Marine ecological footprint indicates unsustainability of the Pohnpei (Micronesia) coral reef fishery

KEVIN L. RHODES[1]*, KIMBERLEY A. WARREN-RHODES[2], SCOTT SWEET[3], MIKE HELGENBERGER[4], EUGENE JOSEPH[5], LINDA NG BOYLE[6] AND KEVIN D. HOPKINS[1]

[1]*University of Hawaii at Hilo, College of Forestry, Agriculture and Natural Resource Management, 200 W Kawili Street, Hilo 96720, Hawaii, USA,* [2]*SETI Institute/NASA Ames Research Center, Moffett Field, CA 94035, USA,* [3]*TerraUnda, PO Box 229, Dumaguete City, Negros Oriental 6200, Philippines,* [4]*Office of Fisheries and Aquaculture, PO Box B, Kolonia, Pohnpei FM 96941, Micronesia,* [5]*Conservation Society of Pohnpei, PO Box 2461, Kolonia, Pohnpei 96941, Micronesia, and* [6]*University of Washington, Department of Industrial and Systems Engineering, Seattle, WA 98195, USA*

SUMMARY

Throughout the tropics, developing countries and territories are highly dependent on nearshore marine resources for food and income, however information on the sustainability and proper management of these fisheries is lacking. In Pohnpei, Micronesia, the sustainability of a coral reef finfishery was assessed by comparing coral reef fish demand to coral reef biocapacity using a marine ecological footprint (MEF) analysis. Based on geo-referenced satellite and aerial imagery, Pohnpei and surrounding atolls have 184.2 km² of coral reef habitat with a sustainable finfish yield of 573–1118 t yr⁻¹, however total harvest was estimated at 4068 t yr⁻¹, exceeding biocapacity by 360–710%. The MEF was supported by observed impacts to coral reef resources, including (1) long-term declines in fish spawning aggregation density, (2) reductions in mean size, age and fecundity of key commercial species, (3) reliance on undersized fish, and (4) decadal declines in mean size and abundance of fishes of iconic value and critical to ecosystem maintenance. The commercial fishery was responsible for 68% of finfish catch volume, while reef fish consumption, at 93 kg person⁻¹ yr⁻¹, was among the highest in the region. To sustainably meet current demand, up to 833 km² of additional reef area would be required. The study illustrates the MEF, at least rudimentarily, reflects biological reality on local reefs and represents a valuable analytical tool in a marine policymaker's toolbox.

Keywords: biocapacity, consumption, ecological overshoot, marine ecological footprint, Micronesia, overfishing

INTRODUCTION

As a vital source of food and income, coral reef fisheries are integral to the socioeconomic fabric of most tropical Pacific coastal communities (Dalzell *et al.* 1996). Yet, coral reef resources have declined worldwide (Bellwood *et al.* 2004; Wilkinson 2008) while demand has grown (Bell *et al.* 2009; Gillet & Cartwright 2010), creating a reliance on fish for income rather than subsistence (see for example Sadovy 2005; Gabrié 2011). As a result, demand is outstripping supply (see Newton *et al.* 2007) and food insecurity now threatens many Pacific jurisdictions (Bell *et al.* 2009). With climate change predicted to reduce coastal fish catch volume by up to 50% by 2100 (SPC [Secretariat of the Pacific Community] 2011), the need to effectively manage existing resources has never been greater.

Among Pacific island countries and territories (PICTs), reliable information on coral reef fisheries is scarce (Gillet & Lightfoot 2002; Sadovy 2005; Zeller *et al.* 2006; Rhodes *et al.* 2011*a*). Given this information gap, catch reconstructions have been used to identify fisheries trends and status (Zeller *et al.* 2006, 2007), and have revealed heavily impacted (for example American Samoa, Commonwealth of the Northern Mariana Islands; Zeller *et al.* 2006, 2007) and collapsed (for example Guam; Zeller *et al.* 2007) fisheries, while the status of other regional fisheries remains largely unknown.

To estimate resource sustainability, ecological footprint analyses have been used to compare production (also referred to as biological capacity or biocapacity) to demand (Folke *et al.* 1997; Wackernagel & Rees 1998). Marine ecological footprints (MEFs) can similarly be used to measure the marine ecosystem area(s) appropriated by human populations to supply seafood and other marine-based products and services, and determine whether current demand meets or exceeds biocapacity (Folke *et al.* 1991, 1998; Wackernagel & Rees 1998). In theory, MEFs provide a means of quantifying both the readily observed and hidden ecosystem support provided by marine systems and offer an easily understood metric for policymakers to gauge demand and associated impacts (Warren-Rhodes *et al.* 2003; Venetoulis & Talberth 2008).

