FISH and FISHERIES

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Assessing and managing data-limited ornamental fisheries in coral reefs

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Abstract

Coral reefs support numerous ornamental fisheries, but there are concerns about stock sustainability due to the volume of animals caught. Such impacts are difficult to quantify and manage because fishery data are often lacking. Here, we suggest a framework that integrates several data-poor assessment and management methods in order to provide management guidance for fisheries that differ widely in the kinds and amounts of data available. First, a resource manager could assess the status of the ecosystem (using quantitative metrics where data are available and semi-quantitative risk assessment where they are not) and determine whether overall fishing mortality should be reduced. Next, productivity susceptibility analysis can be used to estimate vulnerability to fishing using basic information on life history and the nature of the fishery. Information on the relative degree of exploitation (e.g. export data or ratios of fish density inside and outside no-take marine reserves) is then combined with the vulnerability ranks to prioritize species for precautionary management and further analysis. For example, species that are both highly exploited and vulnerable are good candidates for precautionary reductions in allowable capture. Species that appear to be less vulnerable could be managed on a stock-specific basis to prevent over-exploitation of some species resulting from the use of aggregate catch limits. The framework could be applied to coral reef ornamental fisheries which typically lack landings, catch-per-unit-effort and age-size data to generate management guidance to reduce overfishing risk. We illustrate the application of this framework to an ornamental fishery in Indonesia.

Keywords Aquarium trade, curio trade, data-poor fisheries, ornamental fisheries, productivity susceptibility analysis, sustainable fisheries management

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Introduction

Global trade in coral reef species that are displayed in aquaria and used as curio and jewellry is large and expanding. Trade in coral reef species for ornamental purposes originates from at least 45 countries and removes an estimated 20–24 million fish, many millions of corals and shells, and 9–10 million additional invertebrates per year from coral reefs (Wabnitz *et al.* 2003; Tissot *et al.* 2010).

The impacts of the ornamental trade on individual stocks and coral reefs are difficult to quantify and manage due to limitations of conventional approaches to fisheries stock assessment when few data are available. Furthermore, the majority of fish caught for the ornamental trade originate from developing countries with low institutional and management capacity. Removals on this scale in the absence of assessments and effective management measures pose risks to the sustainability of target stocks, the sustainability of stocks that are incidentally captured or killed in pursuit of target species, and to the productivity and biodiversity of the ecosystems that support the trade as well as myriad other ecosystem services (reviewed in Thornhill 2012).

In this paper, we discuss the limitations of conventional stock assessment methods, describe alternative methods for estimating the status of ornamental fisheries and the coral reefs that support them and propose a framework for assessing and managing coral reef ornamental fisheries based on estimated vulnerability, stock status and ecosystem state.

Assessments of stock status and ecological impact are important for the management of any fishery. Certain attributes of coral reefs and the species targeted for the ornamental trade may render them especially vulnerable to over-exploitation, increasing the need for assessment and management. For example, species caught for display in aquaria are often quite perishable and can suffer high mortality rates during capture and in transit (Sadovy and Vincent 2002; Gonzales and Savaris 2005; Schmidt and Kunzmann 2005). Moreover, coral reefs often have lower rates of net productivity and biomass levels compared to other marine ecosystems such as temperate reefs in upwelling systems (Valiela 1995) – suggesting that removals of large amounts of fish could have relatively large impacts on low productivity coral reefs (Bellwood *et al.* 2004). Instances of over-exploitation have been documented in the literature (reviewed in Thornhill 2012). One such case is anemonefish (Pomacentridae *Amphiprion* spp.), which declined by over 80% as a result of collection in the Cebu region of Philippines (Shuman *et al.* 2005). Recent research suggests that over-exploitation of fish stocks affects not only individual stocks, but can result in the ecological transformation of coral reefs (Hughes *et al.* 2007; McClanahan *et al.* 2011).

In commercial capture fisheries, the convention is to assess the status of individual stocks that experience fishing mortality using complex models to synthesize catch data, information on the age-structure of the catch, independent surveys of fish abundance and other information. These data are then used to generate estimates of biomass levels relative to unfished stocks (historical levels), productivity of the stock and fishing mortality that would be expected to produce maximum sustainable yield (Hilborn and Walters 1992; National Research Council 1998).

Ornamental fisheries in coral reefs present special difficulties for this conventional approach to assessment and management. Many of these challenges are described in a 2003 review of the proposed Marine Aquarium Trade Coral Reef Monitoring Protocol (Donaldson 2003). Conventional survey methods – such as long-term catch accounting and fishery-independent surveys – are very difficult to implement in many coral reefs due to lack of funding, limited institutional capacity of local agencies to conduct assessments, and the inadequacy of conventional fishery survey methods for monitoring multispecies ornamental fisheries. Hence, data that can be used to assess the status of ornamental stocks are often scarce. Moreover, coral reefs host highly diverse assemblages of species, some of which are exploited by the ornamental fishery as well as by other fisheries (e.g.

Hodgson and Liebeler 2002; Wabnitz *et al.* 2003; Gomez and Mingoa-Licuanan 2006; Vincent *et al.* 2011). Coral reefs, like most marine ecosystems, are impacted by a variety of factors in addition to fishing, including climate change, ocean acidification and nutrient pollution (Hoegh-Guldberg 1999; Gardner *et al.* 2003; Lesser 2004). These confounding variables make isolating the impacts of ornamental fisheries difficult, in part due to lack of historical data and lack of unfished reserves as reference areas (Donaldson 2003). Lack of historical data and marine reserves also limits the amount of information available for establishing baseline conditions and biological reference points that are essential for assessing stock status and informing management (i.e. to determine whether current biomass and fishing mortality rates are above or below sustainable levels). Furthermore, conventional stock assessments often rely on measured relationships between fish size and age so that size data (relatively easy to collect) can serve as a proxy for age (relatively difficult to collect). In many ornamental fisheries, neither size nor age data are collected. Even when available, size data may be a poor proxy for age for certain coral reef species – for instance some surgeonfish (Acanthuridae) – due to asymptotic age-growth curves (i.e. cessation of growth after a certain age; Choat and Robertson 2002; Donaldson 2003). Finally, juvenile fish are sometimes preferentially targeted, skewing size and age distributions (reviewed in Thornhill 2012).

