Spawning potential surveys reveal an urgent need for effective management

Jeremy Prince,[1] Watisoni Lalavanua,[2] Jone Tamanitoakula,[2] Epeli Loganimoce,[2] Tevita Vodivodi,[3] Kalisiana Marama,[3] Pitila Waqainabete,[3] Frank Jeremiah,[3] Diana Nalasi,[3] Laitia Tamata,[4] Mosese Naleba,[2] Waisea Naisilisili,[2] Uraia Kaloudrau,[3] Lepani Lagi,[3] Kalisiana Logatabua,[3] Rosemary Dautei,[5] Rahul Tikaram[5] and Sangeeta Mangubhai[2]

Summary

Since 2014, a Fijian programme of sampling reef fish catches has measured 16,404 fish from 180 species. A new stock assessment technique called length-based spawning potential ratio assessment has been applied to these data to develop stock assessments for 29 of the most common species in catches. More than half of the species (17) are assessed as having less than a 20% spawning potential ratio (SPR), an international limit reference point above which fish stocks should be maintained to minimise the risk of long-term stock decline. Fourteen of these species are estimated as having <10% SPR, the international reference point for SPR_{CRASH} below which fish populations are expected to collapse. Closer examination of species with a low SPR suggests that spear-gun fishing and gillnetting are currently posing the biggest threat to reef fish sustainability in Fiji. Our results suggest an urgent need to reform the management of Fiji's reef fish stocks so that fish are not caught before reproducing they have had a chance to replace themselves and keep populations stable. To this end, the existing regulation of minimum size limits and mesh sizes needs to be revised, and the implementation of additional restrictions on fishing methods should be considered.

Introduction

With the aim of assessing the status of Fiji's reef fish stocks, a group of non-governmental organisations – funded by the David and Lucile Packard Foundation – have been working collaboratively with Fiji's Ministry of Fisheries staff since late 2014 to sample reef fish catches. In March 2018, those partners participated in a workshop where they pooled their data to estimate the size at maturity for 46 of the main reef fish species in Fiji (Prince et al. 2018). In August 2018, the partners met again to develop stock assessments using their estimates of size at maturity and the size composition of the catch data they had collected. This article provides an initial report of those analyses.

In Fiji, and most other Pacific Island countries and territories, there are too many reef fish species and insufficient data on catch trends and biology to apply standard methods for assessing trends in biomass (total weight). A new technique – called the length-based spawning potential ratio (LBSPR) assessment – has been developed specifically for fish stocks for which only data on catch size composition can feasibly be collected (Hordyk et al. 2015a, b; Prince et al. 2015a). The LBSPR methodology enables catch size composition to be used with an estimate of local size at maturity to produce a snapshot estimate of a fish population's spawning potential ratio (SPR). SPR is a measure of a population's potential to continue replenishing itself and whether it is likely to be declining, stable or increasing. Left unfished, fish complete their full life span and fulfil their natural reproductive (spawning) lives, achieving 100% of their natural spawning potential. When fishing occurs, the average life span of the fish in any population is reduced, because some fish are caught before completing their natural life span, thereby reducing the population and its spawning potential below the natural unfished level (100%). SPR is the proportion of the natural unfished spawning potential remaining in the population when it is being fished. Studies from around the world have shown that down to around 20% SPR fish populations still retain the capacity to rebuild their numbers after fishing, although the rate at which a fish stock can rebuild declines as SPR falls to around 20% (Mace 1994). The level of 20% SPR is internationally known as the 'replacement level', around which populations are expected to maintain their current level but have little ability to rebuild. Below 20% SPR the supply of young fish to the population is expected to decline over the succeeding years, while 10% SPR is commonly called 'SPR crash', below which populations are likely to decline rapidly and, if not corrected, is likely to result in local extinction.

Using the concept of SPR to assess fish stocks is similar to assessing human population trends by estimating how many of children from one couple will survive to adulthood. On average, if couples have 2.1 children surviving through to adulthood, populations replace themselves and remain stable. Above the replacement level for human reproduction, populations grow, and below that they decline. With fish populations, 20% SPR provides the same replacement level reference point as 2.1 surviving children per couple; both

[1] Biospherics Pty Ltd, POB 168 South Fremantle, WA 6162 Australia. Email: biospherics@ozemail.com.au
[2] Wildlife Conservation Society – Fiji Program, 11 Ma'afu Street, Suva, Fiji Islands
[3] Ministry of Fisheries, Research Division, Lami, Fiji
[4] World Wide Fund Pacific, 4 Ma'afu Street, Suva, Fiji
[5] Institute of Applied Science, University of the South Pacific, Laucala Bay, Fiji

are pivotal reference points around which populations of humans and fish either increase or decline.

This collaborative project aimed at measuring the SPR of the main reef fish species caught in Fiji, with the hope of providing information to fisheries managers and local communities on the state of their stocks, and to facilitate discussions about the need for new or more effective reef fish management measures.

