYM) to synthesise the population dynamics of skipjack and bigeye tunas in the Pacific Ocean, and investigate the response of these tuna species to El Niño, La Niña and neutral phases of ENSO. SEAPODYM is an age-structured, spatio-temporal model that integrates both environmental data and fisheries-dependent and independent data. We summarised the outputs of SEAPODYM using wavelet analyses to assess the impact of ENSO on the abundance and distribution of adult and juvenile tuna age classes.

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Material and method

SEAPODYM is an ecosystem model developed for exploring spatial tuna population dynamics under the large-scale influence of fishing and environment effects. Skipjack and bigeye biomass of both adult and young (immature) fish were analysed over the period 1980–2001 (terminating in 2001 as it was the last year for which the large-scale environmental data were available, Uppala et al. 2005). The resolution of the model was two degrees and one month. The Pacific Ocean was divided into nine regions (Fig. 1 – middle panel); spatial boundaries of these regions were the Longhurst biogeochemical provinces and a division of the eastern equatorial Pacific into two units using the boundary of the Western and Central Pacific Fisheries Commission.

We used the Oceanic Niño Index (ONI) (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml) to represent ENSO. ONI is a continuous three-months mean of sea surface temperature anomalies for the Niño 3.4 region and is a reliable index of ENSO at the Pacific scale. In our study, we chose ONI values > 0.9 to qualify an event as El Niño, and values < -0.9 for La Niña. These limits were the standard deviation of ONI time series and are used by

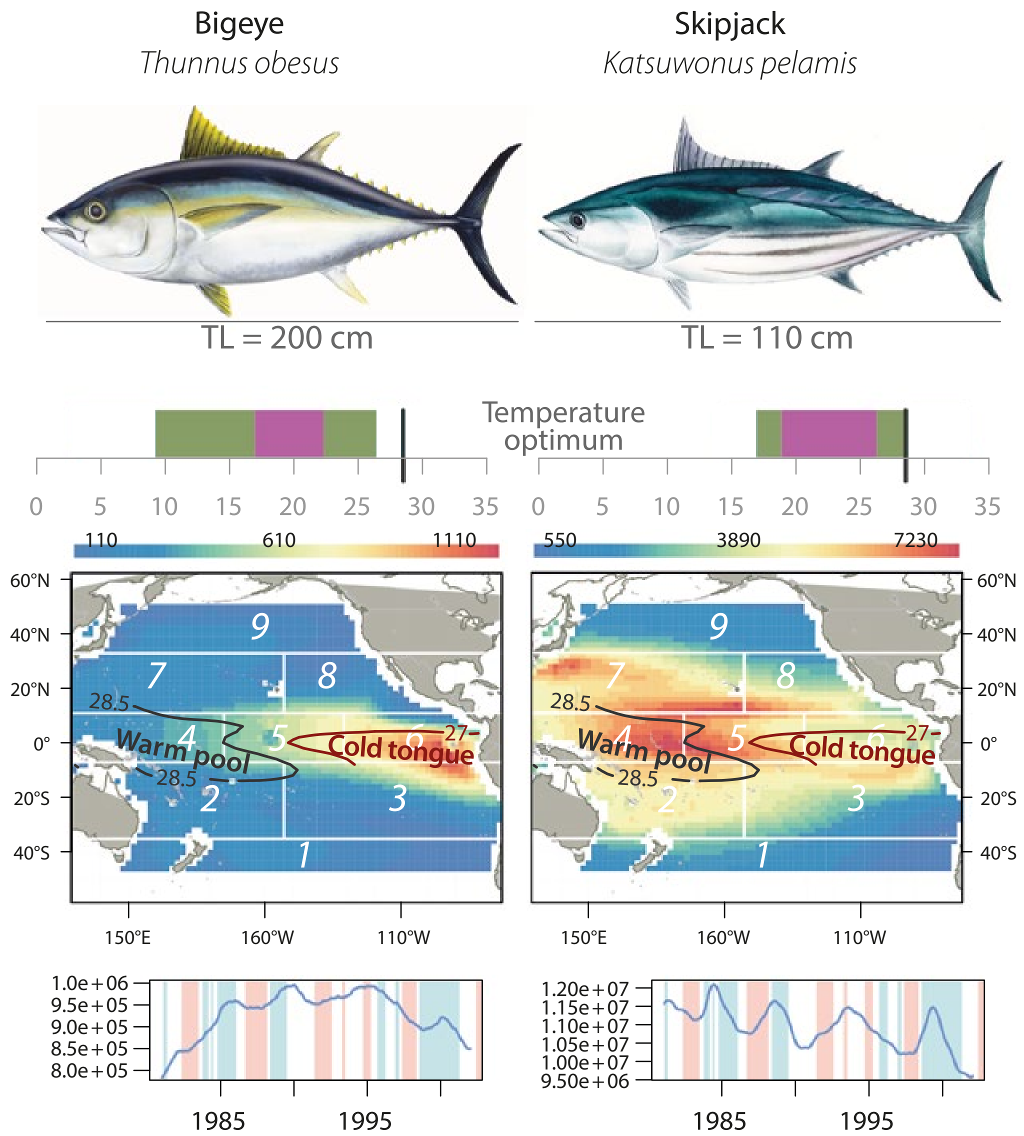


Figure 1. Optimum temperature (shown below fish illustrations) with tolerance and preference, respectively, in green and purple (Boyce et al. 2008). The vertical black line refers to the lowest surface temperature of the warm pool (28.5°C). The maps show the mean adult biomass distribution predicted by SEAPODYM over the entire period (1980–2002) for each species, with high biomass shown in red and low biomass in blue. The biomass values indicated above the maps are expressed in tonnes per 2° square. The white lines are region delimitations. The two bottom graphs show the total biomass evolution through time predicted by SEAPODYM, with El Niño events and La Niña events shown as pink and blue rectangles, respectively.

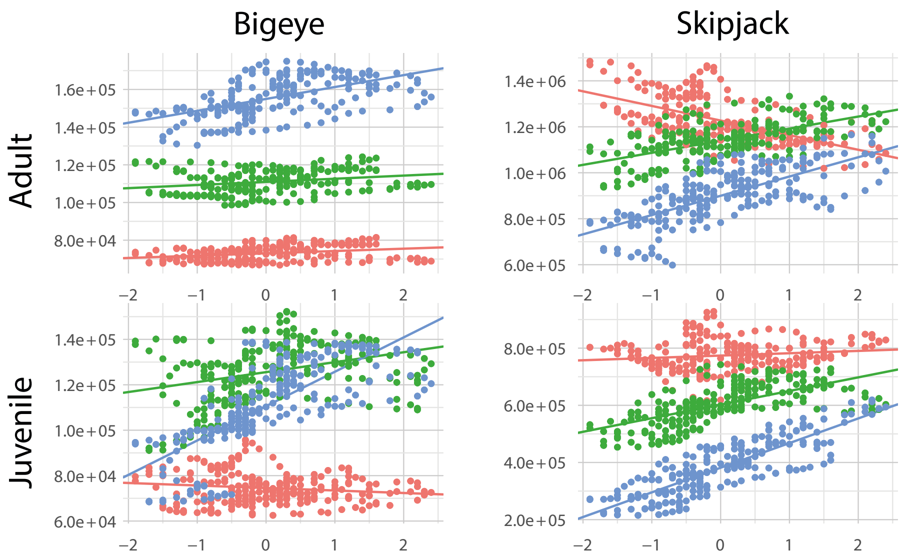
the US National Oceanic and Atmospheric Administration to classify ENSO events.

