Marine ecological footprint of the live reef fish food trade[1]

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Introduction

The demand for live seafood in Asia has spawned a lucrative trade in live coral reef fish that in 1995 had a global annual retail value of over USD 1 billion (Johannes and Riepen 1995; Cesar et al. 1997). There are concerns that the live reef fish food trade is inflicting an unacceptably heavy impact on coral reefs and reef resources in Southeast Asia and the Indo-Pacific.[5] These areas contain over 90 per cent of the world's coral species and include the highest global marine biodiversity (Norse 1993). Because these reefs provide over one billion people in Asia with food (Barber and Pratt 1997; Bryant et al. 1998), their destruction and overexploitation threaten current and future regional food security and socioeconomic development (Barber and Pratt 1997; Williams 1997).[6] This article examines the marine ecosystem area appropriated by major Asian economies, particularly that of Hong Kong, to satisfy their demand for live reef fish food products. Hong Kong was chosen as the focus of the article for two reasons. First, it is the largest trader and major consumer of live reef food fish in the world. Second, in contrast to other demand-side economies (e.g. Singapore, mainland China), data are available to examine Hong Kong's role in the trade, facilitating an in-depth analysis of its marine ecological footprint. However, even the available data for Hong Kong are known to be incomplete, making it difficult to determine the true scale of live fish imports into Hong Kong (Lau and Parry-Jones 1999).

Marine ecological footprints

The concept

Marine ecological footprints (MEFs) measure the marine ecosystem area appropriated by human populations to supply seafood and other marine products and services (Folke et al. 1991; Folke et al. 1998).[7] Because these products and services are often not fully reflected in conventional economic and trade analyses, MEFs are important tools for calculating the "hidden" support provided by natural marine ecosystems and the real "costs" of that support (Folke et al. 1997). MEFs can be computed for global, regional and local (e.g., country or city) scales, or they can focus on specific activities such as mariculture or the live reef fish food trade (FT) (Folke et al. 1997; Wackernagel et al. 1999; WWF 2000). MEFs are calculated either as ratios (e.g. the number of times above or below sustainable levels) or as spatial areas (e.g. km² of appropriated coral reef).[8]

Surface needed to produce the consumed quantity	=	SC	=	C/P
Consumption of a defined area	=	C		
Production per hectare	=	P		
Actual productive surface of defined area	=	AS		
Marine ecological footprint (MEF)	=	**SC/AS**		

Case study: Marine ecosystem appropriation by the FT

The high revenues of the FT in Southeast Asia and the Indo-Pacific are counterbalanced by two serious ecological problems: *i)* overexploitation of target species and *ii)* cyanide fishing (Johannes and Riepen 1995; Barber and Pratt 1997). In this article, we apply the MEF concept to coral reef fisheries in order to answer the following questions: What proportion of Southeast Asia's and the Indo-Pacific's coral reef fisheries production is needed to supply the FT in Asia, and in particular, Hong Kong's annual demand for live reef fish; and, Can this demand be sustained by available reef resources?

Sustainable coral reef fisheries production in the Indo-Pacific and Southeast Asia

To estimate the impact of the FT, the sustainable production of coral reefs must be considered. Because production is a function of many factors, we present a range of optimistic to pessimistic scenarios based on varying production linked to coral reef health, reef fishery maximum sustainable yields, and fishing pressure.

Estimates of coral reef area, health and fishery yields

The sections below outline our assumptions for subsequent calculations and analyses.

i) *Coral reef surface area.* Coral reefs comprise approximately 0.1 to 0.5 per cent of the world's ocean floor (Spalding et al. 2001).[9] Thirty per cent of the world's coral reefs are in Southeast Asia, with 18 per cent of the total located in Indonesia and the Philippines (Wilkinson 1998). We assume the following coral reef surface areas (Spalding et al., 2001): *i)* global—284,300 km²; *ii)* Southeast Asia—91,700 km²; and *iii)* Indo-Pacific—259,600 km² (excluding the eastern Pacific).[10] While these figures are based on a restricted definition of a coral reef (see footnote 9), limiting the area to known, mapped shallow-water reefs, we employ these estimates because near-surface reefs are the most biologically productive and economically important fisheries (Munro 1996), they are the main targets of the FT, and higher figures may overestimate total global reef habitat (see foot-

note 9). However, for comparison, sensitivity analyses with higher reef area values were run and are discussed in the following sections as upper bounds for coral reef production.

