American Fisheries Society Symposium 83:17–42, 2015
© 2015 by the American Fisheries Society

Building an Expert-Judgment-Based Model of Mangrove Fisheries

JAMES HUTCHISON*
Department of Zoology, University of Cambridge
Downing Street, Cambridge CB2 3EJ, UK

DAVID P. PHILIPP
Illinois Natural History Survey, University of Illinois
1816 South Oak Street, Champaign, Illinois 61820, USA
and
Department of Natural Resources and Environmental Sciences
University of Illinois
1102 South Goodwin Avenue, MC 047, Urbana, Illinois 61801, USA
and
Fisheries Conservation Foundation
1816 South Oak Street, Champaign, Illinois 61820, USA

JULIE E. CLAUSSEN
Illinois Natural History Survey, University of Illinois
1816 South Oak Street, Champaign, Illinois 61820, USA
and
Department of Natural Resources and Environmental Sciences
University of Illinois
1102 South Goodwin Avenue, MC 047, Urbana, Illinois 61801, USA

OCTAVIO ABURTO-OROPEZA
Center for Marine Biodiversity and Conservation
Scripps Institution of Oceanography
9500 Gilman Drive, La Jolla, California 92093, USA

MAURICIO CARRASQUILLA-HENAO
Department of Biology, University of Victoria
3800 Finnerty Road, Victoria, British Columbia V8W 3N5, Canada

GUSTAVO A. CASTELLANOS-GALINDO
Marine Programme, WWF Colombia
Carrera 35 No. 4A-25, Cali, Colombia
and
Leibniz Center for Tropical Marine Ecology (ZMT)
Fahrenheitstrasse 6, Bremen 28359, Germany
and

---

* Corresponding author: jtwh3@cam.ac.uk

Grupo de Investigación en Ecología de Estuarios y Manglares
Departmento de Biología, Universidad del Valle
Calle 13 #100-00, Cali 25360, Colombia

MATTHEW T. COSTA
Center for Marine Biodiversity and Conservation
Scripps Institution of Oceanography
9500 Gilman Drive, La Jolla, California 92093, USA

PEDRAM D. DANESHGAR
Marine and Environmental Biology and Policy Program, Monmouth University
400 Cedar Avenue, West Long Branch, New Jersey 07764, USA

HANS J. HARTMANN
LIttoral, ENvironnement et Sociétés (LIENSs), Université de La Rochelle
UMR 7266 CNRS-ULR, 2 rue Olympe de Gouges, La Rochelle Cedex 17000, France

FRANCIS JUANES
Department of Biology, University of Victoria
3800 Finnerty Road, Victoria, British Columbia V8W 3N5, Canada

MUHAMMED NAEEM KHAN
Department of Zoology, University of the Punjab
New Campus, Lahore 54890, Pakistan

LINDY KNOWLES
Bahamas National Trust
Post Office Box N-4105, The Retreat, Village Road, Nassau, The Bahamas

ERIC KNUDSEN
Ecologists Without Borders
606 Columbia Street NW, Suite 106, Olympia, Washington 98501, USA
and
Sustainable Fisheries Foundation
601 Rainier Street, Snohomish, Washington 98290, USA

SHING YIP LEE
Australian Rivers Institute and School of Environment, Griffith University
Gold Coast Campus, Southport, Queensland 4222, Australia

KAREN J. MURCHIE
Department of Biology, College of The Bahamas
Post Office Box F-42766, Freeport, Grand Bahama, The Bahamas

JOHN TIEDEMANN
Department of Biology, Monmouth University
400 Cedar Avenue, West Long Branch, New Jersey 07764, USA

PHILINE ZU ERMGASSEN
Department of Zoology, University of Cambridge
Downing Street, Cambridge CB2 3EJ, UK

Mark Spalding
Department of Zoology, University of Cambridge
Downing Street, Cambridge CB2 3EJ, UK
and
Global Marine Team, The Nature Conservancy
Department of Zoology, University of Cambridge
Downing Street, Cambridge CB2 3EJ, UK

Abstract.—Mangroves are critically important habitats for fisheries, both for their resident fish, crustacean, and mollusk populations and as nursery grounds for the target species of offshore fisheries. However, the spatial variation in the benefits provided by mangroves to fisheries is poorly understood. Based on expert knowledge of mangrove ecology and fisheries biology, we developed a preliminary model of the spatial distribution of benefits to fisheries from mangroves. The preliminary model covers the environmental factors that determine the amount of fish, crustaceans, mollusks, and other fishery target species produced by mangrove areas (termed “potential fish production”) and the socioeconomic variables that determine the level of fishing in any given location. The combination of these two outputs gives the predicted catch. Potential fish production is predicted to be highest where there is high freshwater and nutrient input to mangroves, such as in large estuaries. At large seascape scales, total mangrove area is also an important driver. Fishing effort is highest close to human populations, which provide both the fishers and the markets for their catch. The model is qualitative and has not been parameterized with field data and, as such, should only be considered as a first step towards understanding the spatial variation in the benefits that mangroves provide to fisheries.

Introduction

Mangrove forests are critically important fish habitats, both as nursery grounds (Manson et al. 2005; Nagelkerken et al. 2008) and in supporting large populations of resident fish (Castellanos-Galindo et al. 2013). Mangroves enhance fish communities by providing refuge from predation and sustaining high levels of primary productivity (Alongi 2009), which in turn serves as the basis of a complex food web. The importance of mangroves for fish also makes them important for people. In the Gulf of California, for example, mangrove-related species make up 32% of the small-scale fisheries in the region, giving the mangrove fringe a median value for fisheries of US$37,500/ha (Aburto-Oropeza et al. 2008). Paw and Chua (1991) find a similar figure of 32% for Malaysian fisheries and a much higher figure of 72% for the Philippines.

Mangroves provide a range of other valuable ecosystem services in addition to fish production, including coastal protection, carbon storage, and sediment trapping (Lee et al. 2014). Mangroves provide coastal protection by physically slowing the movement of water as it passes through the aerial root systems (Alongi 2008; McIvor et al. 2012a, 2012b). This function also serves to trap sediments that settle out of the water column as the flow rate decreases (Victor et al. 2004), protecting adjacent ecosystems such as coral reefs and sea grasses that are vulnerable to sedimentation. Carbon is stored both in the aboveground biomass of the mangroves and in the sediments, with soil carbon values averaging 1,023 Mg/ha in Indo-Pacific forests (Donato et al. 2011). The sum value of the many ecosystem services mangrove forests provide is therefore potentially high. For example, in Southeast Asia, ecosystem services from mangroves have been estimated to have a mean value greater than $4,000/ha (Brander et al. 2012).

While mangroves are extremely valuable, they are also highly threatened. As much as a third of the world's mangroves have been lost over the past 50 years, largely through conversion for aquaculture or agriculture, and mangrove deforestation rates have remained among the highest of any forest type (Duke et al. 2007; Spalding et al. 2010; Van Lavieren et al. 2012). Mangrove deforestation has had major impacts on fisheries; in the Gulf of Thailand alone, the cost of mangrove loss to fisheries was estimated at $12,000–408,000 per year in the early 1990s (Barbier et al. 2002). The protection and restoration of mangroves is therefore gaining political and economic support (e.g., Cayubit 2014; Vong 2014).

Our understanding of the value of the ecosystem services that mangroves provide is growing (e.g., Barbier 2012; Siikamäki et al. 2012; Pendleton et al. 2012). Nevertheless, the spatial variability in ecosystem service provision remains poorly quantified for most services, including fisheries. A better understanding of this variability is needed both for more robust valuation and to comprehensively incorporate ecosystem services into management practices (Koch et al. 2009). Information on the spatial distribution of ecosystem service provision would also be valuable for decision makers and conservation practitioners seeking to maximize conservation with limited resources.

Expert judgment is one option for developing ecosystem service models in the absence of complete data. Examples of the use of expert judgment include the development of matrix models that estimate the delivery of a suite of different services for each land cover type within a landscape (e.g., Costanza et al. 1997; Burkhard et al. 2012). However, expert judgment can also be used to develop models for delivery of specific services by specific ecosystems (e.g., Lonsdorf et al. 2009; Haines-Young 2011).

Here, we describe the use of expert judgment to develop a conceptual model of mangrove fishery catches. We then used available global data sets to represent the key drivers in this model, allowing us to qualitatively predict mangrove fishery catches. The model was developed prior to, during, and after a small expert workshop, held within The Second International Symposium on Mangroves as Fish Habitat in Mazatlán, Mexico in April 2014. This is an initial attempt at model development based on a short and relatively simplistic expert consultation process. As such, the results should primarily be considered a proof of concept rather than a finished work, although we believe that even at this stage the model offers some useful insights into the drivers of mangrove fisheries and the spatial variability in the relative importance of this ecosystem service around the globe.

Methods

Conceptual framework

We used a four-stage process to model the benefits that humans derive from fish production by mangroves. The four stages are

1. **Potential fish production:** This is the amount of fish, crustaceans, mollusks, and other fishery target species predicted to be produced by a pristine system, free from human influences. It is based purely on the environmental drivers, of which mangrove extent is one.
2. **Fish production:** This is the amount of fish predicted to be produced by the system, once the influence of human activities such as fishing, pollution, and mangrove degradation is taken into account.
3. **Modeled catch:** This is the amount of fish predicted to be caught. It depends on fish production, as well as fishing effort,

which is driven by socioeconomic factors, particularly population density.

4. **Modeled value:** This is the value of the modeled catch. This can be measured as the market value of the fish caught, which depends on the fish species and on various socioeconomic factors, or it can be measured in terms of the protein that the fishery produces, the people it feeds, or the livelihoods it supports.

