Global Effects of Local Human Population Density and Distance to Markets on the Condition of Coral Reef Fisheries

JOSHUA E. CINNER,*# NICHOLAS A. J. GRAHAM,* CINDY HUCHERY,* AND M. AARON MACNEIL†

*Australian Research Council Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, QLD 4811, Australia
†Australian Institute of Marine Science, PMB 3 Townsville MC, Townsville, QLD 4810, Australia

Abstract: Coral reef fisheries support the livelihoods of millions of people but have been severely and negatively affected by anthropogenic activities. We conducted a systematic review of published data on the biomass of coral reef fishes to explore how the condition of reef fisheries is related to the density of local human populations, proximity of the reef to markets, and key environmental variables (including broad geomorphologic reef type, reef area, and net productivity). When only population density and environmental covariates were considered, high variability in fisheries conditions at low human population densities resulted in relatively weak explanatory models. The presence or absence of human settlements, habitat type, and distance to fish markets provided a much stronger explanatory model for the condition of reef fisheries. Fish biomass remained relatively low within 14 km of markets, then biomass increased exponentially as distance from reefs to markets increased. Our results suggest the need for an increased science and policy focus on markets as both a key driver of the condition of reef fisheries and a potential source of solutions.

Keywords: fisheries, human-environment interactions, social-ecological systems, socioeconomics

Efectos Globales de la Densidad de Población Humana Local y la Distancia a los Mercados sobre la Condición de Pesquerías en Arrecifes de Coral

Resumen: Las pesquerías en arrecifes de coral soportan a millones de personas pero han sido severamente y negativamente afectadas por actividades antropogénicas. Realizamos una revisión sistemática de datos publicados sobre la biomasa de peces de arrecifes de coral para explorar la relación entre la condición de las pesquerías en arrecifes y la densidad de las poblaciones humanas locales, la cercanía del arrecife a los mercados y variables ambientales clave (incluyendo el tipo de arrecife geomorfológico, la superficie del arrecife y la productividad neta). Cuando solo se consideraron covariables de densidad y hábitat, la alta variabilidad en las condiciones de la pesquería a densidades bajas de la población humana resultó en modelos explicativos relativamente débiles. La presencia o ausencia de asentamientos humanos, el tipo de hábitat y la distancia a los mercados de pescado proporcionaron un modelo explicativo mucho más robusto para a condición de las pesquerías en arrecifes. La biomasa de peces permaneció relativamente baja a menos de 14 km de los mercados, pero más allá de 14 km la biomasa incrementó exponencialmente a medida que incrementó la distancia entre arrecifes y mercados. Nuestros resultados sugieren que los mercados, como un factor clave de la condición de las pesquerías en arrecifes y como una potencial fuente de soluciones, requieren una mayor atención de la ciencia y la política.

Palabras Clave: Interacciones humano-ambiente, pesquerías, sistemas socio-ecológicos, socioeconomía

#email joshua.cinner@jcu.edu.au
Paper submitted February 1, 2012; revised manuscript accepted June 9, 2012.
Introduction

The condition of coral reefs, the fisheries they support, and their related ecosystem functions are all negatively associated with local human population size and density (e.g., Bellwood et al. 2011; Mora et al. 2011). At the local level, human population density can be related to several key mechanisms that may directly affect reefs, including fishing effort, nutrient loading through fertilizer use, and coastal construction (Mora et al. 2011). Scientific understanding of the severity of human effects on reef systems has been shaped in a large part by the results of studies demonstrating relations between human populations and the condition of coral reefs (e.g., Bellwood et al. 2011; Mora et al. 2011). However, many of these studies failed to consider the role of other social and economic drivers of exploitation, such as market access and development. Consequently, researchers have tended toward Malthusian conclusions and policy prescriptions that favor the exclusion of humans, such as establishing fisheries closures and controls on human populations (Mora et al. 2011). The danger in focusing solely on human population size or density is that other important drivers of unsustainable exploitation may be largely ignored by managers and policy makers (Berkes et al. 2006) and thus lead to insufficient governance and diminished outcomes. In particular, results of local and regional studies show that alternative social and economic drivers such as markets and economic development can affect fisheries as much as local human population size or density (e.g., Cinner & McClanahan 2006; Cinner et al. 2009; Brewer et al. 2012). Here, we explored whether local and regional studies of socioeconomic drivers among reef fisheries are applicable at larger spatial extents by conducting a global analysis that considers how environmental conditions, local human population density, and proximity to markets explain the condition of coral reef fisheries.