A wavelet analysis was used to study how biomass was related to ENSO through time. It allowed us to test whether tuna abundances fluctuated in response to the four to seven years dominant frequencies of ENSO, and to quantify the temporal lag between the two times series on this frequency range. To visualise changes in abundance for each tuna species and maturity class in each zone with ENSO, we correlated each biomass (adjusted for the lagged response) with the ONI index.

Results and discussion

Skipjack and bigeye tunas have different ecologies. Bigeye has a lower turnover rate[5], occupies habitats between the ocean's surface and thermocline, and undergoes a daily vertical migration as part of its foraging strategy (Fig. 1 – top left). Given the estimates of current harvest rates and biomass status for bigeye, the stock is considered to be currently fished at an unsustainable rate (Harley et al. 2015). Skipjack has a high turnover rate, lives in the surface layer, and generally inhabits warmer waters (Fig. 1 – top right). Given the estimates of current harvest rates and biomass status, the stock is considered to be fished at a sustainable rate (Harley et al. 2015). SEAPODYM estimated that the skipjack biomass was mostly concentrated in the equatorial western and central Pacific (regions 4 and 5) whereas the estimated bigeye biomass (or vulnerability) was concentrated mostly in the eastern Pacific (region 5 and 6) (Fig. 1 – middle). In general, SEAPODYM predicted skipjack density to be higher in the warm pool and bigeye density to be higher in the cold tongue. For both species, the biomass is concentrated in the equatorial region. SEAPODYM predicted a decreasing biomass for skipjack over the simulation period (Fig. 1 – bottom). A decrease in biomass is also predicted for bigeye in the latter third of the simulation (Fig. 1 – bottom). For both species, there are regular biomass fluctuations over the time series.

Our results highlight that the impact of ENSO on biomass depends on species, maturity (adult or juvenile), and the species' location in the Pacific. Adult and juvenile bigeye increased in abundance in the eastern Pacific (region 6) during El Niño (positive ONI value), and decreased during La Niña (negative ONI value) (Fig. 2). Changes in



	Bigeye	Correlation	Lag	Skipjack	Correlation	Lag
Adult	Region 6	0.54	−2.5	Region 4	−0.59	−0.2
	Region 5	0.24	−0.5	Region 5	0.62	−1.4
	Region 4	0.28	0.2	Region 6	0.70	−1.3
Juvenile	Region 6	0.75	−0.9	Region 4	0.13	−2.2
	Region 5	0.33	1.6	Region 5	0.64	−0.2
	Region 4	−0.15	0.6	Region 6	0.85	−0.5

Figure 2. Modelled biomass from SEAPODYM function of ONI for bigeye tuna (left) and skipjack tuna (right) and for adult tuna (top) and juvenile tuna (bottom) coloured by Pacific region (region 4 in red, 5 in green and 6 in blue – see Fig. 1 for region delimitations). The bottom table presents both the correlation (with the lag) and the corresponding lag (in years) between each quantity and ONI time series.

[5] The turnover rate of a fish stock is the percentage of the stock replaced every year. A high turnover means a quick replacement.

abundance in the western and central Pacific (regions 4 and 5) were within the variances observed during neutral years for both El Niño and La Niña. A shift in the western boundary by approximately 30° of longitude to the west was observed (Fig. 3). Little movement in the gravity centre[6] was observed (Fig. 3). Skipjack abundance (adult and juvenile) increased in the central and eastern Pacific (regions 5 and 6) during El Niño events (Fig. 2). A decrease in the western Pacific (region 4) during El Niño was observed for adults but not for juveniles (Fig. 2). An eastward shift of up to 70° of longitude was observed for the eastern boundary of the skipjack population (Fig. 3). This effect was evident in both juvenile and adult skipjack tuna but more pronounced in juveniles. Little movement in the gravity centre was observed (Fig. 3).

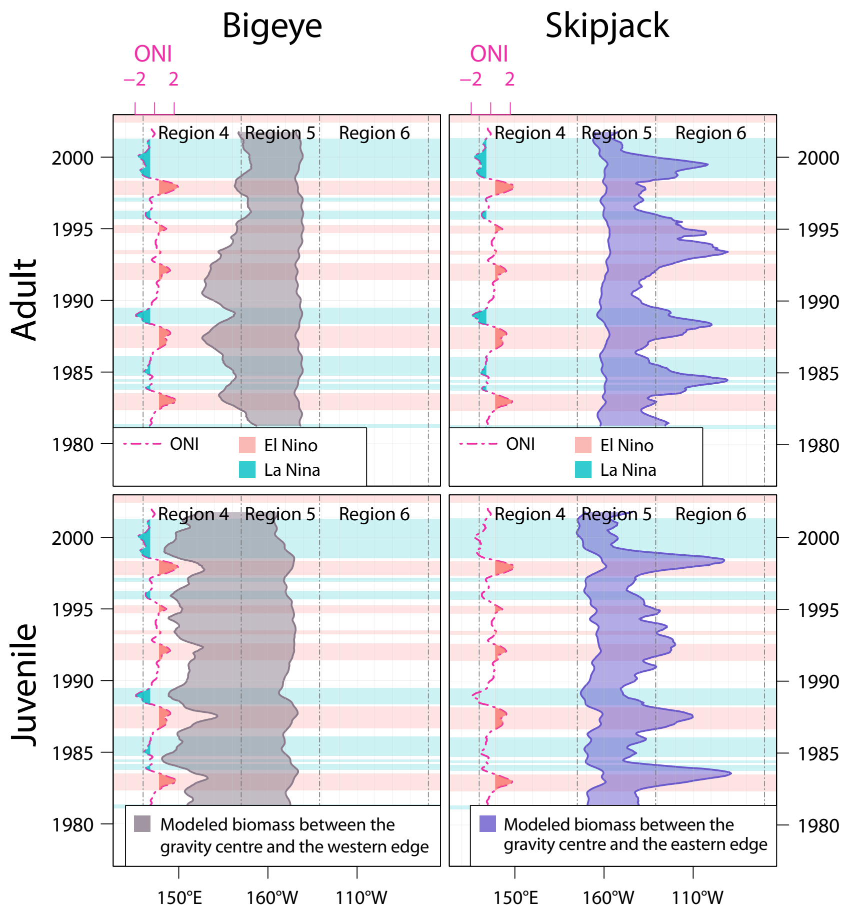


Figure 3. Space-time graphic for adult tuna (top) and juvenile tuna (bottom) representing bigeye biomass (left) and skipjack biomass (right), with ONI time series (pink dot and dash line) and with El Niño events (pink rectangles) and La Niña events (blue rectangles) for each plot.