In this study, we develop a model for the potential fish production. We then develop a model for fishing pressure and use this to calculate the modeled catch. In this first version of the model, we do not consider the difference between potential fish production (from a theoretical pristine system) and fish production (from a system influenced by human activities such as fishing, pollution and degradation). We also did not incorporate value into our model for reasons discussed below.

Workshop methodology

Prior to the workshop, we compiled a list of potential drivers of mangrove fishery value from a literature review (Hutchison et al. 2014a). We convened an expert workshop to discuss, advise, and drive the selection and weighting of these drivers in the model. Initially, the participants were briefed on the approaches used in developing conceptual models of this sort. A simple conceptual model developed by two of us (J. Hutchison and M. Spalding) prior to the workshop was presented together with an explanation of the sort of data sets that might be used to represent the drivers in the model. Each driver was then discussed to elucidate its relationship and relative importance to mangrove fisheries and thus its role in our overall model. This process had three stages:

1. Discussion of environmental and human impact drivers: This was carried out in three groups, with participants assigned to groups based on their expertise. Following the group discussion, each group described their conclusions to the rest of the participants giving them the opportunity to add further input.
2. Discussion of socioeconomic drivers: This was carried out with all participants present.
3. Voting: The relative importance of each driver in the model was assessed through a voting process. Each participant was given three votes to assign to environmental drivers and two for socioeconomic drivers, reflecting the greater number of environmental variables in the model.

The final selection of drivers for the model was driven by feedback from the workshop on which drivers were most important. However, it was also limited by the drivers for which global spatial data sets were either readily available or could be easily developed from existing data sets.

Environmental drivers.—In our conceptual model (Figure 1), potential fish production is determined by environmental factors. All the environmental drivers considered at the workshop are listed below, along with a summary of the conclusions reached. The voting scores for these drivers are shown in Table 1. Based on the workshop conclusions and voting, we used mangrove area, mangrove biomass (as a proxy for primary productivity), freshwater input, and nutrient input as our driver variables in the model of potential fish production.

- **Mangrove area/linear extent:** The benefits to fisheries from mangroves are likely to be proportional to the area of mangrove. Numerous studies have demonstrated relationships between different aspects of mangrove area and fishery yields in different parts of the world (e.g., de Graaf and Xuan 1998; Carrasquilla-Henao et al. 2013). Habitat benefits to fisheries come primarily from the area of mangroves that are in contact

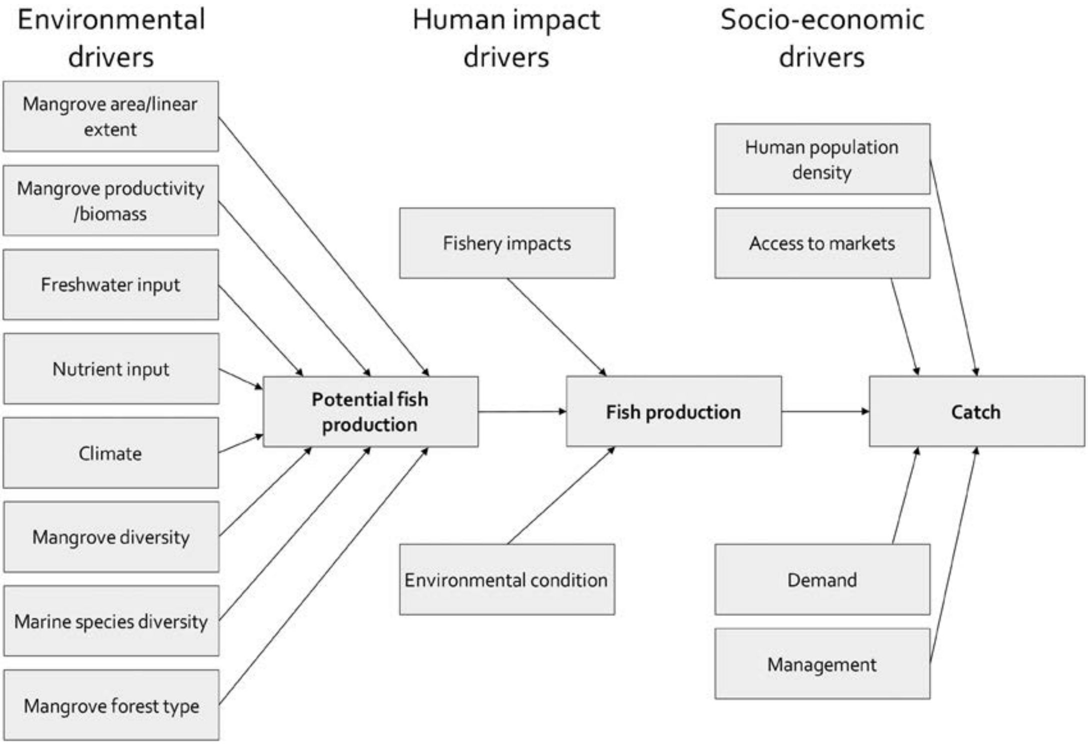

Figure 1.—A conceptual model for the first three stages of mangrove fisheries valuation, showing the drivers that influence each stage. Note that the output of each stage is a driver of the following stage.

with the water, so the fringe area of mangrove may be more important than total area. Recent work in the Gulf of California suggests that there is a constant ratio between fringe area and the square root of the total area (Aburto-Oropeza et al. 2008), but this ratio may be influenced by local geomorphic settings and tidal range (Lee 2004). The consensus among the expert group was that we should use total area rather than fringe area, as even parts of the mangrove that are infrequently inundated may still benefit fisheries through the contribution of leaf litter to the food chain. Because fish production by mangroves is expected to be proportional to mangrove area, we used the other drivers to generate potential fish production and modeled catch per unit area of mangrove, in a 30 arcsecond grid. National and regional estimates were then generated by multiplying these by the area of mangrove in each grid cell, which was derived from the U.S. Geological Survey (USGS) Global Distribution of Mangroves layer (Giri et al. 2011).

- **Primary productivity/biomass:** Primary productivity in mangroves comes from trees, but also from periphyton, microphytobenthos, and phytoplankton. It is likely to be positively correlated with fish production, as it provides the basis for a detrital food chain that ultimately supports species of value to fisheries. Mangrove productivity varies at least 10-fold, from 3.4 Mg ha^{-1} year^{-1} in Florida (Ewe et al. 2006) to 30.9 Mg ha–^{1} year^{-1} in Japan (Khan et al. 2009), due to climatic factors, nutrient availabil-

Table 1.—Environmental drivers: summary of the decisions made by workshop participants and the votes and relative importance (percentage of total votes received) of each driver in the model of potential fish production. Relative importance is the percentage of the total votes received by each driver while the adjusted importance is the percentage of votes received by drivers used in the final model: mangrove primary productivity, nutrient input, and freshwater input. Mangrove extent was also used but only for the purpose of calculating total benefits to fisheries (See Appendix A for detailed methods).

Driver	Relationship	Votes	Relative importance	Adjusted importance
Mangrove extent	Fish catch α mangrove area	12	32.4	–
Mangrove perimeter	Fish catch α mangrove perimeter	2	5.4	–
Mangrove primary productivity	Positive	3	8.1	21.4
Nutrient input	Positive up to a threshold, then plateau, then drop	5	13.5	35.7
Freshwater input	Positive	6	16.2	42.9
Rainfall	Positive but only as part of freshwater input	0	0.0	–
Sea surface temperatures	Possibly upper and lower thresholds, but little influence between these.	0	0.0	–
Mangrove diversity	Possibly positive	1	2.7	–
Fish diversity		3	8.1	–
Mangrove forest type	Probably important, but relationship unclear. Partly accounted for by freshwater and nutrients	5	13.5	–

ity, and forest age. The expert panel felt that primary productivity would positively influence potential fish production but only as a relatively minor driver in the model. There are currently no available maps of mangrove primary productivity, but we used a map of mangrove above-ground biomass as a proxy (Hutchison et al. 2014b).

- **Freshwater input:** Freshwater input has been demonstrated to be positively correlated with fish and prawn production in mangroves and other estuarine habitats (e.g., Vance et al. 1985; Meynecke et al. 2006). The expert panel agreed that freshwater input would positively influence potential fish production, giving it the second greatest number of votes after mangrove area. Maps of sea surface salinity from satellite sensors do exist, but they tend to be unreliable in coastal areas and are generally of poor resolution. Instead, we developed our own map of freshwater influence based on the watersheds and river mouth locations from the USGS HydroSHEDS layer (Lehner et al. 2006) coupled with rainfall data from the World Clim Bioclim data set (Hijmans et al. 2005).
- **Nutrient input:** Nutrient enrichment increases primary production by mangroves and other producers such as phytoplankton and algae, as well as

having some detrimental effects such as increased mangrove mortality (Lovelock et al. 2009). Increased nutrients may also increase the palatability of these producers to grazers (Boyer et al. 2004). Under certain conditions, highly elevated nutrient levels lead to hypoxia and the formation of dead zones (Diaz and Rosenberg 2008), but these are spatially rare and for the purposes of this model they were ignored. The expert panel felt that nutrient input would be positively correlated with fish production by mangroves up to a certain threshold, beyond which production would plateau and then eventually drop. Models that map riverine nutrients have been produced but generally only at very coarse resolution or for a small number of large river mouths. For our model, we therefore used modeled watershed sediment output from the Reefs at Risk project (Burke et al. 2011). This layer was developed to be a proxy of sediment, nutrient, and pollutant delivery, modeled using watershed soil type, slope, land cover, and precipitation.