Methods

We conducted a systematic literature search with Google Scholar to identify relevant peer-reviewed studies of coral reefs. Our search terms were “biomass” + “reef” and “biomass” + “fish.” To be included in our analyses, the study had to examine total reef-associated fish biomass, including all major trophic groups and families of fish (excluding cryptic or nocturnal groups in most cases because they likely contribute very little to total biomass of reef fishes); provide enough information that each site could be located with geographic information system (GIS) software; report biomass values in a format that could be extracted from the text, graphics, tables, or appendix; and report data for fished sites. No-take protected areas were excluded. An exception to the last criterion was that we included several remote protected areas that had been designated as no-take areas just before sampling (approximately 3 years). In these areas it would be unlikely for ecological outcomes of protection to affect the biomass of fishes (McClanahan et al. 2007). In cases where fish biomass at a single site was reported in multiple studies, we used the most recent study.

Our analyses included 17 studies and 102 comparable records of fish biomass from 16 countries (Supporting Information). We standardized biomass for analyses (grams per square meter). We collected data on human population density on land from the Socioeconomic Data and Application Centre (SEDAC) gridded population of the world database (CIESIN & CIAT 2005) (Supporting Information). We used ARC GIS software to access spatial data on the main cities and provincial capitals of the world and calculated the shortest distance from the reef to the closest provincial capital as a measure of distance to market. Human population density and distance to market were uncorrelated ($r = -0.24$).

We also examined relations between fish biomass and key environmental variables hypothesized to influence the condition of reef fisheries (Supporting Information): distance to the nearest border of the Coral Triangle (an area of high coral reef species richness that encompasses Indonesia, Malaysia, Philippines, Papua New Guinea, Timor-Leste, and Solomon Islands); reef area (provided within each study and standardized to square kilometer); ocean productivity (average monthly ocean net primary production for 2005–2010 in milligrams carbon per square meter per day [O’Malley 2011]); and broad geomorphology (island, continental, or atoll or bank) determined from ReefBase (Tupper et al. 2011). Results of other studies conducted at a finer scale show relations between fish biomass and other environmental variables (e.g., habitat complexity and substrate type [e.g., Cinner et al. 2009]); however, these variables were not readily available from most studies.

We used a suite of Bayesian negative-binomial models to examine how estimates of reef fish biomass relate to local population density, distance to market, and environmental variables as potential drivers of fisheries conditions (Supporting Information). We developed a set of candidate negative-binomial models that expressed different relations between biomass and these potential drivers of fisheries conditions (Supporting Information). These models included a null (intercept-only) baseline model; linear and quadratic models to capture linear or curvilinear relations respectively; mean-switchpoint and piecewise linear models to capture threshold behavior (i.e., a marked change in the relation between an ecosystem driver and associated state variable); and a composite dual piecewise linear model that allowed for different market effects between populated and unpopulated areas (Supporting Information). In particular, we were interested in evidence of threshold behavior and the
potential for differential effects of markets between populated and unpopulated areas. In addition, we ran the models both with and without data from the northwestern Hawaiian Islands, where fishing was prohibited shortly before the surveys had been conducted (Williams et al. 2011). To make exact inference on the basis of our data and given our set of nonstandard models, we used the PyMC MCMC package (Patil et al. 2010) for the Python programming language to develop Bayesian models (http://python.org). To compare relative evidence for each model, we used the deviance information criterion (DIC). We checked for evidence of model fit with Bayesian p values (Gelman et al. 2004). We considered models with DIC values >2 units lower than the next ranked model and weights >0.60 to have substantial evidence of being the best model.

**Results**

At a country level, Kiribati, Belize, and the Netherlands Antilles had the highest average fish biomass, but there were few records for these areas (Fig. 1(a)–(b)). The United States (which had 29 records, separated into Caribbean and Pacific reefs) had high average biomass and the highest published values of biomass. Despite having well-studied reefs, Australia had published biomass estimates for a limited number of species; thus, these estimates could not be compared with estimates from other regions and were consequently not included in our analyses.