Methods

The LBSPR assessment methodology compares the size of the fish being caught with the size at which they reach sexual maturity. If fish are all caught before reaching sexual maturity their populations have little spawning potential (i.e. 0% SPR). On the other hand, if there is little fishing effort, fish live close to their natural life spans, thus allowing them to grow larger than their size at maturity, with some attaining the natural average maximum size (L_∞) of the population; when this happens, SPR is close to 100%. The LBSPR algorithms enable this information in catch size composition, relative to size at sexual maturity, to be quantified in terms of SPR and relative fishing pressure (F/M, where F is 'fishing mortality', and M is 'natural mortality').

The data inputs required for the LBSPR methodology are:

1. Catch size composition data that are indicative of the size of the adult fish in a population. If the type of fishing being conducted fails to catch the largest size classes of a fish species, then the estimate of SPR produced for that species will be too small.

2. Estimates of the size at which fish become adults (size at maturity) which is defined by L_{50} and L_{95}, the sizes at which 50% and 95%, respectively, of a population are observed to be mature.

3. The two life history ratios that are characteristic of each species of fish. The life history ratios are:

    a. the relative size at maturity; this is the size of maturity (L_{50}) divided by the average maximum size a species can naturally attain without fishing (L_∞); and

    b. a species' natural rate of mortality (M), which is the rate at which fish die due to natural causes, divided by the von Bertalanffy growth parameter K, which is a measure of how quickly each species grows to the average maximum size (L_∞).

Community members recording fish size and gonad maturity stage, Macuata District, Fiji. (image: Laitia Tamata, WWF)

The first two of these data inputs need to be measured locally for each fish species because they vary from place to place; but, the more technical life history ratios are estimated generically from the available scientific literature as they are characteristics of species and families of species, and remain relatively constant across their entire range (Holt 1958; Prince et al. 2015a,b).

For this analysis the algorithms needed to apply the LBSPR methodology were accessed at the freely available website: http://barefootecologist.com.au

Data inputs

Length and maturity data

The data used for this analysis have been compiled from 13 sets of size and maturity data from catch data collected around Fiji for this purpose.

In late 2014, the World Wide Fund for Nature (WWF) began working with the local reef management committee (*Qoliqoli* Cokovata Management Committee), and communities living in Macuata District along the north coast of Vanua Levu in the Northern Fisheries Division, training a network of community members to measure fish length and assess each fish's stage of maturity (juvenile or adult and male or female, if possible). Through initial community-based workshops, 20 species were selected to focus on, based on: 1) the importance of these species to communities, 2) community perceptions about whether the species were declining, and 3) the extent to which local fish names coincided with scientific names so that the species being sampled could be reliably identified to the species level. WWF staff also conducted sampling of the same species at the Labasa fish market. Throughout 2017, WWF also set up community-based sampling projects around Savusavu on the south side of Vanua Levu, Tavua on the north coast of Viti Levu and the Yasawa Islands off the northwestern coast of Viti Levu in the Western Division. Each of these programmes focused on a list of species decided on by each community, but also collected data on some additional species.

In 2016, the Wildlife Conservation Society (WCS) also conducted similar training to communities in Bua on the west coast of Vanua Levu, training community members to measure four main species in their own catches. In partnership with fish sellers and the Suva City Council, WCS staff also began a programme of market sampling at the Bailey Bridge market in Suva, which mostly sources its fish from the Northern Fisheries Division, and the Labasa fish market. Sampling at the Labasa fish market was also undertaken by Kolinio Musudroka.

In late 2016, staff from the University of the South Pacific's Institute of Applied Science collected catch composition and catch rate data in communities in Ba Province along the north coast of Viti Levu, and on Gau Island in Lomaiviti Province. They also spent several weekends collecting length and maturity data for the locally important emperor fish, *Lethrinus harak*.

Beginning in 2016, the Ministry of Fisheries's Research Division established multiple market sampling programmes from Nadi in the southeast of Viti Levu, around to Rakiraki in the west, where Western Division staff assisted them.

Size at maturity estimates

Initial estimates of size at maturity were determined by an analytical workshop in March 2018 (Prince et al. 2018); where significantly more data have since been added to the dataset, initial estimates have been revised for the analysis. Table 1 presents the inputs used for this analysis, and the results by species. In this table size at maturity has been revised for this analysis and have been indicated with an asterisk; none of the revised estimates are very different to the original March 2018 estimates.

Life history ratios

The estimates of life history ratios used for the LBSPR assessment (Table 1) were developed through a synthesis of all available age, growth and maturity studies for Indo-Pacific species (Prince unpubl. data).

Results

The database used for this assessment contained 16,404 records of fish caught in Fiji from 180 species.