Purse-seine fishing effort is higher in the central Pacific during El Niño (Evans et al. 2015; Williams and Terawasi 2015). Minimising purse-seine catches of bigeye is currently a conservation focus for the Western and Central Pacific Fisheries Commission to improve the conservation status of bigeye (FFA 2015). The predicted changes in bigeye abundance by SEAPODYM suggest that it is unlikely that purse-seine fishing, which principally catches juvenile bigeye tuna, would be fishing a significantly higher biomass of bigeye in the central Pacific during El Niño than during neutral phases. It is plausible that the increased purse-seine effort during El Niño in the central Pacific results in greater localised depletion of bigeye, which in turn may be relevant for managing the rebuilding of the bigeye stock. Monitoring catch per unit effort (CPUE) rates of bigeye in the central Pacific could provide an indicator for this effect. If CPUE rates increase or remain constant this may trigger the need to evaluate whether additional conservation measures for the central Pacific region may be warranted during such events. Similarly, monitoring the CPUE of longline catches of bigeye in the central Pacific may be warranted given the predicted increase in adult biomass during El Niño and the potential for higher depletion rates if CPUE increases.

Previous studies have hypothesised that changes in the location of purse-seine fishing effort reflect the potential tracking of the warm pool-cold tongue convergence zone by skipjack tuna (Lehodey et al. 1997; Suarez-Sanchez et al. 2004). The results from the SEAPODYM simulations estimated only relatively small changes in the gravity centres of adult and juvenile skipjack during El Niño and La Niña (Fig. 3). Notwithstanding that these small changes are important, they suggest that the movement in general is only a small proportion of the populations that are resident in each region. This may help explain why catches of skipjack similar to those of neutral years are maintained in the western Pacific during El Niño. Similarly, Lehodey and colleagues (1997) noted that purse-seine effort shifts westwards before El Niño conditions terminate, and proposed that this may be due to skipjack moving back towards the western Pacific due to foraging conditions (upwellings) becoming more preferable. The SEAPODYM results suggest that this pattern may not be due to skipjack movement but rather that purse-seine fishing conditions become more favourable in the period just before El Niño terminates. The

[6] The gravity centre is the modelled mean longitude of the population biomass, and is used as a proxy for the mean position of the population biomass.

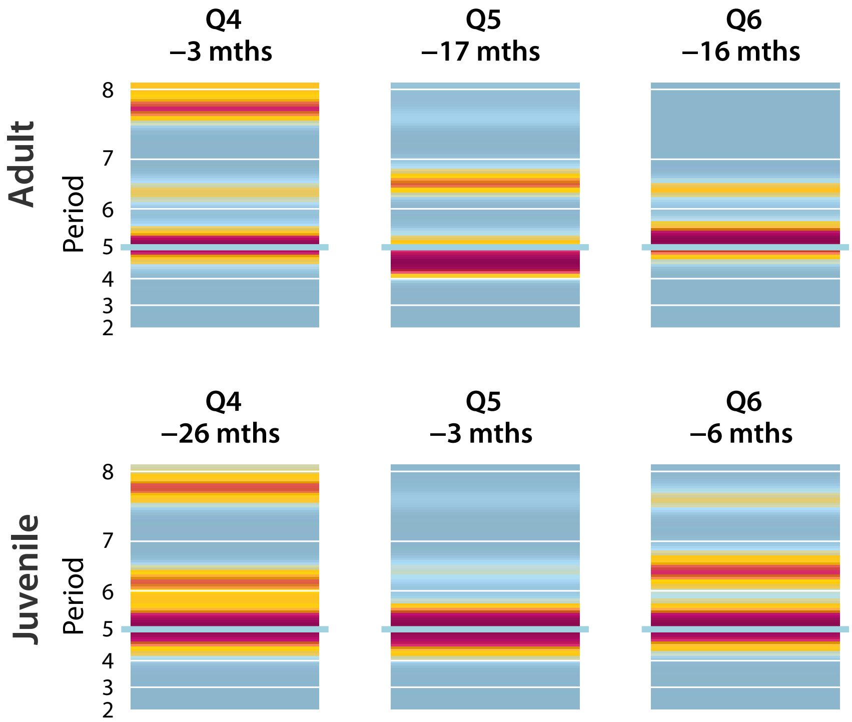


Figure 4. Average coherency over time between ONI and skipjack tuna abundances in the western Pacific (first column), central Pacific (second column) and eastern Pacific (third column), both for adult (top) and juvenile (bottom) fish. The five-year band is the average fluctuation period of ENSO.

two-degree resolution of the forcing used in this optimisation of SEAPODYM may not be sufficiently fine enough for the movement dynamics to be fully captured, and this may dampen the temporal variability of the biomass within the large regions of this study.

Our SEAPODYM simulation predicted a lack of synchrony between changes in skipjack abundance and the eastward and westward shifts in the convergence zone during the onset and cessation of El Niño, indicating that skipjack movement may not be as responsive as previously hypothesised. We detected closer synchrony between adult skipjack and the onset of El Niño with decreased abundance in the western Pacific occurring three months after the peak in El Niño. Peaks in juvenile abundance in the central Pacific were observed three months after the peak in El Niño (Fig. 4 top). Peaks in adult abundance in the central Pacific, however, were evident 17 months after the peak in El Niño (Fig. 4 bottom). Skipjack reach maturity at approximately 10 months. The observation of maximum abundance at 17 months is interpreted as adult and juvenile skipjack moving eastwards with El Niño, enhanced spawning in the central Pacific due to the favourable habitat El Niño generates, and this recruited biomass remaining in the central Pacific for a period of time after El Niño rather than shifting westward with the convergence zone at the cessation of El Niño. Recent studies examining mixing rates (Kolody and Hoyle 2015; Schaefer et al. 2015) and stock structure (Grewe et al. 2015) support hypotheses of large horizontal movements as the exception rather than the rule for equatorial tuna in the Pacific Ocean (Schaefer et al. 2015).

Our approach for this study was based on the assumption that SEAPODYM provides a realistic description of tuna population dynamics. An important next step is the validation of the generality of these results with additional analyses of catch and effort data (independent of SEAPODYM) from ENSO events that were not included in the optimisation of SEAPODYM (e.g. the 2015–2016 El Niño). Understanding how skipjack and bigeye respond to the Modoki Niño is also warranted. The Modoki Niño (Ashok and Yamagata 2009) is an El Niño with main sea surface temperature anomalies in the central Pacific rather than in the eastern Pacific in the classical ("canonical") El Niño (Kug et al. 2009). In our time series the results were less conclusive for the period between 1992 and 1996, which coincides with Modoki Niño events. Modoki Niño was common during 2000–2013. The ERA-interim optimisation of SEAPODYM includes this period and could be used to investigate this phenomenon in more detail.

The analyses presented here improve our global understanding of the drivers of movement for mobile species under climatic variability, an aspect highlighted by Evans et al. (2015) as a research priority to ensure the sustainable management of tuna fisheries in the western and central Pacific Ocean. Understanding when and why tuna move is required to adapt fisheries management policies. These results from SEAPODYM contribute to the broader debate concerning the use of tuna for improving food security and public health in Pacific Island countries and territories (Bell et al. 2015).

