Developing a system of sustainable minimum size limits to maintain coastal fisheries in Solomon Islands

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Abstract

Since 2014, the World Wide Fund for Nature (WWF) has worked with local fishing communities around Ghizo Island in the Western Province of Solomon Islands to assess the status of reef fish stocks and inform sustainable management. An article in the previous issue of the *SPC Fisheries Newsletter*[5] described the catch sampling programme conducted, and the species assessments that resulted. This article describes how those data were used to develop pragmatic advice about how the fishery could be made sustainable. We used a multi-species yield model to evaluate alternative ways of grouping the 96 fish species that made up 95% of surveyed catches, into a pragmatically few minimum size limits. For alternatively optimised minimum size limit groupings, the analysis estimated the aggregate sustainable yield and the number of species left prone to eventual local extinction by high fishing pressure. Our results make explicit the cost, in terms of biodiversity and food security, of not effectively managing the reef fish fishery, indicating that eventually, approximately 70% of the potential yield, and more than 50% of the species will be lost. On the positive side, the implementation of just four multi-species MSLs could prevent local extinctions and sustain more than 90% of the potential reef fish yields, even under regimes of high fishing pressure. If the abundance of larger- and medium- bodied species can be restored and maintained with effective MSLs before depletions become too severe, a simpler arrangement of three MSLs for the main 20–30 larger-bodied species may well achieve similar results.

Introduction

The depletion of reef fish stocks across the South Pacific poses a major threat to both food security and the preservation of biodiversity (Newton et al. 2007; Sale and Hixon 2015). Highly prized, large-bodied groupers, snappers, parrotfish and wrasses have become harder to catch and smaller, less common and more expensive in markets everywhere. Once common, these species are now rare or locally extinct in many places. Researchers are predicting that many species will face global extinction if effective management is not implemented (Sadovy et al. 2003; Dulvy and Polunin 2004). Most Pacific Island countries and territories (PICTs) have yet to develop the administrative capacity needed to tightly manage fishing pressure or the amount of fish being caught. Therefore, 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 to replace themselves.

Prince and Hordyk (2018) demonstrated with simulation modelling, that even under very heavy fishing pressure, fish stocks can be sustained by setting MSLs to protect fish until they have completed at least 20% of their natural unfished level of spawning potential (20% SPR). In addition to sustaining stocks, setting MSLs to protect 20% SPR prevents fish being caught before reaching their full growth potential, thus ensuring that fishing communities attain optimal yields. Prince and Hordyk (2018) also demonstrated that for most fish, the size at which 20% SPR is achieved can be simply approximated by multiplying a species' length at maturity (L_m) by a factor of 1.2. By circumventing the need for complex yield-per-recruit analyses, this simple rule of thumb greatly simplifies the process of establishing MSLs for data-poor fisheries. However, even with this simplification, setting MSLs for the large number of reef fish species that typically comprise PICT catches remains technically challenging, and implementing large numbers of species-specific MSLs is impractical. Our catch sampling programme around Ghizo Island in the Western Province of Solomon Islands (Prince et al. 2020) recorded that 15 species numerically comprised ~50% of the catch, while 96 species comprised ~95% of the catch. Clearly implementing and enforcing individual MSLs for each species in such an assemblage is virtually impossible. Instead, species need to be grouped into pragmatically few MSLs, in a way that sustains as much potential productivity as possible, and prevents any individual species from being badly depleted.

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Gizo fish market, Solomon Islands. (image © Andrew J. Smith, WWF-Australia)

Prince et al. (2018) described the application of a novel multi-species yield-per-recruit model that was developed specifically for the purpose of grouping species in Fiji into MSLs. This paper describes the application of the same multi-species yield-per-recruit model to the data collected by WWF in the Western Province of Solomon Islands (Prince et al. 2020).

Methodology

The multi-species yield-per-recruit model was developed to evaluate the trade-offs between yield and species vulnerability, which result from grouping diverse species assemblages into differing numbers of MSLs (Prince et al. 2018). For any number of MSL groupings, the analysis estimates the expected aggregate sustainable yield, and the number of species left prone to eventual extinction under high fishing pressure. As with standard yield-per-recruit modelling, this analysis is equilibrium-based, estimating 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 stabilise around, if the modelled conditions were applied constantly into the future.

The model proceeds by:

1. First estimating the MSL for each species in the assemblage being analysed in order to optimize that species' long-term sustainable yield and reproductive potential (SPR).

2. The species-specific MSLs are then grouped into all the possible number of groupings. In this case, from 1 to 96, because there are 96 species in the analysis (see below). Groupings are initially formed using the similarity of the species-specific MSLs, with the overall MSL for each group being set to the average of the species-specific MSLs in that 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 optimise the expected yield from each group by giving greater weight to the most productive and abundant species in each group.

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

Model output

The trade-offs associated with each of the alternative groupings of MSLs are calculated and plotted in terms of the: 1) relative yield expected at equilibrium from each species in the assemblage; 2) aggregated relative yield expected at equilibrium from the entire species assemblage; and 3) number of species expected to have gone extinct at equilibrium.