Initially, we were interested in determining whether our size data for each species varied by region, so we developed separate assessments for the four to fivc most common species in our database. The confidence intervals around these assessments overlapped, suggesting that there were no significant differences for any of the species between Viti Levu and Vanua Levu. It is possible that this lack of obvious regional differences is due to the geographic distribution of our sampling, rather than a 'real' lack of regional differences. The species composition of catches we sampled varied markedly between locations, suggesting there were real differences, thus complicating our comparisons. Groupers and larger-bodied emperor fish and parrotfish were prevalent in samples from the north coast of Vanua Levu, farthest away from Fiji's main population centres and markets on Viti Levu, while smaller-bodied species were mainly found on Viti Levu where they dominate catches. It is possible that we failed to observe regional differences for any species because inevitably we ended up comparing a large sample from one location producing a robust estimate of SPR with narrow confidence intervals, with a relatively small sample size from the other region producing a relatively preliminary assessment with broad confidence intervals.

Table 1. Tabulated input parameters and results. Column headings are defined in the text. An asterisk next to a species name indicates the size at maturity estimate has been revised since Prince et al. 2018.

Species	*M/K*	*Lm/L∞*	*L∞*	L_{50}	L_{95}	Sample size	SL_{50}	SL_{95}	*SPR*	*F/M*	Type of fishing
Acanthurus xanthopeterus	0.35	0.8	383	306	345	747	180	221	0.41	0.8	Speargun
Caranx papuensis	1.6	0.6	550	330	400	91	184	218	0.76	0.14	Handline and speargun
*Cetoscarus ocellatus**	0.65	0.7	564	395	470	125	447	533	0.1	28.7	Speargun
Chlorurus microrhinos	0.65	0.7	536	375	450	249	366	500	0.26	2.06	Speargun
Crenimugil crenilabis	2.4	0.55	585	322	380	200	412	538	0.34	4.35	Net
Epinephelus coeruleopunctatus	0.75	0.6	660	396	480	179	377	542	0.07	6.54	Speargun and handline
Epinephelus coioides	0.75	0.6	975	585	700	69	388	575	0.04	4.27	Speargun and handline
Epinephelus fuscoguttatus	0.75	0.6	987	592	690	125	264	382	0.14	1.7	Speargun and handline
Epinephelus maculatus	0.75	0.6	662	397	480	118	286	394	0.04	4.7	Speargun and handline
*Epinephelus polyphekadion**	0.75	0.6	715	429	500	435	403	523	0.03	12	Speargun and handline
Hipposcarus longiceps	0.65	0.7	521	365	440	859	322	435	0.1	4.03	Speargun
Lethrinus atkinsoni	0.7	0.7	361	253	330	912	188	247	0.34	0.97	Handline and net
Lethrinus harak	0.7	0.7	331	232	290	1444	215	261	0.1	4.63	Net and handline
Lethrinus lentjan	0.7	0.7	294	206	240	95	188	204	0.23	2.06	Handline and net
Lethrinus nebulosus	0.7	0.7	589	412	500	489	238	307	0.22	1.24	Handline
Lethrinus obsoletus	0.7	0.7	357	250	310	713	208	247	0.05	5.66	Net and handline
*Lethrinus olivaceous**	0.7	0.7	736	515	640	589	574	902	0.3	2.36	Handline and speargun
*Lethrinus xanthochilus**	0.7	0.7	557	390	480	438	237	314	0.49	0.51	Handline and speargun
Lutjanus argentimaculatus	0.5	0.75	589	442	570	755	229	324	0.02	5.04	Handline and speargun
Lutjanus gibbus	0.5	0.75	397	298	380	1700	219	276	0.09	3.29	Speargun and net
Monotaxis grandoculis	0.7	0.7	494	346	420	305	277	366	0.35	1	Handline and speargun
*Naso unicornis**	0.35	0.8	510	408	490	1394	210	300	0.24	1.35	Speargun
Parupeneus indicus	2.4	0.55	591	325	400	178	240	286	0.02	4.43	Net
Plectorhinchus chaetodonoides	0.5	0.75	583	437	520	176	246	339	0.08	2.75	Speargun
Plectropomus areolatus	0.75	0.6	708	425	520	828	444	613	0.05	10.5	Speargun and handline
Plectropomus laevis	0.75	0.6	830	498	675	165	279	385	0.18	1.6	Speargun and handline
*Plectropomus leopardus**	0.75	0.6	730	438	540	118	211	255	0.17	1.56	Speargun and handline
*Scarus rivulatus**	0.65	0.7	444	311	380	747	231	265	0.01	10.2	Speargun and net
*Siganus vermiculatus**	1.9	0.55	440	242	270	398	218	286	0.4	0.83	Net

Although we may have failed to detect real differences between regions, we chose to proceed by aggregating our data from across all regions so as to increase sample sizes as much as possible, and broaden the number of species we could assess. In this context, however, it should be remembered that, although our data have been collected from many sites, the data for each species predominantly come from one or more regions.