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Mainstreaming fish spawning aggregations into fishery management calls for truly precautionary approach[1]

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Abstract

Many marine fishes mate in massive and spectacular gatherings at predictable times and places. These spawning aggregations are often attractive targets of fishermen. Many commercially important fish species exhibit aggregation-spawning and many have undergone serious declines from overfishing. It is timely to explore whether the exploitation of spawning aggregations makes species particularly susceptible to overfishing, and, if so, why, and how we can better manage these species. I present evidence that aggregate fish spawners are especially vulnerable, due to both increased catchability (lethal effects) and to biological factors (non-lethal effects). For these species to continue contributing to food security and livelihoods while retaining their ecosystem function, a truly precautionary approach is essential to reduce the risk of declines and compromise the chance of recovery, particularly in the case of small-scale commercial fisheries of low productivity species and where management and monitoring are lacking. There is a pressing need to mainstream spawning aggregations into marine resource management.

Introduction

Marine fishes are the last remaining animal resources that we still take in huge quantities from the wild. They provide about one-fifth of our global protein supply and are massively important for food security and livelihoods (FAO 2014). Yet roughly 60% of capture fisheries today, for which there is sufficient information (a small proportion of global fisheries), are either collapsed or overfished and need management for rebuilding (e.g. Pitcher and Cheung 2013; Worm et al. 2009). Many of the remaining and less-well documented fisheries are also likely to be fully or overfished. Despite the rapid growth in mariculture (or fish farming), which has helped to increase supply, this does not take pressure off wild populations on which millions of people will continue to depend and, hence, must be adequately safeguarded.

Many exploited marine fishes have as their sole means of reproduction the formation of large temporary gatherings and many face growing threats to their population when these become more accessible to fishing during temporary periods of high abundance (Sadovy de Mitcheson and Erisman 2012). Over 60% of reef fish aggregations of known status have declined or disappeared (Russell et al. 2014; www.SCRFA.org). In Cuba, for example, an unusually detailed dataset spanning decades of monthly landings show that groupers (Epinephelidae) and snappers (Lutjanidae) that aggregate most predictably at a small number of spawning sites underwent more marked and sudden declines than species in the same commercial fishery that have longer reproductive seasons and less predictable spawning aggregation patterns (hence lower catchability) (Sadovy de Mitcheson and Erisman 2012). The closely related, similar-sized, tropical western Atlantic Nassau, *Epinephelus striatus*, and red, *E. morio*, groupers make for an interesting comparison. The Nassau grouper forms relatively few, brief and large aggregations that are heavily fished and little managed, or only managed after they become severely reduced; the species is now endangered (according to the International Union for Conservation of Nature Red List) and being considered for listing under the United States Endangered Species Act; most of its aggregations have disappeared or became severely reduced (Sadovy de Mitcheson et al. 2008). Although its congener does not form spawning aggregations and its catchability increases only slightly during the reproductive season, its fisheries remain viable.

But the problem is by no means isolated to reef species. In east Asia, seasonal spawning aggregations are formed by the large yellow croaker, *Larimichthyes crocea*, once one of the four major coastal fisheries of China (Liu and Sadovy de Mitcheson 2008). This fishery collapsed after peaking at about 200,000 tonnes in the mid-1970s after which time catches declined by over 90% in 20 years.

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Fishing was mainly on spawning aggregations and overwintering grounds, with loss of important inshore nursery habitat to development also implicated in declines. The species has never recovered despite massive and expensive restocking programmes and management measures. Wild fish are now uncommon and fetch high market value when encountered (e.g. Liu and Sadovy de Mitcheson 2008). What is little understood for these, and many other temperate, deepwater and tropical species that aggregate to spawn and that have declined markedly over the last few decades is the specific role that fishing on their spawning aggregations has had in their declines. Understanding this is critically important for successfully managing species exploited on their spawning aggregations.

Whatever the ultimate evolutionary driver(s) of aggregation-spawning (i.e. for the benefit of adults, for eggs and/or larvae, or for both), the immediate benefits of aggregation-fishing are obvious, with large numbers of fish becoming predictably and efficiently available, and catchability (fishing effectiveness) increasing markedly for many species when they assemble. Monitoring and management of such fisheries, whereby both fish and fisher behaviour temporarily change, can be particularly challenging. Conventional management theory focuses on addressing the "lethal" effects of removals and the maintenance of sufficient spawning biomass (Hilborn and Walters 1992) and does not distinguish an aggregated from a non-aggregated fish or typically consider "non-lethal" effects (such as depensation or behavioural effects).

Spawning aggregations in global fisheries

Congregatory reproduction in pelagic egg producing marine fishes is characterized by intense bouts of multiple gamete release, constituting brief, passive and massive sources of sperms and eggs within large groups of temporarily gathered males and females (Fig. 1). Irrespective of spatial or temporal scales, all involve events with tens, hundreds, thousands or tens of thousands of conspecifics gathering predictably and consistently and for the purpose of spawning (Colin 1996; Domeier 2012). Aggregating demersal egg layers, such as capelin, flying fish, herring or triggerfish head for the substrate they need to deposit their eggs. Many pelagic spawning reef fishes migrate seasonally to outer reef slopes, channels and promontories. Seamounts, estuaries and other coastal habitats are the destinations of deep water and tropical and temperate coastal species, from croakers to orange roughy, cod to haddock, rabbitfish to mullet. A handful of large ocean patches are the preferred spawning grounds for highly mobile pelagic fishes, such as certain tunas, marlin and small pelagic fish, from sardines to herring.

The numbers of fish that gather seasonally to spawn in any one location can be, or once were, massive. Prior to large-scale fishing, enormous shoals of gravid Atlantic herring, *Clupea harengus*, "became absolutely a nuisance" in the Chesapeake Bay area (Buffon 1793), the implication being that fish far exceeded fishing effort. Aggregate-spawning species, from subsistence to small-scale/artisanal to industrial scale fisheries, are of enormous economic and food security value so it is of utmost importance to understand the impact of aggregation-fishing on such species and how they can best be managed. Of the top 20 fish species, by weight, supplying global fisheries (FAO 2014), many undergo regular spawning migrations, aggregate to spawn and are exploited at these times. Examples range from Alaska (walleye) pollock, *Theragra chalcogramma*, Atlantic cod, *Gadus morhua*, capelin, *Mallotus villosus*, and Atlantic mackerel, *Scomber scombrus*, to largehead hairtail, *Trichiurus lepturus*, European pilchard *Sardina pilchardus* and herring. Among coral reef fishes, more than 100 species exhibit this reproductive habit and, for many of these, aggregation times mark the fishing season. Although the catches and natural productivities of these reef fishes are orders of magnitude less than those of major temperate species, producing tens of tonnes rather than tens of thousands or even millions of tonnes annually, they are nonetheless critically important for hundreds of thousands of communities that depend on them (Fig. 3). Their low productivity makes them very susceptible to overfishing and slow to recover (Sadovy de Mitcheson and Colin 2012). In small-scale fisheries, just a few boats have the capacity to remove a large proportion of a single aggregation in a single season (pers. obs.).

