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Thresholds and multiple scale interaction of environment, resource use, and market proximity on reef fishery resources in the Solomon Islands

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ABSTRACT

Reef fish are critical in maintaining the ecological function of coral reefs and providing food security for coastal communities in developing countries. Reef fishery stocks are under increasing threat from factors such as climate-related habitat degradation, land use practices, and resource extraction related to human population growth, direct consumption and increasing connectivity between the in situ fishery and fish markets. This study investigates how reef fish stocks are related to environmental, localised resource use and market proximity indicators across 51 sites in the Solomon Islands. Hard coral cover is the best indicator of total target fishery biomass, with cover of less than around 31% associated with significantly less biomass than sites with higher coral cover. Direct resource use indicators such as fish consumption and fish sale pressure were poor predictors of target fish biomass. Distance of the fishery resource from community, provincial sub-station, provincial capital and national capital are all significantly and positively correlated with biomass for four key fishery families: Acanthuridae (surgeonfish), Scaridae (parrotfish), Lethrinidae (emperor), Lutjanidae (snapper). Multiple spatial scale relationships are evident between market proximity indicators and Lutjanidae and Scaridae families. Thus, while pooled target fishery biomass is constrained by environment, analysis at fishery family resolution reveals the effects of anthropogenic impact through market proximity on constraining fishery biomass distribution in the Solomon Islands. This study highlights the need for reef fishery managers and conservation practitioners to focus attention on proximity of resources to markets to sustain the ecological health of reef dominated ecosystems.

1. Introduction

Coral reefs are highly biodiverse ecosystems that directly provide goods and services to around 500 million people (Moberg and Folke, 1999; Wilkinson, 2002). They are also susceptible to change. Anthropogenic influences such as overharvesting, nutrient overload, and climate change are having profound negative effects on the condition of coral reefs (Friedlander and DeMartini, 2002; McClanahan, 2002; Pandolfi et al., 2003; Bruno and Selig, 2007). Overfishing is thought to be one of the most influential anthropogenic factors affecting the condition of coral reefs (Jackson et al., 2001), resulting in a high proportion of global coral reef fisheries that are already fully or over-exploited (Newton et al., 2007). The impacts of direct harvesting on the condition of coral reef fisheries have been thoroughly considered (Jennings and Polunin, 1997; Dulvy et al., 2004a; Graham et al., 2005). However, less is known of the role of fish markets in driving resource use and ultimately reef conditions.

Reef fisheries have value in both direct consumption and market sale. Capacity of the fishermen to sell their catch is dependent on whether there is a market for the product and if so, whether it is logistically and economically viable to get the product to market for sale. Improvements in transportation technology and storage (Zann and Vuki, 2000; Kronen et al., 2006) and higher market value is placing increased pressure on coral reef fisheries. At a local scale, proximity to provincial markets has resulted in a reduced mean trophic level of fish catch, suggesting preferential sale of higher trophic level fish in domestic trade (Cinner and McClanahan, 2006). Markets may also influence how fisheries are governed, since weaker customary marine tenure regimes, which can exclude outside fishing pressure, have been positively associated with proximity to provincial markets (Cinner, 2005). Global market demand for specific marine species such as the live reef food fish trade or macro – invertebrates can have a profound influence on their rate of harvest (Sadovy et al., 2003; Berkes et al., 2006).

Local subsistence pressures, national urban markets, and international demand for certain species combine in ways that are not well understood. In order to properly manage coral reef ecosystem health, it is important to understand how factors operating at

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multiple spatial scales can influence the condition of reef resources (Caddy and Seijo, 2005). Independently, studies have shown that environmental, resource use, local markets, and global markets can influence the condition of reef resources. However, there are no studies that have simultaneously examined how these factors operate at multiple spatial scales to influence reef fishery condition. This is important in determining focused resource management to aid development, and in conservation planning through threat identification.

Here we assess the effect of environment, resource use and proximity of fish markets to fish stock on reef fishery biomass. Specifically, we ask "how is in situ reef fishery biomass related to aspects of environmental conditions, harvesting and market proximity?" To answer this question we examine whether in situ biomass of: (1) target fish species and (2) key fishery families is related to three environmental, four resource use and nine market proximity indicators across 51 sites in the Solomon Islands.

1.1. Study sites and local context

The Solomon Islands is a double chain archipelago of around 1000 islands and islets situated in the southwest Pacific between 5–12°S and 152–170°E, set on a NW–SE axis. The study sites span the majority of the double chain (Fig. 1), and are characterised by steep sloped fringing reef, or barrier reef topography with intermittent expansive lagoons (Green et al., 2006a). The national population of around 510,000 (Solomon Islands Government, 1999) consume an estimated 45.5 kg yr^{-1} of fish per capita (Crossland and Philipson, unpublished data), with 83% of households involved in fishing (Oreihaka, unpublished data). The annual national production from subsistence and artisanal fisheries is estimated to be 11,150 ton with a value of more than US$12.4 million (Kile, 2000). With relatively recent improvements of fishing equipment (Sabetian and Foale, 2006), refrigeration and increasing market access, reef resources have become depleted (Richards et al., 1994).

The nation comprises nine provinces, each with a capital (Fig. 1), through which the majority of domestic trade passes. Provincial sub-stations scattered throughout the provinces provide basic medical aid and schooling and often have associated subsistence markets. Coastal communities have small-scale artisanal fisheries, where fish are largely consumed or bartered. Community based customary marine tenure, whereby communities and clans have spatial and temporal rights to reef resources, predominates throughout the nation, providing some degree of local ownership (Aswani, 2002). Outside the national and provincial capitals there is minimal infrastructure and amenity (Solomon Islands Government, 1999). The primary means of passenger and goods transportation are inter-provincial shipping, privately owned fibreglass boats with outboard motors, and dugout canoes.

2. Methods

2.1. Sampling

2.1.1. Fishery condition

The ecological component of this research is derived from a Rapid Ecological Assessment (REA) (Green et al., 2006a), using Underwater Visual Census (UVC) (Green et al., 2006b). The objective of the survey was to determine the diversity and condition of coral reef ecosystems in the Solomon Islands over a large geographical area. Once a general area had been selected, specific requirements including continuous reef track and exposure were standardised. The REA was carried out over a period of 34 days, reducing seasonality as a confounding factor in reef or fish conditions. The Nature Conservancy biological assessment was performed prior to any intention of performing this study.