Since Donaldson's (2003) review, additional methods have been developed for assessing and managing data-poor fisheries (Honey *et al.* 2010). Unfortunately, few of these methods appear to be suitable for coral reef ornamental fisheries. Several depend on the availability of over 10 years of catch records (Honey *et al.* 2010), which may be rare for ornamental fisheries. Other approaches are likewise limited in the case of ornamental fisheries by the lack of catch-per-unit-effort (CPUE) trend data and lack of historical catch and effort data. For instance, the MPA-based decision tree method (Wilson *et al.* 2010) can generate a total allowable catch (TAC) expected to result in sustainable yield, but requires CPUE trend data and size-structure information inside and outside well-enforced marine reserves, which serve as proxies for unfished conditions in order to provide a relative measure of stock status at local scales. Length-based methods that allow managers to infer stock status from the proportions of different life stages (e.g. juveniles, spawning adults and megaspawners) in the catch (e.g. Cope and Punt 2009) are also difficult to apply to ornamental fisheries due to the lack of size frequency data (distribution of fish sizes in the catch) and of demographic data necessary to correlate fish size with age. Length-based methods are also compromised by asymmetric age–size relationships in some coral reef species (Choat and Robertson 2002), as well as by targeting of juvenile fishes. Virtual population analyses (Mohn and Cook 1993; Lassen and Medley 2001) that simulate the population in order to project population trends may be possible in cases where data on stock growth and removal rates are available; however, these cases are likely rare among coral reef ornamental fisheries.

Alternative approaches

The paucity of data available for assessing coral reef ornamental fisheries demands enhanced monitoring and research programs to produce better data in the future. However, new approaches to estimate stock status are needed now, so that the risk of unanticipated depletions and ecosystem impacts resulting from excessive fishing can be reduced.

One starting point for assessment and management is to focus on ecosystem status in relation to the ornamental fishery as a whole, rather than on individual stock status. Coral reefs can exist in different states characterized by their fish diversity, coral diversity, extent of coral cover, extent of macroalgal cover and other variables (Bellwood *et al.* 2004; Hughes *et al.* 2007). Some attributes appear to contribute to the resistance of marine ecosystems to disturbances or their ability to persist in a particular state and recover from both natural and anthropogenic perturbations. These include ecological redundancy, species complementarity, genetic variation within species, relatively high productivity and recruitment rates (Palumbi *et al.* 2008) and fish abundance (McClanahan *et al.* 2011).

In coral reefs, changes from 'healthy' or coral-dominated states that produce multiple ecosystem services, such as fisheries and tourism value, to 'unhealthy' or macroalgal-dominated states that produce fewer ecosystem services are often correlated with, and in some cases mediated by, changes in the diversity and abundance of herbivorous fish, urchins and other grazing organisms (Bellwood *et al.* 2004; Hughes *et al.* 2007; Mumby *et al.* 2007). Conceptually, changes in fish diversity and abundance should be related to changes in metrics describing reef state, such as macroalgal cover, grazing intensity and coral cover (McClanahan *et al.* 2002; Graham *et al.* 2003; Bellwood *et al.* 2004). Moreover, some of these relationships between metrics and reef state could be non-linear; for example, when ecological redundancy of grazers is exhausted by overfishing, the removal of the last remaining grazing species results in a sudden reduction in grazing intensity (reviewed in Bellwood *et al.* 2004). Variability in metrics may also be expected to change close to such non-linear thresholds, as the system becomes less regulated (Scheffer *et al.* 2001).

Because fishing is only one of a number of factors that affect coral reefs, the importance of fishing as a risk factor should be assessed prior to designing management interventions. Generally, risk assessment methods such as the Ecological Risk Assessment for the Effects of Fisheries (ERAEF) can be used to assess the role of fisheries in determining the status and potential trajectory of marine ecosystems (Hobday *et al.* 2007). Specifically, this framework defines risk as the probability that particular (fisheries) management objectives are not met and assesses risk using a hierarchical set of methods that range from qualitative (e.g. surveys of expert and local knowledge), to semi-quantitative (e.g. productivity–susceptibility analysis) and fully quantitative (e.g. dynamic models). At the first stage, ERAEF qualitatively identifies potential impacts and higher risk activities (e.g. fishing practices) for a semi-quantitative or quantitative (model-based) assessment. After stage one and stage two (semi-quantitative assessment), only a small subset of higher risk activities should be left for more quantitative analyses when data and improved understanding of ecosystem dynamics are available or required based on the results from stages one and two. Comparisons of fished sites to well-enforced marine reserves can also be used to assess the impact of fishing relative to other factors. High densities of exploited species in marine reserves relative to levels on fishing grounds with similar habitat quality would suggest that fishing contributes importantly to fish stock depletion.

While coral reef fisheries tend to be data poor, rich data sets exist on other aspects of coral reef structure and function and can be used to drive a semi-quantitative assessment of the risks to coral reefs posed by ornamental fisheries. Coral reef researchers have been collecting time series data over many years on several coral reef ecosystem-status metrics, including coral cover, macroalgal cover, fish species richness and total fish biomass on a large number of reefs with various levels of protection from fishing and showing a wide range of states, from ‘healthy’ (i.e. high levels of live coral cover, low macroalgal cover, high fish diversity) to ‘unhealthy’ (i.e. low levels of coral cover, high levels of macroalgal cover, low fish diversity) (Marks 2007; Sweatman *et al.* 2008; Wilkinson 2008). A recent analysis of these metrics in the Indian Ocean indicates that thresholds may exist in relation to total fish biomass (McClanahan *et al.* 2011), summarized in Table 1.

