Developing a system of sustainable minimum size limits for Fiji

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Introduction

The depletion of reef fish stocks across the South Pacific poses a major threat to both food security and preservation of biodiversity (Newton et al. 2007; Sale and Hixon 2015). Highly prized large-bodied grouper, snapper, parrotfish and wrasse have become harder to catch and more expensive in markets everywhere. Once common, some species are now rare or locally extinct in many places. Researchers are predicting that many species face global extinction if effective management is not implemented (Sadovy et al. 2003, 2013; Dulvy and Polunin 2004). Most Pacific Island countries and territories (PICTs) have yet to develop the administrative capacity that is needed to tightly manage fishing pressure or the amount of fish being caught; thereby, the simplest and most effective way to sustain reef fish stocks will be to protect species with minimum size limits (MSLs) until they reproduce sufficiently in order to replace themselves.

In a parallel study, we demonstrate with simulation modelling that even under very heavy fishing pressure, fish stocks can be sustained by setting MSLs that protect fish until they have completed at least 20% of the breeding that they would naturally carry out, if there were no fishing activities (Prince and Hordyk in prep.). This level of reproduction, which is referred to as 20% of the spawning potential ratio (SPR), is internationally recognised as a limit reference point that stocks should be maintained above to prevent the recruitment of young fish from declining (Mace and Sissenwine 1993). In addition to sustaining stocks, setting MSLs to the size at which 20% SPR is achieved, also prevents fish being caught before fulfilling their potential for growth, and so ensures that optimal yields are attained. In that analysis, Price and Hordyk also demonstrate that for most of the main reef fish, the size at which 20% SPR can be approximated in a simple manner is by using a factor of 1.2 to multiply a species size of maturity (SoM), which is defined here as the size at which 50% of fish become adults ($L_{50\%}$). This rule of thumb can simplify this process and thereby circumvent the need for complex yield-per-recruit analyses to set MSLs – especially for data-poor fisheries. However, even with this simplification, setting MSLs in many of the PICTs that are scattered across the expanse of the Pacific Ocean is a challenging prospect. This attempt has been made difficult due to the large numbers of species from catches that have not been studied in depth, along with the impracticality of implementing large numbers of species-specific MSLs for an assemblage of species that appear to be similar.

This article describes a study undertaken in Fiji in order to address this challenge. The study, which was supported primarily by the David and Lucile Packard Foundation and NZAID, involved a unique collaboration of international scientists from Biospherics Pty Ltd, Australia, University of British Columbia (UBC) and local scientists from the Fiji Ministry of Fisheries, Wildlife Conservation Society (WCS), and World Wide Fund for Nature (WWF), in order to co-ordinate a programme of data collection and analysis to determine the size of maturity (SoM) of the most common fish species consumed or sold in Fiji. We expect this result to be broadly applicable across the tropical Pacific and Indian Oceans, although the size limits applied to each group of species may need to be adjusted between PICTs, depending on local water temperatures at different latitudes.

Methodology

Determining size of maturity

Good estimates of the size of maturity for the main species in a catch are the most critical input for any analysis of MSLs. Maturity in fish is studied most precisely with microscopic techniques that require access to expensive histological techniques and laboratories. In countries without these resources, SoM estimates made in other countries have commonly been borrowed and are assumed to apply. It is, however, becoming increasingly evident that SoM and body size in fish vary considerably between countries, mainly in relation to water temperature and latitude. In the absence of fishing, the further from the equator fish mature at, the more they will grow to larger sizes (Pauly 2010).

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When this project was initiated, the size of maturity had been determined for only three Fijian species, by Lasi (2003) using microscopic techniques. To address this gap in information on the SoM for most coral reef fish in Fiji, the collaborating partners initiated a programme to collect macroscopic size of maturity data on as many fish species as possible. The macroscopic techniques we have applied are less precise than microscopic techniques, but cheaper and less technical, and they simply require trained observers to cut fish open in the field and gauging maturity from the appearance of sex organs (gonads). Partners trained representatives of communities from Bua, Macuata, Ba, Serua, Tavua and Kadavu on how to examine their own catch, and used their own staff members to sample fish in the main fish markets of Suva (Viti Levu) and Labasa (Vanua Levu). Over three years, this collaboration sampled 13,901 fish of 129 species.

An analytical workshop that involved all the partners was held recently in Suva (27–29 March 2018). Attendees developed initial estimates of SoM for 31 species using their separate datasets, including comparative estimates from multiple regions for five species. The workshop concluded that with the data available, some difference in SoM between areas could not be entirely excluded; however, for the species studied, geographical differences appeared to be small enough to allow the data from all areas to be combined to estimate a single SoM for species, and to implement a single system of MSLs across Fiji.