A list of target fishery species was compiled based on advice from the Solomon Islands Department of Fisheries and Marine Resources, local scientists, managers and fishermen (Green et al., 2006b). We pooled all target species prior to analysis. Key fishery families including Acanthuridae, Lethrinidae, Lutjanidae, Scaridae and Serranidae were also assessed. Selection of families was based on: (1) their importance for both income generation and food security in Solomon Islands and (2) adequacy of data to perform analyses. The chosen families also exhibit medium to low resilience to overfishing (Froese and Pauly, 2008; Cinner et al., 2006). The five fishery families comprised 53% of all target species. All fish count data were standardised to km^2 prior to analysis.

2.1.2. Environment

Environmental factors heavily influence fish abundance distribution (Bellwood and Hughes, 2001; Holbrook et al., 2002; Beger and Possingham, 2008; Munday et al., 2008). We quantified three environmental variables to determine the importance of physical attributes in explaining the biomass of target fishery species and families: (1) percent living hard coral cover, (2) spatial gradient, and (3) island area (Table 1). Hard coral cover was measured during the REA using line intercept techniques (Hughes, 2006). At se-

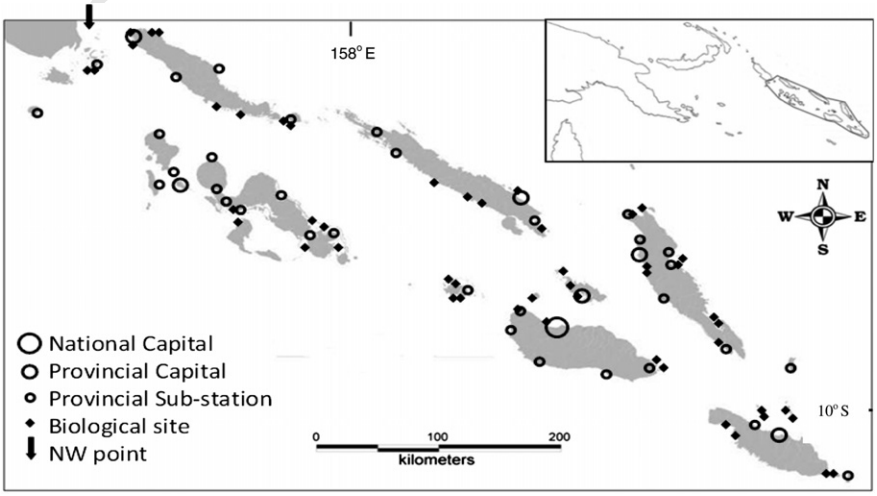

Fig. 1. Location map of the Solomon Islands with study sites, major population centres, and NW point identified. Grey polygon within inset is enlarged area.

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ven of the 51 sites hard coral cover was not measured. To correct for this we performed a multiple imputation using five iterations. Multiple imputation works by imputing each missing value with one or more possible values (Rubin, 1987). In this instance the data matrix used to determine missing values was comprised of all variables in Table 1. The mean of the five generated values for each of the seven datum points was used. Biomass variability has been shown to be influenced by large scale spatial gradients (Bellwood et al., 2005). To evaluate this effect, a position was marked (6°36′53″S, 156°3′16″E), which represents the northwest convergence point of the most northerly and westerly sites (Fig. 1). Direct distance from this northwest point to each of the sites was measured. We also measured island area (m^2), defined as the size of the most proximal landmass with visible vegetation across all 51 sites, as a potential proxy for catchment size. Both distance from NW point and island area were measured using GoogleEarthPro. Area of Kia, Choiseul, Fauro, Ngatokae, Guadalcanal, Makira, Malaita, and Savo islands were provided by the Solomon Islands Ministry of Lands, Housing and Survey.

2.1.3. Resource use

It has been previously shown that reef fishery biomass is impacted by direct human use (Jennings and Polunin, 1997; Dulvy et al., 2004a; Newton et al., 2007; Sandin et al., 2008; Williams et al., 2008). To determine how human population and fisheries related activity may impact reef fish biomass, we examined the following resource use indicators: (1) total human population, (2) population consuming fish, (3) population selling fish, and (4) population employed in fishing (Table 1). The first step in associating human population and resource was to approximate resource use boundaries for all sites. Where possible, boundaries were drawn on 1:150,000 digital maps by people with site specific expert opinion, defined as Solomon Island people with local knowledge of study sites. Interviews were conducted in Honiara, the national

Table 1
Fishery biomass, environment, resource use and market proximity indicators assessed. Acronyms: REA, Rapid Ecological Assessment; GEP, GoogleEarthPro; SIC, Solomon Islands 1999 national census; SIDLHS, Solomon Islands department of Lands, Housing and Survey; SA, Solomon Airlines; SIWD, Solomon Islands Works Department; SC, Shipping companies.