Here, we use the MEF to compare coral reef fisheries (hereafter finfisheries, unless otherwise noted) demand with biocapacity and to assess whether present demand is sustainable or in excess of biocapacity (Catton 1982; Wackernagel *et al.* 2002). If in excess, a system's natural capital

*Correspondence: Dr Kevin Rhodes Tel: +1 512 638 5997 e-mail: klrhodes_grouper@yahoo.com
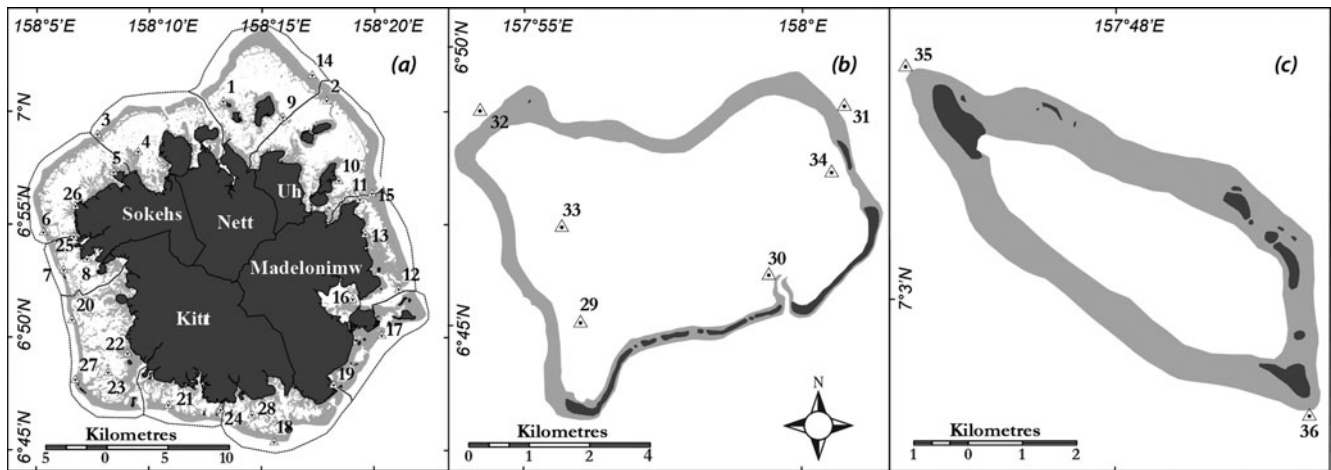
Figure 1 (*a*) Map of Pohnpei with five municipal (solid line, land) and section (dotted line, water) boundaries. The Kehpara Marine Sanctuary (Station 27, bottom left) encompasses the spawning aggregation of squaretail coralgrouper *Plectropomus areolatus* where underwater visual census was conducted. (*b*) Map of Ant Atoll. (*c*) Map of Pakin Atoll. Numbered triangles identify station locations for the 2005 rapid environmental assessment of the coral reef (Conservation Society of Pohnpei 2006). Land = dark grey; coral reef = light grey.

and ability to provision ecosystem services can deteriorate (such as loss of fish habitat from coral reef degradation) (Catton 1982; Costanza *et al.* 1997). For Micronesian finfisheries, previous MEF analyses (Warren-Rhodes *et al.* 2003; Newton *et al.* 2007) have relied on the United Nations Food and Agricultural Organization (FAO) fisheries statistics (FISHSTAT) and/or short-term data taken by regional fisheries organizations (such as the SPC). FISHSTAT data are reliant on member country input, which is frequently inaccurate and lacks taxonomic resolution (for example Zeller *et al.* 2006, 2007). In contrast, we used comprehensive finfish catch data taken directly from the fishery to improve the accuracy of the MEF and help define appropriate management responses.

In Micronesia, recent studies have characterized the commercial sector of the finfishery and identified an over-reliance on juveniles, the use of unsustainable fishing methods (Rhodes *et al.* 2008), and population-level impacts to highly valuable commercial finfish, such as declines in mean fish size, age and fecundity (see Rhodes *et al.* 2011*b*). Other regional studies have identified potential ecosystem impacts from overfishing both top predators (Houk *et al.* 2012) and lower trophic level species (Bejarano *et al.* 2013).