These measures are estimated assuming that both moderate fishing pressure (F = 0.3), which even without MSLs is expected to produce pretty good yields and minimise species extinctions, and heavy fishing pressure (F = 0.9), which is expected to depress yields and maximise species extinctions. These default reference levels of fishing pressure (F) can be adjusted within the model, but were used throughout this analysis. An important constraint of the model's configuration is that fishing pressure is applied equally across all species (i.e. no targeting of preferred species).

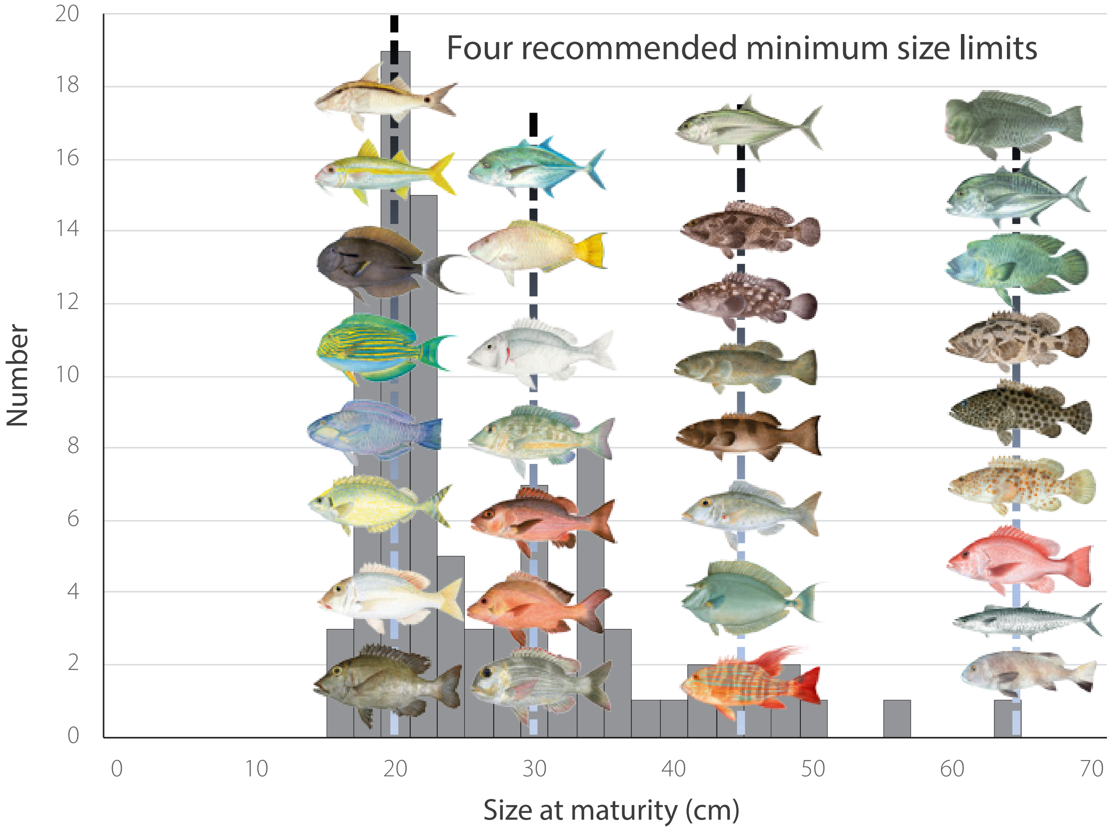

Figure 1. Frequency histogram (grey bars) of the 96 size-at-maturity estimates used in this analysis. The four dashed lines indicate the distribution of MSLs estimated to be optimal by scenario 3. Scenarios 1 and 2 suggest setting the third MSL at 40 cm rather than 45 cm. The thumbnail pictures of fish indicate some of the main species included in each of the four MSL groupings.

The final outputs of the modelling are 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 comprising the assemblage being modeled. A list of 96 species was developed for this purpose on the basis that these species comprised ~95% (by number) of the catches sampled around Ghizo Island (Prince et al. 2020).

Size at maturity

Size at maturity for each species was specified, with estimates of the size classes at which 50% (L_{50}) and 95% (L_{95}) of individuals mature. We estimated L_{50} and L_{95} for 63 of the 96 species modelled from our own samples (Prince et al. 2020, Table 3). For one other species (*Bolbometopon muricatum*), estimates were available from the literature (Hamilton et al. 2008). Comparing L_m estimates between Solomon Island and Fiji for the same species (Prince et al. 2018, Table 1), we estimated that, on average, the Solomon Island estimates were 0.81 of the Fijian estimates (SD = 0.146, n = 36). We understand this difference to be a result of Solomon Islands' lower latitude and warmer water, resulting in low oxygen levels in coastal waters, causing reef fish to complete their life cycles at smaller body sizes (Pauly 2010). We used this factor (0.81) to estimate unknown L_m values in Solomon Islands from our Fijian L_m estimates for the same species. Figure 1 depicts a frequency histogram of all 96 L_m estimates used in this analysis.