Commonly used indicators of coral reef status, such as species richness and coral cover, appear to be late indicators – manifesting only after coral reefs have changed significantly (reviewed in Hughes *et al.* 2010). Fish density is a relatively easy-to-measure metric that can be used to indicate the status of the reef and the ‘health’ of the reef system (including the fisheries it supports) before the ecosystem transitions to undesirable states that are difficult to recover from (McClanahan *et al.* 2011). The management goal in this framework is to maintain the coral reef system in a desirable state (i.e. low macroalgal cover, high coral cover and high fish diversity) by limiting total fishing mortality from all coral reef fisheries to levels that maintain fish density above 640–850 kg ha^{-1} in the case of Indian Ocean reefs, for which these thresholds were developed (McClanahan *et al.* 2011). The fact that these levels correspond roughly to typical levels associated with sustainable yield (0.5 of unfished biomass, using the highest observed level of fish density in the Indian Ocean dataset as a proxy for unfished biomass – McClanahan *et al.* 2011; and using fish density as a proxy for biomass) suggests that maintaining fish in this range may maintain coral reefs in relatively desirable states and also result in sustainable fishery yields; however, whether these yields will be at maximum sustainable yield is uncertain. The observation that fish density levels below 300 kg ha^{-1} in Indian Ocean reefs corresponded to typical levels associated with overfished stocks (0.25 of unfished biomass; McClanahan *et al.* 2011) suggests that reductions in fish density or biomass below this level could result in dramatic

Table 1 Summary of thresholds in Indian Ocean coral reef state metrics in relation to fish density (from McClanahan *et al.* 2011).

Fish density (kg ha^{-1})	Threshold
1130	Change in variance of macroalgal cover
850	Change in variance of macroalgae/ coral cover ratio
640[1]	Change in predation rates on urchins
500	Macroalgal dominance
300[2]	Changes in species richness, fish community structure, urchin biomass, calcifying algae cover and live coral cover

[1]Corresponds to 0.5 unfished biomass, associated with sustainable yield in many fisheries, using density as a proxy for biomass.
[2]Corresponds to 0.25 unfished biomass, associated with overfished levels in many fisheries, using density as a proxy for biomass.

reductions in species richness, fish community structure and coral cover as well as in large reductions in yield as a result of overfishing. Use of fish density ratios as reference points rather than the biomass ratios more commonly used in fisheries management (e.g. B/Bmsy) can be confounded at large spatial scales due to patchiness in fish distribution (i.e. higher patchiness would result in less correspondence between fish density and biomass, which is usually estimated as density x area) but may be applicable at relatively small spatial scales at which distribution is more homogeneous.

Because these thresholds have only been determined for Indian Ocean coral reefs, care should be taken before using them for managing fisheries in other areas. Coral reefs vary significantly between regions and oceanographic provinces; hence, each coral reef region and fish at different trophic levels should be analysed to determine whether thresholds related to fish density or biomass exist, if so what they are, and whether this methodology is directly applicable to fish targeted by the aquarium trade.

Some ornamental fish species or demographic categories within a species (e.g. juveniles or males) are more highly desired and targeted than others (Sadovy *et al.* 2001; Stevenson *et al.* 2011; Rhyne *et al.* 2012). Maintaining total fish biomass on a reef above threshold levels, or indeed any aggregate catch or effort limit that applies to all species, will not necessarily protect fish from over-exploitation, either in terms of stock collapse or in terms of the loss of their ecological function. Therefore, additional methods are needed to assess the vulnerability of individual stocks. Productivity susceptibility analysis (PSA) is a potentially suitable method to address this need in ornamental fisheries.

Productivity susceptibility analysis can be used to estimate the productivity of a stock (and capacity to recover from fishing pressure), as well as its susceptibility to a fishery; information on productivity and susceptibility is then combined to estimate overall vulnerability to fishing (Stobutzki *et al.* 2001; Patrick *et al.* 2009). Stock productivity is quantified for a PSA using life-history and population growth data, including population growth rate (r), maximum age, maximum size, von Bertalanffy growth coefficient (k), estimated natural mortality, measured fecundity, breeding strategy, recruitment pattern, age at maturity and mean trophic level (Patrick *et al.* 2009; Table S1). Susceptibility in PSA parameterizes the likelihood of overfishing according to ease of capture and management of the stock (Patrick *et al.* 2009, Table S1).

Life-history traits are scored in a PSA, as are characteristics of the fishery that affect the susceptibility of each species to capture. While the use of life-history data that have been verified in the field is ideal, the information needed for a provisional PSA is often available from the primary and gray literature, FishBase (Froese and Pauly 2012) and local fishers. Data on catch, effort, age or size are not required for PSA. This makes PSA applicable to ornamental fisheries where information is often lacking, but some type of management guidance is needed. The PSA approach does have limitations; management guidance is restricted to an assessment of the vulnerability of the stock to fishing pressure. However, the vulnerability score can be used to prioritize or trigger management action. PSA does not result in standard fishery management reference points such as sustainable-yield estimates (i.e. catch levels that would be expected to result in relatively large yields over many years) or biomass thresholds for over-exploitation (i.e. biomass levels below which the population is unable to sustain yield).

Productivity (p) and susceptibility (s) are individually ranked in the PSA from low-to-high on a scale of 1.0–3.0 (Patrick *et al.* 2009; Table S1). Low productivity/high susceptibility scores indicate relatively high vulnerability to fishing, whereas comparatively high productivity/low susceptibility scores indicate more robust stocks. When productivity and susceptibility are graphically represented on an x-y scatter plot, the stock's vulnerability (v) can be quantified as the Euclidean distance from the plot's origin to the p vs. s point on the graph (Patrick *et al.* 2009; note that p is plotted from high–to-low whereas s is plotted from low-to-high when making this determination).

The PSA approach for integrating data of varying quality is flexible and also enables the use of knowledge from diverse sources, including local fishers. The PSA includes five data-quality levels, ranging from no data to a full stock assessment, to expand the range of usable sources of information. More reliable, robust data are given a score of one, whereas complete absence of data is given a score of five. The data-quality index incorporates uncertainty into the analysis. For example, without weighting data with respect to quality, data-poor stocks might receive inflated vulnerability scores due to lack of information; the data-quality parameter thus controls for inflated scores resulting from limited data. Because some parameters may be more or less valuable for estimating productivity and susceptibility of a specific stock, higher weights can be applied to attributes that are more important for that stock (Hobday *et al.* 2007, 2011).