Consequently, our assessments primarily reflect the status of each species in the region from which most of the samples were collected, rather than some sort of countrywide average for each species. In general, small-bodied species tend to reflect the fishery around Viti Levu, while and large-bodied species tend to reflect the fishery along the north coast of Vanua Levu.

Ideally, for this approach, samples sizes greater than 1000 individuals would always be available for analysis so that the largest individuals in each population are fully represented (Hordyk et al. 2015b). This is because the LBSPR analysis is strongly influenced by the size of the largest fish in a sample, relative to the average maximum size inferred from size at maturity. The largest individuals in a population are the rarest, meaning there is a high chance that small samples will fail to fully represent them.

Statistical studies show that sample sizes of 1000 are required to ensure the largest individuals are fully represented (Erzini 1990). Under-representation of the largest size classes with small samples sizes results in lowered estimates of SPR.

In the real world of Pacific reef fish sampling, sample sizes of more than1000 individuals are rare, and so it is necessary to use whatever data are available. In our experience, sample sizes greater than 100 are worth analysing (Prince et al. 2015b), and if the length frequency histogram coherently describes an adult mode, an indicative assessment can be made (i.e. heavily fished, moderately fished or lightly fished). If sample sizes can then be increased to more than 1000 individuals with the same input assumptions, the original SPR assessment may increase by 0–30% SPR, but almost invariably the originally preliminary estimate proves indicative of the final estimate.

For many of reef fish species in Fiji, sample sizes were too small (<100) to make an assessment worth attempting. From the data on 16,404 fish from 180 species we were able to use 14,641 records to develop assessments for 29 species (Table 1).

- Three species assessments have more than 1000 individual measurements of paddletail snapper (*Lutjanus gibbus*), thumbprint emperor (*Lethrinus harak*) and bluespine unicornfish (*Naso unicornis*), and are considered complete and unlikely to change to any significant extent with additional data. Only a large revision of our estimate of size at maturity is likely to change these assessments.

- Twelve species assessments are based on 400–1000 individuals of Pacific yellowtail emperor (*Lethrinus atkinsoni*), Pacific longnose parrotfish (*Hipposcarus longiceps*), squaretail coralgrouper (*Plectropomus areolatus*), mangrove jack (*Lutjanus argentimaculatus*), surf parrotfish (*Scarus rivulatus*), yellowfin surgeonfish (*Acanthurus xanthopterus*), orange-striped emperor (*Lethrinus obsoletus*), longface emperor (*Lethrinus olivaceus*), spangled emperor (*Lethrinus nebulosus*), yellowlip emperor (*Lethrinus xanthochilus*), camouflage grouper (*Epinephelus polyphekadion*) and vermiculate rabbitfish (*Siganus vermiculatus*), and can be considered robust, although some marginal change (0–10% SPR) might be expected if >1000 samples can eventually be collected. A large revision in estimates of size at maturity would also change these estimates.
- Fourteen species assessments have more than 300 individuals of humpnose big-eye bream (*Monotaxis grandoculis*), steephead parrotfish (*Chlorurus microrhinos*), whitespotted grouper (*Epinephelus coeruleopunctatus*), Indian goatfish (*Parupeneus indicus*), many-spotted sweetlips (*Plectorhincus chaetodonoides*), blacksaddled coralgrouper (*Plectropomus laevis*), spotted parrotfish (*Cetoscarus ocellatus*), brown-marbled grouper (*Epinephelus fuscoguttatus*), highfin grouper (*Epinephelus maculatus*), leopard coralgrouper (*Plectropomus leopardus*), pink ear emperor (*Lethrinus lentjan*), brassy trevally (*Caranx papuensis*) and orange-spotted grouper (*Epinephelus coioides*), these should be considered preliminary, but can be assumed to be indicative of their likely status. These assessments might change appreciably (0–30% SPR) if samples can be increased to more than1000. Building up the samples sizes is also likely to improve their estimates of size at maturity, which could also affect their assessment.

Taking these qualifications into consideration, our 29 assessments present a coherent and internally consistent view of the status of Fiji's reef fish stocks, which even with the addition of new data are unlikely to be significantly altered, even as the assessment of some species are improved.

More than half of the species (17) are assessed as having <20% SPR, the international limit reference point above which fish stocks should be maintained to minimise the risk of stock decline. Fourteen of these species are estimated as having <10% SPR, the international reference point for SPR_{CRASH}, below which fish populations are expected to collapse. On the other hand, five species have 20–30% SPR, which internationally would class them as currently sustainable, and seven species have 30–76% SPR levels, which, using the same international reference points, would rate them as either well-managed and/or moderately fished.

Discussion

Combined, these 29 assessments provide a 'big picture' view of the extent to which overfishing is currently affecting Fiji's reef fish. However, before discussing that big picture, several species-level caveats and qualifications are necessary.