The current study aimed to quantify the MEF for the Pohnpei (Federated States of Micronesia [FSM]) finfishery to address the following questions: (1) Is the current demand for finfish sustainable, based on MEF estimates? and (2) Does the MEF match biological reality? Empirical demographic and biological data were collected through island-wide surveys, with biocapacity estimated from coral reef area and commonly cited yield values. This study furnishes the first detailed overview of the subsistence fishing sector for the region, with local contemporary empirical biological data supporting the development of an accurate island-level coral reef MEF

METHODS

Study location

Pohnpei (6° 59′ N, 158° 12′ E) is one of four FSM states, composed of eight islands and atolls, including the main island of Pohnpei (hereafter, Pohnpei) (Fig. 1*a*) and the nearby atolls of Ant (6° 46′ N, 158° 0′ E, 12 km west-south-west of Pohnpei) (Fig. 1*b*) and Pakin (7° 3′ N, 157° 48′ E, 30 km west-north-west of Pohnpei) (Fig. 1*c*). We studied the finfisheries in these three areas. In 2010, 34 789 people inhabited Pohnpei (Federated States of Micronesia 2013), while Pakin was only sparsely populated and Ant was uninhabited. All are subject to fishing. With one exception, the 13 small-scale no-take marine protected areas (MPAs) in Pohnpei and four MPAs in Ant are largely unenforced, while *c.* 50% of Pakin is a community-enforced MPA.

Airport and business, household and market surveys

To estimate total finfish demand, surveys were conducted between 2006 and 2009. These included airport, business, household and fish market surveys.

Business and airport surveys

To gauge exported reef fish volume, destination and origin, airport surveys were conducted opportunistically on outbound flights over 21 days between 11 May and 5 June 2009. Exporters and exports were identified as commercial or private, and the source of the fish was recorded (namely purchased or captured directly). We assumed the surveyed export fish volumes and purpose of export (namely private or commercial use) were representative of other times of the year. Within the same year, businesses, restaurants and schools using reef fish were also sampled to identify the source, volume

and frequency of purchase, and we report these as annual values.

Household and fisher surveys

Island-wide household surveys were conducted to detail the demography, volume and composition of the finfishery. The survey included 594 out of 5970 households (9.9%) in 143 villages. Households were selected haphazardly, with total sample sizes for each municipality set *a priori* at 10% (Federated States of Micronesia 2002). For each household, surveys recorded the number of fishers, number of fishing days, average estimated daily capture volume, trips per week and number of days spent fishing strictly for subsistence. Commercial fishers were asked to estimate the average number of days that fish were sold and the percentage of income derived from sales. For catch volume, the number of commercial and subsistence fishers were combined with respective weekly catch volumes to estimate total and sector-specific annual catch volumes.

Coral reef biocapacity

Coral reef biocapacity is the total annual seafood volume that can be supplied by reefs in the area. For any given year, Pohnpei's coral reef biocapacity ($BC_{P, Coral}$) is:

$$BC_{P,Coral} = \Sigma(A_x \cdot Y_x),$$

where X represents an individual reef, A_x is reef area (km^2) and Y_x is maximum sustainable seafood yield (t km^{-2} yr^{-1}) (Newton *et al.* 2007; Ventoulis & Talberth 2008). In this context, maximum sustainable yield refers to the largest average yield of seafood derived from coral reefs that can be sustainably removed over the long term (OECD [Organization for Economic Cooperation and Development] 1998).

Coral reef area and mapping

To produce coral reef maps and analyse reef surface area, a combination of topographic maps in the form of digital raster graphics (DGRs), hydrographic charts, and aerial and satellite imagery was used, namely: (1) a 1:25000-scale United States Geological Survey (USGS) topographic map (USGS 2002); (2) Defense Mapping Agency (DMA) hydrographic charts 81435 and 81453 (US National Geospatial-Intelligence Agency 2008*a*, *b*), with information taken from USGS 1:25000 scale topographic maps (NIMA 5842 I NW, 5842 I NE, 5843 II SW, 5843 II SE–Series W856) (USGS 2002); (3) aerial photography (5.6–6.9 m resolutions from 1995 and 1.1–1.4 m resolutions from 2002); and (4) 60-cm pan sharpened, geo-referenced Quickbird satellite imagery (from 2005). We adopted the USA's National Oceanographic and Atmospheric Administration (NOAA) guidelines for benthic habitat mapping (1:6000 scale) (Analytical Laboratories of Hawaii 2002). Remotely sensed imagery at fine scales (0.6–6 m pixels) allowed for visual interpretation of shallow water coral features to depths of 30–40 m, depending on water clarity during data acquisition (Rohmann & Monaco 2005).