Following the evaluation of individual stock vulnerability, it is important to estimate the degree to which stocks are depleted and/or exploited, so that management priorities can be set. If well-enforced marine reserves or lightly fished areas with comparable habitat to fishing grounds are present, fish densities (kg ha^{-1}) obtained using a fishing survey in such areas can be compared with fish densities on the fishing grounds to estimate the level of stock depletion (Babcock and MacCall 2011). Export data or local knowledge may also provide insight into relative exploitation levels.

Each of these methods – coral reef threshold identification, PSA and depletion/exploitation status determination – generates a different kind of management guidance. We propose a 5-step framework for integrating them in order to provide management guidance for coral reef ornamental fisheries with different kinds and amounts of data availability:

1. Assess ecosystem risk of fishing using quantitative ecosystem thresholds or ERAEF.
2. Assess vulnerability to fishing using PSA.
3. Estimate relative levels of depletion and/or exploitation using density ratios or other export information.
4. Prioritize precautionary management by identifying stocks that are highly exploited/depleted and vulnerable to fishing (candidates for reduced fishing pressure) and stocks that are lightly fished/not depleted and resilient (candidates for increased fishing pressure).
5. Prioritize for further assessment and management based on vulnerability, exploitation status and economic importance.

Below, we illustrate how the tools we have described can be integrated using this framework to develop management guidance for an ornamental fishery in Indonesia.

Practical application

Assessing ecosystem risk of fishing

To assess the risk posed by ornamental fisheries to Indonesian coral reef ecosystems, we evaluated the relationship between fish density and several indicators of ecosystem health (i.e. coral cover, macroalgae cover, macroalgae:coral cover and fish species richness). The data used in our analysis were generated by fishery-independent surveys of 217 coral reefs in five regions of the greater Indonesian basin (details in Table S2). Sites without observations across all the necessary variables were removed from the sample, resulting in a total of 42 coral reef locations that were included in the analysis. For these data, a non-parametric statistical method for assessing non-linear relationships (Andersen *et al.* 2009) was used to evaluate thresholds in the ecosystem health variables with respect to fish density with no *a priori* assumptions about the distribution of the data. The data were normalized, allowing comparisons of indicators of ecosystem health across coral reefs in Indonesia, and normality assumptions were tested using a Shapiro–Wilk test (Shapiro and Wilk 1965). The 'R software' package 'changepoint' (Killick and Eckley 2011; R Development Core Team 2012) was used to identify the point at which the slopes of plots of ecosystem health indicators vs. total fish biomass change most rapidly (Supporting Information). These changes in slope identify thresholds for changes in ecosystem state.

The results of this analysis provide a preliminary estimate of average unfished density in Indonesian marine reserves (1100 ± 193 kg ha^{-1}; $n = 30$) and suggests that several ecological thresholds may exist at different levels of fish density. Variance in macroalgal cover increases at fish density levels <807 kg ha^{-1}. The ratio of macroalgae to living hard coral cover increased at fish density levels below 491 kg ha^{-1}, which is approximately 0.5 of the unfished density (Table 2). Thresholds for three additional metrics occurred at fish densities below 300 kg ha^{-1} (*c.* 0.25 of the unfished density), including fish species richness, the proportion of herbivorous fish and live coral cover (Table 2). Data for grazing invertebrates (i.e. urchins) were limited; consequently, we were unable to assess the significance of urchin presence on ecosystem processes in Indonesia. Invertebrate grazing is likely to be important on Indonesia reefs, as it generally appears to be important in coral reef system dynamics (i.e. Bellwood *et al.* 2004 and references within). Based on these results, changes in macroalgal cover and the ratio of macroalgal to live coral – along with the fish densities (807 kg ha^{-1} and 491 kg ha^{-1}, respectively) and the density ratios relative to marine reserve density (0.73 and 0.5, respectively) associated with these changes – are potentially early indicators of fishing affecting ecosystem processes.

From these findings, we can estimate a density-based range for sustainable yield as ≈0.25–0.50 unfished density (300 ± 48 to 550 ± 95 kg ha^{-1}), based on an analysis of previously assessed stocks suggesting that 80% of maximum sustainable yield can be obtained by maintaining stocks within this range; this analysis also suggests that the range is insensitive to life-history characteristics with the exception of the degree to which reproduction and recruitment changes with stock depletion (Hilborn 2010). Fish densities below 300 kg ha^{-1} (~0.25 of the unfished density) are associated with changes in several important metrics, suggesting that this is an important threshold for coral reef ecosystem state and also for maintaining sustainable yields. Fish densities from specific fisheries in Indonesia can be compared to these thresholds and used as the basis for coarse management (e.g. increasing or decreasing total fishing effort). Use of nearby well-enforced marine reserves to generate local estimates of unfished biomass may improve the effectiveness of this method, by correcting for variation among coral reefs within the region.

Table 2 Fish density thresholds as calculated for Indonesian coral reefs.

Fish density (kg ha^{-1})	Threshold
807	Change in variance of macroalgal cover
491[1]	Change in variance of macroalgae/ coral cover ratio
<300[2]	Changes in species richness, proportion of herbivorous fish and live coral cover

[1]Corresponds to 0.5 unfished biomass, associated with sustainable yield in many fisheries, using density as a proxy.
[2]Corresponds to 0.25 unfished biomass, associated with overfished levels in many fisheries, using density as a proxy.