The five assessments producing the highest estimates of SPR are based on sample sizes of less than 500 individuals, and could well change as sample sizes are increased, and size at maturity estimates are revised. While increasing samples sizes can be expected to increase future SPR estimates, improving size atmaturity estimates with more data can result in large changes in either direction to the SPR estimate.

The assessment for the mangrove jack (*Lutjanus argentimaculatus*), cannot be considered indicative of the adult

Assessing mullets' gonad maturity at the fish market. (image Watisoni Lalavanua)

population as it is likely that the actual SPR of this population in Fiji could be much greater. This is because juveniles of this species inhabit shallow mangrove areas where community members catch them, but the species is known to move to deeper water (30–200 m) as they mature (Pember et al. 2005; Russell and McDougall 2008). Apart from spawning females, adult mangrove jacks rarely visit or are caught in mangroves. Our results show that community catches contain almost no adults and have low (<2%) SPR, which is consistent with the fish's known biology and is probably not indicative of the actual status of this stock. The size composition of adults from deeper water is needed to accurately assess this species.

With these caveats in mind, these 29 assessments tend to support the predictions of the March 2018 workshop's theoretical modelling that, without effective management, in the long term, 39 ecologically and locally important reef fish species are vulnerable to being depleted to the point of local extinction (Prince et al. 2018). Based on the difference between size at maturity and size of first capture in Fiji that modelling predicted, the 23 species of reef fish are prone to local extinction. Two of these species, the bumphead parrotfish and the humphead wrasse have been protected by moratoriums on fishing under the Offshore Fisheries Management Decree and Endangered, Protected Species Act and the Convention on International Trade in Endangered Species, and should have been in our samples less often than they were. Many other species identified by the March 2018 workshop were not assessable from our samples because they were uncommon (i.e. less than 100). From these low sample sizes and anecdotal accounts of these species having previously been larger and more numerous, we infer that if we ever have sufficient sample sizes, assessments for these species would reveal their SPR to be lower than for the species we have assessed.

Of the 11 species listed in the March 2018 workshop that we have been able to assess, only 2 were assessed as having greater than 20% SPR: the steephead parrotfish with 26%SPR and the bluespine unicornfish with 24%SPR. The parrotfish assessment might change with better data as it is based on a relatively small sample size (n = 249) and a preliminary aize at maturity estimate. However, the bluespine unicornfish assessment is based on a relatively large sample size (n=1394) and a higher quality size at maturity estimate, so the relatively higher estimate of 24% SPR is more reliable. As with LBSPR assessment studies in other countries, this species commonly stands out as being under lower fishing pressure than other similarly sized species in the reef fish assemblage (Prince 2015b; Cuetos-Bueno 2018). Biological factors that might confer some greater degree of relative resilience for this species are suggested by genetic evidence that unlike many other reef fish, bluespine unicorn fish disperses its larvae relatively broadly (Horne et al. 2013), perhaps maintaining a supply of young fish over fishing grounds from more lightly fished and remote populations. Bluespine unicornfish also forages away from the reef into the water column, which perhaps also make it less vulnerable to fishing for periods of time.

Based on assessments in other countries, the yellowlip emperor (*Lethrinus xanthochilus*) is another species that commonly appears to be less overfished than might be expected purely on the basis of its relatively large body size and expected attractiveness to fishers (Prince 2015b; Prince unpubl. data), and in Fiji we estimated it to have 49% SPR (n = 438). There are few, if any, accounts of this species forming aggregations that can be targeted for fishing during any stage of its life cycle, as apparently it lives very singularly, and is caught almost entirely incidentally while fishing for other species. Perhaps because it cannot be targeted as effectively as other species, such as the bluespine unicornfish, it is more robust to fishing pressure than other species.

In an interesting contrast to the predictions from the March 2018 workshop's modelling, which identified primarily large-bodied species as being prone to local extinction, these assessments suggest that a whole range of small-bodied species are also being very heavily fished, such as surf parrotfish (*Scarus rivulatus*), Indian goatfish (*Parupeneus indicus*), paddletail snapper (*Lutjanus gibbus*), Pacific longnose parrotfish (*Hipposcarus longiceps*), orange-striped emperor (*Lethrinus obsoletus*) and thumbprint emperor (*Lethrinus harak*); all were estimated to have an SPR of less than 10%. These direly low SPR estimates are mainly based on reasonable samples sizes (n >500) and solid size at maturity estimates, and as discussed above, may not reflect the status of stocks throughout Fiji. They do, however, undoubtedly reflect the region from which their samples mainly came (Viti Levu). Starkly illustrating that at least in some areas of Fiji, the 'fishing down of the foodweb' (Pauly et al. 1998) has proceeded to the extent that small-bodied species are now being fished so heavily that stocks are experiencing long-term declines in the recruitment of young fish.