Indicator	Methodology	Included in final analysis?	Information source	References
Fishery condition				
All target species midpoint	Target species functional group site size spectra midpoint value	Yes	REA; Green et al. (2006b)	Dulvy et al. (2004a), Graham et al. (2005), and Jennings and Polunin (1997)
Key fishery family midpoint	Key fishery family site size spectra midpoint value	Yes	REA; Green et al. (2006b)	Dulvy et al. (2004a), Graham et al. (2005), and Jennings and Polunin (1997)
Environment				
Hard coral cover	Transect point sampled	Yes	Hughes (2006)	Arias-Gonzláez et al. (2006), Campbell and Pardede (2006), and Wilson et al. (2006)
Distance from NW point	Distance from the NW convergence point to biological site coordinates.	Yes	GEP; Green et al. (2006b)	Bellwood et al. (2005) and Clau et al. (2005)
Island area	Area (m^2) of the nearest Island to each biological site.	Yes	SIDLHS; GEP	Newton et al. (2007) and Pollnac (1998)
Resource use				
Total population	The sum of all individuals. Standardized to population/km^2 reef.	No	SIC	Dulvy et al. (2004a), Graham et al. (2005), Jennings and Polunin (1997), Newton et al. (2007), and Williams et al. (2008)
Population consuming fish	The sum of all individuals consuming fish. Standardized to population/km^2 reef.	No	SIC	Dulvy et al. (2004a), Jennings and Polunin (1997), and Kronen and Bender (2007)
Population selling fish	The sum of population selling fish. Standardized to population/km^2 reef.	Yes	SIC	Dulvy et al. (2004a) and Jennings and Polunin (1997)
Population employed in fishing	The sum of population employed in the fishing. Standardized to population/km^2 reef.	Yes	SIC	Pollnac (1998)
Market proximity				
Community	Distance from biological site to nearest community, irrespective population size.	Yes	SIDLHS	
Track	Distance from biological site to nearest walking track.	No	SIDLHS	
Provincial sub-station	Distance from biological site to nearest Provincial Sub – station.	Yes	SIDLHS	
Airstrip	Distance from biological site to nearest airstrip.	No	SIDLHS; SA	
Road	Distance from biological site to nearest road, sealed or otherwise.	No	SIDLHS	
Provincial capital	Distance from biological site to nearest Provincial Capital.	Yes	SIDLHS	Cinner and McClanahan (2006)
National capital				
	Distance from biological site to Honiara.	Yes	SIDLHS	Berkes et al. (2006) and Hodgson (1999)
Serviceable wharf	Distance from biological site to nearest serviceable wharf.	No	SIWD	
Shipping	The frequency of large domestic passenger and goods vessels passing biological sites.	No	SC	

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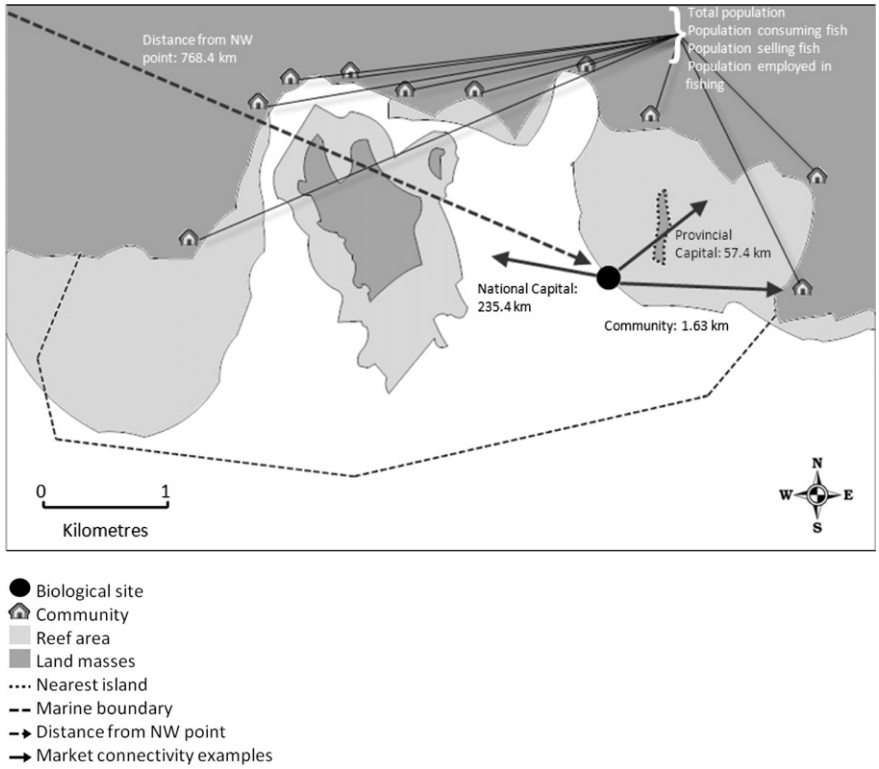

Fig. 2. Site example showing the compilation of the indicators that were assessed across all study sites. All indicators are built around association with the biological site, identified as the black disc.

capital, at the time of the study. This was then built upon and cross-checked through discussions with staff of TNC in Honiara. In all instances the resource users were identified as a single polygon at each site (Fig. 2). Boundary size varied greatly across sites. Generally, the further the biological site was situated from human habitation, the larger the resource use area. It was not feasible to obtain a higher resolution understanding of marine tenure for this study as has occurred elsewhere in Solomon Islands (Aswani, 2002). The terrestrial boundary was set to include all populations residing within 1 km of the adjacent coastline, consistent across all 51 sites.

We then extracted names and locations of all communities within the determined resource use boundaries from the Solomon Islands Ministry of Lands, Housing and Survey MapInfo database. Based on community name and location we then obtained data for all four resource use variables from the 1999 national census database, which provides the number of individuals involved in each resource use activity at the community level. Data from each community was then pooled to site. A total of 813 communities and 63,073 people (which equates to roughly 12% of the national population) were included in this study. Time lapse between the census date (1999) and biological survey date (2004) was rectified through population adjustments based on provincial population growth rates (Solomon Islands Government, 1999) to provide more realistic resource use estimates.

We measured reef area (km^2) by tracing polygons around all visible shallow water reefs within site boundaries using GoogleEarthPro. In isolated cases where excessive cloud cover or irradiance diminished accuracy, we overlaid reef enhanced 30 m resolution LANDSAT 7 images prior to measurement. To ensure that no significant difference in reef area existed between the two approaches, we compared the size of 10 clear reef images from both GoogleEarthPro and LANDSAT 7, with significant correlation between the means determined ($p \ll 0.001$; $r^2 = 0.99$) using a paired *t*-test. Total reef area across the 51 sites was 831 km^2. All resource use variables were then converted to individuals/km^2 reef area.

2.1.4. Market proximity

We assessed the spatial isolation of each biological survey site to ascertain whether market proximity and transportation regularity is associated with reef fish biomass. We based all measurements on the distance between latitude–longitude coordinates of the biological survey sites provided in Green et al. (2006a) and the nearest representative of each of the following landmarks: (1) community; (2) walking track; (3) provincial sub-station; (4) airstrip; (5) road; (6) provincial capital; (7) national capital; (8) serviceable wharf; and (9) regularity of shipping, as defined in Table 1. The locations of landmarks 1–7 were obtained from the Solomon Islands Ministry of Lands, Housing and Survey MapInfo database. Serviceable wharf locations were determined through the Solomon Islands Works Department records. Regularity of shipping was determined through discussion with provincial shipping companies based in the national capital, Honiara.