Assessing vulnerability to fishing

Following the establishment of aggregate (e.g. multispecies) fish density thresholds for maintaining Indonesian coral reefs and sustainable yields, the next step in our proposed framework is to identify species that are particularly vulnerable to overcollection using PSA (Fig. 1). For this, we gathered life-history and fishery attribute information for coral reef fishes that are caught on Indonesian reefs for the ornamental reef fish trade from the available literature (e.g. Wood 2001; Reksodihardjo-Lilley and Lilley 2007; Rhyne *et al.* 2012). A total of 21 Indonesian reef fish species were selected for the PSA based on their relatively large volume of landings and/or high monetary value in trade (Table 3). For each of these species, productivity and susceptibility data were gathered from peer-reviewed and gray literature (e.g. Aldenhoven 1986; Wabnitz *et al.* 2003; Michael 2005; Rubec and Cruz 2005; Ochavillo and Hodgson 2006; Pitcher *et al.* 2007; Reksodihardjo-Lilley and Lilley 2007; Lilley 2008; Froese and Pauly 2012; Reef Protection International 2012; Rhyne *et al.* 2012; Sustainable Aquarium Industry Association 2012; Thornhill 2012). We conducted the PSA at the country level; however, with information on regional variation in management, fishing practices and demography of fishes, a PSA could be conducted for smaller spatial scales at higher resolution. Where data were not available for a particular region (i.e. within Indonesia) or species, productivity and susceptibility attribute information was inferred based on data from other species within that genus and/or other locations where that species is found.

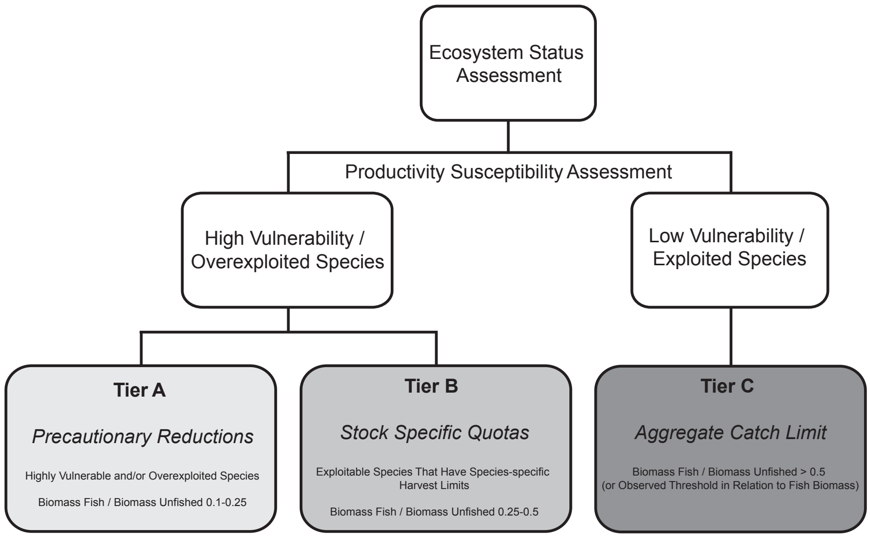

Figure 1 A framework for assessing and managing data-poor fisheries. Step 1: determine fish biomass threshold that is high enough to prevent undesirable ecosystem state change. Step 2: adjust fishing mortality or effort as necessary to maintain fish biomass above threshold. Step 3: determine which species constitute most of the trade, and conduct a productivity susceptibility analysis (PSA) to rank species according to their vulnerability. Heavily exploited and highly vulnerable species fall into Tier A, in which capture is banned or restricted. Less vulnerable but heavily exploited species fall into Tier B and are managed to maintain ratios of fish density in fished areas to fish density in marine reserves or lightly fished areas between 0.25 and 0.50. The rest of the species are managed under the aggregate fish biomass threshold (Tier C) as determined in Steps 1 and 2.

Table 3 Indonesian ornamental reef fish fishery targets by identification number, common name, species name, family, common classification and International Union for Conservation of Nature Red List of Threatened Species status.

ID	Common name	Scientific name	Family	Common classification	IUCN status
1	Clark's anemonefish	*Amphiprion clarkii*	Pomacentridae	Anemonefish	NA
2	False clownfish	*Amphiprion ocellaris*	Pomacentridae	Anemonefish	NA
3	Bicolor angelfish	*Centropyge bicolor*	Pomacanthidae	Angelfish	Least concern
4	Blue devil damselfish	*Chrysiptera cyanea*	Pomacentridae	Damselfish	NA
5	Green chromis	*Chromis viridis*	Pomacentridae	Damselfish	NA
6	Azure demoiselle	*Chrysiptera hemicyanea*	Pomacentridae	Damselfish	NA
7	Goldtail demoiselle	*Chrysiptera parasema*	Pomacentridae	Damselfish	NA
8	Humbug dascyllus	*Dascyllus aruanus*	Pomacentridae	Damselfish	NA
9	Blacktail dascyllus	*Dascyllus melanurus*	Pomacentridae	Damselfish	NA
10	Threespot dascyllus	*Dascyllus trimaculatus*	Pomacentridae	Damselfish	NA
11	Yellow longnose butterfly	*Forcipiger flavissimus*	Chaetodontidae	Butterfly fish	Least concern
12	Bicolor cleaner wrasse	*Labroides bicolor*	Labridae	Wrasse	Least concern
13	Redlip cleaner wrasse	*Labroides rubrolabiatus*	Labridae	Wrasse	Least concern
14	Fire dartfish	*Nemateleotris magnifica*	Ptereleotridae	Dartfish	Least concern
15	Redtooth trigger	*Odonus niger*	Balistidae	Trigger fish	NA
16	Orangespotted filefish	*Oxymonacanthus longirostris*	Monacanthidae	Filefish	NA
17	Peach anthias	*Pseudanthias dispar*	Serranidae	Baselet	NA
18	Banggai cardinalfish	*Pterapogon kauderni*	Apogonidae	Cardinalfish	Endangered
19	Spotted dragonet	*Synchiropus picturatus*	Callionymidae	Dragonet	NA
20	Green mandarinfish	*Synchiropus splendidus*	Callionymidae	Dragonet	NA
21	Hippo tang	*Paracanthurus hepatus*	Acanthuridae	Surgeonfish	Least concern

NA, not assessed.

