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Viewpoint

Transforming management of tropical coastal seas to cope with challenges of the 21st century

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ABSTRACT

Over 1.3 billion people live on tropical coasts, primarily in developing countries. Many depend on adjacent coastal seas for food, and livelihoods. We show how trends in demography and in several local and global anthropogenic stressors are progressively degrading capacity of coastal waters to sustain these people. Far more effective approaches to environmental management are needed if the loss in provision of ecosystem goods and services is to be stemmed. We propose expanded use of marine spatial planning as a framework for more effective, pragmatic management based on ocean zones to accommodate conflicting uses. This would force the holistic, regional-scale reconciliation of food security, livelihoods, and conservation that is needed. Transforming how countries manage coastal resources will require major change in policy and politics, implemented with sufficient flexibility to accommodate societal variations. Achieving this change is a major challenge – one that affects the lives of one fifth of humanity.

1. Introduction

Ever-expanding human impacts are continuing a substantial decline in the capacity of coastal marine ecosystems to provide crucial goods and services (MEA, 2005; Jackson, 2010; Lotze et al., 2006). In addition to local stressors such as overfishing and

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pollution, coastal seas now suffer from warming, ocean acidification, and catastrophic weather events directly related to our releases of greenhouse gases, particularly CO_2 (Doney, 2010). The deteriorating ecological capacity of coastal ecosystems to deliver services directly impacts coastal communities that depend on adjacent waters for their food and livelihoods.

Globally, tropical coastal seas share ecologies, environmental problems and solutions, fall predominantly within developing countries, and are home to more than one fifth of the global population. Here, we use the most up-to-date demographic data available to compute the number of people living within 100 km of a tropical coast, and the number expected there in 2050. We review current and projected trends in climate and ocean chemistry to visualize the tropical environment at mid-century, and, because loss of corals is one of the major changes occurring, we model the effects of loss of coral cover on fishery productivity in reef waters. These analyses collectively reveal how stresses on coastal seas will change and where priorities for management should lie: Tropical coastal waters, already subject to widespread degradation, are going to deteriorate further in their capacity to provide environmental goods and services unless we substantially improve management. More of the same is not enough.

Given this context, we explore technological issues in managing coastal development, fisheries, aquaculture, and pollution, and suggest ways to create a holistic management approach within jurisdictions and across regions. In doing this, we recognize the special challenges facing developing countries in providing for development and food security, while also advancing biodiversity conservation, as well as the imperative of building a management regime that is responsive to a changing environment. Our approach tailors solutions to communities' specific socio-political circumstances, includes a new perspective on marine spatial planning, and brings renewed attention to a suite of pernicious socio-economic factors, including the fact that costs and benefits are rarely distributed equitably across socio-economic classes (Daw et al., 2011). These issues must be substantially remedied to achieve real improvements in sustainability and quality of life for millions of coastal people.

2. Methods to anticipate trends and identify management priorities in tropical coastal seas to 2050

Many researchers have used modeling to predict the near term and longer term changes that may occur in response to climate shifts mediated by anthropogenic stressors. Our intention was to look specifically at how expected changes in the medium term will affect the health and productivity of tropical coastal seas, and in turn the effect on coastal communities and economies. Our approach is threefold: (1) a spatial analysis of projected human population growth in tropical coastal areas, (2) an attempt to predict impacts of local and global stressors on resource availability and livelihoods in the tropics, including the indirect effects of climate change on tropical nearshore fisheries, and (3) a prioritization, based on both these analyses, suggesting where and what kind of focused management is most urgently needed, with an accompanying recommended framework for action.

2.1. Population projections and potential impacts on tropical coastal seas

For spatial analyses of tropical coastal seas, we used Environmental Systems Research Institute's (ESRI) ArcGIS software suite (v. 9.3.1), including ArcInfo, ArcCatalog and ArcMap; ESRI ArcView (v. 3.2a); and QGIS (v. 1.80), defining the tropics as the area bounded by the Tropics of Cancer and Capricorn, 23°26′16″ latitude N and S respectively (Epoch, 2012), and coastal seas as those within the continental shelves (depths from 0 to 200 m in the Shuttle Radar Topography Mission (SRTM) 30 Plus, global, gridded terrain data) (Becker et al., 2009). SRTM 30 Plus is a globally seamless topography and bathymetry grid, comprised of the shuttle-based topography of the earth (SRTM) dataset, combined with bathymetry from a satellite-gravity model (Becker et al., 2009). Grid cell size is 30-arcseconds, which corresponds to about 926 m at the equator. We used the Millennium Coral Reef Mapping Project (2010) validated and unvalidated data layers of warm water coral, found primarily between 30°N and 30°S latitude, using all coral types represented in the data layer, and then converted the vector-based data layer to a 30 arcsecond cell sized grid in order to facilitate spatial overlay with the human population data.

The 2011 LandScan (Bright et al., 2012) global, gridded (30-arcsecond) dataset was used to represent terrestrial human population counts. This data layer is the highest resolution "ambient population (average over 24 h)" currently available (Bright et al., 2012), and is based on an algorithm which uses spatial data and image analysis technologies and a multi-variable dasymetric modeling approach to disaggregate census counts within an administrative boundary (Bright et al., 2012). Population counts are reported for each 30-arcsecond grid cell; since grid cells based on Euclidean coordinate systems are not uniform in area as one moves away from the equator, the values are numbers of humans per cell rather than their density.

We defined the terrestrial 'coastal region' as the region within 100 km of the shoreline regardless of elevation. We started with the Global Self-consistent Hierarchical High-resolution Shorelines (GSHHS) global coastline polygon data layer (NOAA, 2013), then deleted the Antarctic polygons as well as any polygons that did not intersect a polygon version of LandScan land delineation in the high resolution, level 1, GSHHS_h_L1 file. ArcCatalog was used to convert all polygon vertices from the edited GSHHS data layer into points in order to perform a geodesic buffer on said points, thereby accurately representing scale at any given point on the Earth's surface, regardless of a given point's distance from the equator. We created a geodesic buffer of 100 km around each of the GSHHS shoreline points and then converted the resulting buffered polygon file into a single, 30-arcsecond grid. Since the resulting grid depicted a 100 km buffer on both sides of the shoreline, and because the GSHHS shoreline did not perfectly align with the LandScan shoreline, we created a grid for the marine and the terrestrial sides of the 100 km buffer, using the LandScan grid as a mask.