2.2. Data analysis

Both target fishery species and key fishery families were analysed using size spectra analysis. Size spectra has previously been applied to temperate (Jennings et al., 2001) and coral reef (Dulvy et al., 2004b) systems. Individual fish were placed into size classes based on total length (TL), estimated through UVC. The width of the size class used represented a compromise between measurement precision, sample size and the number of classes required to fit a suitable function (Shin et al., 2005). In this study 6 × 5 cm size classes were used, with fish TL ranging from 11–40 cm. Log_{10} (individuals/km^2) was applied to the six size classes, across target fishery species and key fishery families. Fish larger than 40 cm could not be used in the analysis due to insufficient abundance, despite being good indicators of fishing pressure (Green

et al., 2006a). Midpoint height was then derived as the sum of the logged size class values divided by the number of size classes (6) to provide a measure of biomass (Graham et al., 2005). Higher midpoint values represent higher fishery biomass.

To address multi-collinearity of indicators, we used variance inflation factor (VIF) analysis, which quantified the effect of across-variable correlation by inflating the standard error of the regression coefficient. Based on a conservative upper output value of 4 (Hair et al., 1998), population consuming fish was deemed to be highly multi-collinear (VIF = 16) across target fishery species and key fishery families, and was therefore omitted from further analysis. Once population consuming fish was removed, all other indicators had a VIF < 4. Collinearity was then addressed using Spearman's rank correlation coefficient analysis between all remaining pairs of indicator variables (Table 2). For this study we set variable inclusion between ρ (rho) = −0.5 and ρ (rho) = 0.5 due to clustering of multiple variables between ρ of ±0.5 and ±0.6.

Once the variable set was reduced we used regression tree analysis (Brieman et al., 1984) to examine how environmental, resource use, and market proximity indicators influenced the biomass of target fishery species and key fishery families. Regression tree analysis works on the process of binary recursive partitioning. This method allowed continuous variable response to be observed in a categorical, hierarchical manner, whereby variable thresholds were displayed at node points, with each node point representing a bivariate relationship between a single indicator variable and the response. The bifurcation point (threshold) for each bivariate correlation is defined as the point of maximum error reduction, with data homogeneity increasing with subsequent bifurcations (De'ath and Fabricius, 2000). One important advantage of using regression tree analysis was that it is non parametric, allowing non normality of input variables and model heteroscedasticity. The analysis also provided a strong visual display of high order interactions not revealed in standard regression. By nature, regression trees overfit data (Maindonald and Braun, 2007). This was addressed using 10-fold cross validation whereby the data matrix was split into 10 groups of equal size. A cross-validated regression tree was produced using only nine of the 10 groups, predicting biomass midpoint for the omitted 10th group. This process was repeated until all ten groups of biomass were predicted. The entire procedure was performed 50 times, with a unique set of ten groups each time. The modal tree with the smallest error was then produced.

In the context of this study, each tree represents the relationship between the respective fishery biomass midpoint and the ten retained indicator variables. The indicator variable with the strongest correlation with biomass midpoint across all study sites was in the first computation at the top of the tree. Study sites were then split into two groups, one with high biomass and one with low biomass, determined by maximum error reduction. The point at which the split occurs has been defined as the threshold. The group that moves to the left of the first split included the lower indicator variable values, and the group that moves to the right, the higher indicator variable values. The length of the vertical line represents the proportion of model deviance explained by the indicator variable above. The process is then repeated on each of the two 'branches' created. At each two-way computation the number of sites reduces as a consequence of splitting, until the point of minimal model deviance was achieved.

3. Results

3.1. Correlation analysis

Spearman rank correlation coefficients computed among all indicator variables allowed the retention of nine of the original

Table 2
Spearman rank correlation coefficient results table for environmental, resource use and market proximity indicators from Solomon Islands. Correlations of ρ (rho) > ±0.5 and subsequently omitted indicators are italicised.

	Hard coral cover	Distance from NW point	Island area	*Total population*	Population selling fish	Population employed in fishing	Community	*Track*	Sub-station	*Airstrip*	*Serviceable wharf*	*Road*	Provincial capital	National capital
Distance from NW point	−0.49***													
Island area	−0.13	0.03												
Total population	0.28*	−0.18	−0.01	*0.70***										
Population selling fish	−0.1	0.25	0.01	*0.30**	*0.40***									
Population employed in fishing	−0.04	−0.15	−0.23											
Community	−0.01	−0.31*	−0.02	−0.45***	−0.3*	−0.02								
Track	−3.00E-3	0.19	−0.02	−0.47***	−0.34*	−0.30*	0.30*							
Sub-station	0.15	0.21	0.16	−0.35*	−0.26	−0.44**	0.16	*0.58***						
Airstrip	0.04	0.28*	0.17	−4.00E-3	0.03	−0.25	−0.08	0.23	*0.52***					
Serviceable wharf	7.00E-3	0.11	0.13	−0.39**	−0.32*	−0.37**	0.38**	0.34*	*0.53***	*0.52***				
Road	0.25	−0.34	−0.1	−0.65***	−0.57***	−0.28*	0.25	0.35*	0.28*	−6.50E-3	0.24			
Provincial capital	0.11	−0.13	2.40E-3	*0.53***	−0.28*	−0.2	0.33*	0.34*	0.14	−0.097	0.23	0.31*		
National capital	0.22	−0.46	−0.03	−0.43**	−0.43**	−0.24	0.36**	0.18	0.12	−0.19	5.00E-5	*0.60***	0.14	*0.56***
Regularity of shipping	0.14	−9.80E-3	−0.08	−0.01	0.09	0.02	0.22	0.03	−0.03	0.05	0.17	−0.05	0.04	

* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

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16 variables, based on a threshold of $\rho = \pm 0.5$ (Table 2). We retained percent hard coral cover, distance from NW point and island area as environment indicators; population selling fish and population employed in fishing as resource use indicators; and community, provincial sub-station, provincial capital and national capital as market proximity indicators.