Biomass distribution

To provide weighting factors for species within each MSL group, the multi-species yield analysis requires starting estimates of relative species composition of the unfished (virgin) biomass. These assumptions are not as critical to the analysis as L_m estimates, and mainly affects how species are grouped when a suboptimally low number of MSL categories (two to three) are being modelled. In that context, the model prioritises the creation of MSL categories to optimise the yield of species (and groups of species), with larger biomass, at the expense of those with less biomass. As our interest focuses on solutions with a larger number of MSL categories (four to ten) estimated to achieve close to 100% of potential yields and zero species extinctions, our results are relatively insensitive to our assumptions of initial estimates of relative virgin biomass.

We based our estimates of virgin biomass composition on a synthesis of published studies:

- Biomass surveys of relatively remote and/or pristine locations: Friedlander et al. (2010) surveys of Kingman Reef in the Line Islands of the central Pacific, Friedlander et al. (2012) surveys of Coco Park off Costa Rica, and Williamson et al. (2006) 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.
- 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 tends to be dominated by larger-bodied predatory species, and is distributed relatively uniformly across the main family groups (acanthurids, lethrinids, lutjanids, scarids, serranids). We weighted our modelled biomass composition accordingly.

For our base case scenario 1 (Table 1, left-hand column), we aimed to reflect the species composition of the catches we sampled around Ghizo (Prince et al. 2020, Table 2), which contained relatively high proportions of small- to medium-bodied emperors, goatfish and snappers. The exception to this being that, because Hamilton et al. (2016) documented an historic depletion of *Bolbometopon muricatum*, we assumed a much higher biomass of *B. muricatum* than was actually observed by our catch monitoring. Extending the idea that the catch composition we observed (Prince et al. 2020) has been impacted more broadly by historic fishing (Hamilton and Matawai 2006; Hamilton et al. 2016), we also developed an alternative initial biomass composition. For this alternative biomass, we assumed the proportion of large-bodied serranids and the labrid *Cheilinus undulatus* was higher than we observed (Table 1, right-hand column), and this assumed virgin species composition was used for scenarios 2 and 3.

Table 1. Assumed composition of the initial (virgin) biomass in Western Province, Solomon Islands, by family, used to parameterise the multi-species yield analyses. Left-hand column shows the initial biomass composition used for the base case model (scenario 1), which reflects the species composition of sampled catches (Prince et al. 2020); right-hand column has a higher proportion of serranid and labrid biomass than indicated by current catch compositions and was assumed for scenarios 2 and 3.

Family	% biomass Scenario 1	% biomass Scenarios 2 and 3
Acanthuridae	8.0	6.8
Carangidae	5.3	4.5
Labridae	1.7	4.0
Lethrinidae	20.4	17.5
Lutjanidae	14.7	12.6
Mullidae	1.2	1.0
Scaridae	18.8	16.0
Serranidae	20.3	29.3
Siganidae	2.3	1.9
Pelagic predators	4.5	3.9
Caesionidae and scads	2.1	1.8
Haemulidae	0.9	0.8
Total	100	100

Size selectivity

The minimum size at which each species is caught is an important input parameter for this analysis. This is called the size selectivity of fishing and is specified with SL_{50} and SL_{95}, respectively, the size at which 50% and 95% of individuals encountering fishing gear are retained or "selected" for catching. These two parameters are estimated by the length-based spawning potential ratio (LBSPR) assessment, and for scenarios 1 and 2 we used our own estimates for the species we had assessed (Prince et al. 2020). For species we could not assess due to small sample sizes, we used the results of our parallel studies in Fiji (Prince et al. 2018) and Palau (Prince et al. 2015) to determine whether their size selectivity was typically similar to L_m, or smaller. If similar, we assumed that their size selectivity was the same as our Solomon Islands L_m estimate. For larger-bodied species for which size selectivity smaller than L_m was indicated (*B. muricatum, Caranx ignobilis, Cheilinus undulatus, Epinephelus caeruleopunctatus, E. fuscoguttatus, E, polyphekadion, E. tauvina*) we assumed SL_{50} = 30 cm and SL_{95} = 40 cm. For medium-bodied species in which selectivity smaller than size at maturity was indicated (*Caranx melampygus, C. papuensis, C. sexfasciatus, Cetoscarus oscellatus, Chlorurus microrhinos, Naso annulatus*) we assumed SL_{50} = 25 cm and SL_{95} = 30 cm.

Our multi-species yield analysis assumes the same size selectivity when modelling the impact of both low (F = 0.3) and high (F = 0.9) fishing pressure regimes; when in reality, fishers respond to stock depletion by targeting progressively smaller fish. Because the results of our LBSPR assessment (Prince et al. 2020) suggested relatively moderate fishing pressure on assessed species, we might assume that should the reef fish resource be depleted further, the size selectivities we observed will decline. To model this eventuality, we developed scenario 3 to explore the possible impact of

Jeremy Prince showing how to measure various species of reef fish in Gizo, Solomon Islands. (image © Andrew J. Smith, WWF-Australia)

smaller than current patterns of size selectivity. For scenario 3, we assumed the same higher initial biomass of large-bodied serranids and labrids used in scenario 2 (Table 1, right-hand column), and that the SL_{50} and SL_{95} of species would decline to around the size of the smallest size classes observed in our sampling of catch compositions. Smaller-bodied species were assumed to be selected at SL_{50} = 15 cm and SL_{95} = 20 cm, medium-sized species at SL_{50} = 20 cm and SL_{95} = 30 cm, and the largest species at SL_{50} = 30 cm and SL_{95} = 40 cm.