ii) *Coral reef health.* Coral reef health significantly affects fisheries production, with healthier reefs being more productive (Chou 1998). Coral reef health is typically assessed based on total live coral cover. For health status, we employed data from Bryant et al.'s (1998) comprehensive survey, which revealed the following percentages for coral reefs in the Southeast Asia and the Indo-Pacific regions, respectively: "excellent" condition—3% and 20%; "good"—15% and 40%; "fair"—26% and 30%; and "poor"—56% and 10%.

iii) *Coral reef fishery yields.* We base optimistic reef fishery yields on McAllister (1988) and pessimistic yields on Dalzell (1996). McAllister showed total reef fishery production of 3–18 tonnes per square kilometer per year (t km⁻² yr⁻¹) for reefs in poor to excellent health. Dalzell reviewed sustainable yields from tropical reef fisheries, which varied from 0.1–44 t km⁻² yr⁻¹. From this and other reviews (Russ 1991; McClanahan 1995), it seems reasonable to conclude that while total yields much higher than 5 t km⁻² yr⁻¹ are possible for some reefs in Southeast Asia and the Indo-Pacific, those well in excess of 15 t km⁻² yr⁻¹ are rare.

iv) *Reef fishery finfish and grouper yields.* The reef fishery yields reviewed above include both finfish and invertebrates (Dalzell 1996). The FT, however, focuses heavily on finfish, and in particular, on groupers and larger reef fish. Based on Cesar (J. McManus, pers. comm., as cited in Cesar 1996), we assume finfish constitute two-thirds of total yields. Groupers comprise 0 to 15 per cent of the finfish yields, depending upon the reef's health status and the degree of fishing pressure (Russ 1991; Cesar 1996).

v) *Fishing pressure.* Fishing intensity also reduces yield, with catch rates of grouper and other top predators declining (down to one-third or one-half of virgin reefs in less than five years) as fishing pressure intensifies (Dalzell 1996). We assume that half of the coral reef surface area (for any

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9. The full range of estimates for global coral reef cover is 284,300 to 4 million km²: *i)* 617,000 km² from Smith (1978); and *ii)* 0.6 to 4 million km² from Kleypas (1997).

10. Spalding et al.'s (2001) global coral reef surface area of 284,300 km² is broken down into the following regional categories: *i)* Middle East—21,600 km²; *ii)* Indian Ocean—32,600 km²; *iii)* Southeast Asia—91,700 km²; *iv)* Pacific Oceans—115,900 km²; *v)* Caribbean—20,000 km²; and vi) Atlantic Ocean—1600 km². The Indo-Pacific region has an estimated 261,200 km2 of coral reefs (259,600 km² excluding E. Pacific) and is defined as including Southeast Asia, the Indian Ocean, the Red Sea, Northern and Southern Pacific Oceans, and the Arabian Gulf (Spalding et al. 2001). The differences between the various estimates arise because of the way that coral reefs are defined—in particular the maximum depth to which reef growth (typically from 150 m to less than 30 m) is restricted by ambient light levels.

health condition) is under heavy fishing pressure, which reduces estimated yields by 50 per cent, and that half is under moderate or light fishing pressure, which we assume has a negligible effect on long-term yields.

Final yields adopted for our analyses are shown in Figure 1. From these analyses, it can be seen that coral reefs in excellent and good condition could furnish approximately 80 to 90 per cent of grouper yields in Southeast Asia and the Indo-Pacific, whereas those in fair and poor condition would contribute only 10 to 20 per cent of the total (Fig. 2). These results underscore the critical importance to fisheries in these regions of keeping reefs in good condition and rehabilitating reefs in less healthy states.