Table 3
Significant correlations for all target species and key fishery families and indicator variables, including the sequential pathway followed through the regression trees, to reach bivariate correlations between fishery and indicators.† Denotes each of the significant bivariate correlations between fishery and indicator variables. ‡ Denotes sequentially, the thresholds that sites pass through to reach significant bivariate correlations. For example, within all target species[a], where hard coral cover is >31.25%[b], provincial capital[c], best describes biomass across 46 sites[d], with $P^e = 0.016$, $R^{2f} = 0.12$ and a positive slope[g]. Q4

Fishery	†	‡	Indicator and threshold value	*n*	*P* value	R^2	Slope
All target species[a]	1	a	Hard coral cover	51	0.004	0.16	–
	2	a	Hard coral cover >31.25%[b]				
		b	Provincial capital[c]	46[d]	0.016[e]	0.12[f]	+[g]
Acanthuridae	1	a	Community	51	0.018	0.11	+
Scaridae	1	a	Provincial capital	51	0.006	0.13	+
	2	a	Provincial capital ⩽58.08 km				
		b	Distance from NW point ⩽517.4 km				
		c	National capital	15	0.018	0.36	+
Lethrinidae	1	a	Community	51	0.038	0.06	+
	2	a	Community ⩽3.65 km				
		b	Population employed in fishing	43	0.037	0.1	–
Lutjanidae	1	a	Provincial capital	51	0.004	0.16	+
	2	a	Provincial capital ⩽28.53 km				
		b	National capital	13	0.02	0.16	+
	3	a	Provincial capital ⩾28.53 km				
		b	Community	38	0.003	0.22	+
	4	a	Provincial capital ⩾28.53 km				
		b	Community ⩽3.39 km				
		c	Provincial sub-station	31	0.007	0.23	+
Serranidae	1	a	No significant correlation				

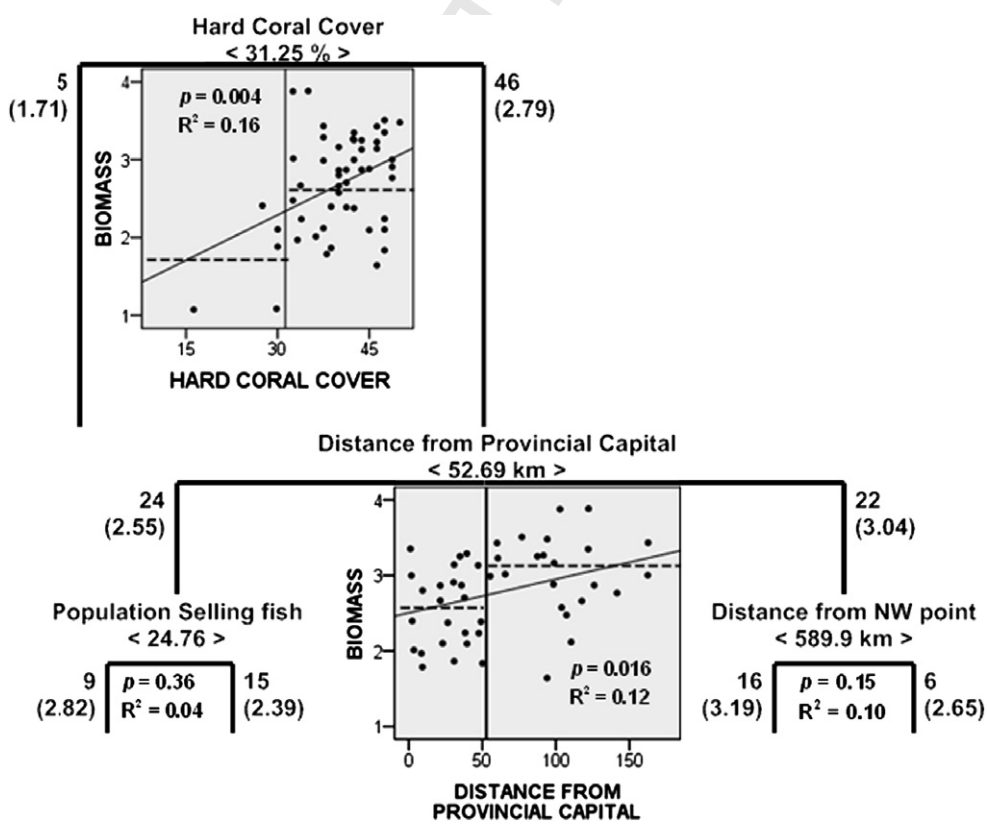

Fig. 3. Regression tree analysis of all target fishery species from Solomon Islands. Coral cover is the best indicator of all target species biomass, with a threshold of 31.25%. Above this threshold, distance from provincial capital explains biomass distribution with a threshold distance of 52.69 km. Each split (nonterminal node) is labelled with the variable and its value that determined the split. Left of nonterminal node is less than and right, greater than. Between each node point, adjacent to vertical lines are: (1) number of sites in model at that point and (2) biomass midpoint value at that point displayed in brackets. Length of vertical lines represents the proportion of model deviance explained by the variable above. Only significant ($p \leqslant 0.05$) bivariate relationships are represented as scatter plots. The vertical line through the plots indicates the threshold point and horizontal lines represent the mean biomass either side of the threshold.