Other biological parameters

Biological parameters describing the growth and longevity of each species are required by the model in the form of the two life history ratios (LHRs) that characterise the life history strategies of species and entire families of fish:

1) *M/K* which is a species' natural rate of mortality (*M*), divided by the von Bertalanffy growth parameter *K*, a measure of how quickly each species grows to the average maximum size (L_∞); and

2) L_m/L_∞ the relative size at maturity, which is L_{50} divided by L_∞.

Approximations of individual life history parameters – asymptotic size (L_∞), the rate of natural mortality (*M*) and the rate of growth to asymptotic size (*K*) – are also required. The LHRs assumed here are the same as assumed for our parallel LBSPR assessments (Prince et al. 2020, Table 1). These average estimates by family were derived from a database of over 1300 published age and growth studies, which was compiled for a meta-analysis of teleost LHR to be published elsewhere (Prince et al. in prep). In the case of the family Caesionidae, there are no estimates in our database, so we assumed they are the same as for Carangidae. This we rationalized on the basis that the similar lightly scaled and semi-pelagic body shapes and behaviours might suggest similar life history strategies and LHRs. Estimates of L_{50} for each species were then used together with the assumed L_{50}/L_∞ of the family to estimate L_∞. The LHR database was used to estimate average *M* by species. Where no prior estimates of *M* were found for a species, the average of similar-sized species in the same family was assumed. With the assumed *M* and the estimate of *M/K* for each family, a value of *K* was estimated for each species.

Results

Base case results

With our base case scenario 1, the model estimates that with optimal management, the 30 most important species comprise >85% of the catch. The 10 most important species in order of importance are: humpback red snapper (*Lutjanus gibbus*), pink ear emperor (*Lethrinus lentjan*), two-spot red snapper (*Lutjanus bohar*), longfin emperor (*Lethrinus erythropterus*), blue-line surgeonfish (*Acanthurus lineatus*), streamlined rabbitfish (*Siganus argenteus*), humpnose bigeye bream (*Monotaxis grandoculis*), Pacific longnose parrotfish (*Hipposcarus longiceps*), yellowcheek parrotfish (*Chlorurus bleekeri*), orangespined unicornfish (*Naso lituratus*) and bumphead parrotfish (*Bolbometopon muricatum*).

Without size limits, the model estimates that 92.5% of the potential yield can be obtained if fishing pressure is managed at moderate levels (F = 0.3); nevertheless, in the long term, three large-bodied species are still prone to extinction (Table 2). With heavy fishing pressure (F = 0.9) and without MSLs, the relative potential yield falls to 74% and 22 of the 96 species assemblage are predicted to be prone to extinction. These 22 species are denoted by double asterisks in Table 3 and also depicted across the bottom two panels of Figure 2. Those most at risk are the large- and medium-bodied groupers, parrotfish and wrasses, many of which we observed to already be rare in the catch composition (Prince et al. 2020).

If only one MSL were implemented, the model suggests that this should be set at 20 cm (Table 2). With moderate fishing pressure, the single small MSL results in a slightly lower relative yield than no MSL (88% vs 92.5%), and only reduces the species vulnerable to extinction from three to two. With heavy fishing pressure, a single 20 cm MSL improves potential yield from 74% to 82%, but only reduces the number of large-bodied species at risk of extinction from 22 to 21. The model suggests a single small size limit at this stage of the analysis because of the predominance of small-bodied species in the assumed virgin species assemblage, and the assumption that all species are targeted equally. With these assumptions, the model optimises yield under high fishing pressure and a single MSL by protecting the assumed large biomass of small-bodied species, at the expense of protecting the assumed smaller biomass of larger-bodied species. The reason that under moderate fishing pressure potential yield initially falls and the extinction of only one species is prevented is that, a single small MSL provides little or no protection to vulnerable medium- and large-bodied species, but causes some of the smaller species that, even without an MSL would have been sustained, to go underfished.

The model optimises two MSLs by giving protection to small species with a 20-cm MSL, and medium-bodied species with a 40-cm MSL (Table 2). With two MSLs and moderate fishing pressure, only one species remains prone to extinction and potential yield increases to 89%. With heavy fishing pressure, relative potential yield increases from 74% to 85%, but 10 large- and medium-bodied species remain prone to extinction (*Bolbometopon muricatum, Caranx ignobilis, Cheilinus undulatus, Epinephelus coioides, E. fuscoguttatus, E. tauvina, Lutjanus bohar, Lethrinus erythracanthus, Naso annulatus, Plectorhinchus albovittatus*).