Aerial photos were often best for visualizing reef areas because of absence of cloud cover and were cross-referenced with other georeferenced data sources, including satellite imagery, DGRs and hydrographic maps. The georeferenced imagery, maps and charts provided four possible data sources for creating reef area polygons to calculate areas in the geographical information system (GIS). The end product was a single multi-part polygon, created by digitizing the visible reef sections (Rohmann & Monaco 2005).

Ant and Pakin reef areas were estimated from medium resolution imagery (NOAA 2004). Owing to image resolution and lack of bathymetric contours, atoll reef area estimates may be regarded as minima.

Coral reef cover, health and sustainable yields

Since coral cover significantly affects biocapacity, with healthier reefs being more productive (Bell & Galzin 1984; Jennings *et al.* 1996; ISRS [International Society for Reef Studies] 2004; Jones *et al.* 2004; Graham *et al.* 2006; Bruno & Selig 2007), we assumed that (1) living coral cover is a key measure of coral reef health (Gomez *et al.* 1994; ISRS 2004; Bruno & Selig 2007) and (2) that healthier coral reefs produce more fish than less healthy, degraded reefs. While coral cover alone cannot fully capture reef fish productivity, it is a widely adopted measure of reef health (Gomez *et al.* 1994; ISRS 2004; Bruno & Selig 2007). There is evidence that coral reef and reef-associated fish abundance increases as habitat increases and that reduction of coral cover rapidly causes decline in reef fish abundance and diversity (Bruno & Selig 2007). The degradation of coral reefs, whether from human or natural sources, has thus been widely shown to have detrimental effects on both fisheries production and ecosystem function (Gomez *et al.* 1994; McClanahan 1995; Jennings & Polunin 1996; Moberg & Folke 1999; White *et al.* 2000). As such, in this study, we associated increases in coral health and cover with increasing finfish yield.

The current study relied on the rapid ecological assessment (REA) data on coral cover (Conservation Society of Pohnpei 2006) using the methods outlined in Devantier *et al.* (1998). The REA represents the only known reliable coral cover data for Pohnpei. For the REA, 36 stations (Pohnpei) were assessed, with each station consisting of a shallow (< 10 m) and deep (>10 m) dive (0–50 m depth) covering 1 ha in total. Stations included barrier, inner (lagoon) and mangrove-fringing reefs. Live coral cover (to the nearest 5%) was estimated based on six ecological and six substratum attributes. Living coral cover ranged from 10% to >75%, with >50% cover being widely found in stations of all exposure regimes and distances from the mainland. We estimated biocapacity by averaging coral cover over multiple combined REA stations (Fig. 1*a*). For Ant (five stations, nine dives) and Pakin (two stations, nine dives), biocapacity and average coral cover values were estimated by combining all dives for each respective atoll.

We adopted the coral reef health categorizations of Gomez *et al.* (1994), based on cover percentages: ≤25% cover = 'poor'

health; 26–50% = 'fair'; 51–75% = 'good'; and >75% = 'excellent' and applied point estimates for finfish and seafood (including invertebrates) yields to each health category. 'Coral reef fishery yields and fish yields' express seafood catch as number of coral reef fish per reef area (Dalzell *et al.* 1996, p. 427); 'sustainable yield' reflects yields that remove only the annual surplus production without depleting the population biomass (Dalzell *et al.* 1996, p. 429). Similar to Newton *et al.* (2007), we consider coral reef fishery yields as comprising all finfish that derive energy from coral reefs and associated habitats for a major proportion of their lifespan, including coral reef and coral reef-associated fishes inhabiting coral-fringed mangroves and lagoons, sandy bottom and seagrass habitats, as examples, and which were represented in REA assessments (Conservation Society of Pohnpei 2006), fish surveys (Rhodes *et al.* 2008; this study) and coral cover assessments (this study).

Previous studies have shown coral reef fishery yields (seafood) vary from < 1–40 t km^{-2} yr^{-1}, depending on health, geographic location, fishing intensity and topography, among other factors (McAllister 1988; Russ 1991; Dalzell 1996; Polunin & Roberts 1996; Halls *et al.* 2006). Higher yields represent values for virgin or lightly fished reefs rarely observed today (but see Marten & Polovina 1982; Dalzell 1996; White *et al.* 2000; Maypa *et al.* 2002). In the FSM, including Pohnpei, reefs are no longer considered pristine (see Victor *et al.* 2006; Zeller *et al.* 2006, 2007; Houk *et al.* 2012). Globally, high yields (for example > 20 t km^{-2} yr^{-1}) are no longer widely valid, and average maximum sustainable yields are 5–8 t km^{-2} yr^{-1} with a range of 1–15 t km^{-2} yr^{-1} (Marshall 1980; McAllister 1988; McClanahan 1995; Dalzell 1996; Newton *et al.* 2007).