Implications of aggregation-fishing

Fishing on spawning aggregations is heavily implicated in the declines of many species, although it is challenging to distinguish such impacts from those attributable to the sum of fishing activities on all life history stages of target species. The distinction is important, however, for applying appropriate management and can best be understood perhaps by comparative analyses. A semi-quantitative treatment of 36 species of aggregating and non-aggregating species across a range of taxa, life history types, maximum body size (FishBase 2015) and conservation status (IUCN 2015) suggest that threat is negatively associated with a qualitative measure of catchability, independent of body size (another threat factor) (Fig. 2). Robinson and Samoilys (2013) developed a framework examining extrinsic (fishery-specific) and intrinsic (population-specific) factors in relation to catchability. They identified clusters of low and high levels of relative vulnerability to fishing linked to life history characters such as longevity, type of aggregating behaviour, and fishery factors such as management

Figure 1.

- *a. Top. Twinspot snapper (*Lutjanus bohar*) spawning in Palau, showing the massive and highly concentrated release of eggs that occurs predictably over just a few hours each year. Image: Tony Wu (www. tonywublog. com).*
- *b. Second from top. Spawning group of endangered Nassau grouper,* Epinephelus striatus, *has formed within a much larger spawning aggregation. Spawning seems to be structured; this group consists of a leading female (dark colour) and multiple males (bicoloured). Image: Doug Perrine/ SeaPics.com.*
- *c. Third from top. The camouflage grouper,* Epinephelus polyphekadion, *spawns in sub-groups in large aggregations but when numbers are depleted, intraspecific interactions are few. Image: Yvonne Sadovy de Mitcheson*
- *d. Bottom. The short spawning season of the corvina,* Cynoscion othonopterus, *in Mexico, produces high landings to meet Easter demand but once demand drops, the glut results in falling prices and much wastage. Image: Octavio Aburto / iLCP.*

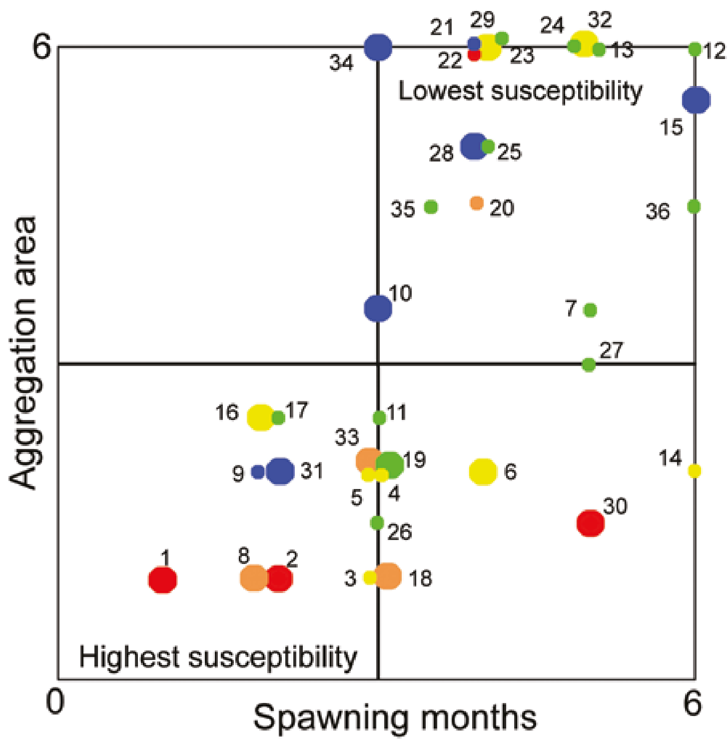

Figure 2. Thirty-six species of exploited aggregating and non-aggregating species of varying size (from 21 to 458 mm TL: FishBase 2015) and conservation status (IUCN 2015) plotted according to a qualitative indicator of catchability. The indicator combines length of spawning (1–6 months) and spatial concentration from 1 (highly concentrated when aggregated to spawn and easy to target) to 6 (no aggregate-spawning hence no change in susceptibility to catch) using available biological information (IUCN 2015). Each dot represents one fish: small dots are < 100 cm TL and large ones > 100 cm TL. Colours refer to IUCN Red List status: Red = critically endangered (CR); orange = endangered (EN); yellow = vulnerable (VU); blue = near threatened (NT); green = least concern (LT). Dot numbers: (sciaenids 1–4, lutjanids 5–7, epinephelids 8–15, gadid 16, clupeid 17, sparids 18–25, serranids 26–27, scombrids 28–34, acanthurid 35, siganid 36).

and accessibility. These various analyses suggest that, all else being equal, species that aggregate to spawn and are targeted on their aggregations are more likely to be threatened than non-aggregators, especially when their catchability is elevated. Of all 163 groupers and 134 seabreams (Sparidae) globally, many of those that aggregate to spawn are the most threatened species within their taxa, although other life history characters such as longevity and late sexual maturation are also relevant to level of extinction risk under exploitation (e.g. Sadovy de Mitcheson et al. 2013).

How does fishing impact on spawning aggregations?

A major question is whether the declines in fisheries that heavily target spawning aggregations are just a matter of overfishing (i.e. lethal effects) and failure of management systems to adequately account for increased catchability, or whether there are other, non-lethal, effects involved. Put another way: Is removing a fish from a spawning aggregation the same, in terms of its effect on reproductive output, as taking the same fish in the non-reproductive season, as is assumed by conventional stock assessments? If not, what are the implications for management?

Selectivity

Fisheries management is primarily concerned with populations (or "stocks"), biomasses (weights) and numbers; rarely does it address inter- and intra-individual differences, despite the fact that many longer-lived fishes have complex reproductive lives associated with which mature individuals contribute differentially to reproduction. Is there evidence that selective removal of reproducing fish of particular size classes, genotypes, or by sex can affect reproductive output in the short or long term, or that the act of removal itself negatively affects reproduction or other population components? Possible effects range from physical disturbance of spawning and reduction of egg output, to disruption of reproductive processes such as mate selection, sex change schedules or spawning mode, or there could be genetic impacts. In the Patagonian hake, *Merluccius hubbsi*, and brown-marbled grouper, *E. fuscoguttatus*, for example, males arrive at spawning grounds prior to females and in the hake they stay longer, leaving one sex exposed to fishing for longer (Pajaro et al. 2005; Robinson and Samoilys 2013). In a range of marine fishes, offspring size and/or quality increases with female age and/or size while in some species larger females spawn for longer periods and more frequently than smaller females (e.g. Hixon et al. 2014). In such cases, size-selective fishing on gathered ripe adults could have implications for reproduction through sex ratio shifts or egg production. Significant and differential exposure to fishing by size or sex could have genetic consequences (Hutchings and Fraser 2008) or influence sex change schedules in species with social control of male to female, or female to male sex change (Sadovy de Mitcheson and Erisman 2012).

Depensation

For a phenomenon of abundance, such as congregatory-spawning, whereby benefits are somehow derived from coming together to spawn in large and concentrated numbers, it is reasonable to predict that thresholds of animal numbers or density might exist below which reproduction may be negatively affected, or recovery impeded (e.g. Hutchings and Reynolds 2004). Positive relationships between population size or density and various indicators of fitness are referred to as Allee effects, and negative rates of population growth that occur below a critical population level are termed depensation (Berec et al. 2006).