Not all of the productivity and susceptibility attributes identified in Patrick *et al.* (2009) will be equally relevant for determining the vulnerability of a stock. For example, this study did not include management strategies because the fishes of interest are not subject to different levels of management (e.g. quotas) or enforcement in Indonesia. Where there is variation in management across species, this variation can be captured by the PSA in the characterization of susceptibility to capture. Following the default recommendations of Patrick *et al.* (2009), all attributes within the PSA were weighted with an equal score of 2, with the exception of survival after capture and release which was adjusted to account for the importance of post-capture mortality in ornamental fisheries (Table S3). The weightings provide a qualitative but flexible way to incorporate knowledge about factors that may be particularly important – relative to other factors – in determining the vulnerability of particular stocks. For ornamental species, survival after capture is a uniquely important factor, so we gave it a higher weighting relative to the other factors. Fishes caught for the aquarium trade must remain alive in order to maintain their value and species vary in their vulnerability to post-capture mortality while in the chain of custody. High mortality post-capture of a species can lead to further collection to meet demand. To incorporate these considerations, the attribute of survival after capture and release was weighted on a scale of 1–4, with 1 representing the lowest and 4 representing the highest probability of mortality in the chain of custody or within several weeks of purchase.

Productivity susceptibility analysis scores for the 21 ornamental reef fish targets are shown in Table 4 and Fig. 2. Numerous fish species received similar vulnerability scores due to their similar productivity and susceptibility characteristics (Fig. 2). Generally, these stocks could be characterized as moderately to highly productive and moderately to highly susceptible. Banggai cardinalfish (*Pterapogon kauderni,* Apogonidae), anemonefish (*Amphiprion* spp., Pomacentridae), bicolor angelfish (*Centropyge bicolor,* Pomacanthidae) and file dartfish (*Nemateleotris magnifica,* Ptereleotridae) were the least productive fish stocks, whereas wrasses (*Labroides* spp., Labridae) and damselfish (Pomacentridae besides *Amphiprion* spp.) had higher productivity (Table 4). Yellow longnose butterfly (*Forcipiger flavissimus,* Chaetodontidae), peach anthias (*Pseudanthias dispar,* Serranidae) and several damselfish stocks were among the targets that were least susceptible. In

Table 4 Productivity, susceptibility, vulnerability, and vulnerability category for prioritizing management action for the 21 ornamental reef fish targets.

ID	Common name	Productivity	Susceptibility	Vulnerability	Vulnerability Category
18	Banggai cardinalfish	2.1	2.76	1.98	High
2	False clownfish	2.3	2.5	1.66	High
1	Clark's anemonefish	2	2.2	1.56	High
19	Spotted dragonet	2.6	2.47	1.53	High
20	Green mandarinfish	2.7	2.37	1.4	Moderate
10	Threespot dascyllus	2.4	2.22	1.36	Moderate
4	Blue devil damselfish	2.3	2.11	1.31	Moderate
13	Redlip cleaner wrasse	2.7	2.26	1.3	Moderate
5	Green chromis	2.6	2.22	1.29	Moderate
8	Humbug dascyllus	2.6	2.22	1.29	Moderate
3	Bicolor angelfish	2.2	2	1.28	Moderate
15	Redtooth trigger	2.3	2.06	1.27	Moderate
14	Fire dartfish	2.2	1.94	1.24	Moderate
9	Blacktail dascyllus	2.6	2.11	1.18	Moderate
7	Goldtail demoiselle	2.4	2	1.17	Moderate
21	Hippo tang	2.7	2	1.04	Low
6	Azure demoiselle	2.5	1.89	1.02	Low
17	Peach anthias	2.4	1.78	0.98	Low
11	Yellow longnose butterfly	2.5	1.82	0.96	Low
12	Bicolor cleaner wrasse	2.7	1.91	0.96	Low
16	Orangespotted filefish	2.5	1.8	0.94	Low

contrast, Banggai cardinalfish, anemonefish and dragonets (*Synchiropus* spp., Callionymidae) were the most susceptible (Table 4).

As a result of their low biological productivity and high susceptibility to fishing pressure, Banggai cardinalfish was the most vulnerable stock examined in the PSA (Fig. 2, Table 4). This finding is consistent with the International Union for Conservation of Nature Red list, which recognized Banggai cardinalfish as 'Endangered' in 2007 (Allen and Donaldson 2007). This species was also proposed for listing under CITES Appendix II, but this proposal was ultimately withdrawn (Lilley 2008; Vagelli 2008). Additionally, species of anemonefish, the green mandarinfish (*Synchiropus splendidus,* Callionymidae) and the spotted dragonet (*Synchiropus picturatus,* Callionymidae) ranked as highly vulnerable in the PSA (Fig. 2, Table 4), which is consistent with previous studies on anemonefish and dragonets from other locations (Edwards and Shepherd 1992; Sadovy *et al.* 2001; Shuman *et al.* 2005; Jones *et al.* 2008; Rasotto *et al.* 2010).

Data-quality ranges from high to moderate for the majority of the stocks evaluated; species-specific data were used for each attribute for 71.4% of the stocks (Table S3). The exception was information on species-specific fecundity for a few species; in several instances, fecundity data for similar species in the same geographic area were used. Weighted data-quality scores for all 21 stocks ranged from 1.3 to 3.0 for productivity, 1.3 to 2.0 for susceptibility and 1.3 to 2.8 for vulnerability (Table S4). The data-quality index (Patrick *et al.* 2009) suggests high data quality is <2.0, moderate 2.0 to 3.5 and low is >3.5. The Banggai cardinalfish had the highest data quality among the 21 stocks, which is unsurprising in light of concerns about over-exploitation and resulting research and conservation programs directed at this species (e.g. Kolm and Berglund 2003; Ndobe and Moore 2008). It is notable that the orangespotted filefish does very poorly in captivity due to dietary requirements (Wabnitz *et al.* 2003; Michael 2005) and, as a result, was weighted with a survival coefficient of 4. Despite this, the orangespotted filefish still ranked with a low vulnerability in the PSA, a finding that highlights the limitations of the PSA approach. Further refinement of the PSA approach will be necessary to fully account for the large differences in the nature of food and ornamental fisheries, including the effects of post-capture survival in ornamental fisheries. Managers will still need to carefully consider the life-history characteristics of collected species, particularly the