Subsequent to the workshop, the datasets were amalgamated, which made it possible to estimate SoMs for 46 species (Table 1). Many of these estimates are based on relatively small samples (31 have samples sizes <100, 21 of which have samples sizes <50), which together with our reliance on macroscopic examination might reduce their precision. However, as a part of this project a meta-analysis of the literature for Indo-Pacific reef fish has been conducted by compiling a database that contains 469 SoM estimates. Checking our SoM estimates against this database reveals a consistent pattern of our Fijian estimates,

Table 1. Estimates of the size (in mm) at which 50% (L_{50}) and 95% (L_{95}) mature and samples sizes (n) for 46 species of Fijian reef fish that have been developed through the collaborative fish sampling project undertaken by project partners.

Species	L_{50}	L_{95}	n
Acanthurus nigrofuscus	298	380	51
Acanthurus xanthopterus	306	385	105
Caranx papuensis	330		30
Chlorurus microrhinos	375	450	92
Crenimugil crenilabis	322	380	164
Epinephelus caeruleopunctatus	396	480	131
Epinephelus coiodes	585	700	28
Epinephelus cyanopodus	405	440	12
Epinephelus fuscoguttatus	592	690	72
Epinephelus maculatus	397	480	78
Epinephelus ongus	326	400	43
Epinephelus polyphekadion	412	470	57
Hipposcarus longiceps	365	440	515
Lethrinus atkinsoni	253	330	428
Lethrinus erythracanthus	356	420	26
Lethrinus harak	232	290	899
Lethrinus lentjan	206	240	95
Lethrinus nebulosus	412	500	75
Lethrinus obsoletus	260	310	386
Lethrinus olivaceus	498	640	377
Lethrinus xanthochilus	390	480	254
Lutjanus agentimaculatus	442	570	24
Lutjanus bohar	468	550	46
Lutjanus gibbus	298	380	666
Lutjanus quinquelineatus	184	210	21
Lutjanus semicinctus	223	260	25
Monotaxis grandoculis	346	420	182
Naso unicornis	371	450	110
Parupeneus barberinus	325	400	44
Parupeneus cyclostomus	260	280	12
Parupeneus indicus	257	340	32
Plectorhinchus albovittatus	550	675	19
Plectorhinchus chaetodoinoides	437	520	137
Plectorhinchus gibbosus	417	480	15
Plectropomus areolatus	430	520	216
Plectropomus laevis	498	675	23
Plectropomus leopardus	435	525	72
Scarus ghobban	329	360	39
Scarus globiceps	270	390	45
Scarus niger	249	280	13
Scarus rivulatus	292	340	353
Scarus rubroviolaceus	369	400	85
Siganus doliatus	204	220	13
Siganus punctatus	241	260	21
Siganus vermiculatus	236	270	79
Variola louti	350	420	16

which fits into the upper end of published estimates in keeping with Fiji's higher latitudes (~18°S) and suggests internal consistency among our estimates. Three of our estimates can also be compared with those that Lasi (2003) derived by using microscopic techniques and in each case are similar: *Lethrinus atkinsoni* (232 mm, cf. 236 mm); *L. harak* (253 mm, cf. 254 mm); and *L. obsoletus* (260 mm, cf. 240 mm). Despite our reliance on macroscopic techniques and small sample sizes, these comparisons give us some confidence in our estimates.

Size limit clustering analysis

In collaboration with this project, Dr Adrian Hordyk (UBC) developed a novel multi-species yield-per-recruit model to evaluate the trade-offs involved in grouping a species assemblage into differing numbers of MSLs – estimating aggregate yields and the number of species prone to extinction for any number of MSL groupings. As with standard yield-per-recruit modelling, this analysis is equilibrium based, and estimates states that are predicted to exist in the long-term after all transitional dynamics have passed through the modelled populations. In other words, the model estimates the final state that populations will eventually come to rest in, if the modelled conditions were applied constantly into the long-term future.

The model proceeds as follows:

1. First, the MSL is estimated for each species in the assemblage that is being analysed (in this case 74 species) to optimize the long-term sustainable yield and reproductive potential (SPR) for each species, which is approximated for most species by 1.2 x SoM.

2. The species-specific MSLs are then grouped into all the possible number of groupings (in this case from 1 to 74). Groupings are initially formed using the similarity of the species-specific MSLs, with the overall MSL for each group being initially set to the average of the species-specific MSLs in each group. For example, if there are five species in a group with individual species-specific MSLs of 30, 35, 40, 40, 45 cm, the MSL for that group will be 38 cm.