The area, total population and corresponding population density were calculated for the following land regions:

- Terrestrial areas (excluding Antarctica), within 100 km of the global marine coastline.
- Terrestrial areas within the tropics.
- Areas within 100 km of the tropical marine coastline.

We also performed regional analyses, focusing on Southeast Asia, and then zoomed into a selected portion of the Indonesian archipelago within Southeast Asia, as a more localized case aligned with the analysis of potential fisheries impacts (see Box 1. Raja Ampat study).

The 100 km coastline buffer conserved scale at all locations on the globe, however area was not conserved as a function of latitude (Snyder, 1987). In order to calculate area accurately for all of the aforementioned regions, we transformed the native geographic coordinate system to Mollweide, which is a global equal area coordinate system (Snyder, 1987).

Gridded global human population forecast data for the years 2010 and 2050 (Bengtsson et al., 2006) were used to quantify projected changes in human populations in the tropics within 100 km of the coast as well as inland (LandScan data do not provide for projections into the future). The Bengtsson et al. (2006) data are considerably coarser than the LandScan data (30-arcminute vs. 30-arcsecond grid cell resolution), but they are the finest resolution gridded data available for projections through 2050. We used the IPCC SRES (Special Report on Emissions Scenarios) B2 scenario family projection, which "is based on the long-term UN Medium 1998 population projection of 10.4 billion by 2100" (IPCC, 2000).

2.2. Anticipating the impact of climate change on coastal fisheries

Since global climate change is expected to reduce the extent of living coral and associated 3-dimensional habitat complexity across reefs (Donner, 2009), and since coral reefs are a major habitat type in tropical coastal seas, we looked at how changes on reefs will affect fishery production, drawing on global literature (e.g. Ban et al., 2014; Cheung et al., 2013) but also performing a modeling study based on a subregion of Southeast Asia (Raja Ampat, Papua, in the Indonesian archipelago – see Box 1). Specifically, we used an Ecopath with Ecosim model parameterized for the Raja Ampat reefs (Ainsworth et al., 2008), which we extended to include responses of space-limited algae. Then we modeled the effect a progressive 0–100% reduction in extent of coral cover will have on reef community structure, and the effect of these changes on fishery production (see Box 1). This study demonstrates how reef degradation will affect reef fishery production, and thus local livelihoods and the national economy.

2.3. Identifying priority areas for application of systematic MSP

As a first approximation for identifying priorities for immediate management response, we constructed a simple model that ranks areas according to cumulative pressures and potential user conflicts. To approximate the intensity of human impacts on tropical coastal seas around the world we used the 'focalmean' tool in ArcCatalog to extrapolate a population proximity index for each of the grid cells in the continental shelf region of the tropics. 'Focalmean' calculates a new value for each grid cell in an existing grid, based on the value of surrounding grid cells. For our analyses, we used a circular region around each grid cell, which extended out to a radius of 100 grid cells. This approximated a focal mean radius of about 93 km at the equator. We created a source grid for our focal mean calculations by combining the LandScan grid with the continental shelf grid. Each of the grid cells in the shelf region of the source grid had a value of 0, and all of the terrestrial grid cells had the corresponding population count information from LandScan. We masked out all land grid cells in the resulting

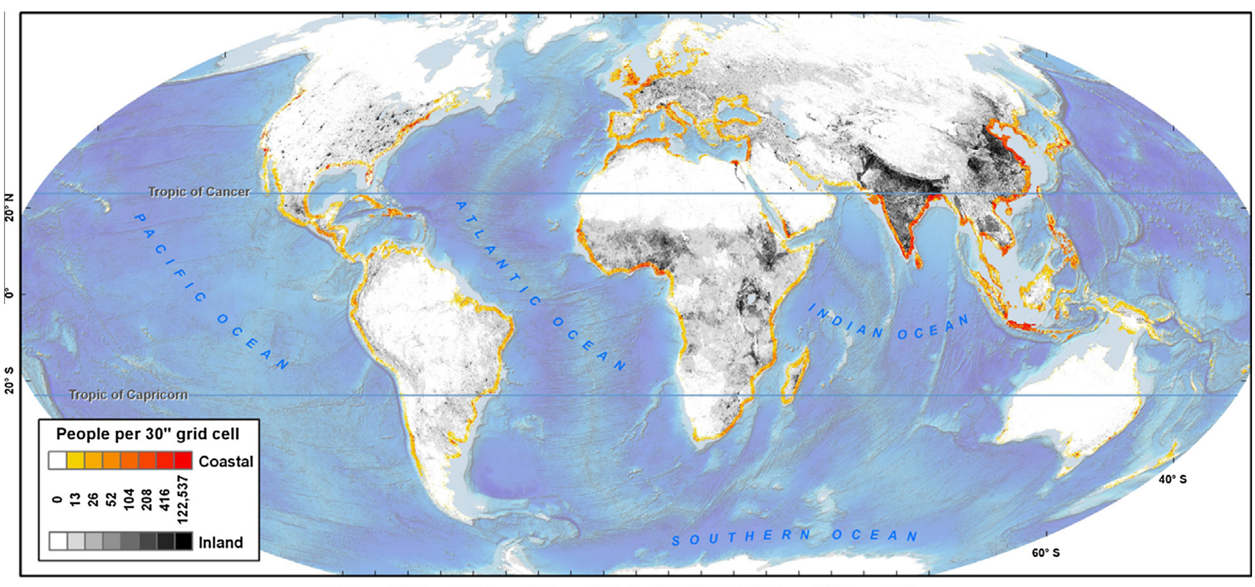

Fig. 1. Global population density emphasizing the coastal region (within 100 km of shore) based on LandScan 2011 data (Bright et al., 2012). Population density is greatest in the tropical coastal region, where 20% of the planet's 7 billion people live on a mere 7% of Earth's total land area at densities averaging 141 km^{-2}.

Table 1
Projected changes in tropical coastal environments by 2050 under three scenarios; BAU, a minimal approach to GHG emissions, MODERATE, a comprehensive response that keeps global temperature increase to +2 °C at 2100, and STRONG, a concerted attempt to reduce GHG concentrations. Differences among scenarios are still small in 2050; real impacts of alternative approaches to GHG management come later in the century. Symbols + and − indicate direction of change while number of symbols indicates severity. Impacts on precipitation are expected to vary geographically with some places experiencing wetter, and some drier conditions.