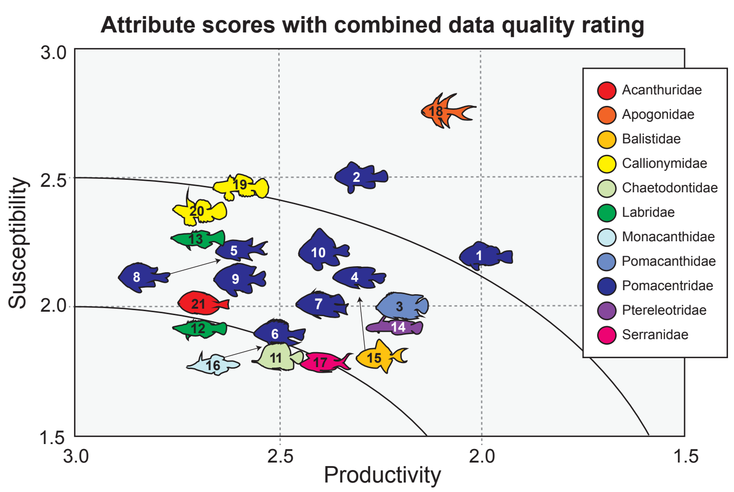

Figure 2 Indonesian ornamental reef fish fishery productivity and susceptibility *x-y* plot by common classification. Each species is labelled according to its reference identification number as follows: 1. Clark's anemonefish, 2. false clownfish, 3. bicolor angelfish, 4. blue devil damselfish, 5. green chromis, 6. azure demoiselle, 7. goldtail demoiselle, 8. humbug dascyllus, 9. blacktail dascyllus, 10. threespot dascyllus, 11. yellow longnose butterfly, 12. bicolor cleaner wrasse, 13. redlip cleaner wrasse, 14. fire dartfish, 15. redtooth trigger, 16. orangespotted filefish, 17. peach anthias, 18. Banggai cardinalfish, 19. spotted dragonet, 20. green mandarinfish and 21. hippo tang. The PSA plot characterizes productivity from high to low (3.0–1.0) and susceptibility from low to high (1.0–3.0). Note that the green chromis and humbug dascyllus received identical productivity and susceptibility scores, resulting in overlapping points on the graph. Fish silhouettes illustrated by M.O. Rock of 7th Rock Studios.

ability to cope with capture and captivity, and use this information to prevent overfishing of vulnerable species. Because life-history information may be lacking for some species involved in the ornamental trade, we recommend the use of PSA data-quality scores and an overall precautionary approach for management decisions (following Patrick *et al.* 2009).

These results suggest that certain ornamental stocks are vulnerable to over collection, and reinforce the need to carefully examine stock vulnerability when making management decisions. Overall, three tiers of vulnerability emerged from this analysis: stocks that were the least vulnerable to collection (scores of <1.1), stocks with a moderate vulnerability to collection (scores of 1.1–1.5) and stocks that were highly vulnerable to capture (scores >1.5; Table 4).

These categories could be used to guide management decisions for Indonesian coral reefs. For instance, stocks that are least vulnerable (i.e. vulnerability scores ≤ 1.1), an aggregate quota could be applied based on observed thresholds in coral reef state metrics (e.g. macroalgal cover) in relation to fish density (McClanahan *et al.* 2011). Among the 21 species evaluated by the PSA, orangespotted filefish (*Oxymonacanthus longirostris*, Monacanthidae), bicolor cleaner wrasse (*Labroides bicolor*, Labridae), yellow longnose butterfly, peach anthias, azure demoiselle (*Chrysiptera hemicyanea*, Pomacentridae) and hippo tang (*Paracanthurus hepatus*, Acanthuridae) would be most suited to this type of management relative to the other stocks evaluated.

Integrating data-poor tools

Productivity susceptibility analysis does not generate specific management reference points such as overfishing limits or sustainable yield levels. When combined with estimates of depletion status, however, stocks can be prioritized for precautionary management and for further data collection and assessment resulting in catch limits or other kinds of specific management reference points. Species with low vulnerability to capture and which show little evidence of depletion (e.g. reserve-based density ratios are above 0.5) could be assigned lower priority for management. Species with moderate vulnerability to capture (i.e. vulnerability scores of 1.1–1.5) could be assessed in more detail, then managed under species-specific quotas (Fig. 1). These quotas could be based on an adaptive management approach that would result in reduced catch of stocks as they approach the lower end of the range of density ratios (fished densities:unfished or lightly fished densities) associated with Pretty Good Yield (generally about 80% of MSY; Hilborn 2010) typical of many fisheries ($Biomass_{fished}$:$Biomass_{unfished}$ of 0.25–0.50, using density as a proxy for biomass).

The majority of stocks evaluated in the PSA fell into the moderate vulnerability range suggesting that they could be suitable for this type of management (11 of 21, 52.4%). These species included goldtail demoiselle (*Chrysiptera parasema*, Pomacentridae), blacktail dascyllus (*Dascyllus melanurus*, Pomacentridae), fire dartfish, redtooth trigger (*Odonus niger*, Balistidae), bicolor angelfish, humbug dascyllus (*Dascyllus aruanus*, Pomacentridae), Green chromis (*Chromis viridis*, Pomacentridae), redlip cleaner wrasse (*Labroides rubrolabiatus*, Labridae), blue devil damselfish (*Chrysiptera cyanea*, Pomacentridae), threespot dascyllus (*Dascyllus trimaculatus*, Pomacentridae) and green mandarinfish (species are listed in increasing order of vulnerability according to the PSA).

Finally, species that are highly vulnerable (i.e. vulnerability scores >1.5) and subject to high exploitation levels could be either banned from capture or very lightly fished while being carefully monitored for over-exploitation (Fig. 1). When marine reserve sites and monitoring data are available, over-exploitation status could be estimated by comparing the ratio of fish density in fished areas to fish density in unfished areas to the range of typical ratios associated with overfishing ($Biomass_{fished}$:$Biomass_{unfished}$ of 0.10–0.25; Hilborn 2010). The results of the PSA suggest that four species – spotted dragonet, Clark's anemonefish (*Amphiprion clarkii*, Pomacentridae), False clownfish (*Amphiprion ocellaris*, Pomacentridae) and Banggai cardinalfish – are the most vulnerable to capture and therefore should be prioritized for reduced harvest and more intensive monitoring and management to avoid over-exploitation (Table 4, Fig. 1).