3. In the next step, the model adjusts the average MSL for each group so as to optimize the expected yield from each group by giving weight to the most productive and abundant species in each group.

4. Finally, the MSLs for each group are optimized for ease of implementation by being rounded to the nearest 5 cm and any resulting change in yield that is caused by the final rounding is estimated (but is usually very small).

Model output

The trade-offs associated with each number of MSL groupings (in this case from 1 to 74) are calculated assuming both moderate (i.e. managed) fishing pressure ($F = 0.3$), which even without MSLs is expected to produce pretty good yields and minimise species extinctions, and heavy (i.e. unmanaged) fishing pressure ($F = 0.9$), which is expected to depress yields and maximise species extinctions. Reference levels of fishing pressure (F) can be adjusted within the model, but these default levels were used throughout this analysis. An important constraint is that fishing pressure is applied equally across all species (i.e. assuming no targeting occurs within the assemblage).

The final outputs of the modelling are:

1. the relative yield expected at equilibrium from each species in the assemblage;

2. the aggregated relative yield expected at equilibrium from the entire species assemblage; and

3. the number of species expected to have gone extinct at equilibrium.

4. lists of species in any number of 5 cm rounded MSL groupings.

Input parameters

Species list

The most fundamental input for the model is the list of species that comprises the assemblage that is being modelled. For this study, a list of 74 main species was developed through the sampling programme that was organised by the project partners, which together, comprise ~95% of the sampled catch.

Size of maturity

At the conclusion of our sampling programme, we had Fiji-derived SoM estimates for 44 of the 74 species that we modelled; while our database contained estimates for 21 of the 30 species for which we had no Fijian estimate.

Fiji lies at relatively high latitudes (~18°S) and the size of fish are apparently larger than most of the estimates in our database; thereby we preferentially used estimates from similarly high latitudes (i.e. 13°–25°), and if there was more than one estimate for a species, we used the average. Where there were only estimates from low latitude countries (<13°) we used the largest of those estimates, otherwise we used the only estimate available. This left nine species for which we had no SoM estimate. For these species, we developed two correlations between the 469 estimates in our database and estimates of maximum size that are published in the fish identification guides of Allen et al. (2003) and Moore and Colas (2016). With those correlations, we could make two estimates of SoM for unstudied species, and we used the average of those estimates in our model.

Biomass distribution

Estimates of relative unfished species composition (i.e., virgin biomass) of the assemblage being analysed provide weightings for species within each MSL group. We based our estimates on a synthesis of published studies as follows:

- Biomass surveys of relatively remote and/or pristine locations: Friedlander et al. (2010) for surveys of Kingman Reef in the Line Islands of the central Pacific region; Friedlander et al. (2012) for surveys of Coco Park off Costa Rica, and Williamson et al. (2006) for surveys of closed areas in the Great Barrier Reef Marine Park in Australia.
- Earlier studies of catch compositions in Palau (Kitalong and Dalzell 1994) and Fiji (Jennings and Polunin 1995; Kuster et al. 2005) when the fish assemblage might have been expected to be less impacted by fishing.
- And estimates of the sustainable catch composition in New Caledonia (Labrosse et al. 2000).

These studies show that in unexploited or lightly exploited states the reef fish biomass of the tropical Pacific region tends to be dominated by larger bodied predatory species, and tends to be distributed relatively uniformly across the main family groups (emperors, snappers, groupers, parrotfish and surgeonfish); thereby, we weighted our modelled biomass composition accordingly.

These assumptions are not as critical to the analysis as the SoM estimates. They mainly affect how species are grouped when a sub-optimally low number of MSL categories (2–4) are being modelled. In this context, the model prioritises the creation of MSL categories in order to optimize the yield of species with a large biomass, at the expense of species with a small biomass. As our interest focuses on solutions with a larger number of MSL categories (5–10) that are estimated to achieve ~100% of potential yields and zero species extinctions, our results are relatively insensitive to our assumptions of initial estimates of relative virgin biomass.

Other biological parameters

Biological parameters that describe the growth and longevity of each species are required in the form of life history ratios, along with the size at which fish are selected for catching.

The life history ratios we derived through a meta-analysis of >500 published studies of the age and growth of Indo-Pacific reef fish will be published separately. We estimated species-specific sizes of selectivity from the size composition of fish catches in Fiji that were determined by our sampling programme.