The model optimises yield with three MSLs by finessing the protection and yield of small- to medium-bodied species with 20- and 35-cm MSLs, while introducing some protection for larger-bodied species with a 65-cm MSL (Table 2). Yields with moderate fishing pressure increase from 89% to 96%, and under heavy fishing pressure from 85% to 90%. This scenario predicts that no species remain prone to extinction with three MSLs.

Four MSLs are optimised, with a 20-cm MSL protecting small-bodied species, and with three MSLs protecting mid- and large-bodied species (30, 40, 65 cm). Under moderate fishing pressure, potential yields only increase from 96% to 97%, and from 90% to 92% with heavy fishing pressure (Table 2). One species (*Naso annulatus*) that was previously protected with a 35-cm MSL, is estimated to be left prone to extinction under heavy fishing pressure, by the 40-cm MSL. This result is due to the model's processes of yield optimisation, averaging and rounding across species groups, and the assumed small biomass of *N. annulatus*. The extinction risk for this species could be remedied by repositioning it within the 30-cm size limit group, which would result in an almost complete loss of production from the species, but given its assumed relatively minor biomass, that would result in only a slightly lower yield than the model's estimated optimum.

The model spaces five MSLs relatively evenly across the size range (15, 25, 35, 50, 70 cm). Yields increase to 99% with moderate fishing pressure and 95% with heavy fishing pressure (Table 2). No species remain vulnerable to extinction, even with high fishing pressure.

With six MSLs, relative yields increase to ~100% of the maximum potential with moderate fishing pressure and 97% with heavy fishing pressure, and no species are prone to extinction with high fishing pressure (Table 2). The model splits the previous 35-cm and 50-cm MSLs with 32 species between three MSLs set at 35, 45 and 55cm.

Additional MSLs are predicted to result in only marginal yield increases (Table 2).

Other scenarios

With scenarios 2 and 3 the initial unfished biomass is assumed to have higher levels of large bodied serranids and labrids. The model estimates that with optimal management the 30 most important species comprise >86% of the catch

Table 2. Tabulated model results for scenarios 1–3, showing for 0–14 minimum size limits (first column) the expected percent of potential yield relative to the maximum possible, and numbers of species extinction at moderate (F = 0.3, columns 2 and 3) and high fishing pressure (F = 0.9, columns 4 and 5), and the number of species grouped into each (25–90 cm) MSL category (columns 6–20).

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)											
Scenario 1					15	20	25	30	35	40	45	50	55	60	65	70
0	92.5	3	74.1	22												
1	88.0	2	81.8	21		96										
2	89.3	1	84.8	10		70				26						
3	95.7	0	89.6	0		59			27						10	
4	96.6	0	91.7	1		54		19		14					9	
5	99.1	0	95.4	0	34		26		23			9				4
6	99.8	0	96.7	0	34		25		16		11		6			4
7	100.0	0	97.7	0	34		21	11	10		10		6			4
8	100.0	0	97.8	0	34		21	11	10		10		6		2	2
9	100.0	0	98.0	0	32		20	18		7	9		6		2	2
14	100.0	0	99.3	0	25	18	11	16	6	7	3	2	4		2	2
Scenario 2																
0	89.5	3	71.1	22												
1	85.4	2	78.3	21		96										
2	89.3	1	84.1	9		70				26						
3	93.2	0	88.5	0		59			27						10	
4	96.6	0	92.4	0		54		19		14					9	
5	96.4	0	93.9	0	34		26		23			9			4	
6	99.6	0	97.1	0	34		25		16		11		6		4	
7	99.9	0	98.0	0	34		21	11	10		10		6		4	
8	100.0	0	98.1	0	34		21	11	10		10		6		2	2
9	100.0	0	98.4	0	32		20	18	7		9		6		2	2
14	100.0	0	99.7	0	25	18	11	16	6	7	3	2	4		2	2
Scenario 3																
0	80.7	9	28.9	50												
1	82.3	5	71.5	33		96										
2	88.5	1	80.4	17		70					26					
3	89.9	0	85.4	2		58					28				10	
4	95.3	0	90.5	0		53		18			16				9	
5	96.1	0	91.3	0		53		17			15		7			4
6	99.4	0	97.3	0		33	25	15			13		6			4
7	99.7	0	98.2	0		33	23	14		8	8		6			4
8	99.8	0	98.3	0		33	23	14		8	8		6		2	2
9	99.8	0	98.6	0		24	34	12		8	8		6		2	2
14	100.0	0	99.8	0	6	27	20	11	6	7	10		5		2	2

and in contrast to scenario 1 includes a range of large bodied species. The ten most important species in order of importance being; humpback red snapper (*Lutjanus gibbus*), pink ear emperor (*Lethrinus lentjan*), longfin emperor (*L. erythropterus*), camouflage grouper (*Epinephelus polyphekadion*), Napoleon wrasse (*Cheilinus undulatus*), squaretail grouper (*Plectropomus aerolatus*), humpnose bigeye bream (*Monotaxis grandoculis*), streamlined rabbitfish (*Siganus argenteus*), blue-line surgeonfish (*Acanthurus lineatus*), Pacific longnose parrotfish (*Hipposcarus longiceps*).