- **Climate:** Climate is likely to influence fishery productivity through precipitation, which determines freshwater input. Temperature may also be important for some species. In particular, the growth rate of invertebrates such as prawns and crabs are directly affected by water temperature (Staples and Heales 1991). However, the expert panel felt that climate was unlikely to be a major driver of potential fish production except through rainfall, which is already covered as part of freshwater input. Neither rainfall nor sea surface temperature received any votes so climate was not used in the model.
- **Mangrove species diversity:** Diversity of mangrove tree species is higher in the Indo-West Pacific than in the Atlantic East Pacific (Spalding et al. 2010). The expert group felt that mangrove diversity might influence habitat complexity or mangrove productivity, which might in turn influence fish production. However, the level of certainty of this effect was low and mangrove diversity received just one vote so was not used in the model.
- **Marine species diversity:** Like mangroves, diversity of marine species in coastal waters is generally higher in the Indo-West Pacific than in the Atlantic East Pacific (Tittensor et al. 2010). The expert group suggested that a greater diversity of fishery target species may give greater resilience to environmental perturbations and overfishing (Jackson et al. 2001). However, the level of certainty of this effect was low and the relationship between diversity and overall yield was not clear. Global data on marine species diversity do exist (Tittensor et al. 2010) but only at coarse resolutions. For this reason and because of the uncertainty of the relationship between diversity and fish production, marine species diversity was not used in the model.
- **Mangrove forest type:** Lugo and Snedaker (1974) classified mangroves as fringe forest, riverine forest, overwash forest, basin forest, or dwarf forest depending on the ecological setting in which they were found. These different forest types will vary in inundation frequency, carbon dynamics, freshwater, and nutrient availability and may differ in the benefit they provide to fisheries (Flores-Verdugo et al. 2014). Forest type scored highly in the voting process, but consensus in the discussion was that its effect on potential fish production would primarily be through its influence on freshwater and nutrient input. There is also no available data set showing where each forest type is found. For these reasons, forest type was not

used in the model. Freshwater and nutrients are, however, included elsewhere.

Human impact drivers.—These drivers were discussed during the workshop and were felt to be important. However, none of them have global data sets that could be used to represent them in the model. Furthermore, the only metrics we might have used to generate a model for fishery impacts were based around population and markets, which were proposed at the same time as key drivers in determining fishing effort. In the absence of better data or models, we decided to use these data sets only in the fishing effort model. We therefore decided to omit human impacts from this preliminary version of the model. However, a summary of the workshop discussion on each human impact driver is included below.

- **Fishery impacts:** Overfishing and destructive fishing practices will reduce fish populations, which may also impact yield. In many fisheries, years of overfishing have led to greatly reduced catches (Worm et al. 2009). However, catches in many multispecies fisheries such as those found in and around mangroves appear to remain more stable even under elevated fishing pressure, although with a reduction in size and trophic level of the species caught ("fishing down the food chain") (Welcomme 1999). This is reflected in the equation we used to relate modeled catch to fishing effort (Figure A.4), which was developed based on studies in coastal lagoons in West Africa (Laë 1997).
- **Environmental condition:** Mangrove degradation, for example through clearance for timber, changes in hydrological regimes and pollution, will reduce the benefits that the mangroves provide to fisheries (Barbier et al. 2002). Pollution may also influence fishery target species directly by reducing water quality (Alongi 2002) and even driving anoxia in the most heavily polluted estuarine systems (Diaz and Rosenberg 2008).

Socioeconomic drivers.—These drivers were used to model fishing effort. All of the socioeconomic drivers identified were thought to be potentially important by our expert group. However, only human population and markets were used due to a lack of data for the other two proposed drivers. Conclusions of the workshop discussions on these drivers are described below, and the voting scores are shown in Table 2.

- **Human population density:** In general, fishing effort will be positively correlated with human population density as these populations provide both the fishers and the demand for the catch. However, this relationship will vary between different fishery classes. For pure subsistence fishing, there will be a strong relationship with population density in the area immediately surrounding the fishery. However, most small-scale fisheries are still at least partly commercial and therefore require a market for their catch, which requires a population center. Fishing effort is therefore likely to be related to population and distance to the nearest market (Brewer et al. 2009). For the highest value fisheries, there may be little or no relationship to local populations, with fishers traveling long distances to the fishing grounds and exporting their catch to other parts of the country or overseas. Our model is primarily aimed at small-scale fisheries, so we used population as the primary driver of fishing effort, modified by distance to the nearest market. We used population data from the Global Rural-Urban Mapping Project population density grid for our model (CIESIN et al. 2011a). We related fishing effort to catch using an equation developed by Laë (1997) for West African lagoon fisheries.
- **Access to markets:** Most commercial

Table 2.—Socioeconomic drivers: summary of the decisions made at the workshop and the votes and relative importance (percentage of total votes received) of each driver in the model of catch. Only population and access to markets were used in the final model due to a lack of data on management or demand. Note that due to the modelling methods used for catch (see Appendix), the relative importance was not directly used in the model.

Driver	Relationship	Votes	Relative importance
Population	Subsistence fisheries—strongly related to population density. Small- to medium-scale commercial—local population provides fishers but also requires market—town of 10,000 within 2 hours' travel. High value commercial (all scales)—may be unrelated to population.	11	47.8
Access to markets	Will increase catch for small- to medium-scale fisheries.	4	17.4
Management	Positive, by reducing overfishing, but may reduce short-term catches.	3	13.0
Demand	Positive, will increase motivation to fish.	5	21.7

fisheries require a market to sell their catch. In small-scale fisheries, the fishers themselves are most likely to sell to intermediaries, who will then transport the catch to a market in a population center. The expert group reached a consensus that a market was any town of great er than 10,000 people and estimated that fish sellers might transport their catches up to 50 km to reach such a market. This is based on small-scale fisheries with little or no refrigeration. Different assumptions would be required for more industrialized fisheries. Locations of towns of greater than 10,000 people were taken from the Global Rural-Urban Mapping Project settlement points data set (CIESIN et al. 2011b).

- **Demand:** Demand for fish will vary not only with population size, but also with the amount of fish in the diet. This varies by country and across different income groups, influenced by cultural traditions and also by the availability of alternative food sources (Dey et al. 2008). Data on fish consumption are available by country from the Food and Agriculture Organization of the United Nations. However, there is no data at finer at finer spatial scales, so for this reason demand for fish was not included in this version of the model.
- **Management:** Well-managed fisheries can generate higher long-term yields than poorly managed ones (although overfishing may lead to higher short-term yields in poorly managed fisheries). There is very little information available on management measures or their effectiveness, especially for small-scale fisheries, so we did not use management in the model.

Model development

Once the drivers had been filtered based on the workshop discussion and voting, and on the availability of data sets to represent them in the model, the remaining drivers were weighted based on the scores from the workshop voting process. The potential fish production model used mangrove area, freshwater input, nutrient input, and mangrove biomass, while the fishing effort model used human population per unit area of mangrove and whether there was a market within 50 km. Modeled catch was then calculated by multiplying the outputs of these two models. Full details of the model development are given in the Appendix.

Results

We used the models for potential fish production and fishing effort to generate the maps shown in Figure 2. The potential fish production map shows the importance of rivers in our model as sources of freshwater and nutrients, with high potential fish production in areas with many large rivers such as West Africa, but low production in dry areas such as the Arabian Peninsula and Australia. The map of fishing effort reflects the distribution of population density, showing a strong contrast between the sparsely populated north coast of Australia and the high population densities in China, India, and much of Southeast Asia. The modeled catch map is a combination of these two inputs.

We used the maps to generate country level summaries of potential fish production, fishing effort, and modeled catch (Table A.1). The countries with the most important mangrove fisheries are generally those with the largest mangrove areas, including Nigeria, Indonesia, Malaysia, Brazil, and Mexico. Australia and Papua New Guinea are exceptions. Both have large mangrove areas, but low modeled fishing effort due to their low population densities. For the same reason, Indonesia has lower-than-expected modeled catch levels. Despite this, its huge area of mangrove means that it remains one of the top-ranked countries for total catch.

Discussion

Model results

This work represents a first output from an effort to develop a global model and map of the spatial variation in mangrove fisheries. It has important limitations, but we believe it provides a proof of concept for this way of using expert judgment, and that even this current version provides some insights into the importance of mangroves for fisheries.

Not surprisingly, the importance of total mangrove area is highlighted—the six highest ranked countries by total predicted catch from mangrove fisheries all have more than 500,000 ha of mangrove. Fishing effort is also important, as demonstrated by lower catches for Papua New Guinea, Australia, and Indonesia, which all have large areas with low fishing effort. Fishing effort is modeled using population density close to the mangroves, meaning that the highest scoring countries have large mangrove areas that are also close to people and markets. This has important implications for conservation and development; the most valuable areas of mangrove for fisheries are those closest to human populations, which in many places are also likely to be under the greatest threat. Traditionally, conservation effort has emphasized the importance of preserving pristine wilderness areas that remain intact due to their remoteness from people (e.g., Mittermeier et al. 2003; Graham and McClanahan 2013; McCauley et al. 2013). This is in contrast to some of the international agreements where nations have regularly stressed the need to protect not only biodiversity, but also ecosystem services (CBD 2010). To maintain or enhance ecosystem services such as fish production, we need to focus conservation and management efforts particularly on those areas close to people, despite the fact that they are likely to already be far from pristine.