Estimates of total sustainable reef fisheries production in Southeast Asia and the Indo-Pacific

Based on the assumptions above, coral reef production values for Southeast Asia and the Indo-Pacific are indicated in Table 1.[11, 12] Sensitivity analyses for all factors were run, resulting in a range of estimates. However, for simplicity we report the point estimate we believe to be the most representative value for current coral reef fisheries production, which assumes coral reefs to be typically in fair to poor condition in this region (Bryant et al. 1998) and a midpoint figure for fishery yields (i.e. a total of about 10 t seafood km^{-2} yr^{-1} and 5 t finfish km^{-2} yr^{-1}) from Dalzell (1996). With these assumptions, total sustainable production of coral reef finfish and groupers, respectively, in the Indo-Pacific is estimated at approximately 650,000 t yr^{-1} and 50,000 t yr^{-1}. Within Southeast Asia, annual coral reef sustainable production is 135,000 t of finfish and 7300 t of groupers. Southeast Asia, therefore,
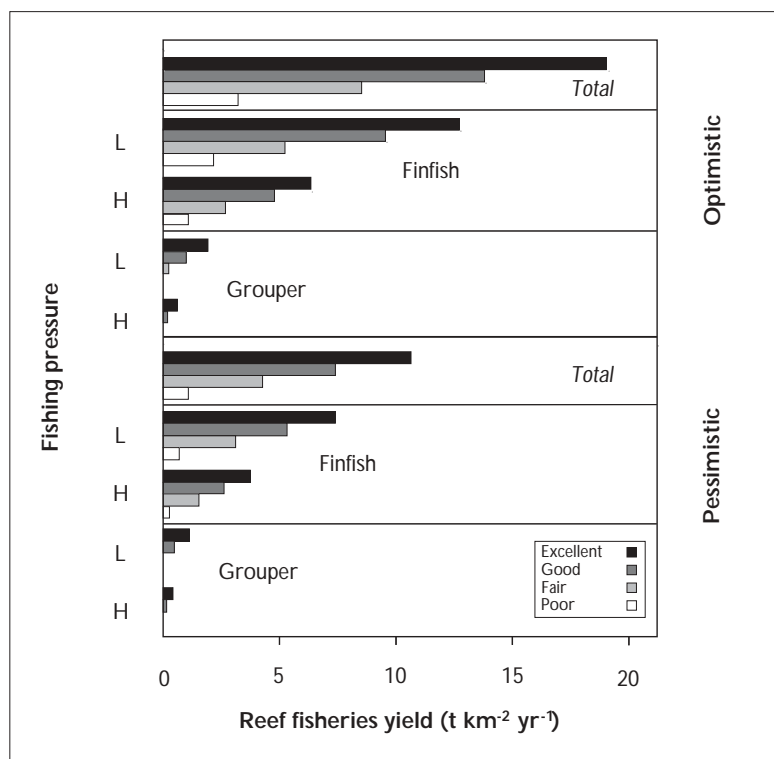