In Table 1, the final column lists the main capture methods for our samples, with the first method named being the principal method used in our sampled areas. Excluding mangrove jack from this discussion, for reasons outlined above, it is interesting to note that all species with <20% SPR are primarily caught by speargun fishing, which nowadays means mainly night-time speargun fishing, or by gillnetting. Species estimated to have >20% SPR are predominantly caught by hook and line. This comparison suggests that, currently, the practices of speargun fishing and gillnetting are the greatest threat to reef fish sustainability in Fiji. These two methods have in common: a) the fact that they are used in nursery grounds, in the case of night-time speargun fishing shallow coral reef flats, and in the case of gill nets seagrass flats; and b) both are very effective at catching small immature fish.

The only fish species caught by speargun that we assessed to have a high SPR (41%), is yellowfin surgeonfish (*Acanthurus xanthopterus*; n = 747), which was mainly sampled in the Northern Division (n = 611). This is a medium-sized, less preferred species of surgeonfish that only tends to be fished heavily when the preferred larger-sized surgeonfish species have been depleted. It has, however, proved prone to eventual depletion in many places. Unless this result is an artefact of the current dataset, or an indication that our current size at maturity estimate is too small, it suggests that depleted stocks of larger-bodied groupers, parrotfish and surgeonfish along the outer coral edges on Vanua Levu's north coast are caused by spearfishers now heavily targeting medium- and small-bodied species.

Improving the management of Fiji's reef fishes

Implementing the 'set size' system of minimum size limits, which is being discussed in Fiji (Prince et al 2018a), could go a long way to stabilising and increasing SPR levels among the main reef fish stocks by ensuring fish are caught and released, or not speared, until they have fulfilled at least 20% SPR (Prince and Hordyk 2018).

Research and experience from other jurisdictions suggest that with the support and goodwill of fishers, speargun fishing and hook-and-line fishing in shallow water can both be effectively size selective, as small fish can be avoided or released alive. Gill nets, however, commonly catch a range of sizes according to the size of mesh being used, and fish are normally badly damaged in the net and unlikely to survive after being returned to the water. To some extent gill nets can be size selective, with the regulation of minimum legal mesh sizes to ensure smaller fish cannot be caught. Fiji has regulations governing minimum mesh size limits, such as 1.25 inches for whitebait and sardines, and 2 inches for other fish. However, at least for 'other fish', our results show that many net-caught species have a very low SPR, suggesting that the current mesh size regulations are either too small, or not being complied with. The LBSPR analytical framework can easily be used to develop or review such policies and our results suggest this would be a useful exercise.

The size of fish that each type of fishing gear and method catches can also often be improved by regulating the time and place they are used (e.g. not fishing in nursery areas). Such regulations need to be developed with a deep knowledge of local geography and fish habitats, and can only be effectively implemented and enforced with the support of local communities. While there is a clear role for the national government in establishing regulations regarding minimum size limits and legal types of fishing gear, spatial and temporal regulations that help make fishing more size selective will also need to be developed and implemented through local management committees of the Fiji Locally-Managed Marine Area network.

Our results are likely to ignite discussion about the impact of night-time speargun fishing, which takes a wide variety of species as well as small juveniles. Theoretically, at least, night-time speargun fishers could be taught to comply with minimum size limits, thereby making this fishing technique sustainable. However, operating at night in the shallow coral reef nursery grounds of many species, they are likely to find compliance challenging and much less rewarding than current practices.