	Change in typical tropical coastal environment by 2050 relative to 2000		
Parameter	BAU	Moderate	Strong
Average global temperature (Rogelj et al., 2012)	+1.7 °C	+1.2 °C	+0.8 °C
Tropical sea temperature (Meehl et al., 2012)	+1.5 °C	+1.0 °C	+0.6 °C
Sea level rise (Jevrejeva et al., 2012)	40 cm	30 cm	20 cm
pH (Change re 2013, IPCC, 2007)	7.95 (−0.15)	8 (−0.1)	8.05 (−0.05)
Water column stability (IPCC, 2007)	+++	++	+
Precipitation (IPCC, 2007)	+++/−−−	++/−−	+/−
Storm intensity (IPCC, 2007)	+++	++	+

focal mean grid. The shelf region greater than 100 km from a coast received a population proximity index score of zero, since those areas were assumed to receive negligible direct impacts from urbanization. We acknowledge that certain ocean-based activities (e.g. offshore mineral extraction) will have impacts not captured by our approach.

3. Results I: A look into the future

3.1. Changes in coastal populations and environment

The 100 km wide coastal strip comprises 21% of all land, and is occupied by over 2.6 billion people (Fig. 1) at densities from <20 km^{-2} to >15,000 km^{-2}, and an average density (97 km^{-2}) over twice that of inland regions (41 km^{-2}). Over half these people (1.36 billion) live on tropical coasts (just 7% of all land) at even higher densities (145 km^{-2}). Tropical coasts hold 9 of 19 coastal megacities (>10 million people each), and are most densely populated (mean of 198 km^{-2}) in South and Southeast Asia (Balk, 2011; von Glasow et al., 2013).

Analysis of the 2010 and 2050 population projection data (Bengtsson et al., 2006) reveals that across the world's tropics, the coastal population is expected to grow by 45% to 1.95 billion people by 2050, while the number of people occupying the inland tropics will grow by 71% to 2.26 billion. However, the total area of inland tropical land is four times that of coastal regions, so tropical population density in 2050 is projected to be 57 km^{-2} inland and 199 km^{-2} on coasts. Coastal communities will generate increased local environmental stresses, although improved management may keep some or all of this increase unrealized.

Table 1 presents three averaged projections of the physico-chemical state of tropical coastal environments in 2050, using three alternative scenarios developed by the international community associated with the IPCC to describe different policy approaches to GHG emissions. The business-as-usual (BAU) scenario uses RCP8.5 (Vuuren et al., 2011) which approximates the earlier SRES A1FI scenario (Rogelj et al., 2012), and involves high levels of fossil fuel use and minimal efforts to reduce GHG emissions. It is the future to which we are currently moving. By 2050, under this scenario, global temperatures will approximate 1.7 °C warmer relative to the year 2000, rising towards 4.0 °C warmer in 2100 (Fig. 3 in Rogelj et al., 2012). The MODERATE scenario, RCP4.5 (similar to SRES B1), involves strenuous efforts to rapidly reduce emissions such that atmospheric concentration of CO_2 is

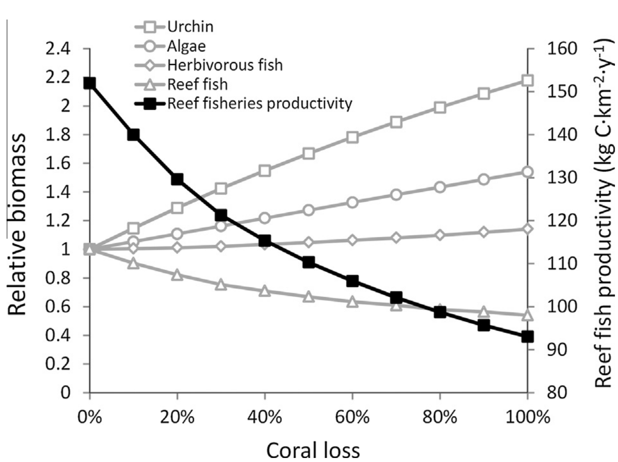

Fig. 2. Effects of habitat loss (coral biomass) on the relative biomass and reef fishery production of an exploited coral reef in Papua, Indonesia (model parameterized for Raja Ampat archipelago).

Box 1 Modeling effects of climate change on fishery production in Raja Ampat

The Raja Ampat archipelago is a representative coral reef system, currently rich and productive. We simulated a loss of coral biomass, incrementally reducing the biomass of coral from 100% of its current (2008) value, to 0%. Throughout these simulations, current fishing effort was maintained. The model of Ainsworth et al. (2008) includes mediation effects that simulate non-trophic dependencies in the ecosystem such as the protection from predators offered by coral to fish. For this study, we have added an additional effect to represent space-limited growth of benthic algae: as coral biomass declines, benthic algal productivity increases. We subsequently ran a more detailed set of simulations in which we drove the model directly with the declines in biomass consequent on coral loss for 7 functional groups of reef fish as reported by Wilson et al. (2006). This second approach removes assumptions in the model concerning the dependency of fish on coral.

As coral was eliminated in our primary simulation, the ecosystem shifted towards algal dominance which led in turn to a 14% increase in herbivorous fish and a 117% increase in sea urchins (Fig. 2). Shrimp also increased due to a loss of reef-associated predators. However, reef fish biomass, which is the traditional target of local fisheries, decreased on average by 46%, with some reef-dependent groups showing severe depletions (small reef fish 97%, medium reef fish 61%, large planktivores 78%). Biodiversity decreased as measured by both the Shannon index (−4%) and the Q90 index (−10%), in accordance with field observations (Jones et al., 2004). This suggests a major structural shift and likely loss of resilience (Vitousek et al., 1997; Western, 2001). Overall reef fishery production fell to about 60% of initial yield once coral loss reached 100%.