Value and limitations of the model

This first version of the model is conceptual, based on the knowledge and opinions of the authors. It has not been parameterized using field data on fish biomass, fishing effort, or catch, and for this reason it can only be used to make qualitative statements about

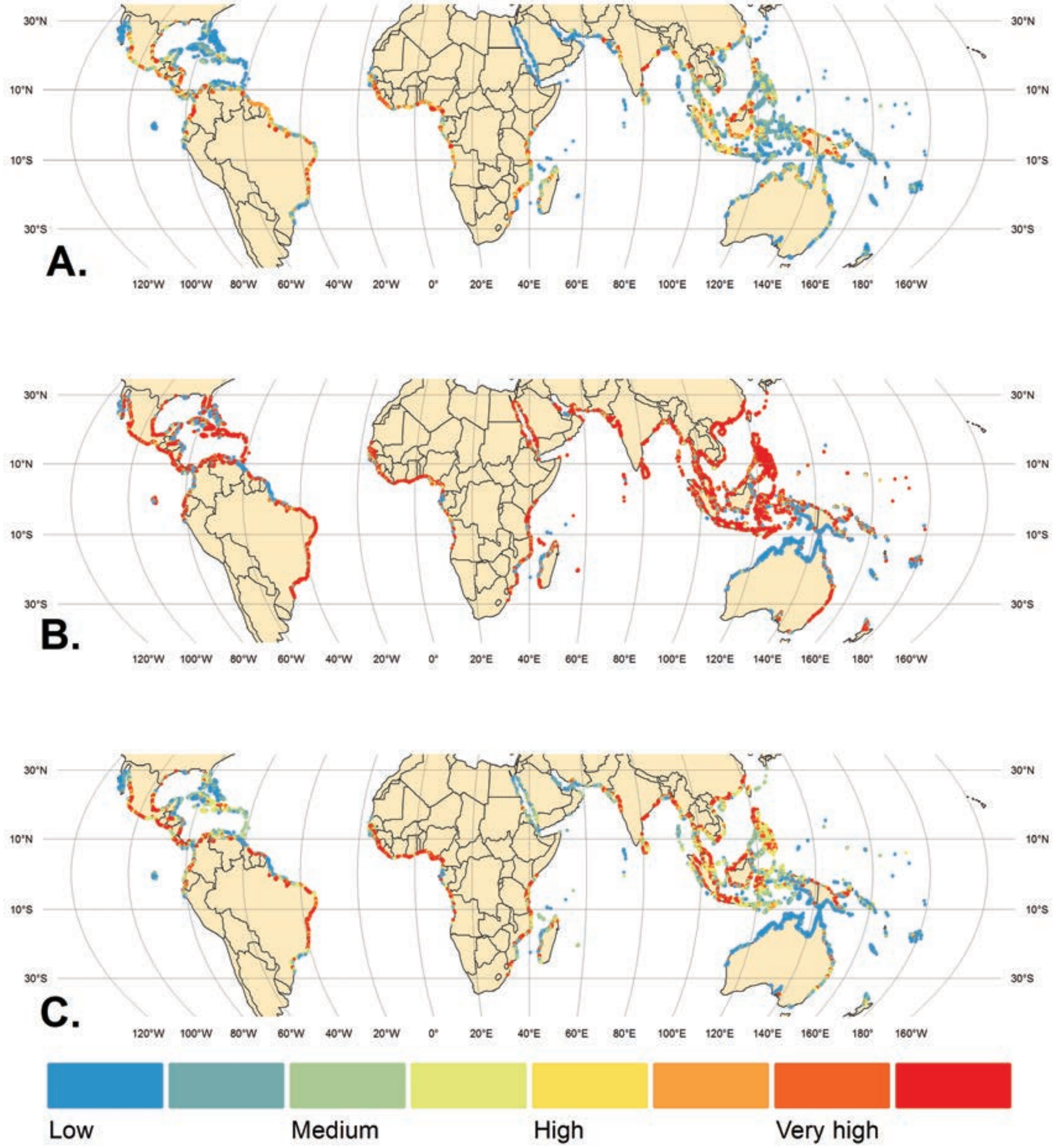

Figure 2.—Maps showing the outputs of the various stages of the model: A. Potential fish production, B. Modeled fishing effort, and C. Modeled catch.

mangrove fisheries. The primary value of the model is as a proof of concept, demonstrating the approach that can be used to elucidate the spatial variation in the ecosystem service of fish production by mangroves. It is a first step to be built upon using more sophisticated modeling techniques and through the use of field data for parameterization.

A key limitation of this first draft model is that it does not attempt to cover the value of mangrove fisheries. The monetary value of a fishery can be expressed as the amount of fish produced multiplied by the price of that fish, minus the cost of its production. However, price and cost are key determinants of effort, which in turn is a major driver of total catch. Accurately representing this circularity requires a more complex modeling approach (e.g., Barbier et al. 2002), but this was both beyond the expertise of our expert panel and beyond the scope of this preliminary modeling attempt. Additionally, value is a complex concept, especially in small-scale fisheries that have a subsistence aspect, and cannot necessarily be fully expressed in monetary terms. Much of the catch may never reach a market or may be traded for other nonmonetary goods. Such values could be expressed in terms of livelihoods supported or dietary protein produced by a fishery.

The elements that we have modeled are based on a number of major simplifying assumptions, a few of which could have a major impact on the model output and are therefore worth highlighting. The first is that the model ignores the negative impacts of people on the ecosystem service through degradation and pollution of the mangroves. This is likely to be important in some locations. Nigeria, for example, is the top-ranked country by total catch predicted by the model. However, much of Nigeria's mangrove area is polluted by oil (Osuji and Ezebuiro 2006), which is likely to heavily impact the fishery. There may also be impacts of overfishing that are not considered in the model; Welcomme (1999) suggests that although yields from small-scale mixed species fisheries remain stable over a range of fishing effort, they can be reduced if fishing effort exceeds a threshold level. Mangrove fisheries also include single species fisheries for crabs and mollusks, and some of these show declining catches due to overfishing (e.g., Beitl 2011). Human impacts are likely to be focused in areas with high population density, which might temper the importance of these areas for fisheries.

The model in its current form is only applicable to small-scale inshore fisheries. For example, it assumes that mangrove fishers will be local residents, which is valid for small-scale fisheries but not for fisheries for high-value species such as penaeid prawns. Northern Australia has very low fishing effort in the model due to its low population density. However, the Northern Prawn Fishery landed 6,600 Mg of prawns along this coastline in 2012 (Barwick 2013), mostly using boats greater than 22 m long, which are able to spend many days at sea and travel many kilometers from their home port to the fishing grounds. A similar modeling approach could be applied to these fisheries but would require the assumptions and data sets for the modeling of fishing effort to be revised. Similarly, the model does not include recreational fisheries, which have very high values in some locations.

Finally, the model only seeks to predict the catch in fisheries in and around mangroves. It does not assess the dependence of those fisheries on the mangrove habitat or the extent to which the presence of mangroves enhances catches. It is true that fisheries would still exist in the absence of mangroves, as other, less-structured estuarine and coastal habitats also produce fish. Indeed, much of the benefit that mangroves provide to fisheries comes through their connections to other habitats such as sea grass beds and coral reefs, with a number of species shown to move between these habitats at different life stages (e.g., Manson et al. 2005; Kimirei et al. 2013). Assessing the extent to which mangroves enhance fisheries over the background level provided by unstructured habitats would require data on fish density inside and outside mangrove habitats, collected using comparable methods (Blandon and zu Ermgassen 2014a, 2014b). We have found very few data meeting these criteria.

Next steps

The model presented in this paper is primarily a proof of concept rather than a finished work and could be improved in a number of ways. A few main areas are obvious targets for further work:

- Improving the conceptual model: This could be achieved through the inclusion of human impacts on mangroves and fish stocks, so that catch can be calculated using modeled fish production rather than potential fish production (see Figure 1). There are also other drivers that may be important but were not included in this version of the model. Fish diversity and mangrove forest type were both identified as potentially important in the workshop, but were not included due to uncertainty over their effects and a lack of suitable data sets to represent them. Tidal range was also mentioned at the workshop but not formally discussed, and has been shown to be correlated with mangrove prawn catch (Lee 2004).
- Improving the use of expert judgment: There is a large body of literature on the best ways of using expert judgment to model ecosystem services. The authors were largely unaware of this literature at the time of the workshop. In future workshops, we would include a measure of confidence in the different modeling steps based on the level of scientific evidence supporting each step, as well as the degree of consensus among the expert group (Jacobs et al. 2015). In addition, the simplistic voting method used may not give an accurate estimate of the weightings attached to each driver in the model. This could be improved using an approach that allows each expert to weight the relative importance of each model driver, ideally as part of a Delphi process allowing for discussion of the initial weightings followed by another weighting opportunity (Martin et al. 2012).
- Developing model versions for different fisheries: in our initial reviews of mangrove fisheries, we identified four broad fishery classes—mixed inshore fisheries, inshore mollusk and crustacean fisheries, offshore fisheries (primarily prawn), and recreational fisheries (Hutchison et al. 2014b). Each of these would have a different set of weightings or even different drivers, particularly for the fishing effort part of the model. The current model focusses primarily on inshore fisheries, a combination of the first two classes. There is an established precedent for using population as a proxy for fishing pressure in small-scale fisheries such as these (e.g., Burke et al. 2011; Teh et al. 2013). For larger-scale fisheries, it is likely to be a much less important factor as the larger boats used are able to travel long distances to remote fishing grounds, and to freeze their catches on board for the return journey.
- Parameterizing the model with fishery catch data: This step would enable us to move from a qualitative model to a numerical model, capable of predicting actual fish catches around the world. We have carried out a literature review and collected data on fish catch and fish abundance in mangroves which might be suitable for this (Hutchison et al. 2014a). However, the data are very variable in quality and the data set is relatively small, with developing countries having particularly poor coverage. We also investigated global databases such as that held by the Sea Around Us Project (Pauly 2007), but we found that the resolution was too coarse for use in a spatial model at the scale of individual mangrove forests. This step therefore represents a significant challenge, but it is an important one: the resulting model could be used to demonstrate the dependence of fisheries in different countries on mangroves and could therefore be a crucial tool to influence policy for mangrove conservation.
- Reporting multiple value metrics: along side efforts to improve and parameterize

the model, it will be important to consider how value can be quantified beyond simple measures of captured biomass. Value can be measured in many ways, and these should include metrics such as livelihoods as well as monetary values.