Exploratory analyses revealed no relations between fish biomass and most of the environmental variables that we hypothesized would affect the condition of reef fisheries (distance to Coral Triangle, $r = 0.025$, $n = 102$, $p = 0.804$; reef area, $r = 0.140$, $n = 63$, $p = 0.272$; ocean productivity, $r = −0.047$, $n = 102$, $p = 0.641$ [Supporting Information]). Except for broad geomorphology, with fish biomass significantly higher in atolls ($F_{2,99} = 37.0$, $p < 0.001$), these factors were excluded from further analyses.

Our first set of models followed convention and examined how well human population density and environmental variables explained fish biomass. In the model with the highest weight of evidence, fish biomass declined exponentially as human population increased and was higher in atoll reefs (Fig. 2a). However, high variability of fish biomass at sites with low human population density was not well captured by this relation. For example, unpopulated sites had an extremely wide range of biomass values, 25–384 g/m$^2$. Thus, local human population density did not explain fish biomass particularly well for less-populated sites. However, population density appeared to constrain fish biomass because there were no sites with high population density and high fish biomass, whereas unpopulated sites contained the highest biomass.

Given the high biomass values among unpopulated sites, we examined the relation between fish biomass and distance to market in the presence or absence of humans and found that reef fish biomass was better explained by including proximity to markets than by environment and population density alone. Biomass remained relatively unchanged from 0 to 14 km from markets (5.4–89 km 95% CI) but then increased exponentially with distance to market along separate populated and unpopulated
trajectories given geomorphology (Fig. 2b & Supporting Information). That biomass increased as distance to market increased among unpopulated sites helped explain the high variability in reef fish biomass at sites with no local human population. These results did not change substantively when data from the northwestern Hawaiian Islands were excluded (Supporting Information). In particular, with the northwestern Hawaiian Islands excluded, the model with the highest weight of evidence was a piecewise model that included distance to market (84% of the weight of evidence), and the model with the second-highest weight of evidence was a dual piecewise model of population and distance to market similar to the relation shown in Fig. 2b (10% of the weight of evidence). Thus, distance to market is a critical factor both with and without inclusion of the recently protected northwestern Hawaiian Islands.

Discussion

Our analyses revealed 2 key findings. First, reef fish biomass is constrained by density of the local human population (i.e., there were no sites with high population and high fish biomass), but high variability in fish biomass at low densities of human population resulted in weak explanatory power. Importantly, many sparsely populated and uninhabited sites appeared heavily exploited. This finding suggests that something in addition to local population density is affecting the condition of reef fisheries.

Another key finding was that distance to market had a strong explanatory role in the structure of reef fish biomass globally. That reef fish biomass declines as human population density increases has been reported previously (Bellwood et al. 2011; Mora et al. 2011); however, the majority of studies among reef systems have not examined the influence of markets (but see Cinner & McClanahan 2006; Brewer et al. 2012; Cinner et al. 2012). Our results are broadly consistent with those of several field-based studies from the Indo-Pacific which show that the condition of reef fisheries is better explained by distance to market and economic development than by density of local human population alone (Cinner & McClanahan 2006; Cinner et al. 2009). Our analyses extend these regional findings to a global extent, and our results provide additional evidence of the role of both populations and markets in driving the exploitation of reef fisheries. Reef fisheries near markets were generally in poor condition, but conditions started to improve approximately 14 km away from markets. This finding may be a function of transportation costs, the relatively low value of most demersal reef fish (although some fish sold live in the aquarium trade and trade in live reef food fishes can be expensive), and the economics associated with fish preservation (frozen or dried reef fish often fetch a lower price than fresh), which together may reduce incentives for harvesting demersal fishes far from markets. Additionally, markets can profoundly influence how common-pool resources, such as fisheries, are used and managed in ways that can directly affect reef systems. Markets may provide incentives to exploit reef species that may not have been harvested previously (e.g., live-reef food fish, beche-de-mer, sea urchins; Berkes et al. 2006; Scales et al. 2006): provide more stable prices for fish, which can create incentives for continuous harvests (Schmitt & Kramer 2010); and contribute to the breakdown of common-property management systems that regulate resource use (Ruddle 1994). However, the role of markets on resource management is not always negative. Where strong common-property institutions exist, commercialization of resources can create incentives to limit access (Hviding 1996), and consumer-driven certification programs have the potential to create incentives for sustainable fishing (Gulbrandsen 2009).