Although evidence for depensation at anything other than low population levels is weak and sufficient information for the majority of species is scant, quantitative assessments across a taxonomic range of exploited marine fish taxa show that depensation cannot be ignored. Hilborn et al. (2014) examined over 100 stocks depleted to less than 20% of their maximum observed stock size and could not rule out depensation at low stock sizes because they had examined so few populations at very low levels (i.e. 1% of unfished biomass). Myers et al. (1995) came to similar conclusions but did detect some evidence of depensation in several stocks of salmon and a herring. Using meta-analyses Keith and Hutchings (2012) found considerable variability among 104 exploited marine fish species in standardized *per capita* population growth changes with abundance. Evidence for an Allee effect was found in Atlantic cod and pollock, both of which are aggregate-spawners (e.g. Rowe and Hutchings 2004).

As we learn more about the biocomplexities of fish reproductive processes from field observations and experimental work, signs of Allee-like effects are emerging with indications of possible underlying causation (e.g. Liermann and Hilborn 2001). In Atlantic cod and halibut, *Hippoglossus hippoglossus*, for example, stress or physical disruption exhibited by aggregated animals subjected to fishing gear can influence complex mating behaviours and sexual selection (mate choice, mate competition), and could ultimately affect reproductive success and population growth (e.g. Dean et al. 2012; Rowe and Hutchings 2004). Physical disturbance of aggregations by fishing was one of two likely reasons of the rapid collapse, within a few years of initiation, of the Namibian orange roughy, *Hoplostethus atlanticus*, fishery (Oelofsen and Staby 2005). In Pacific herring, *Clupea harengus pallasi,* pheromone concentrations from milt that trigger spawning in sexually mature fish drop below critical thresholds at reduced numbers (Carolsfeld et al. 1997).

Economically, a further consideration has emerged. Exploited fishes were once safeguarded because as their numbers declined they became increasingly expensive to exploit, reaching economic lower limits before biological lower limits of fishery viability. However, this "safety valve" vanishes for particularly desirable species when consumers can afford to pay almost any price, and price increases with rarity. In such cases, ecological extinction can precede economic extinction – the so-called anthropogenic-Allee effect (Courchamp et al. 2006). The Chinese bahaba, initially fished mainly on its aggregations, is highly prized for its swim bladder in Chinese markets; as the species approaches extinction, the price of a single large swim bladder rocketed to over USD 600,000 in 2015 in China, stimulating interest and sales despite its protected status in China (Apple 2015; Sadovy and Cheung 2003). Expensive tuna face the same situation (Collette et al. 2011). Such economic shifts make enforcement particularly challenging

Within large and highly concentrated spawning aggregations, severely reduced fish numbers could affect fertilisation success or the outcomes of predation, including fishing. The Nassau and camouflage groupers form small mating groups of a single female and multiple males within the larger aggregation, a mode of reproduction referred to as "group spawning" (Fig. 1b). In Nassau groupers, direct observations suggest lower rates of courtship and colour changes in these mating subgroups that could feasibly result in lower overall *per capita* reproductive or fertilisation rates (Brice Semmens, pers. comm.). In camouflage grouper, adults in severely reduced aggregations were rarely seen to interact, unlike in unfished ones (pers. obs.) (Fig. 1c). While this hypothesis has yet to be tested, studies do indicate that in aggregating Atlantic cod, fertilisation rates are sensitive to sperm concentration and in bluehead wrasse sperm numbers and fertilisation rates are higher in multi- as opposed to single-male spawnings (Butts et al. 2009; Marconato et al. 1997; Rowe et al. 2004). Moreover, for several snappers, as the numbers of aggregating adults in a spawning group become reduced, egg predation by specialist egg feeders such as the black snapper, *Macolor niger*, or opportunistic predators such as whale sharks, *Rhincodon typus* and mantas, may become more problematic (Sadovy de Mitcheson and Colin 2012).

Population structure

Largely for practical reasons, fisheries management was long (and largely still is) based around the concept of "stocks", with management units and monitoring typically treating localised demographic effects, such as population structure and localised overfishing, as unimportant (e.g. Stephenson 2002). A stock describes characteristics of semi-discrete groups of fish with some definable attributes of interest to fishery managers. Such groups may or may not be biologically discrete reproductive units (populations) but this reality was largely ignored until relatively recently, mainly because early genetic work on most marine species involving electrophoresis showed little intraspecific variation (Cadrin and Secor 2009).

In tropical aggregate spawners, molecular, fishery and field research have revealed spatial scales from extremely localised to regional patterns of population distribution, of much relevance for determining units for management. For example, localised (subnational) measures are important when there is high larval retention and limited adult movement. Considering larval dispersal kernels from a single managed spawning aggregation of squaretail coral grouper, *Plectropomus areolatus*, for example, Almany et al. (2013) predicted that 50% of larvae settled within 14 km of the study site in Papua New Guinea. On the other hand, a combination of local and regional approaches to management within several genetically isolated regions in the Caribbean for the Nassau grouper is clearly needed (Jackson et al. 2014).

Challenges and opportunities in managing spawning aggregation fisheries

There is nothing inherently wrong with fishing on spawning aggregations, if it is done right. At subsistence levels this was done for centuries and, if properly managed, commercial targeting of spawning fish can be sustained (e.g. Bering sea Pollock stock, Morell 2009). For some species it is the only time that fish are readily accessible for fishing while others, such as capelin and herring are sought specifically for roe. However, such fisheries are particularly challenging to monitor and manage, and evidently need a more precautionary approach than non-aggregating species. On the other hand, there are excellent opportunities for efficient management if enforcement effort can be concentrated on small areas for brief periods each year on well understood spawning aggregations. What does history and experience tell us about the challenges and opportunities for the management of large- and small-scale spawning aggregation fisheries?

For many fisheries, closed reproductive seasons and areas were amongst the earliest of all management measures. In the 1660s for example, for groundfish in North America, according to the Massachusetts legislature "no man shall henceforth kill any codfish, hake, haddock, or pollock to dry for sale in the month of December or January because of their spawning tyme" (Armstrong et al. 2013). In Palau, a traditional management tool was used to restrict the harvest of migrating rabbitfish and groupers in the early 1990s after declines in landings were noted. And while spawning aggregations or associated migrations were often a focus of subsistence fisheries in many tropical countries, where traditional knowledge of their timing and locations was often detailed, their protection was among the first measures to be considered by communities if fish numbers declined, as in Palau, Kiribati and Papua New Guinea (e.g. Hamilton et al. 2005; Johannes 2002). However, with the breakdown of traditional practices and following growing commercialisation (including export) of inshore fisheries, fishing continued and management and enforcement did not keep pace. In temperate regions although many fisheries are managed for fishing effort and biomass, the science largely ignores non-lethal effects and data can be sparse for species with spatially varying catch histories (Cope and Punt 2011).