- Developing fine-scale models for local use: ecosystem services are increasingly used in planning—few countries have detailed knowledge of the value of their mangrove fisheries, but conceptual models could be developed at more local scales, with the advantages of higher resolution data sets and the potential of testing the findings against field data.

The value of mangrove fisheries is widely accepted and yet there are currently no global models or tools to assess such value in specific locations or to reveal global patterns in the variability of this value. At the same time, pressures for development in coastal areas are leading to widespread degradation and loss of mangroves. Better understanding of their value could provide a powerful tool to reduce further mangrove loss and encourage restoration. Through the workshop and subsequent modeling, we are confident that we have developed a valuable proof-of-concept model. With ongoing investment, we hope to build a tool that will generate a model of mangrove fisheries value, but also improve understanding of modeling approaches to enable application at finer scales.

References

Aburto-Oropeza, O., E. Ezcurra, G. Danemann, V. Valdez, J. Murray, and E. Sala. 2008. Mangroves in the Gulf of California increase fishery yields. Proceedings of the National Academy of Sciences of the United States of America 105:10456–10459.

Alongi, D. M. 2002. Present state and future of the world's mangrove forests. Environmental Conservation 29:331–349.

Alongi, D. M. 2008. Mangrove forests: resilience, protection from tsunamis, and responses to global climate change. Estuarine Coastal and Shelf Science 76:1–13.

Alongi, D. M. 2009. The energetics of mangrove forests. Springer Verlag, New York.

Barbier, E. B. 2012. Progress and challenges in valuing coastal and marine ecosystem services. Review of Environmental Economics and Policy 6:1–19.

Barbier, E. B., I. Strand, and S. Sathirathai. 2002. Do open access conditions affect the valuation of an externality? Estimating the welfare effects of mangrove-fishery linkages in Thailand. Environmental and Resource Economics 21:343–365.

Barwick, M. 2013. Northern prawn fishery data summary 2013. NPF Industry Pty, Caloundra, Queensland, Australia.

Beitl, C. M. 2011. Cockles in custody: the role of common property arrangements in the ecological sustainability of mangrove fisheries on the Ecuadorian coast. International Journal of the Commons 5:485–512.

Blandon, A., and P. S. E. zu Ermgassen. 2014a. Corrigendum to "Quantitative estimate of commercial fish enhancement by seagrass habitat in southern Australia" [Estuar. Coast. Shelf Sci. 141 (20 March 2014) 1–8]. Estuarine Coastal and Shelf Science 151:370.

Blandon, A., and P. S. E. zu Ermgassen. 2014b. Quantitative estimate of commercial fish enhancement by seagrass habitat in southern Australia. Estuarine Coastal and Shelf Science 141:1–8.

Boyer, K. E., P. Fong, A. R. Armitage, and R. A. Cohen. 2004. Elevated nutrient content of tropical macroalgae increases rates of herbivory in coral, seagrass, and mangrove habitats. Coral Reefs 23:530–538.

Brander, L., A. Wagtendonk, S. Hussain, A. McVittie, P. H. Verburg, R. S. de Groot, and S. van der Ploeg. 2012. Ecosystem service values for mangroves in Southeast Asia: a meta-analysis and value transfer application. Ecosystem Services 1:62–69.

Brewer, T. D., J. E. Cinner, A. Green, and J. M. Pandolfi. 2009. Thresholds and multiple scale interaction of environment, resource use, and market proximity on reef fishery resources in the Solomon Islands. Biological Conservation 142:1797–1807.

Burke, L., K. Reytar, M. Spalding, and A. Perry. 2011. Reefs at Risk revisited. World Resources Institute, Washington, D.C.

Burkhard, B., F. Kroll, S. Nedkov, and F. Müller. 2012. Mapping ecosystem service supply, demand and budgets. Ecological Indicators 21:17–29.

Carrasquilla-Henao, M., H. A. González Ocampo, A. Luna González, and G. Rodríguez Quiroz. 2013. Mangrove forest and artisanal fishery in the southern part of the Gulf of California, Mexico. Ocean & Coastal Management 83:75–80.

Castellanos-Galindo, G. A., U. Krumme, E. A. Rubio, and U. Saint-Paul. 2013. Spatial variability of mangrove fish assemblage composition in the tropical eastern Pacific Ocean. Reviews in Fish Biology and Fisheries 23:69–86.

Cayubit, R. A. 2014. DENR-8 starts P1-B mangrove rehab project. Available: www.mb.com.ph/denr-8-starts-p1-b-mangrove-rehab-project/. (January 2015).

CBD (Convention on Biological Diversity). 2010. Cop 10 - Tenth meeting of the Conference of the Parties to the Convention on Biological Diversity. Decision X/2. Strategic plan for biodiversity 2011–2020. United Nations Environment Programme, Nagoya, Japan.

CIESIN (Center for International Earth Science Information Network), Columbia University, International Food Policy Research Institute, The World Bank, and Centro Internacional de Agricultura Tropical. 2011a. Global Rural-Urban Mapping Project, (GRUMP), version 1: population density grid. NASA Socioeconomic Data and Applications Center, Palisades, New York.

CIESIN (Center for International Earth Science Information Network), Columbia University, International Food Policy Research Institute, The World Bank, and Centro Internacional de Agricultura Tropical. 2011b. Global Rural-Urban Mapping Project (GRUMP), version 1: settlement points. NASA Socioeconomic Data and Applications Center, Palisades, New York.

Costanza, R., R. d' Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R. V. O'Neill, J. Paruelo, R. G. Raskin, P. Sutton, and M. van den Belt. 1997. The value of the world's ecosystem services and natural capital. Nature (London) 387:253–260.

de Graaf, G. J., and T. T. Xuan. 1998. Extensive shrimp farming, mangrove clearance and marine fisheries in the southern provinces of Vietnam. Mangroves and Salt Marshes 2:159–166.

Dey, M. M., Y. T. Garcia, K. Praduman, S. Piumsombun, M. S. Haque, L. Li, A. Radam, A. Senaratne, N. T. Khiem, and S. Koeshendrajana. 2008. Demand for fish in Asia: a cross-country analysis. Australian Journal of Agricultural and Resource Economics 52:321–338.

Diaz, R. J., and R. Rosenberg. 2008. Spreading dead zones and consequences for marine ecosystems. Science 321:926–929.

Donato, D. C., J. B. Kauffman, D. Murdiyarso, S. Kurnianto, M. Stidham, and M. Kanninen. 2011. Mangroves among the most carbon-rich forests in the tropics. Nature Geoscience 4:293–297.

Duke, N. C., J.-O. Meynecke, S. Dittmann, A. M. Ellison, K. Anger, U. Berger, S. Cannicci, K. Diele, K. C. Ewel, C. D. Field, N. Koedam, S. Y. Lee, C. Marchand, I. Nordhaus, and F. Dahdouh-Guebas. 2007. A world without mangroves? Science 317:41–42.

Ewe, S. M. L., E. E. Gaiser, D. L. Childers, D. Iwaniec, V. H. Rivera-Monroy, and R. R. Twilley. 2006. Spatial and temporal patterns of aboveground net primary productivity (ANPP) along two freshwater-estuarine transects in the Florida Coastal Everglades. Hydrobiologia 569:459–474.

Flores-Verdugo, F., F. Amezcua, J. M. Kovacs, D. Serrano, and M. Blanco-Correa. 2014. Changes in the hydrological regime of coastal lagoons affect mangroves and small scale fisheries: the case of the mangrove-estuarine complex of Marismas Nacionales (Pacific coast of Mexico). Pages 81–91 *in* F. Amezcua and B. Bellgraph, editors. Fisheries management of Mexican and Central American estuaries. Springer, Dordrecht, Netherlands.

Giri, C., E. Ochieng, L. L. Tieszen, Z. Zhu, A. Singh, T. Loveland, J. Masek, and N. Duke. 2011. Status and distribution of mangrove forests of the world using earth observation satellite data. Global Ecology and Biogeography 20:154–159.

Graham, N. A. J., and T. R. McClanahan. 2013. The last call for marine wilderness? BioScience 63:397–402.

Haines-Young, R. 2011. Exploring ecosystem service issues across diverse knowledge domains using Bayesian belief networks. Progress in Physical Geography 35:681–699.

Hijmans, R. J., S. E. Cameron, J. L. Parra, P. G. Jones, and A. Jarvis. 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25:1965–1978.

Hutchison, J., A. Manica, R. Swetnam, A. Balmford, and M. Spalding. 2014b. Predicting global patterns in mangrove forest biomass. Conservation Letters 7:233–240.

Hutchison, J., M. Spalding, and P. zu Ermgassen. 2014a. The role of mangroves in fisheries enhancement. The Nature Conservancy, Bethesda, Maryland and Wetlands International, Wageningen, Netherlands.

Jackson, J. B. C., M. X. Kirby, W. H. Berger, K. A. Bjorndal, L. W. Botsford, B. J. Bourque, R. H. Bradbury, R. Cooke, J. Erlandson, J. A. Estes, T. P. Hughes, S. Kidwell, C. B. Lange, H. S. Lenihan, J. M. Pandolfi, C. H. Peterson, R. S. Steneck, M. J. Tegner, and R. R. Warner. 2001. Historical overfishing and the recent collapse of coastal ecosystems. Science 293:629–637.

Jacobs, S., B. Burkhard, T. Van Daele, J. Staes, and A. Schneiders. 2015. "The Matrix Reloaded": a review of expert knowledge use for mapping ecosystem services. Ecological Modelling 295:21–30.