Scenario 2, which assumes the same "current" pattern of size selectivity as scenario 1, produces almost the same results as the base case scenario (Table 2). The potential relative yield with no MSLs is slightly lower with moderate (89.5% vs 92.5%) and high fishing pressure (71.1% vs 74.1%), but the number of species expected to be prone to extinction with no to four MSLs and the estimated optimal length of MSLs are almost identical.

In contrast, the results of scenario 3, which modelled the effect of the size selectivity being smaller than currently observed, were markedly different (Table 2 and Figure 2). With no MSLs and moderate fishing pressure, relative potential yields fell from >92% in scenario 1 to 81% in scenario 3, and with no MSLs and high fishing pressure, from >74% to just 29%. Some 50 of the 96 species are predicted to be prone to extinction with high fishing pressure and no MSLs, up from just 22 species in scenario 1 (Table 3; Fig. 1). Consequently, the potential benefit to be gained from introducing MSLs is much greater, with all species extinctions being prevented, and >90% of the relative potential yield being achieved, even under heavy pressure, with four or five MSLs. The distribution of the MSLs as they are progressively added, is also a little different. A 45-cm MSL being the second to be added, instead of the smaller 40-cm MSL in scenarios 1 and 2, and is eventually preferred in the optimal arrangement of four or five MSLs.

Discussion

Depending on the scenario assumed, these results suggest that without management between 20 and 70% of the potential yield of reef fish, and between 22 and 50 of the 96 species modeled, will eventually be lost from the Western Province reef fish assemblage, but that extinctions could be prevented, and >90% of the yield protected, by a system with as few as four or five MSLs.

The slight discrepancies between scenarios, for example with 1 and 2 suggesting the third MSL at 40cm, and scenario 3 suggesting it should be set at 45cm, is indicative of the fact that yield curves for fish have broad flat tops. This allows relatively optimal yields to be obtained over a wide range of size classes, especially, when the yield curves are aggregated across groups of fish, as they are in this analysis. As these results illustrate, the effect of an MSL is determined by both its size relative to the L_m of the species, and the level of fishing pressure applied. Thus, relatively optimal yields for each species maybe attained over relatively broad size bands, so that relatively large shifts in MSL, often make relatively little difference to potential yield and SPR (Prince and Hordyk 2018). This confers some flexibility on the process of setting the MSLs. A fact our modelling explicitly takes advantage of, forcing the model into a final step, that rounds the optimized estimates of MSL to the nearest 5cm, simply to make them more pragmatic for eventual implementation. Our observation is that this constraint rarely makes a noticeable difference to the estimate of potential yield.

Compared with scenario 1 in which the potential yield under heavy fishing pressure increases from 91.7 to 95.4% with the addition of a fifth MSL, scenarios 2 and 3 predict yield gains of ~1% with the addition of a fifth MSL. This suggests that the four-MSL system (20, 30, 40–45 and 65 cm) could be the optimal trade-off between yield, conservation and simplicity of implementation. On the basis that we prefer scenario 3's assumptions of a higher original biomass of larger-bodied serranids and labrids, along with smaller sizes of selectivity in the event of resource depletion, we prefer the MSL arrangement suggested by that scenario (i.e. 20, 30, 45 and 65 cm). Although within the context of the above discussion, we remain flexible with regard to this recommendation. The grouping of species within these four MSLs is provided in Table 3 and partially illustrated in Figure 1.

All modelling is limited by the simplifying assumptions used to approximate the real world. The effects of these assumptions need to be considered when interpreting modelled results. The most important assumptions to be mindful of here are:

1) the size at which fish are selected for catching is fixed at the sizes we observed in our samples for scenarios 1 and 2, and for scenario 3 the smaller sizes we observed in more depleted regions of the Pacific (Prince et al. 2020); and

2) fishing pressure is applied equally across all species.

Should smaller sizes than assumed start being caught as stocks are depleted, the effect of this first assumption will be that we have under-estimated the long-term loss of species and yield under the heavy fishing pressure scenarios. The second assumption will cause our results to overemphasize the need to protect small-bodied species with MSLs.

Observing reef fish fisheries across the Pacific Islands clearly reveals that the size of the fish being selected for catching depends on each fishery's depletion. Where large species are available to be caught, fishers target them in preference to catching smaller fish. As large fish become scarce, fishers respond by targeting progressively smaller fish. This is seen by comparing catch compositions between countries,