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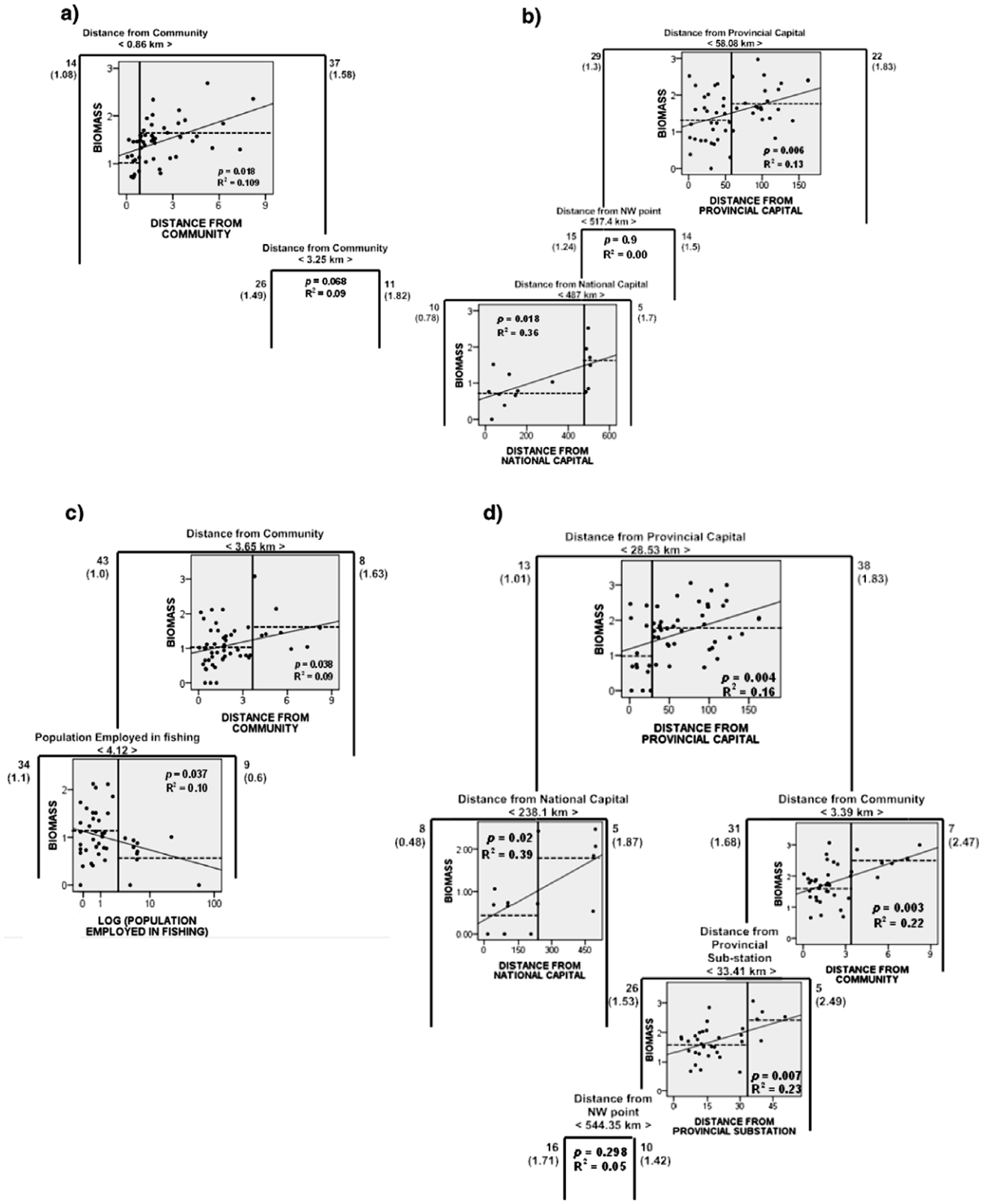

Fig. 4. Regression tree analyses of key fishery families from Solomon Islands. Acanthuridae biomass (a) is explained by distance to community. Scaridae biomass (b) is explained by distance from provincial capital across all sites, and then best explained by distance from national capital when within 58.08 km of provincial capital and 517.4 km of the NW point (Fig. 5). Lethrinidae biomass (c) is correlated most strongly with distance from community across all sites, and where in situ stock is within 3.65 km of the nearest community, population employed in fishing is best at explaining biomass distribution. Lutjanidae biomass (d) is explained by proximity to provincial capital, and proximity to national capital when within 28.53 km of provincial capitals. When further than 28.53 km from provincial capitals, proximity to community explains biomass distribution, and when within 3.39 km of communities, distance to provincial sub-stations explains the distribution.

3.2. Regression tree analyses

3.2.1. All target species

In the analysis of all target species, the biomass midpoints related significantly to aspects of environment and market proximity (Table 3). The complete model explained 37% of the deviance, inclusive of non-significant indicators (Fig. 3). Below a threshold of 31% hard coral cover mean midpoint was 1.71 compared to 2.79 above the 31% threshold. Where hard coral cover was greater than 31%, distance from provincial capital was significant in explaining biomass midpoint; with higher biomass further from provincial capitals. In summary, all target species biomass midpoints were highest where hard coral cover is >31%, and distance from provincial capitals was >52 km.

3.2.2. Key fishery families

The midpoint distribution for biomass in key fishery families was determined by resource use and market proximity indicators; specifically population employed in fishing, distance from community, provincial sub-station, provincial capital and national capital (Table 3). Surprisingly, none of the environmental indicators showed a significant correlation with fishery family biomass. For Acanthuridae, distance from community was the only indicator affecting biomass midpoint in the model (Fig. 4a), with 12% deviance explained. Where communities were within 0.86 km of the study site, Acanthuridae mean resource biomass midpoint was 1.08, compared to a midpoint of 1.58 when further than 0.86 km away.

The Lethrinidae model (Fig. 4c) explained 25% of the deviance. Biomass midpoint was 1.0 when the study site was within 3.7 km of the nearest community and 1.63 when at a greater distance. Within 3.7 km of communities, population employed in fishing was significantly correlated to biomass. Lutjanidae showed a complex series of market proximity indicator interaction (Fig. 4d), with the generated model explaining 51% of the deviance. Where the Lutjanidae resource was within 28 km from the nearest provincial capital, mean biomass midpoint is 1.01. For the 13 sites in close proximity to provincial capitals, distance from national capital was also significant, with lowest Lutjanidae biomass midpoint occurring close to provincial capitals and within 238 km of the national capital, irrespective of environment and human resource use indicators. Where sites were farther than 29 km from the closest provincial capital, Lutjanidae mean biomass midpoint was 1.83. In this case, distance from the community is significantly and positively correlated with biomass distribution. Lutjanidae biomass midpoint was significantly lower closer to provincial sub-stations where the resource was distal to provincial capitals and proximal to the nearest community. Serranidae showed no significant relationship with any indicator variables.