For multiple reasons already discussed aggregations are attractive targets to fish, but there are also compelling biological and economic reasons not to fish them if they are not managed. High catchability, reduced cost per unit of catch and high temporal and spatial predictability can readily lead to waste and overexploitation. For the Gulf corvina, *Cynoscion othonopterus*, in Mexico, high demand during the Easter period was met by fishing during its brief aggregation period and good prices gained (Fig. 1d). Approximately 1.5–1.8 million fish are harvested annually from spawning aggregations of Gulf corvina during 21–25 days of fishing (Erisman et al. 2012); however, a post-Easter slump in demand produced a market glut and prices plummeted, leading to wastage. Similarly, seasonal variation in the first sale price of adult plaice and turbot, *Scophthalmus maximus*, were considerably lower when large numbers of ripe fish became available (van Overzee and Rijnsdorp 2014). Even the physical condition (and hence economic value and mortality) of fish can differ between seasons. In the live fish trade, for example, gravid grouper females experience higher rates of mortality than at other times (Patrick Chan pers. comm.), while the flesh of Atlantic cod and other species may be softer or less acceptable (hence cheaper) due to energy transfer from soma to gonads during the reproductive season (FAO no date).

Monitoring and hyperstability

Good monitoring is essential for effective management, and for aggregate-spawners can be done using catch per unit effort (CPUE) on aggregated fish and by underwater visual census for some. Exploited species, or the fishers who exploit them, that change their behaviour over time face a breakdown in the relationship between CPUE and abundance (CPUE is considered a proxy for abundance in stock assessments; its measurement is an important input to fishery models). As populations decline from overfishing, adults continue to concentrate to spawn maintaining CPUE and masking population decline until close to collapse. This condition is termed "hyperstability". Unrecognised by fishers able to maintain their catches from aggregations and undetected by managers seeing stable aggregation catches or CPUE if monitoring focuses only on aggregations, populations can dwindle undetected, becoming so severely reduced that recovery may become compromised, especially if depensation is also occurring (Erisman et al. 2015; Hutchings 2000; Mullon et al. 2005). Mullon and colleagues (2005) attributed "plateau-shaped" trajectories preceding collapses to surreptitiously increasing exploitation combined with a depensatory mechanism at low population levels. These collapses are difficult to predict, happen relatively suddenly, and typify those of many aggregate-spawning species exploited on their aggregations (Fig. 3). Underwater monitoring is well-suited for assessing accessible species in relatively discrete aggregations but the temporal and spatial dynamics of the target aggregation should be well-understood to avoid misleading outcomes (Colin et al. 2003).

Management

There is no one-size-fits-all for managing fisheries of aggregate spawners (Russell et al. 2012). Catchability increases when fish aggregate

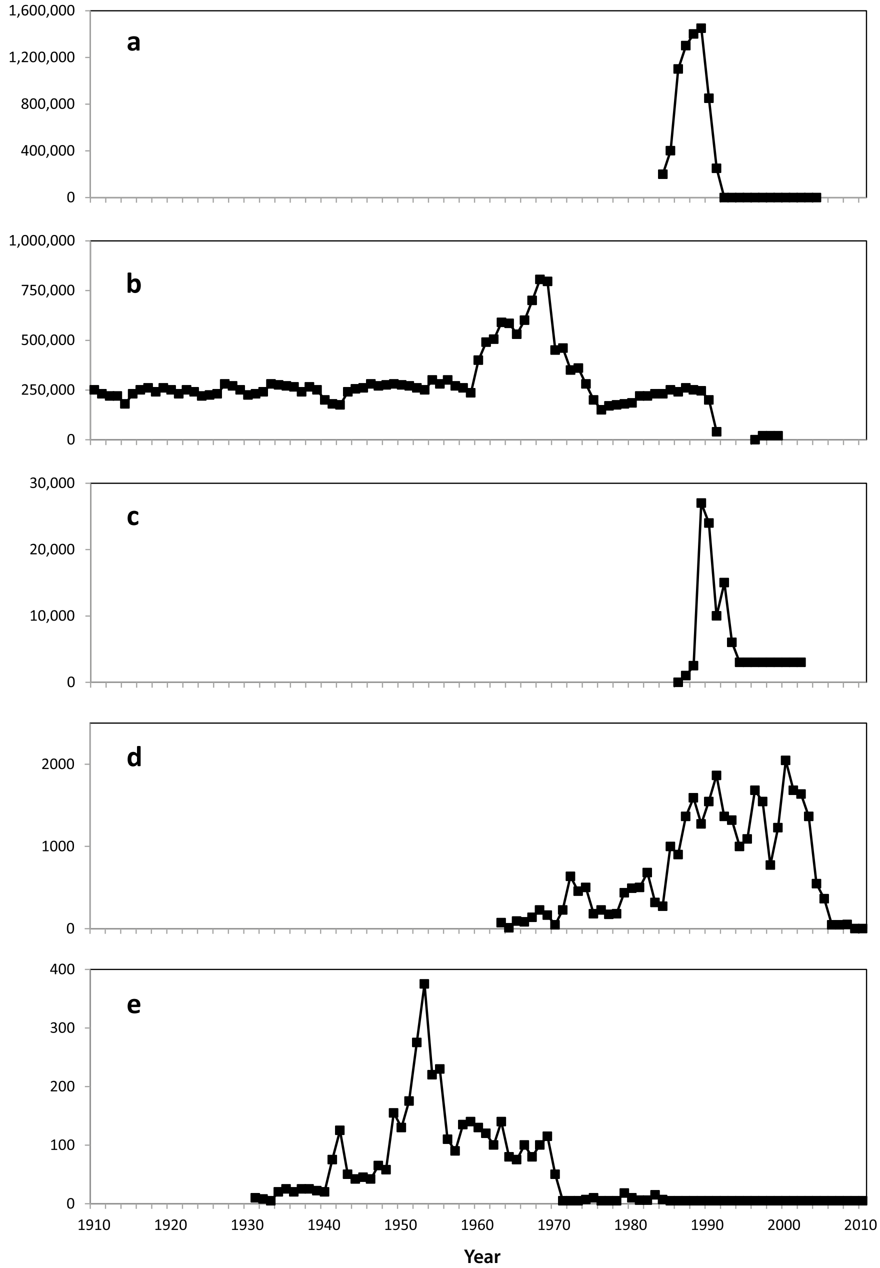

Figure 3. Catch in tonnes from five fisheries of species with very different natural productivities that target spawning aggregations. All illustrated fisheries underwent sudden collapses for reasons not fully understood and for which depensation cannot be ruled out as a possible reason for lack of recovery;

(a) *commercial Alaska (walleye) pollock* Theragra chalcogramma *at the Donut Hole ground (Bailey 2011);*

(b) *commercial Atlantic cod,* Gadus morhua, *Millenium Ecosystem Assessment;*

(c) *commercial orange roughy,* Hoplostethus atlanticus, *Oelofsen and Staby (2005);*

(d) *barred sandbass,* Paralabrax nebulifer, *Erisman et al. (2012) recreational; original data given in numbers of fish were converted to weight at 0.9 kg per fish (B. Erisman, pers. comm.)*

(e) *commercial Gulf and broomtail groupers* Mycteroperca jordani *and* M. xenarcha *(http://www.nmfs.noaa.gov/pr/species/Status%20Reviews/gulf_grouper_sr_2015.pdf).*

to spawn but whether exploited aggregations themselves need management or the fishery as a whole depends on both intrinsic (biological) and extrinsic (fishery) factors (e.g. Grüss and Robinson 2014; van Overzee and Rijnsdorp 2014). Assessing the condition of such fisheries can be very difficult, whether by fishery-dependent or fishery-independent means, while catch data compiled across multiple reproductive units, as is typical, are likely to be insensitive to localised population declines. And, although both hyperstability and catchability are risk factors for fisheries management that can be addressed (e.g. cod, orange roughy) and ignoring them can result in sudden and serious collapses, at a global level very few fisheries specifically address these factors (Hutchings and Reynolds 2004; Oelofson and Staby 2005). Standard fishery monitoring (CPUE, annual catches, etc.) and conventional management tools of effort controls (e.g. total fishers, bag limits) and catch limits (e.g. total allowable catch, quotas) can work for fisheries that focus on spawning aggregations but only if applied at the appropriate biological (fish population) scale; moreover, they typically do not consider possible non-lethal effects, which should also be considered.