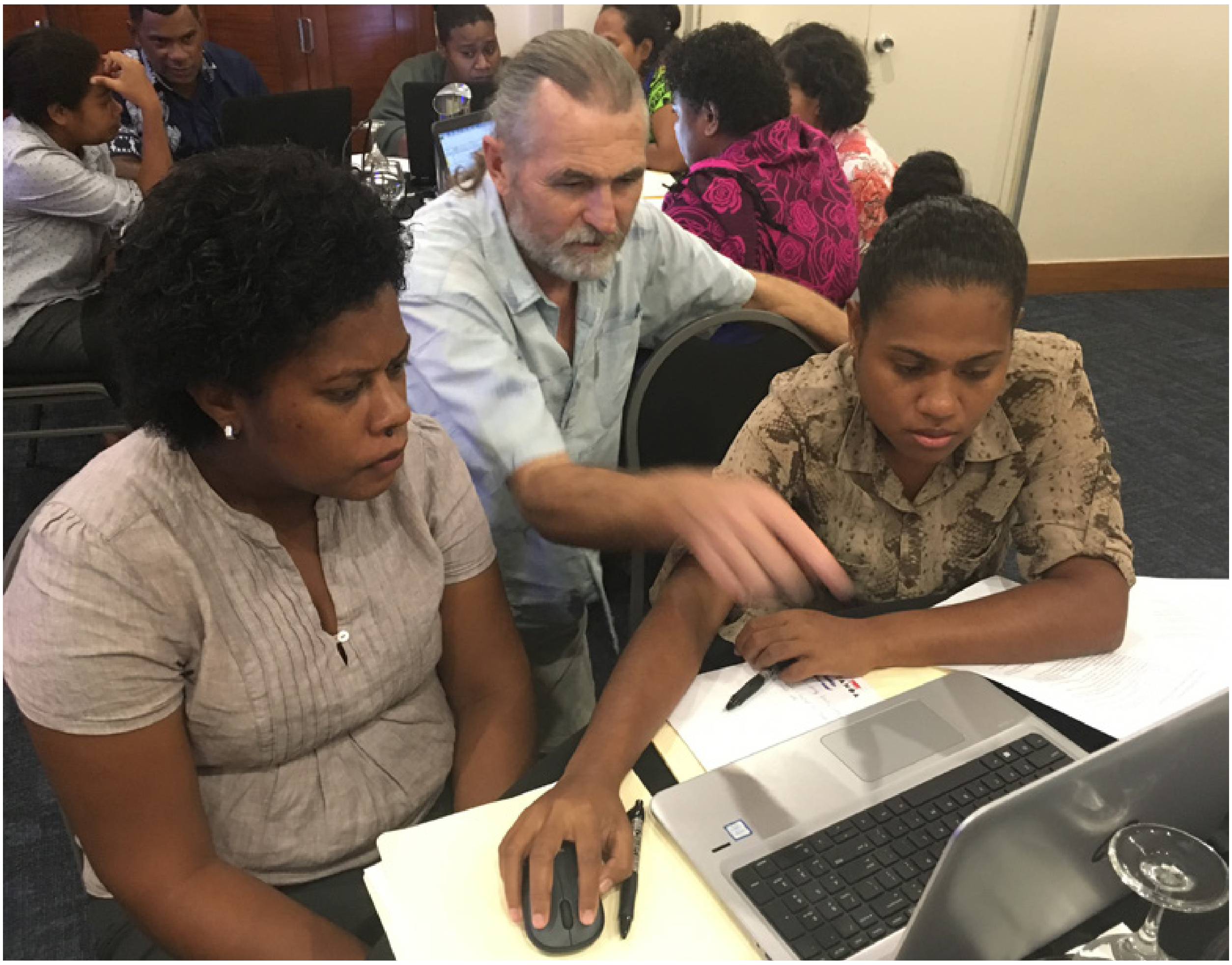
Some fishing practices are inherently difficult to make size selective (e.g. deepwater fishing and trawling catch a wide size range of fish that are mortally damaged in the process). Sustainably managing these types of fishing practices require effectively constraining controls on fishing pressure, supported by real-time monitoring and adaptive management measures. These are governmental capacities that developed countries struggle to deliver to small-scale fisheries such as those for tropical reef fish. Pacific Island countries are also likely to struggle for some time to effectively and adaptively control fishing pressure on reef fish stocks. Consideration, therefore, should be given to prohibiting activities that cannot be made size selective, or at least restricting such activities to remain at a small scale in restricted areas.

On the grounds of good fisheries management, it can easily be argued that communities and government should reconsider implementing and/or enforcing the ban on night-time speargun fishing. A national regulation of this type would probably be controversial and unpopular with many communities, especially as some communities who previously implemented such bans have since failed to enforce them. New Caledonia has implemented a different form of regulation to achieve a similar effect, which might also be more broadly acceptable in Fiji. Fishers may catch fish to feed their families by speargun fishing, but fish caught by speargun fishing cannot be sold in markets (Gillett and Moy 2006). This has the effect of limiting speargun fishing pressure to catches needed only to support local fishing families, while also reserving that part of coastal fisheries resources for local food security. In revisiting the issue of making speargun fishing sustainable, this form of policy deserves discussion.

Conclusion

This study illustrates the cost-effective utility of the new LBSPR methodology for assessing reef fish stocks. Through the collaboration of project partners, the status of 29 species has been determined for the first time, providing a snapshot of coastal fisheries around Fiji. This snapshot shows that overfishing of reef fish is occurring in Fiji parallels observations reported from across Pacific Island countries (e.g. Newton et al. 2007; Sadovy 2005; Sadovy de Mitcheson 2013) and, indeed, the entire tropical Indo-Pacific region (McClanahan 2011).

In conclusion, the assessments clearly show that the inshore fish stocks that communities depend upon are in crisis in many areas. Around the main island of Viti Levu, the



Ministry of Fisheries staff working with Dr Jeremy Prince to analyse data collected on size at maturity of reef fish in Fiji. (image: Sangeeta Mangubhai, WCS)

large-bodied species of groupers, wrasses, parrotfish and surgeon fish were rarely recorded in our samples, and even populations of small-bodied emperors, parrotfish and goatfish were estimated to have had their spawning potential reduced to levels likely to be cause long-term population declines. An almost complete assemblage of larger-bodied species was recorded in our samples from along the northern coast of Vanua Levu, but our results show that in this area these species are all likely to be declining (i.e. SPR<20%) and many rapidly declining (i.e. SPR<10%).