Our more detailed simulations (Ainsworth and Mumby, in press) resulted in a loss of large reef-associated fauna and a shift in community dominance towards smaller-bodied fish, confirming prior field evidence of shifts in size distribution (Graham et al., 2007), and largely confirming the results in Fig. 2. Again we saw an increase in shrimp. Reef fisheries now account for the majority of animal protein consumption in many parts of the coastal tropics (Bell et al., 2009, 2011; Cooley et al., 2009; Smith et al., 2010; Foale et al., 2013), and Newton et al. (2007) showed that rates of resource extraction already exceed sustainable yields in 55% of 49 island nations. Their study assumed that reef habitat quality was uniformly high, and able to sustain an estimated harvest rate of 5 $mt.km^{-2}\ y^{-1}$. Our results project significantly lowered production capacity in 2050 due solely to GHG effects on coral cover.

stabilized at around 450 ppm by 2100. In 2050, average global temperature under RCP4.5 will approximate 1.2 °C warmer than 2000. In the STRONG scenario, RCP3-PD, human emissions of CO_2 fall to very low levels within one or two decades with the outcome that average global temperature approximates 0.8 °C warmer than 2000 in 2050 and begins to decline by 2100. Tropical sea surface temperatures (SST) are approximated from average global air temperature assuming a small time lag due to the relatively higher thermal inertia of sea water. Higher ocean temperatures lead to

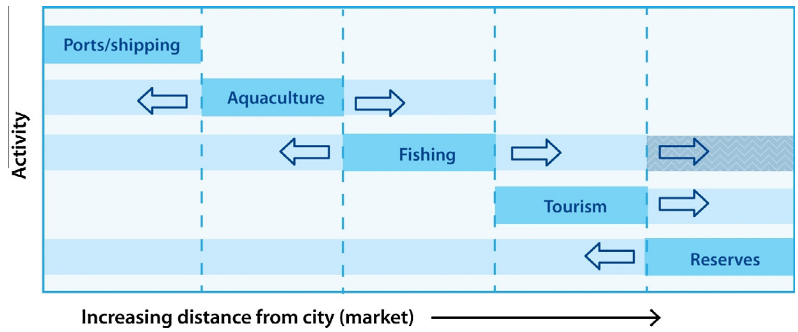

Fig. 3. Example of first-order marine spatial planning to highlight priorities for MSP in tropical coastal waters, based on distance from an urban center or market. Dimensions of zones are arbitrary and need not be the same size. Lighter blue shading and arrows indicate that a particular use of coastal waters can be 'nested' in other zones as a result of second-order planning. Note that small-scale fisheries will usually be possible in all zones, although there may be special catch and gear restrictions within reserves.

thermal expansion which combines with increased melting of land ice to raise sea levels.

In the BAU future, 2050 will see tropical SSTs 1.5 °C warmer (Rogelj et al., 2012), sea level 40 cm higher (Jevrejeva et al., 2012), and rainfall patterns that make currently wet regions wetter and dry regions more arid (Lough et al., 2011). Precipitation is likely to arrive in fewer, more intense storms. Higher SSTs will increase the risk of local thermal anomalies exceeding long-term summer maxima. Currently, thermal anomalies $\geqslant$1 °C above long-term summer maxima (climatology from 1985 to 1995), and lasting four weeks or more result in mass coral bleaching, and coral mortality increases if anomalies are greater or last longer (Eakin et al., 2010). Acidification will exacerbate effects of temperature on corals by slowing recovery from bleaching, and generally curtail reef accretion. Coral reefs will be substantially degraded or lost by 2050 in the BAU future (Hoegh-Guldberg et al., 2007). By 2050 in the MODERATE future the extent of each of these changes will be only somewhat less. (The real difference between these scenarios will appear later in the century.) In our most benign STRONG projection, these impacts will also occur although to reduced extents. The sensitivity of corals to heat stress is such that the predicted +0.6 °C increase in SST will likely increase frequency and severity of mass bleaching events. However, stabilization of GHG concentrations during this century should allow time for adaptation and some continued reef accretion (Hoegh-Guldberg et al., 2007). Under all three scenarios, it is clear that climate change stresses on tropical coastal ecosystems, and particularly coral reefs, are going to increase by 2050.

As well as effects of climate change, coral reefs along with other habitats will experience growing impacts due to local stressors (all growing with growth in coastal populations). The growing impacts will reduce coral reef complexity, in addition to causing degradation of other linked habitats such as seagrass meadows, mangroves, and algal flats (Waycott et al., 2011). In turn, loss of coral cover and 3-dimensional reef structure will reduce the diversity and abundance of small reef fishes (Jones et al., 2004; Wilson et al., 2006), important prey of reef fishery species (Pratchett et al., 2011). These changes are expected to have secondary effects on coastal fisheries production in all tropical seas (see Box 1).

3.2. Impacts on the provision of goods and services

Human populations in tropical coastal areas benefit substantially from goods and services provided by their bordering seas. They also stress and degrade these systems (Lotze et al., 2006). Urban residents, although depending less on food from immediate waters, cause significant pollution, eutrophication and low oxygen 'dead' zones (Doney, 2010; von Glasow et al., 2013) while adding to pressures on fisheries. Climate change and ocean acidification now impose additional and growing stresses on coastal waters (Cochrane et al., 2009; Doney et al., 2012; Bell et al., 2013), while growing populations, rising standards of living, and growing access to international trade add to local pressures (Berkes et al., 2006; Hall et al., 2013).

While global efforts might ameliorate effects of GHG emissions, and rising socio-economic status may further curtail population growth, the difference between sustainable coastal ecosystems and substantially degraded ones in 2050 will be determined by the effectiveness of local management in place. While there are a few exceptional places, all too often, current management of development, habitat destruction, pollution, and overfishing is seriously inadequate, and if this management is not improved we are confident in stating the following: (1) Most coastal fisheries will be chronically overfished or collapsed (Newton et al., 2007; Smith et al., 2010). (2) Loss of reef habitat will further reduce fisheries production and strain food security (Pratchett et al., 2011). (3) Land-based pollution will increase to the extent that hypoxia and harmful algal blooms are routinely present (Fu et al., 2012). (4) Pressures of coastal development will combine with sea level rise and more intense storms to further intrude on and erode natural coastlines, severely reducing mangrove, salt marsh and sea grass habitats (Nicholls and Cazenave, 2010, Waycott et al., 2011; Bell et al., 2013; Saunders et al., 2013). (5) The cost of dealing with these impacts will further strain coastal economies, and the future for people on tropical coasts in 2050 will be substantially more bleak than at present.

Our analysis of future trends outlines the dimensions of cumulative anthropogenic stressors on tropical coastal ecosystems and how their growing impacts will affect livelihoods, food security, and human well-being. But our analysis also suggests that the extent of stress and thus the need for appropriate management response is not uniform across tropical seas – priority locations can be identified. In these priority locations, comprehensive MSP and consequent ocean zoning can and should be launched now.