Results

Based on our assumptions the model estimates that with optimal management the 30 most important species comprise >70% of the catch, with the 10 most important being: blue spine unicorn fish (*Naso unicornis*), thumbprint emperor (*Lethrinus harak*), paddle tail snapper (*Lutjanus gibbus*), pink ear emperor (*Lethrinus lentjan*), vermiculate rabbitfish (*Siganus vermiculatus*), spangled emperor (*Lethrinus nebulosus*), long nose emperor (*Lethrinus olivaceus*), bumphead parrotfish (*Bolbometopon muricatum*), yellowlip emperor (*Lethrinus xanthochilus*), and two-spot red snapper (*Lutjanus bohar*). Together the 17 grouper species that were modelled comprise ~16% of the catch.

Without size limits, the model estimates that 82% of the potential yield can be obtained with moderate fishing pressure ($F = 0.3$) but that in the long-term, nine species go extinct (Table 2; Figure 1). With heavy fishing pressure ($F = 0.9$) only ~42% of the potential yield is achieved and 38 of the 74 species go extinct. The species predicted to go extinct under heavy fishing pressure, and from 0–5 MSLs, are listed in Table 3, which makes it clear that the large and medium bodied species will be the most likely to become extinction.

If only one MSL were to be implemented, then the model suggests this should be set at 25 cm. With moderate fishing pressure, this actually results in a slightly lower relative yield than no MSL (79% cf. 82%) but also reduces the species that are vulnerable to extinction from nine to one. With heavy fishing pressure, a single 25 cm MSL improves a potential yield from ~42% to ~52% and reduces the species at risk of extinction from 38 to 35.

The model optimizes two MSLs by giving protection to both small species with a 25 cm MSL, and larger species with a 55 cm MSL. Under this scenario, with moderate fishing pressure, no species are prone to extinction and potential yield increases ~89%. With heavy fishing pressure 21 species remain prone to extinction but potential yield increases to ~63%.

The model sets three MSLs to protect small species with a 25 cm MSL, mid-sized species with a 50 cm MSL and large species with an 85 cm MSL. Yields under heavy fishing pressure increase to ~74% and >90% with moderate fishing pressure. This scenario predicts that five, mainly mid-sized species, remain prone to extinction at high fishing pressure (*Acanthurus xanthopterus, Cephalopholis argus, Gymnocranius grandoculis, Lutjanus gibbus, Naso hexacanthus*).

Four MSLs are optimized with one (25 cm) protecting small fish and three protecting mid and large species (40, 55, 85 cm). Under heavy fishing pressure potential yields increase to ~83% and ~96% with moderate fishing pressure. Three mid-sized species are still predicted to go extinct with high fishing pressure (*Naso annulatus, N. unicornis, Plectorhinchus albovittatus*).

Table 2. Tabulated modelling results showing for each number of minimum size limits (0–14 first column) the expected percentage of potential yield relative to the maximum possible yield, and numbers of species extinction at moderate (*F* = 0.3) fishing pressure (columns 2 and 3) and high (*F* = 0.9) fishing pressure (columns 4 and 5), and the number of species grouped into each MSL category from 25–90 cm (columns 6 to 20).

Number of size limits	Potential yield with moderate fishing pressure (% of max. possible)	Number of species extinct with moderate fishing pressure	Potential yield with high fishing pressure (% of max. possible)	Number of species extinct with high fishing pressure	Number of species (n) in each size limit category (cm)														
					20	25	30	35	40	45	50	55	60	65	70	75	80	85	90
0	81.7	9	42.5	38															
1	79.0	6	51.6	35		74													
2	88.8	0	63.3	21		49						25							
3	90.2	0	73.8	5		38					25							11	
4	94.6	0	82.9	3		27			22			18						7	
5	95.6	0	84.7	1		27			22			14			7				4
6	96.2	0	92.6	0		20		16		13		14			7				4
7	97.3	0	95.3	0	13	14		11		11		14			7				4
8	97.6	0	95.8	0	13	14		11		11		14		4		3			4
9	98.4	0	96.2	0	13	14		11		11		14		4		3			4
14	99.0	0	98.7	0	7	14	6	11	3	8	4	5	5	4	2	1		3	1