Figure 1. Optimistic and pessimistic estimates of the coral reef fisheries yields for reefs in excellent, good, fair and poor condition under light (L) or heavy (H) fishing pressure.
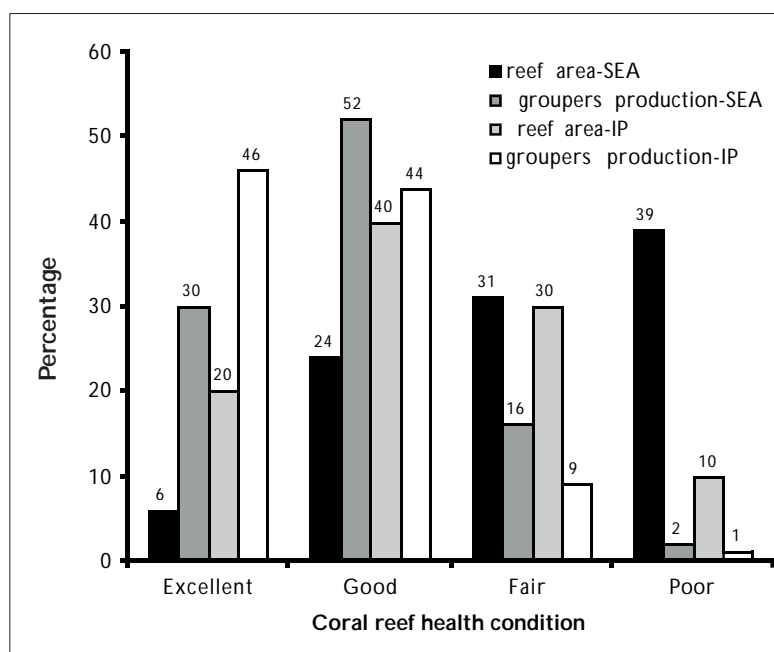
Figure 2. Contributions of high value grouper species production from coral reefs in Southeast Asia and the Indo-Pacific based on varying reef health conditions.

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11. As Bryant et al. (1998) note, their figures may be underestimates, since 90% of the coral reefs in the Pacific remain unexplored and only 10% of the reefs in Southeast Asia have been thoroughly surveyed. A World Bank assessment (see World Bank 1998) of coral reefs in Indonesia presents a more optimistic picture for reef health, with 6%, 24%, 31% and 39% in excellent, good, fair and poor condition, respectively. These percentages are similar to those found in a ten-year (1984–1994) ASEAN-Australia Living Coastal Resources project that surveyed reefs in Malaysia, Indonesia, Singapore, the Philippines and Thailand (see Chou 1998).

12. Sensitivity analyses performed using a combination of coral reef health data from Bryant et al. (1998) and the World Bank (1998) give a larger range than the results shown in Table 1 for the total maximum sustainable production of coral reef fisheries in the Indo-Pacific: finfish: 463,502–1,325,348 t yr^{-1}; groupers: 28,627–103,247 t yr^{-1}.

can potentially supply only about 15 per cent of the Indo-Pacific's total estimated sustainable grouper production. These estimates approximately double when McAllister's (1988) higher yields are used (Table 1).

Table 1. Coral reef surface area and estimated finfish and grouper sustainable yields for Southeast Asia and the Indo-Pacific.

	SE Asia	Indo-Pacific
Coral reef surface area (km²)		
excellent	2,751	36,331
good	13,755	80,915
fair	23,842	74,212
poor	51,352	68,142
Total	91,700	259,600
Total sustainable coral reef finfish production (t yr⁻¹)		
optimistic scenario	286,563	1,251,988
pessimistic scenario	135,258	647,353
Total sustainable coral reef groupers production (t yr⁻¹)		
optimistic scenario	13,828	95,260
pessimistic scenario	7,287	51,557

Notes:
i. Coral reef surface area is based on Spalding et al. (2001).
ii. Coral reef health conditions are from Bryant et al. (1998).
iii. Optimistic scenario assumes total yields of 3–18 t km⁻² yr⁻¹ from McCallister (1988); pessimistic scenario assumes total yields of 1–10 t km⁻² yr⁻¹ from Dalzell (1996).

Estimates of coral reef ecosystem appropriation

Consumption of seafood in Hong Kong and for the FT

The Hong Kong Special Administrative Region is a highly developed metropolitan area supporting nearly 7 million people on a total land area of 1097 km² (actual city built-up area, 120 km²). Hong Kong possesses abundant sea area (1700 km²), but with its own fisheries stocks severely depleted, no local management, little mariculture to supplement fishery yields, and a high and growing demand for seafood, it is almost exclusively dependent upon marine ecosystems beyond its borders for seafood (Warren and Keonig 2001). Total per capita seafood consumption in Hong Kong is 46–60 kg yr⁻¹ (Hong Kong Government Census and Statistics Department 1998; Warren and Keonig 2001).