Scaridae biomass distribution was influenced significantly by market proximity, with the complete model explaining 32% deviance (Fig. 4b). Using Scaridae as an example, a conceptual management framework was produced, represented as threat levels to parrotfish across the Solomon Islands (Fig. 5). The threat levels we applied were derived directly from mean biomass midpoints, from 1 = low threat (high biomass) to 4 = high threat (low biomass). Sites beyond the 58 km provincial capital threshold exhibited the highest biomass (biomass = 1.83; threat = 1). Sites within 58 km of provincial capitals, within 517 km of the NW point, and at least 487 km from the national capital contained less biomass (biomass = 1.7; threat = 2). Sites within 58 km of provincial capitals, and further than 517 km of the NW point had further reduced biomass (biomass = 1.5; threat = 3). Sites within 58 km of provincial capitals, within 517 km of the NW point and within 487 km of the national capital had a dramatically lower biomass (biomass = 0.78; threat = 4).

4. Discussion

We used a multi-scale approach to determine how environmental, human resource use and market proximity indicators influence target fishery species and key fishery family biomass. Hard coral cover appears to be the best indicator of biomass midpoint for pooled target fishery species, but individual fish families are differentially affected by resource use and specific market forces. We have also established biomass thresholds, based on maximum error reduction between fishery biomass and indicator variable correlations (Table 3).

The effect of hard coral cover on pooled target fishery species suggests that reef fish biomass midpoints across the Solomon Islands are currently constrained by habitat. This is in keeping with previous studies performed elsewhere (Campbell and Pardede, 2006; Wilson et al., 2006), which found coral cover to be signifi-

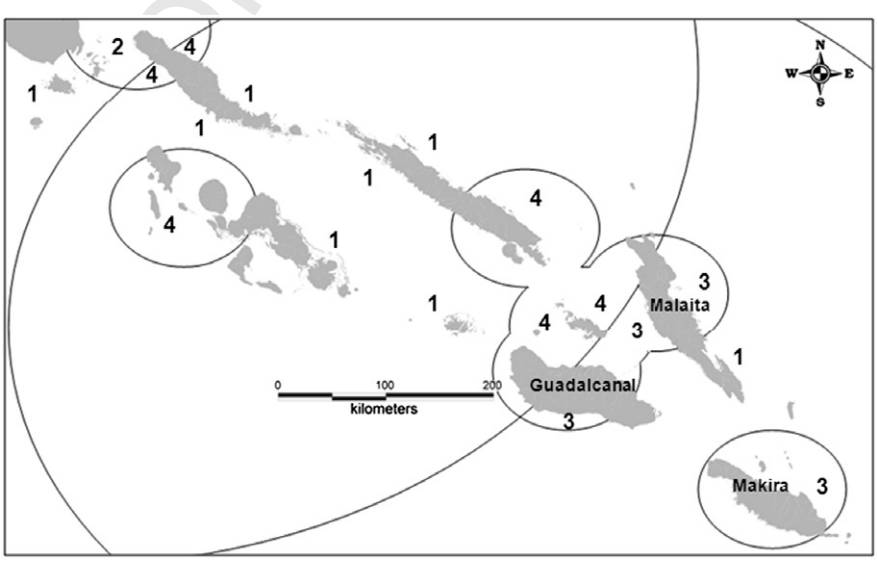

Fig. 5. Conceptual map for the Scaridae (snappers), showing scaled threat to biomass ranging from (1) low threat (highest biomass) to (4) high threat (lowest biomass) areas. The radius of each circle equates to the thresholds shown in Fig. 4b.

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cantly correlated with reef fish biomass. It is vital that coral cover and reef health be maintained in order to sustain a productive fishery which provides goods and services. However, the relative importance of coral cover in controlling fish abundance varies across species and functional groups (Wilson et al., in press).

Market proximity indicators operating at a range of scales were very effective at predicting key fishery family biomass midpoints in the Solomon Islands. Though not all possible biological indicators were assessed, the dominance of market proximity indicators suggests that for the fully exploited Solomon Islands fishery (Newton et al., 2007), key families are heavily influenced by market demand. Continued growth and establishment of new market centres in the Solomon Islands will likely result in a further decline in the biomass of fishery families.

Acanthuridae (surgeonfish) (Fig. 4a) and Lethrinidae (emperor fish) (Fig. 4c) biomass are determined primarily by distance from the nearest community, suggesting localised use with no significant transfer to larger market centres. However, the distance threshold of community effect on Lethrinidae is further than that for Acanthuridae. The difference between the two families could be explained by the resilience of surgeonfish to fishing pressure (Jennings and Polunin, 1996), and the catchability of emperor fish across multiple fishing techniques (Campbell and Pardede, 2006; McClanahan and Cinner, 2008), predominantly hook-and-line and netting in Solomon Islands.

Lutjanidae (snapper) midpoint distribution exhibits market interactions at multiple spatial scales (Fig. 4d). Snapper biomass was lowest in sites close to provincial capitals, and within 240 km of the national capital, suggesting transportation from provincial centres to the central market in Honiara. Where study sites are far from provincial capitals, distance from community explained the Lutjanidae biomass distribution, with lowest biomass found close to communities. Subsequently, where biomass is within 3.4 km of communities, proximity to provincial sub-stations negatively affects the distribution of biomass, suggesting transfer of biomass from communities to provincial sub-station markets.. Here, the negative effect of the provincial and national capital markets on biomass is greater than that of community and provincial sub-station. This is expected, given the size of the populations that depend on the fishery.

Serranidae (grouper and trout) are intermediate to long-lived fish and are vulnerable to fishing, even at low levels of fishing intensity (Jennings and Polunin, 1996; Froese and Pauly, 2008). Grouper and trout had the overall lowest levels of biomass across all sites (Table 3). One explanation for the absence of indicator effects on grouper and trout biomass is that all stocks may be overexploited whereby fish populations are so low that they no longer vary in response to environment, resource use and market proximity.