Khan, M. N. I., R. Suwa, and A. Hagihara. 2009. Biomass and aboveground net primary production in a subtropical mangrove stand of Kandelia obovata (S., L.) Yong at Manko Wetland, Okinawa, Japan. Wetlands Ecology and Management 17:585–599.

Kimirei, I. A., I. Nagelkerken, Y. D. Mgaya, and C. M. Huijbers. 2013. The mangrove nursery paradigm revisited: otolith stable isotopes support nursery-to-reef movements by Indo-Pacific fishes. PLOS ONE 8:e66320.

Koch, E. W., E. B. Barbier, B. R. Silliman, D. J. Reed, G. M. Perillo, S. D. Hacker, E. F. Granek, J. H. Primavera, N. Muthiga, S. Polasky, B. S. Halpern, C. J. Kennedy, C. V. Kappel, and E. Wolanski. 2009. Non-linearity in ecosystem services: temporal and spatial variability in coastal protection. Frontiers in Ecology and the Environment 7:29–37.

Laë, R. 1997. Does overfishing lead to a decrease in catches and yields? An example of two West African coastal lagoons. Fisheries Management and Ecology 4:149–164.

Lee, S. Y. 2008. Mangrove macrobenthos: Assemblages, services, and linkages. Journal of Sea Research 59:16–29.

Lee, S. Y., J. H. Primavera, F. Dahdouh-Guebas, K. McKee, J. O. Bosire, S. Cannicci, K. Diele, F. Fromard, N. Koedam, C. Marchand, I. Mendelssohn, N. Mukherjee, and S. Record. 2014. Ecological role and services of tropical mangrove ecosystems: a reassessment. Global Ecology and Biogeography 23:726–743.

Lehner, B., K. Verdin, and A. Jarvis. 2006. HydroSHEDS Technical Documentation, version 1.0. World Wildlife Fund, Washington, D.C. Available: http://hydrosheds.cr.usgs.gov/webappcontent/HydroSHEDS_TechDoc_v10.pdf. (January 2015).

Lonsdorf, E., C. Kremen, T. Ricketts, R. Winfree, N. Williams, and S. Greenleaf. 2009. Modelling pollination services across agricultural landscapes. Annals of Botany 103:1589-1600.

Lovelock, C. E., M. C. Ball, K. C. Martin, and I. C. Feller. 2009. Nutrient enrichment increases mortality of mangroves. PLOS ONE 4:e5600.

Lugo, A. E., and S. C. Snedaker. 1974. The ecology of mangroves. Annual Review of Ecology and Systematics 5:39–64.

Manson, F. J., N. R. Loneragan, G. A. Skilleter, and S. R. Phinn. 2005. An evaluation of the evidence for linkages between mangroves and fisheries: a synthesis of the literature and identification of research directions.

Oceanography and Marine Biology: An Annual Review 43:483–513.

Martin, T. G., M. A. Burgman, F. Fidler, P. M. Kuhnert, S. Low-Choy, M. Mcbride, and K. Mengersen. 2012. Eliciting expert knowledge in conservation science. Conservation Biology 26:29–38.

McCauley, D. J., E. A. Power, D. W. Bird, A. McInturff, R. B. Dunbar, W. H. Durham, F. Micheli, and H. S. Young. 2013. Conservation at the edges of the world. Biological Conservation 165:139–145.

McIvor, A. L., I. Möller, T. Spencer, and M. Spalding. 2012a. Reduction of wind and swell waves by mangroves. Natural Coastal Protection Series: Report 1. The Nature Conservancy, Bethesda, Maryland and Wetlands International, Wageningen, Netherlands.

McIvor, A. L., T. Spencer, I. Möller, and M. Spalding. 2012b. Storm surge reduction by mangroves. Natural Coastal Protection Series: Report 2. The Nature Conservancy, Bethesda, Maryland and Wetlands International, Wageningen, Netherlands.

Meynecke, J.-O., S. Y. Lee, N. C. Duke, and J. Warnken. 2006. Effect of rainfall as a component of climate change on estuarine fish production in Queensland, Australia. Estuarine Coastal and Shelf Science 69:491–504.

Mittermeier, R. A., C. G. Mittermeier, T. M. Brooks, J. D. Pilgrim, W. R. Konstant, G. A. B. da Fonseca, and C. Kormos. 2003. Wilderness and biodiversity conservation. Proceedings of the National Academy of Sciences of the United States of America 100:10309–10313.

Nagelkerken, I., S. J. M. Blaber, S. Bouillon, P. Green, M. Haywood, L. G. Kirton, J.-O. Meynecke, J. Pawlik, H. M. Penrose, A. Sasekumar, and P. J. Somerfield. 2008. The habitat function of mangroves for terrestrial and marine fauna: a review. Aquatic Botany 89:155–185.

Osuji, L. C., and P. E. Ezebuiro. 2006. Hydrocarbon contamination of a typical mangrove floor in Niger Delta, Nigeria. International Journal of Environmental Science & Technology 3:313–320.

Pauly, D. 2007. The Sea Around Us Project: documenting and communicating global fisheries impacts on marine ecosystems. AMBIO: A Journal of the Human Environment 36:290–295.

Paw, J. N., and T.-E. Chua. 1991. An assessment of the ecological and economic impact of mangrove conversion in Southeast Asia. Towards an integrated management of tropical coastal resources. ICLARM Conference Proceedings 22:201–212.

Pendleton, L., D. C. Donato, B. C. Murray, S. Crooks, W. A. Jenkins, S. Sifleet, C. Craft, J. W. Fourqurean, J. B. Kauffman, N. Marbà, P. Megonigal, E. Pidgeon, D. Herr, D. Gordon, and A. Baldera. 2012. Estimating global "blue carbon" emissions from conversion and degradation of vegetated coastal ecosystems. PLOS ONE 7:e43542.

Siikamäki, J., J. N. Sanchirico, and S. L. Jardine. 2012. Global economic potential for reducing carbon dioxide emissions from mangrove loss. Proceedings of the National Academy of Sciences of the United States of America 100:14369–14374.

Spalding, M., M. Kainuma, and L. Collins. 2010. World atlas of mangroves. Earthscan, London.

Staples, D. J., and D. S. Heales. 1991. Temperature and salinity optima for growth and survival of juvenile banana prawns Penaeus merguiensis. Journal of Experimental Marine Biology and Ecology 154:251–274.

Teh, L. S. L., L. C. L. Teh, and U. R. Sumaila. 2013. A global estimate of the number of coral reef fishers. PLOS ONE 8:e65397.

Tittensor, D. P., C. Mora, W. Jetz, H. K. Lotze, D. Ricard, E. V. Berghe, and B. Worm. 2010. Global patterns and predictors of marine biodiversity across taxa. Nature (London) 466:1098–1101.

Van Lavieren, H., M. Spalding, D. M. Alongi, M. Kainuma, M. Clüsener-Godt, and Z. Adeel. 2012. Securing the future of mangroves. A policy brief. Available from United Nations University, Hamilton, Ontario.

Vance, D. J., D. J. Staples, and J. D. Kerr. 1985. Factors affecting year-to-year variation in the catch of banana prawns (*Penaeus mer-*

guiensis) in the Gulf of Carpentaria, Australia. Journal du Conseil 42:83–97.

Victor, S., Y. Golbuu, E. Wolanski, and R. H. Richmond. 2004. Fine sediment trapping in two mangrove-fringed estuaries exposed to contrasting land-use intensity, Palau, Micronesia. Wetlands Ecology and Management 12:277–283.

Vong, M. 2014. Vietnam to clean river with $4 mil mangroves project. Available: www.thanhniennews.com/youth-science/vietnam-to-clean-river-with-4-mil-mangroves-project-24608.html. (January 2015).

Welcomme, R. L. 1999. A review of a model for qualitative evaluation of exploitation levels in multi-species fisheries. Fisheries Management and Ecology 6:1–19.

Worm, B., R. Hilborn, J. K. Baum, T. A. Branch, J. S. Collie, C. Costello, M. J. Fogarty, E. A. Fulton, J. A. Hutchings, S. Jennings, O. P. Jensen, H. K. Lotze, P. M. Mace, T. R. McClanahan, C. Minto, S. R. Palumbi, A. M. Parma, D. Ricard, A. A. Rosenberg, R. Watson, and D. Zeller. 2009. Rebuilding global fisheries. Science 325:578–585.

Appendix A: Detailed Methods and Results

Detailed methods

This appendix contains the detailed methods and equations used to develop the maps for this paper. It should be noted that these methods and models have not been parameterised with any field data and that the results are therefore preliminary. Much of the methodology was informed by the expert judgment of the authors, gathered at a workshop at the *2nd International Symposium on Mangroves as Fish Habitat* in Mazatlán, Mexico in April 2014. The remaining steps were developed by JH and MS based on background knowledge of the underlying ecology of mangrove ecosystems. The quantitative outputs are perhaps a useful pointer to some real patterns but are primarily intended to help ascertain how such a model could be further developed, using both a more extensive expert consultation and field data for parameterization, work we intend to undertake in the future.

Potential fish production.—Based on the workshop results and the availability of data sets, potential fish production per unit area of mangrove was modelled using freshwater input, nutrient input, and mangrove biomass. The layers were weighted based on the percentage of votes they received at the workshop (Table 1): freshwater input received six votes, nutrient input received five, and primary productivity (represented by mangrove biomass) received three (14 votes in total). The resulting weightings were 14/6 = 42.9 for freshwater input, 35.7 for nutrient input, and 21.4 for biomass. Each layer was scaled so that its maximum value was equal to its weighting, giving the modelled potential fish production a theoretical maximum of 100. Details of the development of each layer and of the scaling methods are given below.