MEF for Hong Kong's role in the FT

As the largest FT importer, Hong Kong's demand accounts for about 60 per cent of the FT (with an estimated 50 per cent re-exported to mainland China, Chan 2001). Hong Kong's estimated annual imports of live reef fish in 1997 were 32,000 t (Lau and Parry-Jones 1999), placing the total annual volume of the FT at 25,000 to 54,000 t, with 15,000 to 31,500 t mainly from grouper but also from other reef fish such as snappers and humphead wrasse (Johannes and Riepen 1995; Lau and Parry-Jones 1999). Based on Hong Kong's estimated annual imports, our results show that this single economy appropriates 3–5 per cent of the Indo-Pacific's, or about 10–25 per cent of Southeast Asia's, estimated sustainable reef fish harvest (Table 2). This corresponds to a minimum MEF for Hong Kong's annual share in the FT of approximately 0.1 to 0.2 hectares per capita. Put another way, Hong Kong appropriates the production from an area of at least 6500 to 13,000 times the size of its own coral reef area.

If Hong Kong's demand for groupers is specifically examined (18,900 t yr⁻¹ in 1997), it can be seen that 140 to 260 per cent of Southeast Asia's total sustainable grouper production is appropriated (Table 2). Although some percentage of Hong Kong's demand is re-exported to China, this total demand exceeds Southeast Asia's entire coral reef fisheries' regenerative capacity for groupers. The implications of Hong Kong's (and southern China's) high and very probably unsustainable appropriation of annual coral reef fisheries production in Southeast Asia are sobering. As our analysis shows, demand in Hong Kong (and southern China) leads to the removal each year of up to one-quarter of Southeast Asia's total sustainable reef fisheries catch and virtually all of its grouper catch. This high appropriation of coral reef resources presumably partly explains why Hong Kong fishing fleets and traders must continually relocate to sustain annual market demand (Sadovy and Vincent 2002).

MEF for the entire FT

On an annual basis, the FT in Asia markets constitutes as much as 40 per cent of Southeast Asia's sustainable coral reef finfish production. For groupers, the trade sells up to four times the sustainable yield of Southeast Asian reefs, or as much as 60 per cent of the entire Indo-Pacific region's annual sustainable grouper production (Table 2). The FT as a whole is a significant consumer of coral reef fisheries resources throughout the Indo-Pacific region, and its annual demand must be considered and integrated into regional coral reef management and protection plans.

Table 2. **Estimates of the appropriated marine ecosystem area and percentage of coral reef production appropriated by Hong Kong and the live reef fish trade (FT).**

	Appropriated ecosystem area (km²)		Percentage of reef fisheries production appropriated	
	SE Asia coral reefs	Indo-Pacific coral reefs	SE Asia coral reefs	Indo-Pacific coral reefs
Hong Kong's total reef fish consumption				
optimistic scenario	10,552	6,838	12	3
pessimistic scenario	22,356	13,224	24	5
Hong Kong's grouper consumption				
optimistic scenario	129,153	53,076	137	20
pessimistic scenario	245,088	98,068	259	37
FT's total reef fish consumption				
optimistic scenario	17,067	11,059	19	4
pessimistic scenario	36,158	21,388	39	8
FT's total grouper consumption				
optimistic scenario	208,886	85,843	228	33
pessimistic scenario	396,393	158,610	432	61

Note: The percentage of reef fisheries production appropriated refers to that from either SE Asia or the Indo-Pacific, but not both —the percentages are not additive. For example, under the optimistic scenario, current consumption by Hong Kong appropriates either 12% of SE Asia's production or 3% of the Indo-Pacific's total.