4. Results II: Building effective management for tropical coasts

4.1. Background

Current management of coastal marine environments suffers from a piecemeal approach, failure to recognize connectivity among local habitat units including critical links with inland systems, weak governance, corruption, and persistence of deeply embedded belief systems that view the ocean as unlimited and open to all (Christie et al., 2005; White et al., 2005; Sale et al., 2008). With many coastal fisheries being replaced by aquaculture

(Sanchirico et al., 2010; Merino et al., 2012), the pressure to improve management may seem lessened – although the profits from aquaculture do not accrue to the same communities nor to as wide a range of individuals, and food security remains an urgent issue (Hall et al., 2013). Many aquaculture operations currently undermine natural habitats and ecological processes, putting coastal communities and economies at risk from loss of shoreline stabilization, hazard mitigation, and pollution filtering. Burgeoning coastal populations, growing international trade in fishery products, and climate change simply ensure that current management approaches will become ever less effective.

Management – of coastal development, habitat, water quality, biodiversity, or fisheries – requires locally focused interventions to change human activities and lower impacts, coordinated across ecologically appropriate spatial scales (Mills et al., 2010). In the past, a great deal of the localized policy response focused on the use of no-take marine reserves and other marine protected areas (MPAs), either singly or as networks of ecologically connected MPAs.

There is evidence that appropriately implemented MPAs can increase the abundance of valuable fisheries species within their borders, and contribute to recruitment in surrounding fishing grounds (Harrison et al., 2012). Suitably placed and sized MPAs can help sustain multi-species fisheries, and reduce the broader ecosystem impacts of fishing where such effects are a major concern (Hilborn et al., 2004). This value can be overstated, however. While some MPAs have proven effective in stemming biodiversity loss, maintaining fish populations, and keeping habitats physically intact, the vast majority of MPAs around the world are not as effective as hoped, due to inadequate use of science (Sale et al., 2005), design flaws, or insufficient management to guarantee compliance with regulations (Agardy et al., 2011). Recently, Edgar et al. (2014) showed that key features underlying the success of MPAs in biodiversity conservation include being: (1) big (greater than 100 km^2), (2) old (established for 10+ years), (3) no-take (not allowing fishing of any type), and (4) remote. Clearly the opportunities to meet these criteria and reap successes in tropical coastal seas are limited and declining given the density of often competing uses.

Marine protected areas rarely do a good job of addressing threats to coastal ecosystems stemming from pollution, land use or invasive species, and they can increase user conflicts rather than abate them (Mascia et al., 2010). Yet MPAs are perhaps the most widely implemented spatial management measures, and experience in designing and zoning MPAs or MPA networks provides a major impetus for development of broad-based spatial governance. It is important to note, however, that the necessary policy shift that more effective management will require is unlikely to come about simply through the designation of more MPAs without these being embedded in broader systematic spatial planning and ocean zoning intended to deal with a broader range of human impacts while fostering appropriate types of use. This is especially true if coastal countries keep their commitments to protecting marine biodiversity (such as CBD targets) by designating very large, remote MPAs that neither address increasing food security challenges (Belton and Thilsted, 2013) nor emerging conflicts among different ocean/coastal uses.

The mismatch between local scale establishment of MPAs and national or international scale policies and agreements aiming to conserve marine biodiversity, coupled with the natural tendency of administrative bodies to be insular, leads to piecemeal efforts. Integrated coastal management or ICM (Olsen and Christie, 2000), now subsumed within ecosystem-based management or EBM (McLeod and Leslie, 2009), is a set of contextual and design principles to accommodate this need for explicit interventions with the need for seamless, regional-scale care of coastal ecosystems. But while ICM has been discussed for over 20 years, examples of its effective implementation are rare (Tallis et al., 2010; Collie et al., 2013). Similarly, while it is increasingly recognized that management should be done at larger scales, including through the large marine ecosystem framework (Sherman, 1986) that identifies 64 large marine ecosystems (LMEs), large-scale management efforts frequently fail to generate the essential buy-in by local communities and stakeholders that is necessary for success (Christie et al., 2005; Tallis et al., 2010). What appears to be needed is a technically simple set of procedures that can enforce a multi-scale perspective and a strongly holistic approach to management despite the diversity of agencies, stakeholders and goals inherent in any attempt to manage coastal waters on a regional scale. We propose making expanded use of marine spatial planning (MSP) and zoning as a framework that will apportion coastal waters for differing activities, while forcing a multi-target and multi-scale approach, and achieving agreed ecological, economic and social objectives (Agardy, 2010; Tallis et al., 2010).

4.2. The promise of marine spatial planning and zoning

MSP has been practiced largely in developed countries, principally focusing on conservation of coastal ecosystems (Agardy, 2010; Tallis et al., 2010; Collie et al., 2013). Use of MSP to facilitate sustainable food production, in concert with other activities, has received very little attention, despite the great dependence on small-scale fisheries in tropical developing countries (Hall et al., 2013), where rural communities have few alternative sources of animal protein (Bell et al., 2009; Kawarazuka and Bene, 2011; Lam et al., 2012). In these countries, effective coastal management must acknowledge this widespread dependence of poor and politically weak communities on the use of fish for food (Lam et al., 2012; Hall et al., 2013). Acknowledging this dependence (Bell et al., 2006, 2009; Mills et al., 2011) is pivotal to reconciling the largely separate agendas for food security and biodiversity conservation (Rice and Garcia, 2011; Foale et al., 2013). A mix of coastal fisheries and appropriate coastal aquaculture is required (Belton and Thilsted, 2013; Merino et al., 2012), and MSP can incorporate both these uses of coastal waters while adjudicating the access conflicts between them and other legitimate uses of the coastal seas (Lorenzen et al., 2010b; Agardy et al., 2012).

Beyond addressing food security challenges, MSP can be expected to help address the issues faced by managers of tropical coastal waters in several ways (Agardy, 2010):

- Protecting ecologically critical areas to allow healthy ecosystem function.
- Separating conflicting uses.
- Facilitating the emergence of sustainable, rights-based governance regimes by delimiting resources and those who can use them.
- Facilitating accrual of benefits to resource users from investments they make to sustain or enhance those resources.
- Addressing management failures caused by inappropriately defined boundaries.

4.2.1. Allowing protection of ecologically critical ecosystem components

As stated previously, MPAs can successfully protect biodiversity and maintain or enhance productivity, including fisheries productivity. However, the odds are diminishing that all essential conditions for effective MPA management will be met because pressures are intensifying as populations and their associated demand for resources increase (Edgar et al., 2014). Furthermore, planners are tending to retreat from efforts to manage heavily used areas because of the complexity inherent in reconciling multiple uses and indirect impacts. MPAs alone will not prevent massive degradation of tropical seas.