- Freshwater input: Freshwater input was calculated using watersheds from the USGS Hydrosheds database (Lehner et al. 2006). We used precipitation data from the WorldClim Bioclim data set to calculate the total volume of precipitation for each watershed, and assumed that all of this volume flowed into the sea at the watershed river mouth. We did not account for evaporation or extraction by humans, which is significant in some regions. The level of freshwater influence was modelled using a Gaussian kernel convolution function to give a smooth decline with distance from each river mouth. The kernel function was calibrated using a map to estimate the range over which freshwater influenced mangroves at several sites with which the authors were familiar, and is shown in Figure A.1. The effect of this freshwater on potential fishable biomass was modelled using a logistic curve which was adjusted based on freshwater values in locations where mangroves are known to be freshwater limited or strongly freshwater influenced. This is based on the assumption that freshwater will benefit fisheries, but that the benefit for a given increase in freshwater will decline as total freshwater input rises. The function also gives a slow initial increase, as small amounts of freshwater will have little effect due to dilution in saltwater. The curve was scaled to give values between 0 and 43, which is the adjusted importance value for freshwater based on the workshop voting (Table 1), rounded to integer values. The curve is shown in Figure A.2.

- Nutrient input: We used modelled watershed sediment output from the Reefs at Risk project (Burke et al. 2011) as a proxy for nutrient input. This layer was developed to be a proxy of sediment, nutrient, and pollutant delivery, modelled using watershed soil type, slope, land cover, and precipitation for some 300,000 watersheds worldwide. It gives a high weighting to agricultural land use as a source of nutrients, but does not include any influence from human, livestock, or industrial waste. We assumed that the dispersion of this sediment would be related to river flow so we used the same Gaussian function to produce the nutrient map as we did for freshwater. As with freshwater, the impact of nutrients on potential fishable biomass was modelled using a logistic curve, this time scaled from 0 to 36. We hypothesised that even small amounts of nutrients from rivers could make a substantial difference to mangrove productivity and fish production in nutrient-poor oceanic mangroves, so we ad-

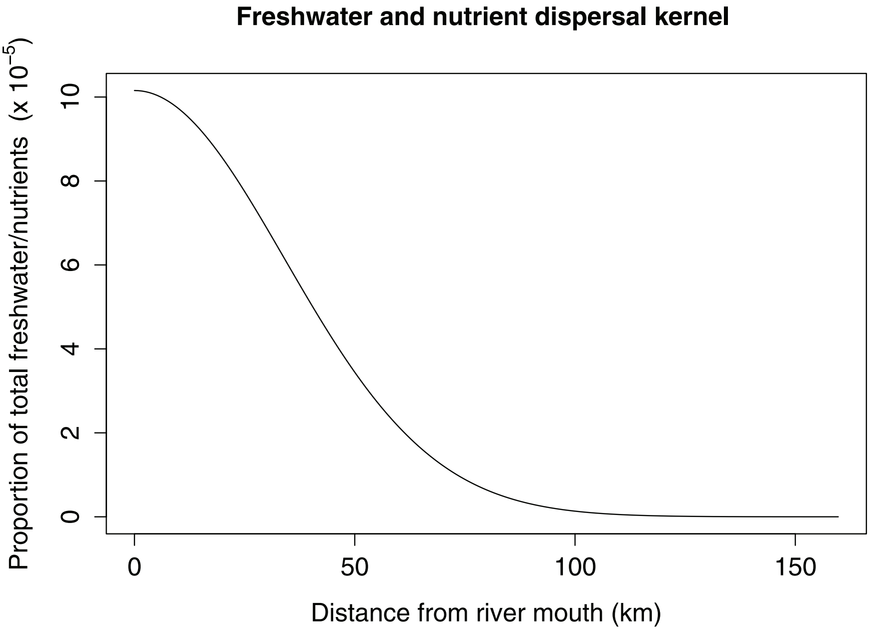

Figure A.1.—The kernel used to generate maps of freshwater and nutrient input from point sources at river mouths. The kernel was roughly calibrated using maps of known riverine influence on mangroves from a small subset of rivers.

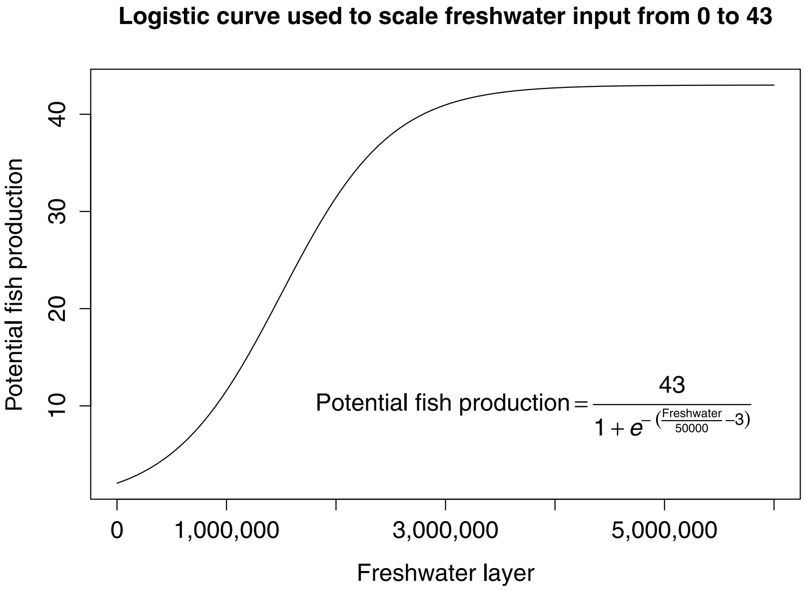

Figure A.2.—The logistic curve used to model the effects of freshwater input on potential fish production. The curve is based on the assumption that freshwater input will increase fish production up to a certain level, at which point it will plateau. The curve is scaled from 0 to 43 to reflect the voting score for freshwater (rounded to integer values).

justed the curve to remove the initial slow increase used for freshwater. Very high nutrient levels would be expected to cause a drop in fish production due to reduced water quality and eutrophication, but this is not included in our model. The curve is shown in Figure A.3.

- Mangrove biomass: Mangrove biomass data were taken from the climate-based model produced by Hutchison et al. (2014). Biomass was assumed to have a linear relationship with fish production. The modelled biomass layer used is in Mg/ha and has a range of 389. It was therefore scaled by multiplying all values by 0.055 to give a maximum value of 21.4, reflecting the weighting of this driver in the model.

The overall equation for potential fish production (PFP) is

$$\text{PFP} = \left(\frac{43}{1+e^{-\frac{\text{Freshwater}}{50{,}000}-3}}\right) + \left[-36+\frac{72}{\left(1+e^{-\frac{\text{Nutrients}}{7}}\right)}\right] + \frac{\text{Mangrove biomass}}{0.055}$$

Fishing effort.—Our fishing effort model used population density adjusted according to whether there was a market within 50 km. Based on consensus in the expert group, markets were defined as towns of 10,000 people or more. The hypothesis underlying the model is that mangrove fisheries without a market within 50 km are likely to be primarily catching fish on a subsistence basis for local consumption, whereas those with access to a market will be catching fish primarily for sale on a commercial basis. We

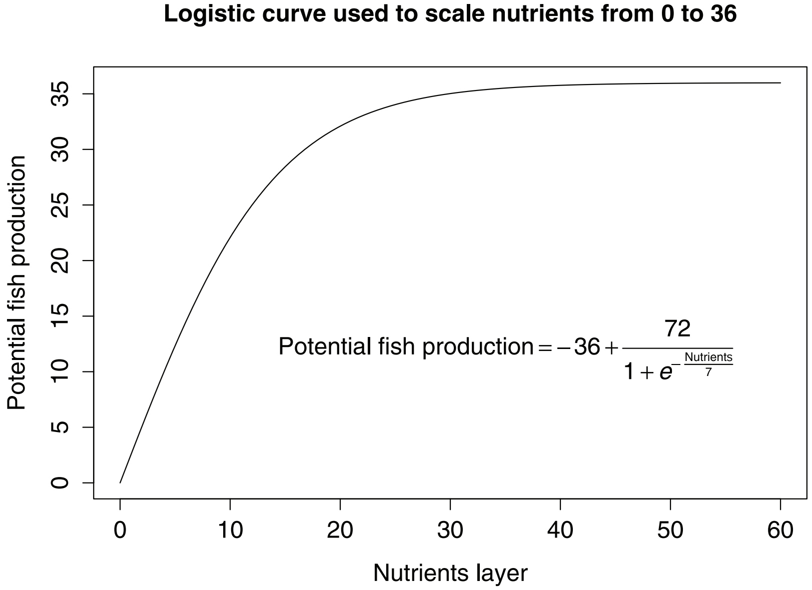

Figure A.3.—The logistic curve used to model the effects of nutrients on potential fish production. As with freshwater, there is assumed to be a positive relationship up to a certain point, followed by a plateau. The curve is scaled from 0 to 36 to reflect the voting score for nutrients (rounded to integer values).

hypothesise that these commercial fisheries will have greater fishing effort per head of population than the subsistence fisheries. Finally, we hypothesise that catch will increase with increasing fishing effort up to a plateau, after which it will remain stable as effort increases further. This relationship is commonly found for small-scale, mixed-species fisheries (Welcomme 1999).