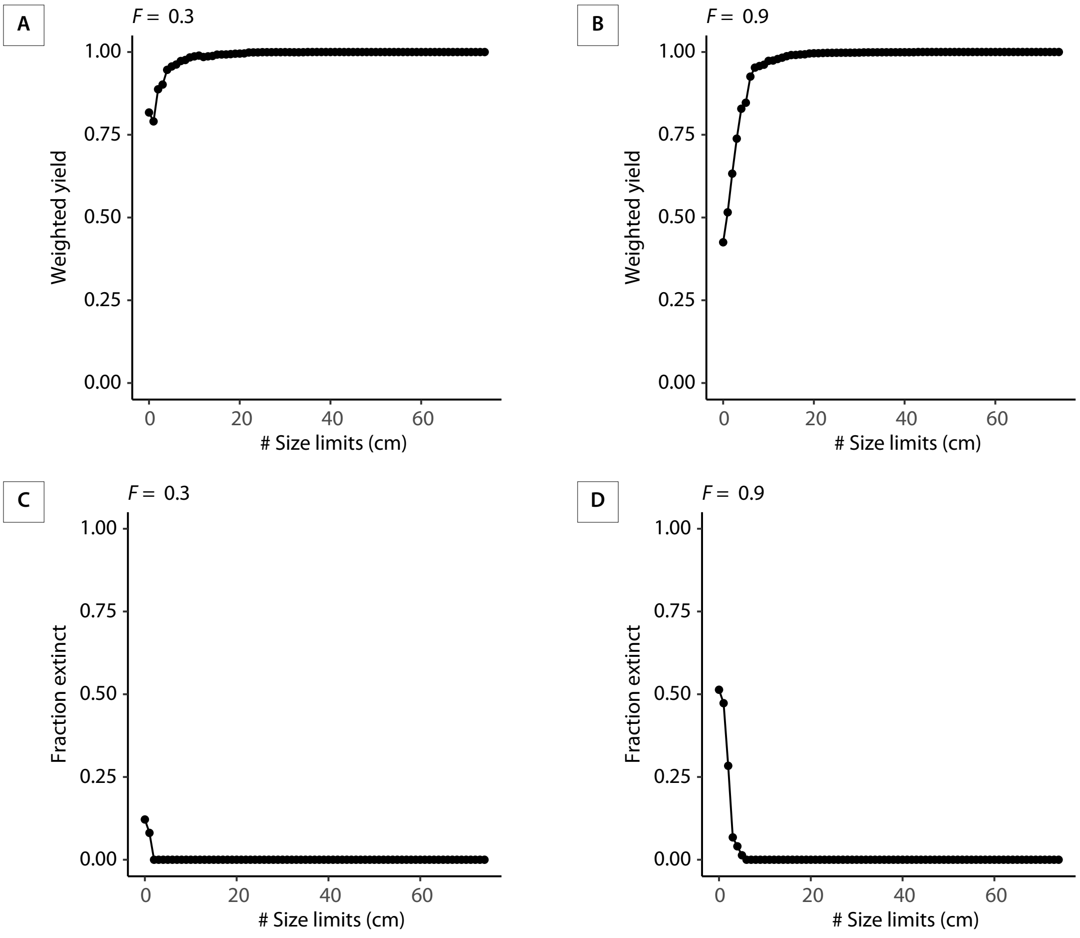

Figure 1. Plots of estimated relative yield (plots A and B) and proportion of the 74 species prone to extinction (plots C and D) by number of minimum size limits (x-axis) under scenarios of moderate fishing pressure (*F* = 0.3) in plots A and C, and heavy fishing pressure (*F* = 0.9) in plots B and D.

Table 3. The species predicted to be left vulnerable to extinction with heavy fishing pressure ($F = 0.9$) under each number of minimum size limits (0–5). Species extinctions are predicted to be prevented with six minimum size limits.