This study provides a range of optimistic (McAllister 1988) to pessimistic (Dalzell 1996) scenarios of total coral reef seafood yield and assigns point estimates to each reef health category (for example reefs with 'poor' health were assigned 1 t km^{-2} yr^{-1} for the pessimistic scenario and 3 t km^{-2} yr^{-1} for the optimistic scenario). We use 5–8 t km^{-2} yr^{-1} as a midpoint value. Based on these assumptions, under a pessimistic scenario, reefs in 'poor' health yield 1 t km^{-2} yr^{-1}, 'fair' = 4 t km^{-2} yr^{-1}, 'good' = 7 t km^{-2} yr^{-1}, and 'excellent' = 10 t km^{-2} yr^{-1}. Under an optimistic scenario, these values are 3, 8, 13 and 18 t km^{-2} yr^{-1}, respectively.

Finfish yields represent two-thirds of total coral reef seafood production (Cesar 1996). Fishing pressure also affects yields (McClanahan 1995; Jennings & Polunin 1996), with moderate-to-light pressure negligible, and heavy pressure reducing yields by 50% (Dalzell 1996).

Marine ecological footprint and consumption per person

Marine ecological footprint
The MEF estimated the coral reef area needed to supply the 2010 population of Pohnpei annually with finfish. To obtain the finfish (*FF*) MEF for Pohnpei (*P*) (= *MEF*$_{P, coral FF}$), the total (*T*) catch volume ($T_{P, coral FF}$ in t yr^{-1}) was divided by biocapacity (*BC*) ($BC_{P, coral FF}$ in t yr^{-1}):

$$\mathrm{MEF_{P,coral\,FF}} = \frac{T_{P,coral\,FF}}{BC_{P,coral\,FF}}$$

An MEF > 1 signifies demand exceeds biocapacity and is unsustainable; MEF = 1 is sustainable; and MEF < 1 indicates demand is below biocapacity. The MEF can also be expressed as the total reef area required to meet demand.

Per person consumption
We calculated the gross per person reef finfish consumption based on current estimated catch volumes divided by 2010 population estimates (Federated States of Micronesia 2013). Net finfish consumption per person was derived by multiplying gross consumption by 0.6 and 0.8 to obtain edible portions (FAO 1989; Bell *et al.* 2009). For total fresh finfish consumption, we added an additional 25% to net finfish consumption per person to reflect pelagic fish consumption (for example see Gillet 2009; Gillet & Lightfoot 2002). Finally, to estimate total finfish consumption and account for non-fresh fish (canned), we added an additional 8% to fresh finfish values (Bell *et al.* 2009).

Biological impacts from fishing

To examine whether the MEF reflected observed changes in local fish populations, we examined data from a long-term study (2001–2013) of a squaretail coralgrouper (*Plectropomus areolatus*) fish spawning aggregation (FSA) and interview-based assessments of the status of green humphead parrotfish (*Bolbometopon muricatum*) (Vulnerable A2d; Chan *et al.* 2007) and humphead wrasse (*Cheilinus undulatus*) (Endangered A2bd+3bd; Russell 2004). We also consulted published regional fishery-dependent assessments (Rhodes *et al.* 2011*b*; Houk *et al.* 2012; Bejarano *et al.* 2013) to gauge whether our MEF values could be considered as a valid indicator of anecdotal and peer-reviewed reports of overfishing.

For squaretail coralgrouper, the current study used data compiled during semi-monthly (March 2001–June 2002), seasonal (January–May 2003–2004) and bimonthly (March–April 2005–2013) density counts using underwater visual census (UVC) methods at the largest known FSA for this species in Pohnpei. Given its size and uniqueness on Pohnpei, and the dispersal range of fish from the FSA (≥ 25 km) (Rhodes & Tupper 2008), we considered this FSA an indicator of population status for the species.