Spatial and temporal management measures far merit greater attention as management measures for aggregating species than they have received to date, and can be very effective and efficient if implemented with other measures and adequately scaled for reproductive units and connectivity. Indeed, relatively small investments in spatial management of spawning aggregations can potentially offer disproportionately large benefits to fisheries and biodiversity conservation (Erisman et al. 2015). For some species, spatial protection must also account for migration pathways to and from aggregations and be adequately buffered for within-year and between-year shifts in core aggregation areas (Nemeth 2012; Robinson and Samoilys 2013). Seasonal measures such as sales bans or catch shares during the reproductive season can address gluts due to market flooding and may be particularly appropriate where capacity is limited to protect spawning sites, or where there is limited knowledge of their locations. Indeed, the best-protected aggregations are those not yet discovered, but which should be seriously considered in the case of projects that seek only to locate aggregation sites without a spatial protection in place or soon to be introduced! Seasonal protection is likely to become increasingly important as we become better able to predict both where and when spawning occurs and better able to relocate spawning sites once found, but continue to be hard-pressed to manage them effectively.

In small-scale tropical coastal fisheries where local communities have a history of taking fish from spawning aggregations in seasonally defined fisheries but little enforcement capacity or biological knowledge, there are both challenges and opportunities for sustaining exploited aggregate spawners. Management is particularly problematic for species of low productivity, particularly when export markets are introduced (which further increases demand). While there is considerable opportunity for management at the local community level in many places, much depends on community perceptions regarding the condition of the resource, the cultural significance of the species involved and the governance system. For example, in Bua Province, Fiji, communities banned the harvesting of groupers during their main spawning month of August but were reluctant to protect a well-known mullet aggregation site due to the cultural practice of holding an annual feast associated with the congregation of two mullet runs. Moreover, it is far from clear what benefits are gained by many source countries when vulnerable species, already limited in supply for domestic markets and exploited heavily from aggregations, are increasingly being exported; serious consideration should be given to ban exports of aggregation-caught fish to preserve local population, supply domestic markets and maximise economic benefits to source countries (e.g. Sadovy de Mitcheson and Ramoica 2015)

At the national level, greater stewardship and supporting policies can come from improved understanding of the cultural and economic importance of small-scale fisheries and implications of exports. A recent web-based pledge campaign for the protection of spawning groupers in Fij, for example, gained much public support (8,500 pledges currently) based on the concept that protecting these fish is also part of protecting a traditional way of life (4FJ 2015). Value chain analyses can help to raise awareness of winners and losers in these fisheries and of the implications for source countries of exporting (Sadovy de Mitcheson and Yin 2015). The globalisation of small-scale fisheries of low productivity and the lack of management, in particular, poses a very real risk in many developing countries but many smaller economies could effectively control their exports (e.g. Fiji banned the export of live groupers due to concerns about overfishing) (Sadovy de Mitcheson and Yin 2015). As examples, both Chuuk and Palau have bans on grouper exports, either seasonally (Chuuk) or all-year (Palau) (pers. obs.).

The bigger picture

"If migration is seen as a phenomenon of abundance, then its protection will require decision-makers to adopt a much more pro-active approach to conservation-in effect, to protect species while they are still abundant" (Wilcove and Wikelski 2008). Much the same can be said for aggregation-spawning species when fisheries are heavily focused on their reproductive aggregations. At stake are not just enormously important sources of fishery production and spectacular natural phenomena, but also important components of marine ecosystems, their biodiversity and other opportunities for income. For example, the collapse of capelin stocks affected other species in the ecosystem at higher levels in the food web (Hopkins and Nilssen 1991). The brief annual cubera, *Lutjanus cyanopterus*, and dog, *L. jocu*, snapper aggregations in Belize are stopping places for migrating whale sharks that time their movements to gorge on the billions of nutritious eggs produced (Heyman et al. 2001). The egg "boons" produced by high numbers of predictably concentrated adults are an exceptionally nutrient-rich trophic injection into the marine food web (Archer et al. 2015; Fuiman et al. 2015) (Fig. 1), while large biomass fluxes accompany seasonal movements of reef fishes (Nemeth 2012). An analysis of Nassau grouper aggregations in Belize showed that the net worth of not exploiting an aggregation could exceed by more than 20 times the value of landed fish (from ecotourism and fishery production) (Sala et al. 2001).

The good news is that managing aggregating marine species can and does work with sufficient knowledge and commitment to enforcement. The annual spawning aggregation of Togiak, Alaska, herring, under management, has produced a 20-year annual harvest of over 18,000 tonnes. Careful management of the largest aggregation of sockeye salmon, *Oncorhynchus nerka*, in the world, in Bristol Bay, Alaska, led to a relatively stable fishery that produced a 20-year average of over 35 million fish harvested per year (Westing et al. 2005). Positive outcomes came from managing plaice spawning aggregations in the North Sea (Rijnsdorp et al. 2012). Several grouper aggregations show increases in mean size and/or catches and numbers following effective protection based on good science (Nemeth 2005; Hamilton et al. 2011). Genetic, fishery and biological information on reproduction of the red seabream, *Chrysophrys* (=*Pagrus*) *auratus,* enabled the determination of appropriate temporal and spatial scales to successfully safeguard their spawning aggregations in a recreational fishery in western Australia (Wakefield 2010).

The bottom line is that evidence strongly suggests that we should fish spawning aggregations at commercial levels only cautiously, and only with adequate management and monitoring. In reality, however, for the great majority of commercial and recreational fisheries globally (i.e. non-subsistence) such conditions are unlikely to be met, and a precautionary approach is urgently called for to manage risk (Hilborn et al. 2001; Pitcher and Cheung 2013). For aggregating species, that risk appears to be particularly acute because of both lethal and non-lethal factors, and especially in the case of low productivity species (many reef and deepwater species in particular). Therefore, where there is insufficient management and enforcement, it is proposed that no fishing of spawning aggregations should occur until appropriate measures are implemented to ensure their sustainable use. There is also a need to conduct further research to ensure that fishery models, certifications, standards and guidelines sufficiently accommodate the risk factors, and that other possible benefits (e.g. ecosystem, ecotourism) are considered. In other words, the sustainable exploitation of fish spawning aggregations needs to be mainstreamed into all aspects of fishery management and fish conservation.

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