Ecologically critical areas can however be protected within the matrix of management and regulations that flow from MSP and ocean zoning. Localized and regional assessments can harness science to quickly and efficiently identify habitats delivering important ecosystem services, including services that regulate and support broader environmental health and allow reefs and associated ecosystems to continue to deliver much-needed fisheries, energy, materials, and other goods into the future (Tallis et al., 2010). In a zoning plan that flows out of a comprehensive, participatory MSP process, these critical nodes can be designated as redline areas, to be protected as strictly as appropriate.

4.2.2. Separating conflicting uses

An important argument for spatial planning arises from the growing extent and diversity of ocean uses: large and small-scale fishing, aquaculture, shipping, wind and wave power, minerals extraction, recreation, and conservation. Many of these uses and interests are inherently incompatible. MSP, and the ocean zoning that emerges from it, provides a means of reducing use and interest conflicts as well as rationalizing the areas over which uses can occur while creating opportunities for establishment of rights-based incentives for sustainable use. Separating and rationalizing allocation of space will create a set of localized goods and services and define the users more explicitly (Sanchirico et al., 2010; Tallis et al., 2010).

4.2.3. Facilitating the emergence of sustainable, rights-based governance regimes

MSP involves the demarcation of areas and may impose boundaries around resources and those entitled to use them. Such boundaries allow development of management policies based on the allocation of exclusive rights to individuals or groups, and use of appropriate management tools for achieving sustainability. Institutional analysis has shown that clear and appropriate boundaries around resources and those entitled to use them are among the key ingredients of successful common pool resource governance (Ostrom, 1990), and allocation of use rights is widely seen as a key strategy for countering perverse incentives in common pool resources such as fisheries (Berkes, 2010).

Different resource, stakeholder and market attributes call for different modes of governance. Uses such as fishing within bounded zones may be governed by bureaucratic, communal or market-based means. Use rights must be big enough in space and time to promote resource conservation and can be integral to the rationalization and reduction of fishing effort. At the same time, the creation of use rights leads to winners and losers and can be contentious. In developing countries with unequal power relations, political marginalization and weak governance, creation of use rights has the potential for 'elite capture' and the further impoverishment of poor people through loss of access to ecosystem services, particularly if MSP is targeted on aggregate economic indicators (Daw et al., 2011).

As well as dealing equitably with groups of widely differing political power, governance systems under MSP must deal effectively with diverse uses and interests on multiple, nested spatial and temporal scales. This requires that governance systems be comprehensive in the sense that they cover the entire area within a jurisdiction and include all legitimate uses and interests. Governance systems also need to operate at multiple, nested scales matching those at which resources and their uses are structured and interact (Berkes, 2010). This could pave the way for nested, place-based institutions: integrated (overall regional oversight), coordinating (across-zone coordination), and specialist zone agencies (e.g. fisheries management in one zone). Polycentrism – networks of governing bodies that may have partly overlapping jurisdictions and roles, and which may arise or dissolve in response to functional needs may be the most realistic vision for achieving this. Indeed, few cases of MSP to date have led to reorganization of governance structures (Collie et al., 2013).

4.2.4. Driving active restoration and enhancement of fishery production

Perhaps the most easily grasped benefit of MSP is that, by establishing boundaries and facilitating the emergence of rights-based governance systems, it can create conditions that foster long-term incentives for resource users to restore degraded resources and ecosystem services. This may be done through complete protection in the most ecologically valuable areas and through fishing within sustainable limits in other areas that are capable of supplying high levels of ecosystems services without further intervention. Sustainable use can be incentivized by having beneficiaries invest in the protection of ecologically critical sites and the effective management or restoration of the wider areas. When these investments take the form of payments to local communities or governments which can adequately manage impacts locally, the resulting 'Payments for Ecosystem Services' may help defray what are sometimes excessive costs of management, including the cost of patrols, research, mitigation measures, etc. (Emerton, 2014; Muradian, 2014, but see also Brockington, 2011; Sullivan, 2012).

More interventionist approaches may be required in areas where demand for ecosystem services exceeds the capacity of the natural system to supply these services and/or the natural system is substantially degraded. We anticipate a need for continued evaluation of existing tools and development of new sorts of interventions, ranging from rebuilding of fisheries stocks or repair of habitat to various forms of aquaculture (Bell et al., 2005, Lorenzen et al., 2010b, Merino et al., 2012). Release of hatchery-reared organisms as part of a well-researched and planned activity might rebuild fishery populations and the ecosystem services, such as grazing of algae, which they provide. By restoring degraded physical habitat or increasing limiting habitat beyond its natural extent (e.g. artificial reef construction) availability of critical habitat might even be enhanced. Aquaculture involves multiple interventions in the species' life cycle and habitat and typically, private ownership of the stock being cultured (Bostock et al., 2010). Given appropriate governance arrangements that allow various levels of exclusive rights and the rapid development of aquaculture technologies for many species, it is likely that many forms of aquatic resource management intermediate between capture fisheries and aquaculture will emerge in the tropical coastal oceans, similar to the diversity of systems found in Asian inland waters where such conditions have existed for some time (Amilhat et al., 2009).

4.2.5. Creating effective cross-boundary and transnational management

Some failures of marine resource management can be attributed to inadequately set boundaries. For example, critical source locations such as spawning grounds may not be protected, or the self-replenishing populations of target species may extend across several management jurisdictions that fail to, or are ineffective in coordinating their management actions (Sale et al., 2005). In addition, climate change is expected in some cases to alter the spatial arrangement of habitats or distributions of species (Cheung et al., 2013). MSP, as visualized here, may facilitate management across boundaries, and the revisions to zoning that will be necessary to correct inadequacies or accommodate change in distribution of habitats.