Number of size limits

0	1	2	3	4	5
Acanthurus xanthopterus	*Acanthurus xanthopterus*	*Acanthurus xanthopterus*	*Acanthurus xanthopterus*	*Naso annulatus*	*Naso unicornis*
Bolbometopon muricatum	*Bolbometopon muricatum*	*Bolbometopon muricatum*	*Cephalopholis argus*	*Naso unicornis*	
Caranx ignobilis	*Caranx ignobilis*	*Caranx sexfasciatus*	*Gymnocranius grandoculis*	*Plectorhinchus albovittatus*	
Caranx sexfasciatus	*Caranx sexfasciatus*	*Cephalopholis argus*	*Lutjanus gibbus*		
Cephalopholis argus	*Cephalopholis argus*	*Cetoscarus oscellatus*	*Naso hexacanthus*		
Cetoscarus oscellatus	*Cetoscarus oscellatus*	*Cheilinus undulatus*			
Cheilinus undulatus	*Cheilinus undulatus*	*Chlorurus microrhinos*			
Chlorurus microrhinos	*Chlorurus microrhinos*	*Epinephelus coioides*			
Epinephelus caeruleopunctatus	*Epinephelus caeruleopunctatus*	*Epinephelus fuscoguttatus*			
Epinephelus coioides	*Epinephelus coioides*	*Epinephelus tauvina*			
Epinephelus cyanopodus	*Epinephelus cyanopodus*	*Gymnocranius grandoculis*			
Epinephelus fuscoguttatus	*Epinephelus fuscoguttatus*	*Lethrinus erythracanthus*			
Epinephelus maculatus	*Epinephelus maculatus*	*Lethrinus xanthochilus*			
Epinephelus ongus	*Epinephelus polyphekadion*	*Lutjanus gibbus*			
Epinephelus polyphekadion	*Epinephelus tauvina*	*Monotaxis grandoculis*			
Epinephelus tauvina	*Gymnocranius grandoculis*	*Naso annulatus*			
Gymnocranius grandoculis	*Lethrinus erythracanthus*	*Naso unicornis*			
Lethrinus atkinsoni	*Lethrinus nebulosus*	*Naso vlaminghi*			
Lethrinus erythracanthus	*Lethrinus xanthochilus*	*Plectorhinchus albovittatus*			
Lethrinus nebulosus	*Lutjanus bohar*	*Scomberomorus commerson*			
Lethrinus xanthochilus	*Lutjanus gibbus*	*Sphyraena barracuda*			
Lutjanus bohar	*Monotaxis grandoculis*				
Lutjanus gibbus	*Naso annulatus*				
Monotaxis grandoculis	*Naso hexacanthus*				
Naso annulatus	*Naso unicornis*				
Naso brevirostris	*Naso vlamingii*				
Naso hexacanthus	*Plectorhinchus albovittatus*				
Naso unicornis	*Plectorhinchus chaetodonoides*				
Naso vlaminghi	*Plectorhinchus gibbosus*				
Plectorhinchus albovittatus	*Plectropomus laevis*				
Plectorhinchus chaetodonoides	*Plectropomus leopardus*				
Plectorhinchus gibbosus	*Scomberomorus commerson*				
Plectropomus laevis	*Sphyraena barracuda*				
Plectropomus leopardus	*Sphyraena jello*				
Scomberomorus commerson	*Symphorus nematophorus*				
Sphyraena barracuda					
Sphyraena jello					
Symphorus nematophorus					

The model spaces five MSLs relatively evenly across the size range (25, 40, 55, 70, 90 cm). Yields increase to ~85% with heavy fishing pressure, and ~96% with moderate fishing pressure. Only one species, *N. unicornis*, remains vulnerable to extinction with high fishing pressure.

Six MSLs are apparently optimal with no species being left prone to extinction under moderate or high fishing pressure. Relative yields remain ~96% of the maximum potential under moderate fishing pressure but increase to ~93% under heavy fishing pressure. The application of additional MSLs is predicted to result in only marginal yield increases (Table 2). In these cases, the model redistributes the small and mid-sized MSL categories, placing them at 25 cm and 35 cm to protect a wide range of the small-bodied emperors, goatfish, groupers, snappers, surgeonfish, parrotfish and rabbitfish (e.g. *Acanthurus lineatus, A. xanthopterus, Cephalopholis miniatus, Epinephelus fasciatus, Lethrinus harak, L. obsoletus, Lutjanus gibbus, Parupeneus barberinus, Scarus ghobban, S. rivulatus, Siganus vermiculatus*), and 45 cm and 55 cm to protect mid-sized groupers, jacks and parrotfish, along with the larger emperors, snappers, surgeonfish and sweetlips (e.g. *Caranx melampygus, Chlorurus microrhinos, Epinephelus caeruleopunctatus, Hipposcarus longiceps, Lethrinus olivaceus, L. xanthochilus, Lutjanus bohar, Naso unicornis, Plectropomus aerolatus, Plectorhinchus chaetodoinoides*) and using MSLs at 70 cm and 90 cm to protect 12 of the largest bodied species (including *Bolbometopon muricatum, Caranx ignobilis, Cheilinus undulatus, Plectropomus laevis* and *Scomberomorus commerson*).

Discussion

Interpreting model results

Our results suggest that without management >57% of the potential reef fish yield and 38 of the 74 species in the modelled assemblage will be lost in Fiji, but that a system of six MSLs set at 25, 35, 45, 55, 70 and 90 cm can protect ~93% of the yield and prevent extinctions.

We should not, however, rush blindly into applying these 'research results' too literally. All models are limited by the simplifying assumptions used within them to approximate the real world. The effects of these assumptions need to be considered when interpreting results. The most important assumptions to be mindful of here are: 1) that the size at which fish are selected for catching is fixed at the sizes we determined from our samples; and 2) that fishing pressure is applied equally across all the species. The effect of this first assumption will be to underestimate the long-term loss of species and yield under the heavy fishing pressure scenarios. The second will cause our results to over-emphasise the need to protect small-bodied species with MSLs.