Impacts on the MEFs from cyanide fishing, mariculture and overfishing

Other activities exacerbate the high levels of exploitation. In addition to overfishing, the use of cyanide in some areas damages coral reefs (Jones and Hoegh-Guldberg 1999; Mous et al. 2000), possibly impairing their capacity to produce fish and seafood. High rates of fish mortalities and poor fishing practices also characterise FT operations, with average mortality rates estimated at 50 per cent between capture and the point of retail sales (Sadovy and Vincent 2002), as well as a heavy focus on reef fish spawning aggregations which cannot withstand heavy fishing pressure (Johannes and Riepen 1995). Lastly, coral reef fish mariculture, which supplements the wild grouper supply for the FT, also engenders negative ecological impacts. Hundreds of millions of juveniles are caught for this industry throughout Southeast Asia and traded internationally around the region. Many of these young fish die from poor culture and transport conditions, while the pollution and use of wild fish to feed cultured groupers is also a matter of some concern (Sadovy 2000; Sadovy and Lau 2002). Coral reef destruction and biomass lost in the above ways are not reflected in trade figures or regulatory initiatives. If such losses were included in our analyses, the MEF estimates would be substantially higher.

Discussion and conclusions

Although the MEF analyses presented in this article are limited to the quality of the underlying data

and assumptions, and reflect only a static picture of coral reef fisheries (e.g. do not incorporate dynamics in seafood demand, such as the reduced demand in Hong Kong following economic downturns, or the complex nature of reef ecosystems) (Holling 1973; Folke et al. 1998; Moberg and Folke 1999), the results are valuable in assisting policymakers to *i)* identify the largest regional "consumers" of coral reef resources, *ii)* assess the ramifications of this consumption, *iii)* quantify the pressures on and limits of coral reef ecosystems' regenerative capacity, and *iv)* identify management and conservation needs at local and regional scales. Our analysis and those of others on the FT highlight an important problem in monitoring and managing the trade: the lack of systematic and accurate data for coral reef fish fisheries and the general paucity of fishery information in Southeast Asia (Watson and Pauly 2001). We recommend that organisations such as the Food and Agriculture Organization of the United Nations and the Asia-Pacific Economic Cooperation (APEC) foster the collection of more accurate and detailed annual statistics on coral reef fisheries.

The MEF analyses presented in this article also suggest that economic assessments of the potential benefits of the FT to source countries in the Pacific must factor in the likelihood for the FT to rapidly lead to overexploitation of their reef resources. Clearly, overexploitation of coral reef fisheries in Southeast Asia and the Indo-Pacific is no longer an issue to be managed solely on the supply end. Demand-side participants in the FT through their

seafood consumption are directly responsible for the significant appropriation of reef fish in these regions and the concomitant ecological impacts; consequently they share a large responsibility for the proper management of the trade on their end. Our analyses reflect the need for institutional actions that include: *i)* reducing coral reef fish capture and protecting healthy reef fish populations from overexploitation by the FT, *ii)* establishing marine protected areas and instituting temporary and permanent closures of at least a portion of the fishing grounds in Southeast Asia, and certainly in the case of spawning aggregations, to allow depleted fisheries to recover (Andersson and Lindroth 2001), *iii)* revitalising local fisheries in demand countries, *iv)* requiring live reef fishermen and traders to adopt codes of responsible fishing practices, *v)* monitoring trade (both export and import), *vi)* taking a precautionary approach to becoming involved in the FT, and *vii)* investigating full-cycle grouper aquaculture to supply reef fish, if it is carried out in a sustainable way (Sadovy and Lau 2002).

Without urgently needed reform, the FT will continue to deprive people in the Indo-Pacific of the full economic benefits from their reef fish resources and the world of its potentially irreplaceable marine biological heritage.

> "It is clear … that the environmental, social and political problems arising from the live reef fishery are not just enormous, but also enormously complex. There is no simple solution. The issues must be addressed at a variety of levels using a variety of regulatory, educational, scientific, and economic tools" (Johannes and Riepen 1995).

Acknowledgements

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