Acknowledgements

Thanks to all those that assisted us with our data collection: Kolinio Musudroka, Maria Rosabula, Unaisi Aiwai, Serupepeli Bulimali, Viliame Salabogi, Meliki Rakuro, Romuluse Raisele, Volau Tiko, Aporosa Nalasi, Alikula Seniceva, Meli Batikawai. Special thanks to all community data collectors from the provinces of Ba, Bua, Kadavu, Macuata, Serua and Tavua, and to all of the fish sellers at Bailey Bridge, Labasa and Lautoka fish markets for their support of the project. Thanks and gratitude also for financial support from the David and Lucile Packard Foundation and NZAID.

References

Cuetos-Bueno J., Hernandez-Ortiz D. and Houk P. 2018. Co-evolution of "race-to-fish" dynamics and declining size structures in an expanding commercial coral-reef fishery. Reviews in Fish Biology and Fisheries. doi.org/10.1007/s11160-018-9542-1

Erzini K. 1990. Sample size and grouping of data for length-frequency analysis. Fisheries Research 9:355–366.

Gillett R. and Moy W. 2006. Spearfishing in the Pacific Islands: Current status and management issues. 5th SPC Heads of Fisheries Meeting,3–7 April 2006. Noumea, New Caledonia: Secretariat of the Pacific Community.

Holt S.J. 1958. The evaluation of fisheries resources by the dynamic analysis of stocks, and notes on the time factors involved. ICNAF (International Commission on North Atlantic Fisheries) Special Publication 1:77–95.

Hordyk A., Ono K., Sainsbury K., Loneragan N. and Prince J.D. 2015. Some explorations of the life history ratios to describe length composition, spawning-per-recruit, and the spawning potential ratio. ICES Journal of Marine Science doi:10.1093/icesjms/fst235

Horne J.B., van Herwerden L., Abellana S., McIlwain J.L. 2013. Observations of migrant exchange and mixing in a coral reef fish metapopulation link scales of marine population connectivity. Journal of Heredity 104(4):532–546. doi:10.1093/jhered/est021

Pember M.B., Newman S.J., Hesp S.A., Young G.C., Skepper C.L., Hall N.G. and Potter I.C. 2005. Biological parameters for managing the fisheries for blue and king threadfin salmons, estuary rockcod, Malabar grouper and mangrove jack in north-western Australia. FRDC Project # 2002/003 Final Report. Murdoch University, Perth Australia. 176 p.

Prince J.D. and Hordyk A. 2018. What to do when you have almost nothing: A simple quantitative prescription for managing extremely data-poor fisheries. Fish and Fisheries 20(2):224–238. doI: 10.1111/faf.12335

Prince J.D., Hordyk A., Mangubhai S., Lalavanua W., Tamata L., Tamanitoakula J., Vodivodi T., Meo I., Divalotu D., Iobi T., Loganimoce E., Logatabua K., Marama K., Nalasi D., Naisilisili W., Nalasi U., Naleba M. and Waqainabete P. 2018. Developing a system of sustainable minimum size limits for Fiji SPC Fisheries Newsletter 155:51–60.

Prince J.D., Hordyk A., Valencia S.V., Loneragan N. and Sainsbury K. 2015a. Revisiting the concept of Beverton-Holt Life History Invariants with the aim of informing data-poor fisheries assessment. ICES Journal of Marine Science 72(1):194–203.doi:10.1093/icesjms/fsu011

Prince J.D., Kloulchad V.S. and Hordyk A. 2015b. Length-based SPR assessments of eleven Indo-Pacific coral reef fish populations in Palau. Fisheries Research 171: 42–58.

Russell D.J. and McDougall A.J. 2008. Reproductive biology of mangrove jack (*Lutjanus argentimacuiatus*) in northeastern Queensland, Australia. New Zealand Journal of Marine and Freshwater Research 42:219–232.

Sadovy Y. 2005. Trouble on the reef: The imperative for managing vulnerable and valuable fisheries. Fish and Fisheries 6:167–185. doi:10.1111/j.1467-2979.2005.00186.x

Sadovy de Mitcheson Y., Craig M.T., Bertoncini A.A., Carpenter K.E., Cheung W.W., Choat J.H., Cornish A.S., Fennessy S.T., Ferreira B.P., Heemstra P.C., Liu M., Myers R.F., Pollard D.A., Rhodes K.L., Rocha L.A., Russell B.C., Samoilys M.A. and Sanciang J. 2013. Fishing groupers towards extinction: A global assessment of threats and extinction risks in a billion dollar fishery. Fish and Fisheries 14:119–136. doi:10.1111/j.1467-2979.2011.00455.x