Observing reef fish fisheries across PICTs reveals that the size of the fish being selected for catching depends on the depletion of a fishery; where large species are available to be caught, fishers target them in preference to catching smaller fish, but as large fish become scarce, fishers respond by targeting progressively smaller fish. This is seen by comparing catch compositions between countries, and between regions close to population centres with those from remote lightly fished areas. Fisheries ecologists call this process fishing down the food web (Pauly et al. 1998). Our model cannot take this into account; instead we assume that the size of fish being selected will remain as measured by our sampling. If this were true some species, and a level of yield, would be protected in the long-term, which is what our model predicts; but in reality, as fishers respond to depleting stocks by targeting smaller and smaller fish the loss of yield and species will be greater than our results suggest. This then sets the sobering context of why effective management of reef fish is needed in Fiji and other PICTs; more than 57% of the potential yield and more than 38 of the 74 species modelled will eventually be lost without it – a reality that has already been observed in many places, including close to the main urban centres of Fiji.

The positive side of our model's inability to describe the flexible way in which fishers target catch (by size and species) is that our results over-emphasise the need to manage small-bodied species if the more highly preferred large-bodied species are successfully managed. Smaller species only begin to be depleted once the larger species become scarce, which leave fishers with no other choice. If the abundance of larger species can be restored or maintained with effective MSLs, there will be less need for the smallest MSL categories. Thus while our results suggest placing MSLs first on the small species, where there is higher biomass, a higher priority should, in fact, be placed on protecting the larger bodied species with MSLs, as this will also give some level of protection to smaller bodied species.

Moving towards implementation

In turning these model results into policies that can be implemented, the human side of this equation will also have to be considered. The job of fisheries managers is after all more about managing humans than fish. Successful implementation requires fisheries science to be blended carefully with an understanding of human nature, and an acceptance of what is humanly possible.

Effective monitoring and enforcement is clearly essential to support successful implementation, especially at the outset to ensure a new system becomes quickly embedded as normal behaviour. The building of community support – so that compliance comes voluntarily, rather than by compulsion through enforcement – reduces the workload of enforcement officers. Two critical factors will largely determine the ease of implementation: how compatible our system is with local fish names, and the degree of hardship caused by implementation.

Species identification and local names

Our modelling implicitly assumes all species can be distinguished from each other and separated into the MSL categories. In reality, many species are so difficult to distinguish from each other that trained fish biologists using Fish-ID books commonly struggle. In Fiji, and throughout the Pacific Islands region, local names are commonly not species-specific, and are more a case of similarly sized species from the same genus or family being lumped together. Without targeted training, community members perceive the specific differences that taxonomists focus on as just being a normal variation within a type of fish – much as people have differing body shapes and facial appearances. To facilitate successful implementation, the system of MSLs that is being developed must work with, rather than against, local naming systems.

In all countries the complex of similarly appearing small-bodied emperors are difficult to distinguish, and Fiji is no exception. At least seven species are found in Fiji, *Lethrinus atkinsoni, L. harak, L. lentjan*, *L. obsoletus, L. ornatus, L. rubrioperculatus, L. semicinctus*, but the average Fijian only distinguishes between those with a longer body shape and more slanting snout, which they call *kabatia*, and those with a deeper body and more vertical snout, which they call *sabutu*. Complicating the situation further, there is apparently some variability in species composition between regions and despite the Ministry of Fisheries' best efforts to standardise and expand these root names with species specific qualifiers (e.g. *kabatia dina, kabatia gusudamu,* or *sabutu dina, sabutu levu, sabutu-ni-cakau*), there are some variation in each area as to which species the root names refer to (A. Batibasaga *pers. comm.*). Given the difficulty that many people have distinguishing these species, it would be easiest to apply the same MSL to this entire group of species. Fortunately, many of the species have SoMs in the 20–24 cm range and the model places them together in the 25 cm MSL, including the most common (overall) species in our samples (*Lethrinus harak*) and the fifth (*L. obsoletus*) and sixteenth (*L. lentjan*) most common; however, the fourth most abundant species *L. atkinsoni* (*sabutu*) has a larger SoM (25 cm) and is placed in the 35 cm MSL. Placing the smaller species into the 35 cm MSL will severely limit catches, as even without fishing few can grow as large as 35 cm, but placing *L. atkinsoni* into the 25 cm MSL will leave it relatively unprotected where fishing is heavy. Given the issue with how these species are most commonly recognised, a trade-off will be required here between grouping these species together in the 25 cm MSL for ease of identification, and fully protecting *L. atkinsoni* with the larger 35 cm MSL.