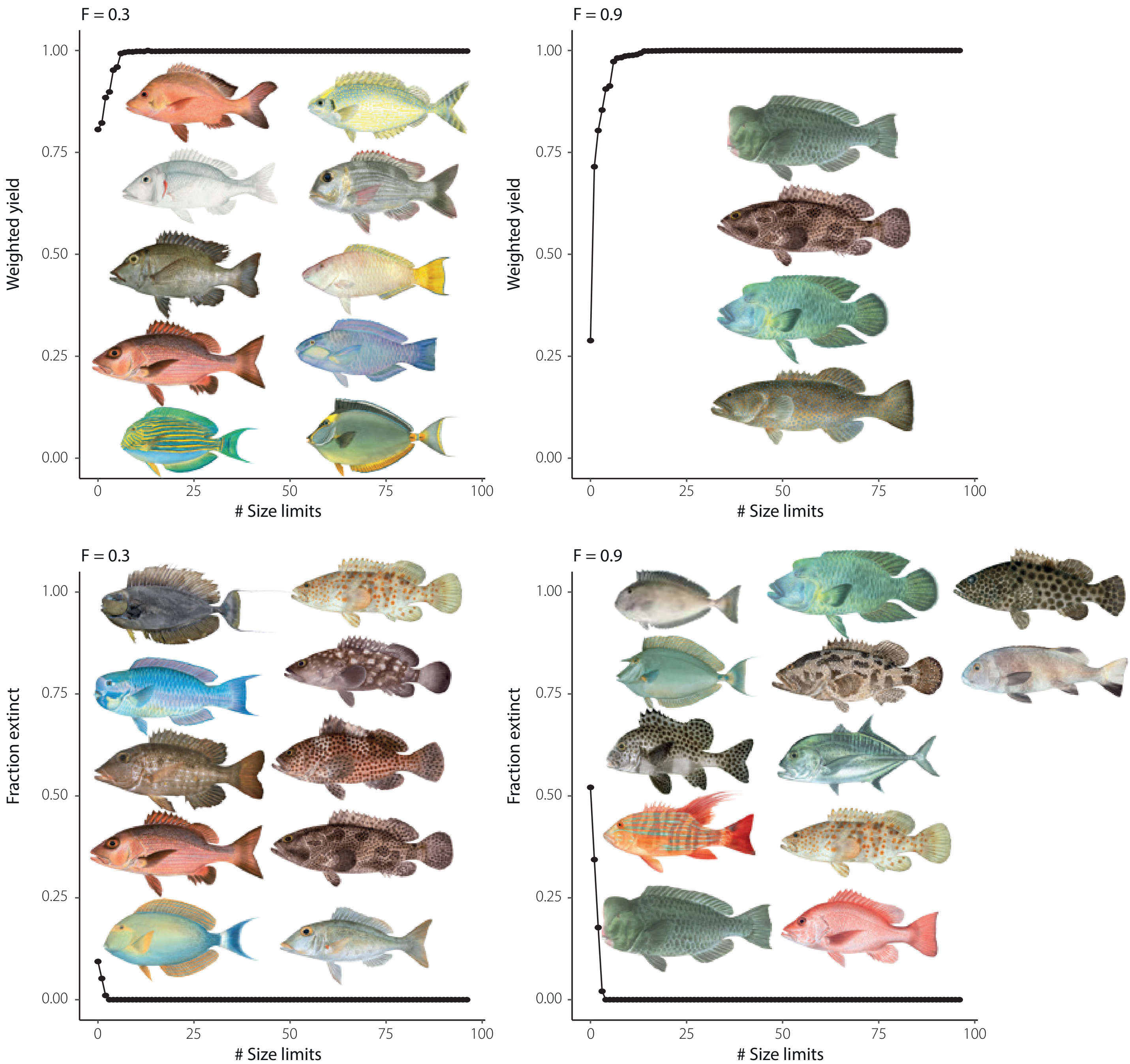

Figure 2. Model results of scenario 3. Top panels plot the estimated relative yield by number of minimum size limits (x-axis), and the bottom plots the proportion of the 96 species prone to extinction limits, under moderate fishing pressure (F = 0.3) in the left-hand plots, and heavy fishing pressure (F = 0.9) in the right-hand plots. Thumbnail pictures in the two top panels illustrate the species predicted by the three scenarios to be among their 10 most productive species with optimal management. Thumbnail fish pictures in the bottom two panels depict the 22 species predicted by all three scenarios to be prone to extinction under heavy fishing (F = 0.9) and without MSLs (Table 3).

and between regions close to population centers, with those from remote lightly fished areas. Fisheries ecologists refer to this process as "fishing down the food web", and "fishing down size structure" (Pauly et al. 1998). At this stage of development, our model cannot take this into account, instead assuming that the size of fish being selected will remain as assumed for that scenario regardless of the state of depletion.

In this analysis, we have tried to account for this reality with scenario 3. Its starker predictions of a 70%, rather than a 20%, loss of yield with heavy fishing pressure, and 50, rather than 22, species being prone to extinction, reveal the impact of our first simplifying assumption. In reality, the assumptions used in scenario 3 are also likely to be conservative. A parallel project north of Madang in Papua New Guinea, where local accounts tell us that 20–30 years ago there was

Table 3. Groupings of species into four minimum size limits as optimized by scenario 3 to prevent species extinctions and produce >90% of relative potential yields. Species predicted to be vulnerable to extinction with no minimum size limits and heavy fishing pressure (F = 0.9) in scenarios 1–3 are indicated with two asterisks, and with one asterisk if only predicted by scenario 3 to be vulnerable to extinction.