Fish densities were counted perpendicular to two fixed transects during a total of three dives made over three consecutive days just prior to full moon (one dive per day) when the species is known to aggregate. Each of the two transects was 110 m long, with one placed at 30 m and the other at 15 m depth. Beginning five days before full moon (dbfm), the first count was made from the 15 m transect inward toward the reef crest to a distance of 15.2 m (shallow water: 110 m × 15.2 m, or 1672 m^2). Four dbfm, a second count was made

from the 15 m transect down to 30 m depth (original width = 50 feet or 15.2. m) (mid-range: 110 m × 15.2 m, or 1672 m^2). A third and final count was made along the 30 m transect to 42 m depth three dbfm, encompassing wall and slope habitats (deep water: 110 m × 24.4 m = 2684 m^2), for a total monitored area of 6028 m^2 over the three-day period. To examine long-term trends in density, we examined counts from each of the individual transects separately against year using a simple linear regression analysis following constant variance testing and Shapiro–Wilk's testing for normality. We present data as individuals per 1000 m^2. To verify that placement of these transects accounted for variations in density throughout the aggregation, technical diving was conducted in 2010 and 2011 along the full length of the FSA, including in areas where fixed transects were placed from 2001 to 2013 (Rhodes *et al.* 2014).

To examine decadal changes in green humphead parrotfish and humphead wrasse populations, we conducted semi-structured interviews with patriarch fishers in Chuuk (n = 7), Yap (n = 7), Pohnpei (n = 7) and Palau (n = 8) in 2012. Interviews were conducted with individuals at residences or meeting houses. Fishers were asked about decadal changes (1970–2010) in the size, abundance, behaviour, distribution and catch of these two long-lived and highly desirable finfishes. No other long-term empirical datasets for these or other coral reef finfishes are known to exist for the FSM.

RESULTS

Airport, business and household surveys

Examination of 72 outbound passengers revealed, on average, 3.4 individuals exported fish daily. Seventy-three per cent of fish originated from storefront markets, 21% from direct catch by the exporter, and 6% from both captured and bought fish. Surveyed individuals exported reef fish 1.2 ± 0.8 times yr^{-1}, with an average export volume of 17.3 ± 13.2 kg flight^{-1}, equivalent to 21 t yr^{-1}. No commercial export was recorded.

Twenty-one businesses, schools and restaurants were surveyed, representing all known entities selling prepared finfish. Ninety per cent of finfish came from storefront markets, with 10% bought directly from fishers. Weekly purchases ranged from 6.8 to 181.4 kg and averaged 27.5 ± 17.4 kg for all businesses, equivalent to 14 - 63 t yr^{-1}.

Three hundred and seventy-six households (63.3%) contained at least one fisher and 23.7% had at least one commercial fisher. Extrapolating this to the total population, Pohnpei has 3779 fishing households, with 2.1 commercial and 1.8 subsistence fishers household^{-1}, totalling 2976 and 4251 commercial and subsistence (7227 total) fishers. Fishers averaged 1.8 days (trips) week^{-1} fishing overall, with 1.2 days strictly for subsistence.

Commercial fishers captured significantly higher volumes of reef fish per trip than subsistence fishers (t-test, t_{183} = 8.04, p < 0.001), with 17.3 ± 1.4 (mean ± SE) kg trip^{-1} (n = 57) and 7.3 ± 0.5 kg trip^{-1} (n = 128) for subsistence fishers. Using 46

fishing weeks yr^{-1} (Kronen *et al.* 2007) together with average trip volumes and catch, annual commercial and subsistence catch was estimated at 2764 t (68% of the total catch) and 1304 t, respectively, or 4068 t in total.

Coral reef biocapacity

We estimated coral reef area in Pohnpei to be 154.4 km^2, including 23.1 km^2 of outer reef, 54.9 km^2 of shallow reef and 76.4 km^2 of inner reef (Fig. 1a). Coral cover was 0–80% and was rated as fair overall (mean = 33.0 ± 2.9%). In total, 79% of stations had poor or fair health status, while only 7% were excellent. Ant and Pakin averaged 39.4 ± 28.9% and 47.5 ± 15% coral cover, respectively. Combining reef area and coral cover estimates with health-based sustainable fishery yields, the coral reef biocapacity for Pohnpei (pessimistic to optimistic range, respectively) was 740–1439 t yr^{-1}. Ant provides an additional 17.7 km^2 of reef area and Pakin another 12 km^2, giving a total reef area of 184 km^2. The total coral reef biocapacity was 859–1678 t yr^{-1}.

We estimated finfish production at 493–959 t yr^{-1} for Pohnpei and 573–1118 t yr^{-1} when Ant and Pakin were included. Heavy fishing pressure, which characterizes Pohnpei, could reduce these yields by up to half. As such, results presented here for yields and biocapacity are likely to be conservative.

Marine ecological footprint and consumption per person

We estimated a total finfish catch volume of 4068 t yr^{-1} and a finfish biocapacity of 573–1118 t yr^{-1}. Based on these figures, Pohnpei's MEF ranges from 3.6 to 7.1, or 360 to 710% over biocapacity. The finfishery would require up to 1017 km^2 of reef area to satisfy current reef fish landings, or 833 km^2 of reef beyond that currently within the range of the fishery.