This adaptive management approach requires many caveats; principal among them is the assumption that biomass ratios associated with Pretty Good Yield (Hilborn 2010) are applicable to ornamental species, which vary widely in their life-history and ecological characteristics. It will be particularly important to characterize the strength of recruitment compensation in ornamental species, as this parameter has the strongest influence on Pretty Good Yield (Hilborn 2010). For this reason, data-poor assessment methods that generate sustainable catch limits (such as the MPA decision tree; Wilson *et al.* 2010) should be applied for priority stocks. Additional monitoring programs (e.g. CPUE trend and size-structure data) may be required for such methods. The prioritization method we suggest (based on vulnerability scores and estimated exploitation/depletion status) should help guide the allocation of scarce monitoring and management resources.

Conclusions

The large volume of ornamental species removed from coral reefs may result in large impacts on fish stocks and ecosystem status, posing risks to sustainability. The data streams that are usually used to assess stock status and ecosystem status – such as catch statistics, effort data, age-structure and size-structure – are generally lacking for coral reef fisheries. While new data are needed to design and evaluate robust fisheries management, it is even more urgent to develop and implement data-poor assessment and management methods to reduce risk of overfishing and ecosystem collapse.

A tiered management approach to data-poor management could be broadly applicable if integrated with data-poor methods. For example, species that are highly vulnerable to fishing can be identified using PSA, which may suggest that catch of these species should be banned or restricted. With more data on the spatial distribution and abundance of a species, rough estimates of exploitation status could be determined based on the ratio of density or biomass in fished areas to levels in marine reserves or lightly fished areas in comparison with ratios typical of overfished stocks (0.1–0.25). Stocks that appear to be robust to exploitation could be identified in a similar way, using PSA to determine their relative vulnerability and biomass ratios in comparison with biomass ratios associated with Pretty Good Yield (0.25–0.5) and adjusting capture levels to maintain biomass ratios in that range. Other species – for instance stocks with high productivity and low susceptibility according to the PSA or stocks that are not major fishery targets – could be managed under an aggregate quota based on quantitative thresholds in ecosystem state related to changes in fish biomass. Adaptive management will be necessary as stock status changes or markets shift over time for different species.

While these proposed thresholds for fish densities associated with Pretty Good Yield and with overfishing are based on commercially fished stocks that differ from ornamental fishery target species in many ways, their correspondence with ecosystem state thresholds for Indian Ocean coral reefs (McClanahan *et al.* 2011) suggests that they may also be useful as management thresholds for ornamental stocks. Moreover, these thresholds may be conservative for certain ornamental species when considered in the context of life-history differences. Long-lived food fishes like grouper (Serranidae) and snapper (Lutjanidae) generally mature later and live longer than many ornamental species (Fig. S1). This is corroborated by PSA analysis: vulnerability scores for food fishes in Indonesia ranged from 1.66 to 2.35 (Apel *et al.* 2012) suggesting that they are somewhat more vulnerable than the ornamental species analysed here (vulnerability scores ranged from 0.94 to 1.98; Table 4; Fig. S1 and/or Table S5). More data will of course be necessary to evaluate the efficacy of this approach and to verify whether the combination of fish density thresholds and PSA is suitable given the specific characteristics of ornamental fisheries (e.g. preferential capture of male/juvenile fish and differential post-capture survival rates). However, it is notable that a similar tiered system, combining an aggregate quota, stock-specific management and prohibitions on collection according to species vulnerability, is already in use in the Maldives to manage the catch of coral reef fish for the aquarium trade with some success (Saleem and Adam 2004; Saleem and Islam 2008).

No matter how management thresholds are derived or how ornamental stocks are assessed, good governance which creates incentives for compliance with science-based goals and rules, coupled with sufficient institutional capacity, will be essential for the sustainable management of coral reef ornamental fisheries. Many coral reef ornamental fisheries are characterized by limited (often decentralized) management capacity as well as weak enforcement of and compliance with regulations. These concerns about institutional, incentive and governance issues in countries that supply most of the ornamental trade highlight the need to carefully craft implementation strategies, build institutional capacity at appropriate levels of governance and promulgate policies that create incentives for stewardship to reduce the need for enforcement (Gutiérrez *et al.* 2011; Ovando *et al.* 2013). Coupled with such improvements, the approach outlined here could be applied under both centralized and decentralized management systems to generate science-based information. This information can in turn be used to reduce the risk of overfishing and changes in ecosystem state for both marine ornamentals and possibly other categories of coral reef wildlife such as fish collected for the live reef fish food trade in ornamental and other data-limited fisheries.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Definitions of productivity and susceptibility as defined by Patrick *et al.* (2009) used in the PSA.

Table S2. Source countries, regions, number of sites, and references for data used to examine the relationship between total fishable biomass and the dependent indicators of ecosystem health for the greater Indonesian basin.

Table S3. Definitions of the attributes, data quality categories, and weightings used in the PSA, modified from Patrick et al 2009 (Tables 1 and 4). This table illustrates the attributes used to assess each species in the PSA and their corresponding weightings. Each attribute was weighted by relative importance for the fishery (producing a weighted attribute score) and then by data quality to produce an overall vulnerability score. Data quality ranged from high to moderate (based on the categories from Patrick *et al*. 2009) for the majority of the attributes evaluated.

Table S4. Data quality scores for productivity, susceptibility and vulnerability attribute for the 21 ornamental reef fish targets.

Table S5. Productivity, susceptibility, vulnerability, and fishery type for comparing life history strategies between 21 ornamental species and 14 live reef fish food fishery species in Indonesia.

Figure S1. Indonesian ornamental reef fish fishery (gray) and live reef fish food fishery (black) productivity and susceptibility *x*-*y* plot by common classification.