Size limit (cm)							
20	Ext	30	Ext	45	Ext	65	Ext
Acanthurus blochii	*	*Acanthurus nigrofuscus*	*	*Acanthurus xanthopterus*	**	*Bolbometopon muricatum*	**
Acanthurus lineatus		*Caranx melampygus*	*	*Caranx sexfasciatus*	*	*Caranx ignobilis*	**
Acanthurus nigracauda	*	*Caranx papuensis*	*	*Epinephelus areolatus*	**	*Cheilinus undulatus*	**
Caesio caerulaurea		*Cephalopholis cyanostigma*	*	*Epinephelus caeruleopunctatus*	**	*Epinephelus coioides*	**
Caesio cuning		*Cetoscarus ocellatus*	*	*Epinephelus maculatus*	**	*Epinephelus fuscoguttatus*	**
Caesio lunaris		*Chlorurus microrhinos*	**	*Epinephelus polyphekadian*	**	*Epinephelus tauvina*	**
Carangoides plagiotaenia		*Choerodon anchorago*	*	*Lethrinus olivaceus*	*	*Lutjanus malabaricus*	**
Cephalopholis miniata	*	*Epinephelus corallicola*		*Lethrinus xanthochilus*	**	*Plectorhinchus albovittatus*	**
Chlorurus bleekeri		*Epinephelus ongus*	*	*Naso annulatus*	**	*Scomberomorus commerson*	*
Epinephelus fasciatus		*Gymnocranius grandoculis*	*	*Naso unicornis*	**		
Epinephelus spilotoceps		*Hipposcarus longiceps*		*Plectorhinchus chaetodoinoides*	**		
Lethrinus atkinsoni	*	*Lethrinus erythracanthus*	**	*Plectropomus aerolatus*	*		
Lethrinus erythropterus		*Lethrinus lentjan*		*Plectropomus leopardus*	*		
Lethrinus harak		*Lethrinus microdon*	*	*Plectropomus maculatus*	*		
Lethrinus ornatus		*Lethrinus obsoletus*	*	*Sphyraena forsteri*			
Lethrinus rubrioperculatus		*Lutjanus bohar*	**	*Symphorus nematophorus*	**		
Lethrinus semicinctus		*Lutjanus ehrenbergii*	*				
Lutjanus biguttatus		*Lutjanus gibbus*	*				
Lutjanus fulvus	*	*Lutjanus monostigma*	*				
Lutjanus kasmira		*Lutjanus semicinctus*					
Lutjanus quinquelineatus		*Monotaxis grandoculis*	*				
Lutjanus rufolineatus		*Naso brevirostris*	*				
Monotaxis heterodon		*Scarus rubroviolaceus*	*				
Mulloidichthys vanicolensis		*Variola albimarginata*					
Naso lituratus		*Variola louti*					
Naso vlamingii	**						
Parupeneus barberinus							
Parupeneus crassilabris							
Parupeneus cyclostomus							
Parupeneus indicus							
Parupeneus multifasciatus							
Scarus dimidiatus							
Scarus ghobban							
Scarus globiceps							
Scarus niger							
Scarus oviceps							
Scarus psittacus							
Scarus quoyi							
Scarus rivulatus							
Selar boops							
Siganus argenteus							
Siganus canaliculatus							
Siganus doliatus							
Siganus lineatus							
Siganus puellus							
Siganus punctatus							

a relatively "normal" Indo-Pacific reef fish assemblage, is recording catch compositions with few fish of body sizes > 20 cm, and in which emperors, snappers are serranids of any size, are virtually absent. Anecdotal accounts about reef fish stocks closer to Honiara and around Malaita Island, as well as published reports (Green et al. 2006) suggest that some regions of Solomon Islands have been depleted similarly. Thus, the predictions above, produced by scenario 3 assuming heavy fishing pressure and no size limits, are probably reasonable for the Western Province over the medium term (15–20 years) but are likely to be conservative over the long term (>20 years) unless effective management is implemented.

The positive side of our model's limitations in describing the flexible way fishers target fish by size and species is that, if the more highly preferred large-bodied species can be successfully managed, our results overemphasise the need to manage small-bodied species. Generally, fishing pressure only intensifies for smaller species once larger-bodied species become scarce, leaving fishers without other choices. If the abundance of larger species can be restored and maintained with effective MSLs, there will be less need for the smallest MSL categories. In this situation, it could be that successfully implementing a simpler three-MSL system for the ~20 main medium- and large-bodied species (i.e. 30, 45 and 65 cm) might circumvent the need for the smallest size limit (20 cm) and the inclusion of a larger number of species.

Conclusions

The cost to Pacific Island countries and territories (PICTs) of leaving reef fish resources unmanaged is undoubtedly going to be great, in terms of lost biodiversity and food security. Our modelling suggests that in the Western Province of Solomon Islands, >70% of yield and >50% of species will be lost. A similar outcome is likely in most other PICTs as well. On the positive side, the results of our multispecies yield analyses suggest that extinctions can be prevented and >90% of the potential yield protected by a system of just four multispecies MSLs set at 20, 30, 40–45 and 65 cm. If the abundance of larger- and medium- bodied species can be restored and maintained with effective MSLs before depletions become too severe, a simpler arrangement of three MSLs (30, 45 and 65 cm) for the main 20–30 medium- and larger-bodied species in the catch, may well achieve similar results.

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