For Pohnpei, our estimated per person (edible) coral reef fish consumption was 70–93 kg person^{-1} yr^{-1}. Inclusion of pelagic species increased the per person fresh fish consumption to 87–116 kg person^{-1} yr^{-1}, and further factoring in non-fresh fish consumption in our estimates increased this figure to 94–126 kg person^{-1} yr^{-1}.

Impacts of fishing in Pohnpei

Regression analysis of UVC transect data indicated significant declines within all three areas of the FSA surveyed (shallow water: $F_{1,25}$ = 8.67; p < 0.01, α = 0.05; $R^2_{adj.}$ = 0.228; mid-range: $F_{1,36}$ = 9.82; p < 0.01l; $R^2_{adj.}$ = 0.193; deep water: $F_{1,31}$ = 5.05; p < 0.04; α = 0.05; $R^2_{adj.}$ = 0.112) in FSA density of squaretail coralgrouper over 13 years (Fig. 2). Fisher interviews (n = 29) revealed an average decline in mean abundance and size of 71% and 80%, respectively, for green humphead parrotfish from 1970–2010 and a 70% drop in mean abundance and size for humphead wrasse across the four jurisdictions surveyed. Changes in habitat were also noted,
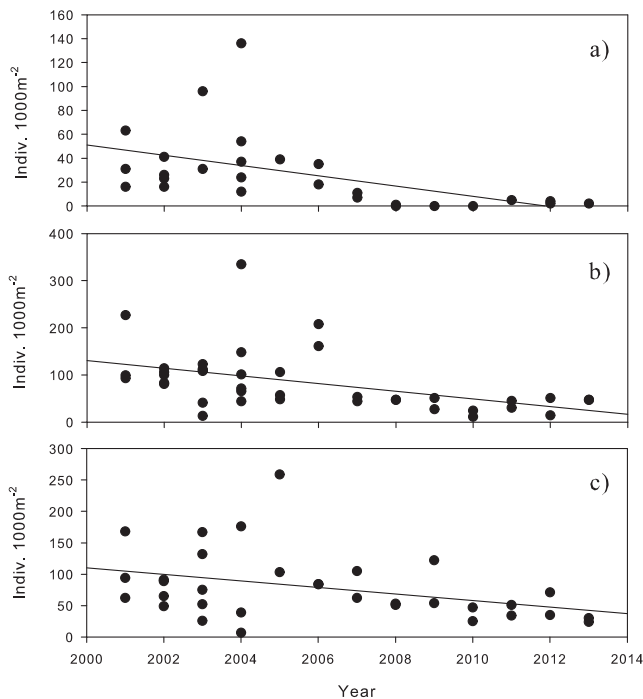
Figure 2 Annual trends (2000–2013) in density (number of individuals m^{-2}) of squaretail coralgrouper *Plectropomus areolatus* as assessed by underwater visual census along fixed transects in (*a*) shallow water (≤15 m), (*b*) mid-range (15 m–30 m) and (*c*) deep water (≥30 m) areas within the Kehpara Marine Sanctuary fish spawning aggregation.

with green humphead parrotfish once common in shallow reef areas (10–12 m) in the 1970s, and now only common below 30 m depth.

DISCUSSION

This study represents the first island-level survey merging catch volume data taken directly from the finfishery with individual coral reef area and health data to produce an MEF. We identified a fishery 360–710% above biocapacity. Compared to previous findings, this study characterizes Pohnpei's finfishery more broadly by including subsistence and other non-marketed catch, and demonstrates that subsistence fishers, while constituting 58% of the fishery, were responsible for only 32% of the total catch. Significantly, Pohnpei's high commercial catch is almost exclusively for domestic consumption, with exports accounting for only 2.2% of the total.

Contributing to Pohnpei's high MEF is an expanding fishery of more than 7200 fishers, many solely reliant on fishing for income. These same fishers overwhelmingly use unsustainable harvesting practices, including nighttime spearfishing (Rhodes *et al.* 2008) and small-mesh (2-cm) nets, commonly exceeding 50 m in length, that non-selectively target a wide range of species. The fishery also targets spawning aggregations and juveniles comprising up to 70%

of the total catch (Rhodes & Tupper 2008). Fisheries-induced impacts catalogued include population-level changes to commercially important species (Rhodes *et al.* 2011*b*), significant declines in grouper FSA fish density (Rhodes *et al.* 2014), and reductions in abundance and mean size for iconic species (such as humphead wrasse), and herbivorous and corallivorous species critical to ecosystem function (Bejarano *et al.* 2013).