Smaller parrotfish are grouped similarly into two groups, which vary and overlap between regions: *rawarawa* being generally applied to *Chlorurus bleekeri*, *Scarus rubroviolaceus, S. globiceps, S. ghobban, S. niger, S. rivulatus*; and *ulavi* mainly to *Hipposcarus longiceps*, but also in some cases to *S. rubroviolaceus* and *S. ghobban*. For ease of implementation it would be best to cover all these species with the same MSL and the model suggests most of the *rawarawa* can be protected with the 35 cm MSL; however, *S. rubroviolaceus* and *H. longiceps* have larger SoMs (36–37 cm) and belong in the 45cm MSL. Being the third most common species in our samples, *H. longiceps* is an important species, and at the risk of causing some confusion with names, may well require the protection of the 45 cm MSL.

Local naming conventions will also necessitate trade-offs between surgeon fish in the *Naso* genus, which Fijians lump together as *ta*. By far the most important species in the catch is *Naso unicornis* (SoM = 37 cm), which the model protects with the 45 cm MSL; however, the minor *ta* species vary in size, *N. brevirostris* (SoM = 25 cm), *N. vlamingii* (SoM = 32 cm), *N. hexacanthus* (SoM = 48 cm), and are placed in the 35, 45 and 55cm MSLs, respectively. For the sake of maintaining yield and protecting the main species *N. unicornis*, the minor species would have to be placed in the same 45 cm MSL, meaning *N. vlamingii* would be over protected and under fished, while *N. hexacanthus* would be left vulnerable to depletion if fishing pressure becomes too heavy.

Trade-offs will also be required among the small-bodied lutjanids if they are to be included in the system of MSLs. Fijians lump many of these species under the name *kake*, which includes the smaller bodied *Lutjanus fulvus* (SoM = 20 cm) and *L. semicinctus* (SoM = 22 cm), which are placed in the 25 cm MSL, and the larger *L. monostigma* (SoM = 33 cm) for which the 45 cm MSL is suggested. However, unlike the species groups discussed above, none of these small snappers are highly targeted or very important in the catch at this time, so the impact of a smaller MSL for *L. monostigma* may be minimal, and leaving these species out of the system entirely might also be considered.

Food security in the short- to medium-term

In developing an implementation strategy, the most important factor to plan around is the short- to medium-term impact on food security.

Implementing a system of MSLs where none has existed before will inevitably cause an initial reduction in the amount of fish that can be legally caught, as small fish that could previously be landed must be left to grow through to the new MSL before they can be legally retained. The extent to which catches will be depressed and the time taken to recover depends on the growth rates of the fish and how depleted the stocks are when the MSLs are implemented.

The small and mid-sized reef fish grow relatively rapidly and most will grow from current sizes through to the MSLs being recommended in just 6–12 months. During that process, although only increasing about 10–20% in average length, they will almost double in weight. This means that if communities comply with the new MSLs, they will have reduced catches for 6–12 months before their catches recover and they are rewarded with a greater weight of fish to catch and higher catch rates than before the MSLs were implemented. After that, their catches and catch rates should continue to gradually improve for anything up to 5–10 years, just depending on how depleted their stocks were in the first place. However, if badly depleted to start with, the catch of larger bodied slower growing species could take 2–3 years to recover to pre-implementation levels before they start increasing above that level.

The issue for successful implementation is that no matter how strongly motivated communities start out being, and how rigorous the monitoring and compliance, or how effective the community education programme is, the reality is that people will not starve themselves, or send children to school hungry, just for the promise of a better future. Instead, they will find some way of being non-compliant to avoid starvation. The bottom line for a successful implementation is the extent to which it threatens food security in the short- to medium-term. If the initial period of 'belt tightening' is too extreme, compliance will be poor, and implementation will fail, because the expected long-term benefits will not materialise, leaving the fledgling system of MSLs dead in the water.

Conclusions

Unmanaged fishing of reef fish poses a major threat to food security and biodiversity for PICTs. The results of our modelling suggest that without effective management >57% of potential yields and more than half the main species will eventually be lost. Our modelling studies suggest that in Fiji a relatively simple form of management with six MSLs set at 25, 35, 45, 55, 70 and 90 cm could preserve ~93% of potential yields and prevent extinctions. The challenge confronting fisheries managers is how to adapt and apply these research results to the reality of managing artisanal fishers in the real world.

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Sampling reef fish at a Fiji fish market (image: Sangeeta Mangubhai).

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