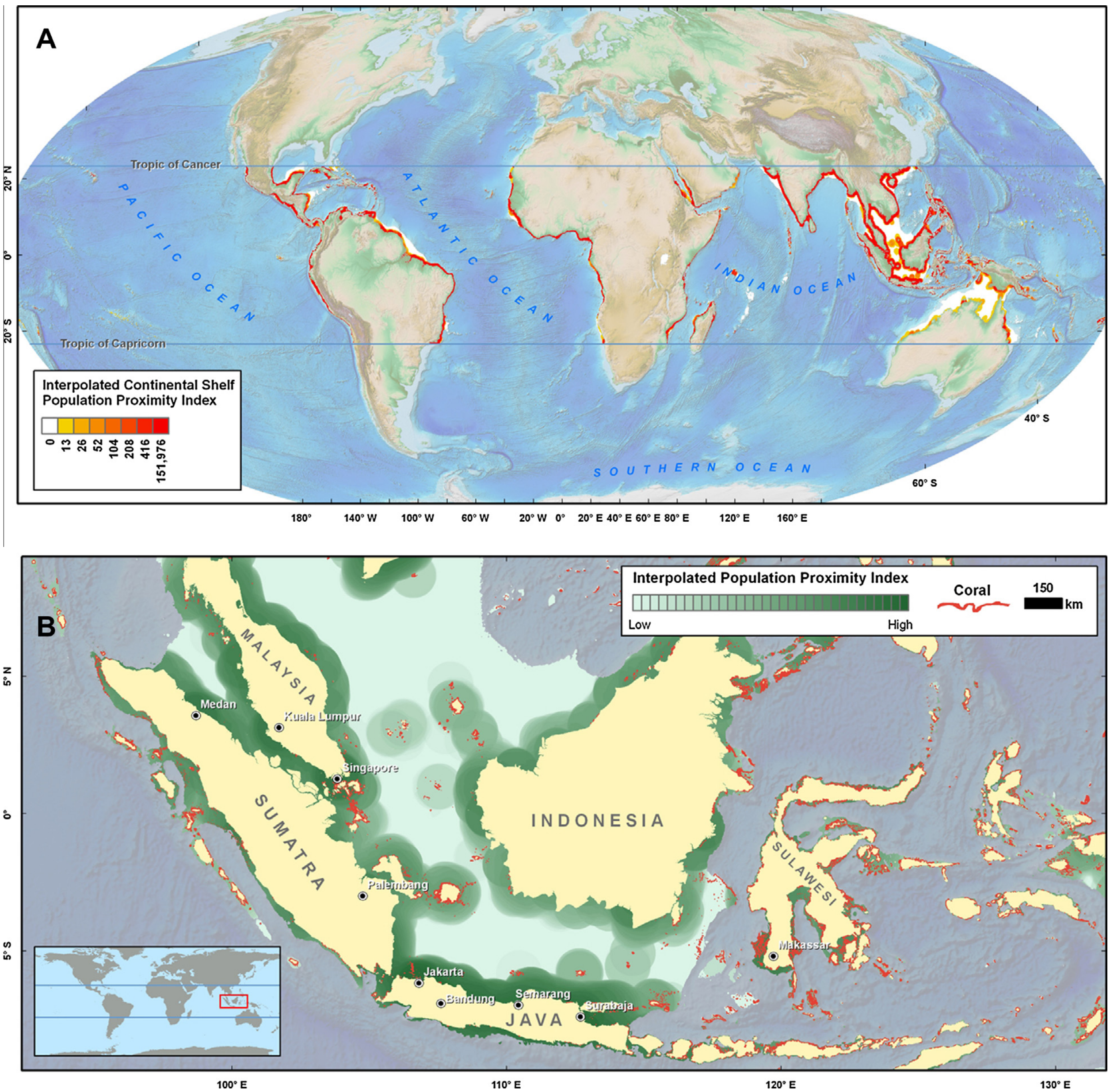

Fig. 4. (a) Map of interpolated human population proximity index for all continental shelf in the tropics. Index is relative and based on a focal mean population for each 30 arcsecond grid cell within the 200 m depth contour and <100 km from the coast. The index is consistently high in Southeast and South Asia while other regions have more coastal seas remote from high density settlements. (b) A portion of the Indonesian archipelago showing the extent to which the population proximity index varies even in densely populated regions. Coral reefs (red color, Millennium Coral Reef Mapping Project, 2010) are shown to experience a broad range of intensity of this index. A first order spatial plan can be achieved by zoning based on index intensity.

Practical guidelines for MSP exist, centered on process, communication and engagement, tradeoffs and valuation, decision support, and recognition that every situation is different (Lorenzen et al., 2010a; Sanchirico et al., 2010; Agardy et al., 2012). The application of MSP across tropical coasts should incorporate national aspirations for the various uses of inshore areas, while achieving united, long-term commitments by stakeholders to act as stewards and strengthen management. These goals can be achieved despite the variation that exists among coastal regions in: (1) the pattern of marine tenure (Foale et al., 2011; McLeod et al., 2009), (2) the nature and extent of law governing tenure (Sanchirico et al., 2010; Techera, 2010), (3) the rates of urbanization, societal and economic change (Daw et al., 2011), and (4) the complexity of local patterns of ecological connectivity (Cowen and Sponaugle, 2009; Jones et al., 2009).

4.3. Identifying priorities for launching comprehensive MSP and zoning

Because tropical coastal seas are vast, needs for effective management are great, and stretch both human and financial resources. Effective systematic use of MSP needs to be guided by priorities that focus management attention where it is most needed, particularly where localized, discreet actions, such as the establishment of small scale MPAs or community-based management regimes, cannot stem the tide of degradation. We suggest that first order priorities for MSP can be identified by a simple measure of distance from urban centers, as a proxy for evaluating where pressures and conflicts are the greatest (Fig. 3). But we took our analysis beyond the simple, linear approach pictured in Fig. 3, to map gradations in intensity of human impacts across the coastal sea by integrating distance and population density as a simple proximity index

Table 2
Management actions available for use within specific zones to achieve best practice management of fisheries, aquaculture, shipping, tourism and other included activities as well as management of water quality, and conservation of habitat and biodiversity. Many actions listed still require significant research and development, and all should be applied in a context of adaptive management with formal evaluation of local effectiveness. Actions are grouped according to the way in which they provide value.