Scaridae (parrotfish) biomass was lowest at sites within 60 km of provincial capitals (Fig. 4b). To the northwest of the national capital, where sites were close to provincial capitals, national capital proximity negatively affects parrotfish biomass. Thus, parrotfish are likely transported to the national capital market from the northwest (Fig. 5). The reason for fish not supplying the capital city market from the southeast is likely attributed to an adequate market to absorb the supply in closer proximity (Solomon Islands Government, 1999). Parrotfish have variable resilience to overfishing (i.e. certain species are resilient while others are not) (Froese and Pauly, 2008). However, parrotfish are highly susceptible to night spearfishing which is common in the Solomon Islands, providing large catches for little effort (Sabetian, 2002; Aswani and Hamilton, 2004). Exposure to night spear fishing may explain the effects of the proximity of provincial and national capitals to parrotfish biomass. In parts of the Solomon Islands, scientific understanding about the ecological role of parrotfish has been combined with local knowledge to promote their conservation in a culturally appropriate manner (Aswani and Hamilton, 2004). While localised understanding and management of coral reef fisheries is vital, our results indicate that forces operating at larger scales have the potential to thwart local management efforts.

Determining thresholds provides insight into the capacity of a reef fishery to withstand a stressor and helps to quantify the point at which the stressor is likely to cause a change in fishery biomass. The inference from the moderately exploited Solomon Islands reef fishery is that around 30% coral cover is a threshold point, below which there is less target fishery biomass. Only 9% of sites in this study have a hard coral cover of <31%, suggesting that there is potential for continued sustainable fishery harvesting if coral cover remains at current levels. This is not the case for the Indo-Pacific in general, with a mean coral cover estimated at 22.1% in 2003 (Bruno and Selig, 2007).

Thresholds determined for fisheries families are spatial, relating to distance from markets at different scales. Our results show that larger markets draw fishery resource from a larger area than small markets, and that fishery families express different spatial thresholds to markets. While there are no previous studies that have determined this relationship at a community, provincial or national scale, Sadovy et al. (2003) demonstrated the regional scale fishing effect of large market demand for the live reef fish trade for consumption in southeast Asia. The price of reef fish at the national capital market in the Solomon Islands does not vary in relation to species or family. It is determined by how fresh the fish is at the time of sale. Reef fish that are presented at the national capital market within a day of capture obtain a price of around US$3.10–$3.70/kg, while fish that are no longer fresh are worth around US$2.20/kg (Tango, H. pers. com). On Wednesdays, fresh fish sells for a lower price due to supply influx shipped from Western Province. The highest price for reef fish is obtained at the national capital market, followed by provincial capital markets. In the smaller provincial sub-station and community markets barter predominates. The primary means of keeping fish fresh during transportation to markets is in large insulated boxes filled with ice. Ice is obtained in the national and some provincial capitals. Therefore we propose that distance thresholds of markets on fishery biomass is not determined by differences in species or families market value, but rather: (1) the susceptibility of particular fishery families' to overfishing (Jennings and Polunin, 1996; Froese and Pauly, 2008), (2) remuneration type (barter or monetary) received at different market scales, (3) the distance travelled and cost to supply the market, and (4) market size. It would be expected that the distance thresholds identified in this study may change over time due to improved technologies and human population growth.

By spatially dividing the landscape into discrete zones, our study reveals diminishing biomass to be associated with: (1) increasing threat complexity and (2) increasing spatial scale of threats (Fig. 5). Coastal populations within threat zone 1 are typified by small communities with high dependence on, and customary ownership of marine resources. Within zone 2, coastal communities are more prolific and are within travelling distance to respective provincial capitals. Sites within zone 3 represent higher population densities (Solomon Islands Government, 1999), and more complex economic systems, especially on Malaita and Guadalcanal. The threat level of 3 for Makira could potentially be an artefact of distance from NW point. Based on our findings, zone 4 represents a priority area for parrotfish management. However fishery families are affected differently by market proximity threats, which should be considered when setting management priorities. If multiple families or a single family crucial to ecological resilience are highly threatened in a given zone, it may be appropriate for managers to invest additional resources to ensuring continued ecosystem function. The scales of threats we identify may

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also have implications for the scale of governance interventions required to help manage reef fisheries. Where there are multiple, larger scale threats facing a fishery, and customary marine tenure is diminished as was found in Papua New Guinea (Cinner, 2005), there is greater opportunity for provincial and national governance systems with greater resources to lead management efforts. Conversely, in low threat areas, where the resource is in relatively good condition, and regulation is strong, community based management might be adequate (Aswani et al., 2007). Between these extremes, a sliding scale of co-management initiatives may be more appropriate.

The key fishery family results show subtle effects of fishing down the food web, whereby piscivore biomass is first to decline, followed by subsequent trophic levels (Pauly et al., 1998). This phenomenon has been identified for reef fisheries in relation to provincial market proximity (Cinner and McClanahan, 2006). In this study, the highest trophic level fish (Serranidae) show the lowest overall biomass and no correlation to the indicators used, suggesting this family is overfished throughout the Solomon Islands. Snapper species (Lutjanidae) are largely piscivores, planktivores or feed on benthic invertebrates (Froese and Pauly, 2008). Proximity to community, provincial sub-station, provincial capital and national capital negatively affects their biomass, suggesting high demand and vulnerability. Susceptibility of higher trophic level fish to hook-and-line fishing (Cinner and McClanahan, 2006) is also likely to be a contributing factor. Parrotfish, which are algal grazers, are influenced by both national and provincial market proximity. Surgeonfish, which are largely herbivorous, and emperors which feed largely on benthic invertebrates (Froese and Pauly, 2008) are affected by distance from community. While the relationship between scales of market pressure and trophic levels identified here are not completely linear, some inference can be made. Based on previous findings, and the evidence in this study, we propose that, as higher trophic level fisheries become depleted at all market scales, the biomass of subsequent trophic levels is driven down by transfer of fishing effort and demand of larger markets, eventually being exploited at all market scales.

In summary, hard coral cover is the best of the tested indicators in determining pooled target fishery species biomass in the Solomon Islands. However, when we increase the resolution to family level, proximity of resource to users is the driving force of fishery condition at multiple spatial scales. The dominance of market proximity in explaining family-level reef fishery biomass suggests that significant consideration be given to the multi-scale spatial arrangement of both resources and their beneficiaries. Moreover, management of resources must vary in accordance with spatial and taxonomic scales of reef fishes and the threats that constrain their biomass.

5. Uncited references

Q2 Carpenter and Allen (1989), Cinner and Pollnac (2004), Friedlander and Parish (1998), and Pandolfi et al. (2005).

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