We used the population density grid from the Global Rural-Urban Mapping Project (CIESIN et al. 2011a) layer to calculate the number of people within 10 km of each mangrove grid cell (potential fishers), and the settlement point layer (CIESIN et al. 2011b) to delimit areas within 50 km of a town of 10,000 people or more. Population per unit area of mangrove was calculated by dividing the population within 10 km of each mangrove grid cell by the total area of mangrove within the same 10-km radius. We used a model developed by Laë (1997) from work in coastal lagoon fisheries for the relationship between fishing effort and proportion of the available fish production caught. The model parameters were adjusted to give two separate curves: one for locations within 50 km of a market, and one for locations without a market within 50 km (Figure A.4). The curves represent the proportion of the available fish production caught for a given number of people per unit area of mangrove, where available fish production is some proportion of the modelled potential fish production. This proportion would vary depending on the fisheries biology of the target species but is unimportant in this context as the potential fish production model uses arbitrary units. The parameters for the curves were set based on expert opinion so that 99% of the available fish production was caught when the population within 10 km reached 500 people/km^2 mangrove for areas within reach of a market or 2,000 people/km^2 mangrove without a market. The equations for the two curves are as follows.

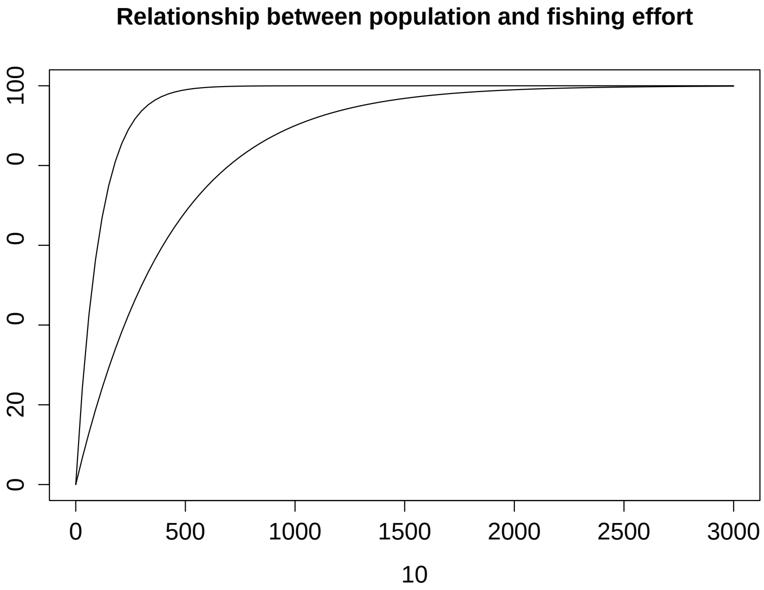

Figure A.4.—The two curves showing our hypothesised relationship between population and the proportion of fish production being caught in locations with and without markets.

With a market,

$$\text{Proportion of fish production caught} = 100\left\{1-e^{-\left[\frac{-\log(0.01)}{500}\times \text{Population}\right]}\right\}$$

Without a market,

$$\text{Proportion of fish production caught} = 100\left\{1-e^{-\left[\frac{-\log(0.01)}{2{,}000}\times \text{Population}\right]}\right\}$$

Modelled catch

Modelled catch was calculated by multiplying the potential fish production by the proportion of fish production caught for each mangrove grid cell. As potential fish production and proportion of fish production caught are both scaled from 0 to 100, catch is scaled from 0 to 10,000. We categorized these numbers as very high, high, medium or low based on quartiles to generate the maps shown in Figure 2. National and regional estimates for potential fish production, fishing effort, and catch were generated by multiplying the value of these layers in each grid cell by the area of mangrove in that grid cell, which was derived from USGS Global Distribution of Mangroves layer (Giri et al. 2011). These were then summed by country. Countries were divided into quartiles and scored as low, medium, high, or very high on their mean potential fish production, mean fishing effort, mean catch per unit area of mangrove, and total modelled catch to generate Table A.1.

Appendix References

Burke, L., K. Reytar, M. Spalding, and A. Perry. 2011. Reefs at Risk revisited. World Resources Institute, Washington, D.C.

CIESIN (Center for International Earth Science Information Network), Columbia University, International Food Policy Research Institute, The World Bank, and Centro Internacional de Agricultura Tropical. 2011a. Global Rural-Urban Mapping Project, (GRUMP), version 1: population den-

Table A.1.—Data on mean potential fish production, fishing effort, catch per unit area of mangrove, and total catch, for each country with more than 5,000 ha of mangrove forest. Countries are ordered by total catch and divided into quartiles, which are classed as low, medium, high, and very high.

Country	Mangrove area (ha)	Potential fish production	Fishing effort	Modelled catch	Total modelled catch
Nigeria	744,000	Very high	High	Very high	Very high
Indonesia	2,823,000	High	Low	Medium	Very high
Malaysia	940,000	High	Medium	High	Very high
Brazil	1,057,000	Medium	Medium	Medium	Very high
Mexico	728,000	Medium	Medium	High	Very high
Burma	507,000	High	High	High	Very high
India	393,000	Medium	High	High	Very high
Bangladesh	433,000	Medium	High	High	Very high
Guinea	242,000	Very high	Medium	Very high	Very high
Guinea-Bissau	353,000	High	High	High	Very high
Mozambique	321,000	High	High	High	Very high
Vietnam	217,000	High	Very high	Very high	Very high
Cameroon	158,000	Very high	High	Very high	Very high
Thailand	248,000	Medium	Very high	High	Very high
Sierra Leone	159,000	Very high	High	Very high	Very high
Philippines	258,000	Medium	Very high	Medium	Very high
Colombia	213,000	Very high	Medium	High	Very high
Senegal	168,000	Medium	High	High	High
Cuba	427,000	Low	Medium	Medium	High
The Gambia	70,000	High	Very high	Very high	High
Panama	154,000	High	Medium	Medium	High
Madagascar	272,000	High	Low	Medium	High
Ecuador	137,000	Very high	Medium	High	High
El Salvador	35,000	Very high	Very high	Very high	High
Tanzania	95,000	Very high	Medium	High	High
Australia	962,000	Medium	Low	Low	High
Guatemala	35,000	Very high	Very high	Very high	High
Venezuela	337,000	Medium	Low	Low	High
Honduras	66,000	Very high	Medium	Very high	High
Nicaragua	73,000	High	Medium	High	High
Pakistan	54,000	High	High	High	High
Papua New Guinea	473,000	Very high	Low	Low	High
United States (Continental)	233,000	Low	Low	Low	High
Costa Rica	39,000	Very high	High	Very high	High
Cambodia	47,000	Medium	High	High	Medium
French Guiana	88,000	High	Low	Medium	Medium
Gabon	138,000	High	Low	Low	Medium
Fiji	110,000	Low	Medium	Low	Medium
Brunei	21,000	Very high	Medium	Very high	Medium
Ghana	13,000	Very high	Very high	Very high	Medium
Kenya	33,000	Medium	High	High	Medium

Table A1.—Continued.

Country	Mangrove area (ha)	Potential fish production	Fishing effort	Modelled catch	Total modelled catch
China	18,000	High	Very high	Very high	Medium
Congo, (Kinshasa)	21,000	Very high	Medium	Very high	Medium
Liberia	13,000	Very high	High	Very high	Medium
Belize	57,000	Medium	Low	Medium	Medium
Suriname	75,000	High	Low	Low	Medium
Haiti	15,000	Medium	Very high	Very high	Medium
Angola	27,000	Very high	Low	Medium	Medium
Dominican Republic	18,000	Medium	Very high	High	Medium
Sri Lanka	23,000	Medium	Very high	Medium	Medium
New Zealand	31,000	Low	High	Medium	Medium
Benin	5,000	High	Very high	Very high	Low
Solomon Islands	46,000	Low	Low	Low	Low
Iran	21,000	Medium	Medium	Medium	Low
Guyana	20,000	High	Low	Medium	Low
Jamaica	10,000	Medium	Very high	Medium	Low
Puerto Rico	8,000	Low	Very high	Medium	Low
Trinidad and Tobago	6,000	Low	Very high	Medium	Low
United Arab Emirates	19,000	Low	Very high	Low	Low
Bahamas, The	81,000	Low	Low	Low	Low
Equatorial Guinea	13,000	Low	Low	Low	Low
Cayman Islands	8,000	Low	Very high	Medium	Low
Micronesia, Federated States of	10,000	Low	High	Low	Low
Saudi Arabia	8,000	Low	High	Low	Low
Eritrea	7,000	Low	Medium	Low	Low
Turks and Caicos Islands	17,000	Low	Low	Low	Low
Palau	6,000	Low	Medium	Low	Low
New Caledonia	25,000	Low	Low	Low	Low

sity grid. NASA Socioeconomic Data and Applications Center, Palisades, New York.

CIESIN (Center for International Earth Science Information Network), Columbia University, International Food Policy Research Institute, The World Bank, and Centro Internacional de Agricultura Tropical. 2011b. Global Rural-Urban Mapping Project (GRUMP), version 1: settlement points. NASA Socioeconomic Data and Applications Center, Palisades, New York.

Giri, C., E. Ochieng, L. L. Tieszen, Z. Zhu, A. Singh, T. Loveland, J. Masek, and N. Duke. 2011. Status and distribution of mangrove forests of the world using earth observation satellite data. Global Ecology and Biogeography 20:154–159.

Hutchison, J., A. Manica, R. Swetnam, A. Balmford, and M. Spalding. 2014. Predicting global patterns in mangrove forest biomass. Conservation Letters 7:233–240.

Laë, R. 1997. Does overfishing lead to a decrease in catches and yields? An example of two West African coastal lagoons. Fisheries Management and Ecology 4:149–164.

Lehner, B., K. Verdin, and A. Jarvis. 2006. HydroSHEDS Technical Documentation, version 1.0. World Wildlife Fund, Washington, D.C. Available: http://hydrosheds.cr.usgs.gov/webappcontent/HydroSHEDS_TechDoc_v10.pdf. (January 2015).

Welcomme, R. L. 1999. A review of a model for qualitative evaluation of exploitation levels in multi-species fisheries. Fisheries Management and Ecology 6:1–19.