MEF and per person consumption in a regional context

The 70–93 kg yr^{-1} finfish consumption in Pohnpei ranks among the highest for PICTs. Previous per person consumption estimates can also be used to generate MEFs by combining current population and reef area parameters. For example, Bell *et al.* (2009) estimated 96.0 ± 6.4 kg person^{-1} yr^{-1} for FSM (based on coastal values), producing an MEF for Pohnpei of 5.4–6.2.

There are limitations to MEF data. Incorporation of fishing pressure can decrease biocapacity by up to half, thereby doubling MEF estimates. Conversely, adding lagoon area as an additional source of productivity increases production estimates. Published yield values from coral reefs and adjacent habitats range from 2.5 to 5 t km^{-2} yr^{-1} (Marshall 1980), which would increase yield by 500–1000 t, reducing our MEF to 1.9–3.8. Such simple sensitivity analyses show that the assumptions underlying MEFs impact the results. Other limitations include, for example, the brevity of airport and business surveys, and coral reef fish yield estimates for subsistence fishing and non-market fish sales (direct sales to households), which were reliant on indirect estimates of fish volume based on household interviews. While refinements are possible, the MEF remains a simple tool, easily understood by fishers and policymakers for assessing coral reef fishery status in developing communities, particularly where technical and economic resources are limited. The coral reef MEF can also play a role in quantifying the linkages between coral reef health, biocapacity, fishing practices, exploitation, sustainability and ecological goods and services in support of management wherever data are scarce (Moberg & Folke 1999; Newton *et al.* 2007).

Ecosystem and biological effects corroborate high MEF

In Pohnpei, commercial finfish landings have been identified as 8–9 times greater than other regional jurisdictions (Yap, Guam and the Commonwealth of the Northern Mariana Islands), despite a reef area only 2–3 times larger (Houk *et al.* 2012). Regionally, Pohnpei had the most commercial species under size at sexual maturity in catches, including the greatest percentage of under-sized herbivores (Bejarano *et al.* 2013). Commercial catches also included the greatest overall abundance of higher tropic level species (Houk *et al.* 2012), many which were immature (see Rhodes & Tupper

2007). These factors, combined with FSA targeting, set the stage for impacts of trophic structure, biodiversity and reef function (for example Sæther 1999; Bellwood *et al.* 2003; Frank *et al.* 2005; Mumby 2006). For Pohnpei, concerns about ecosystem effects from the targeting of macroalgal browsers have already been raised (Bejarano *et al.* 2013), and some former coral-dominated areas are now being overtaken by macroalgae (Conservation Society of Pohnpei 2006).

Anecdotal evidence from fisher interviews and previous rapid ecological assessments also indicated large-scale declines in adults of ecologically important long-lived and late maturing fishes (such as coastal sharks, *B. muricatum* and *C. undulatus*) (Conservation Society of Pohnpei 2006). Allen (in Conservation Society of Pohnpei 2006) documented mostly juvenile *C. undulatus*, while the Conservation Society of Pohnpei (2006) reported low abundances of many targeted reef-fish species. Anecdotal reports also indicate precipitous declines in giant clam (*Tridacna* sp.), coconut crab (*Birgus latro*) and marine turtles (Superfamily Chelonioidea) over the past four decades, which relate to increases in commercial fishing since the 1960s (Rhodes *et al.* 2011*b*). The MEF reflects these wider changes.

Management and enforcement opportunities for improved sustainability

There is urgent need for management strategies that mitigate unsustainable harvest practices and protect juveniles and reproductively active fishes. Actions may include temporal and area restrictions around spawning times, gear and size-at-catch limits, effort reduction, bans or moratoria on the harvest of vulnerable and endangered species, and market mechanisms that increase economic returns to fishers. Given the dominance of undersized fish in catches, the elimination especially of small-mesh nets and night-time spearfishing appears paramount to reducing growth overfishing and depletion of species important to ecosystem maintenance (Bejarano *et al.* 2013). Minimum size-at-sale regulations are needed for some important finfish species, particularly late maturing and long-lived species. As reported by Gillet (2009), enforcement is largely ineffective and marine tenure is absent.

Fishers in Pohnpei are concerned about resource decline and desire reforms that improve their livelihoods (K. L. Rhodes, unpublished data 2013). Given fisher observations of resource declines and inadequacies in the government's management response over at least four decades, local support exists for legislative action and alternative management strategies, particularly expanded enforcement efforts.

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