Human effects on the local environment are not only a function of population size, but also of factors such as the technology used to extract resources, people’s capacity to spatially displace negative environmental effects, demand for specific goods and services, and institutions
and governance systems (e.g., Arrow et al. 1995; York et al. 2003; Dietz et al. 2007). Despite the large scale of our study, the available data made it impossible to incorporate the multitudes of potentially important social and economic drivers or even to tease apart how our distance proxy for markets may be related to population effects at larger regional and national extents. Additionally, national-level social and economic drivers such as gross domestic product and human development may in turn modify these relations. Unfortunately, the scarcity of biomass records for many countries precluded closer analyses of these multiscale relations. Likewise, even though we found that our 2 indicators of human exploitation explained more variation in reef fish biomass at the scale of our study than the environmental variables we tested, a number of potentially important habitat variables (e.g., structural complexity [Cinner et al. 2009]) and social and economic conditions (e.g., proportion of fish traded nationally vs. exported at each market, or whether fisheries were primarily for local consumption or commercial sale) were not available consistently across the studies we included in our analyses. For example, we suggest that the effects of transport surfaces (e.g., paved road, dirt road, water) and levels of infrastructure (e.g., jetties and storage facilities) may influence transportation costs and the effective reach of markets (what geographers refer to as the friction of distance).

Despite these limitations, 2 key science, policy, and management implications arise from our results. First, many reefs in unpopulated areas and in areas of low population density were heavily exploited, contrary to the suggestion that where densities of human populations are low it is unlikely reef fisheries will be overharvested (Foale et al. 2011). We suggest that even coral reef fisheries that are not near population centers need active local management, including policies such as marine protected areas, restrictions on gear use, and reductions in fishing effort (McClanahan et al. 2011). Many researchers use population density as a proxy for fishing intensity when examining effects of humans on marine systems and when using conservation planning tools to develop spatial use maps (e.g., Halpern et al. 2008), but our results suggest that it may also be important to incorporate market effects.

Second, scientists, managers, and policy makers need to explicitly consider the role of alternative socioeconomic drivers, such as markets, in shaping the way resource users exploit coral reef fisheries. The policy instruments most appropriate for managing the effects of local human population density on reef fisheries differ from those appropriate for market based drivers of resource depletion, and our results suggest that both approaches will be crucial for sustaining reef fisheries. We believe anthropologists, economists, and interdisciplinary social scientists need to play a central role in defining the problems and potential solutions to making reef fisheries more sustainable by developing a comprehensive research agenda on markets for reef fishes (e.g., Schmitt & Kramer 2010). To date, this research has largely concentrated on trade in live reef fishes for human consumption (e.g., Scales et al. 2006), but we suggest it be expanded to consider both local and national markets for reef fishes. Managers and policy makers not only require advice on how the negative effects of markets on marine resources can be dampened (Berkes et al. 2006; Schmitt & Kramer 2010), but also on how potential tools of market-based management (e.g., sustainable certification, transferable quotas, adding value to products, providing links to more profitable markets, etc.) can be used effectively among coral reef nations that tend to have poor governance and a populace with low incomes. Some market-based schemes for management of terrestrial resources, such as community markets for conservation (Lewis et al. 2011), serve as good examples and may be applicable to reef fisheries.

Acknowledgments

We thank T. McClanahan and C. Mora for their useful comments on preliminary drafts of the manuscript. We also thank J. Kool for his invaluable assistance in georeferencing the primary productivity data.

Supporting Information

Supplemental methods, modeling, and analyses (Appendix S1), deviance-information-criterion (DIC)-based evidence for top-ranked negative binomial models among published studies (Appendix S2), parameter estimates for top DIC-ranked negative binomial model (Appendix S3), DIC-based evidence for top-ranked negative binomial models among published studies except those from the northwestern Hawaiian Islands (Appendix S4), parameter estimates for top DIC-ranked negative binomial model with sites from the northwestern Hawaiian Islands excluded (Appendix S5), studies included in the analyses (Appendix S6), and a graph of reef fish biomass in unpopulated and populated sites (Appendix S7) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of material) should be directed to the corresponding author.

Literature Cited