Zone	Management actions within zones to achieve			
	Maximize benefits	Limit negative interactions	Capitalize on synergies	Adapt to climate change
Ports/shipping	Add subsurface structural complexity to wharfs and breakwaters to improve shelter for fish (Hair et al., 1994), which can be abundant in ports (McNeill et al., 1992)	Ensure water, sediment quality are adequate for fisheries, aquaculture, and human consumption of fish[*] (Sale et al., 2008)	Dedicate areas for aquaculture of species favored by higher nutrient levels	Defend existing infrastructure from sea-level rise (SLR) or plan its relocation (Nicholls and Cazenave, 2010)
	Use social and financial capital of cities to clean up water quality and create habitats for fish	Develop a systematic approach to identify effective ways to reduce risks from invasive species in ballast water (Bax et al., 2003)	Maximize opportunities for fishing from wharfs, jetties etc.	Ensure all new port facilities are designed for SLR
		Minimize risks that sewage will cause toxic algal blooms (Anderson et al., 2002)		Assess which species are likely to be favored by degraded ecosystems and warmer water and make interventions to enhance production of these species
		Take flexible approach to offsetting habitat loss by using offset funds for ecosystem management		
Aquaculture	Maintain water quality using ICM to provide suitable conditions for aquaculture (Cochrane et al., 2009)	Select sites and specify density of farms to avoid benthic anoxic conditions	Modify aquaculture facilities to provide better settlement habitat for wild juvenile fish	Identify aquaculture species likely to be unaffected or favored by warmer conditions (Bell et al., 2011)
	Establish leasing systems to provide incentives for investment in aquaculture	Stock species (bivalves, sea cucumbers) to assimilate waste products from sea cages	Extract nutrients from chronic run-off by farming seaweeds and harvesting them for fuel and fertilizer	Develop aquaculture systems that can descend to deeper, cooler water
	Partition use of water column to maximize opportunities for co-culture/polyculture	Use sterile animals to avoid outbreeding of escapees with wild stocks	Explore use of aquaculture enterprises to produce cultured juveniles to rebuild wild stocks (Bell et al., 2005)	Use breeding programs to increase resilience of species to ocean acidification (Rau et al., 2012)
	Introduce suitable species for food production with low invasive potential (Lorenzen et al., 2010b)	Manage disease risks and locate farms where dissemination of pathogens is minimized		
Small-scale fisheries	Use management frameworks and approaches to address all drivers of small-scale fisheries (Pomeroy and Andrew, 2011)	Prohibit fishing methods and fisheries that damage fish habitats or prevent habitat recovery	Implement restocking, stock enhancement and sea ranching where they add value to other forms of management (Bell et al., 2008; Lorenzen et al., 2010a)	Use flexible management to follow fish as their distributions change (Cochrane et al., 2009)
	Link fishing rights to human rights (Charles, 2011)	Specify fishing exclusion areas around aquaculture operations	Identify source-sink areas and harvest appropriately (Kritzer and Sale, 2006)	Transfer effort to nearshore pelagic fish as coral reef fisheries decline Bell et al., 2011, 2013)
	Apply primary fisheries management to maintain replenishment potential of stocks (Cochrane et al., 2011)	Minimize overlap of shipping routes and fishing areas		Diversify catches of coral reef fish as species composition changes (Pratchett et al., 2011)
	Exclude industrial fleets from coastal waters	Use fishery reserves to protect spawning aggregations of valuable species (Sadovy de Mitcheson et al., 2008)		Allow fish habitats to migrate landward with SLR (Bell et al., 2011)
	Prioritize food security over export trade			Replace fish habitats lost due to SLR with artificial structures
	Protect fish habitat, including its vegetation, and fish nursery habitats (Bell et al., 2005)			
Tourism	Manage visitor activities to prevent damage to fish habitats	Ensure effluent from resorts does not promote harmful algal blooms	Transplant harvested or cultured corals to enhance reef structure to support more fish	Construct all new infrastructure in preparation for SLR (Nicholls and Cazenave, 2010)
	Create protected areas for recreation	Do not weaken existing zoning or EIA rules to accommodate mass tourism (Lindeman et al., 2003)		
	Encourage locally owned and operated tourism	Manage recreational fishing appropriately		

Biodiversity conservation	Use resource maps of self-recruiting populations to determine critical areas required for maintenance of representative ecosystems (Bell et al., 2006)	Regulate coastal development activities to prevent damage to habitats (Halpern et al., 2008)	Select areas for biodiversity conservation that are sources of recruits for fishery species (Sale et al., 2005)	Manage catchment vegetation to reduce runoff and maintain natural resilience of coral reefs, mangroves and seagrasses (Bell et al., 2011; Burke et al., 2012)
	Map the resilience of habitat to disturbance and quantify the potential benefits and costs of management interventions	Limit fishing to migratory pelagic species in deep water (using exclusion zones around reefs and gear that does not contact substrata) to maintain reef fish communities for diver amenity	Use fees from tourist activities for management (Lindeman et al., 2003)	Transplant thermally tolerant corals to maintain diverse reefs
			Explicitly consider the contribution of fished areas to biodiversity targets	Bring deeper, cooler water to surface to counteract effects of warming on corals (Rau et al., 2012)

[a] Fish is used in the broad sense to denote both fish and invertebrates.

(Fig. 4). Factors determining ecosystem health will usually trend positively with the population proximity index (Halpern et al., 2008, Burke et al., 2012), and this permits a non-linear zonation of activities based on changes in degree of expected human impact (Fig. 4).

Fig. 4a shows the global variation in population proximity index scores. Shelf regions in Southeast Asia and India have the highest index scores and the former also have some of the largest continental shelf expanses in the tropics. The detailed map of a region within Southeast Asia (Fig. 4b) illustrates fine grained details of warm water coral reefs (in red, Millennium Coral Reef Mapping Project, 2010) and gradients of population proximity on the continental shelf. There are an estimated 310 million people (Bright et al., 2012) in this region with 300 million of them living within 100 km of the coast. Mean population density is 160 km^{-2} inland and 197 km^{-2} within 100 km of the coast. Maximum population density is approximately 68,000 km^{-2}. Globally, 26% of the total area of reefs is in shelf regions with a population proximity score of 0. Fifty percent of the total reef area is found in areas with population proximity values of 75 or less. The main point of Fig. 4 is to show that implementing a population priority index for a coastal region is technically straightforward; determining the scores at which to partition the gradient will require common sense, tact, and attention to local data on aspects of environmental quality and tradition of use.

The proximity index can be used not only to highlight priorities for management action and use of MSP; it can also guide marine planning within a priority region. By using the proximity index to guide use of coastal waters, the habitat degradation that often attends urbanization sets the scene for first order allocation of space among uses. For example, zones dedicated to biodiversity conservation will usually be most effective well away from urban centers, whereas aquaculture should be located as close to urban markets as water quality permits (Fig. 3). Food production from small-scale subsistence and artisanal fisheries will be optimized by providing fishers with access to most coastal areas (Fig. 3), and by closing their fishing grounds to larger-scale, commercial fisheries.

The simple distance-based schema in Fig. 3, or one based on our proximity index, is only a starting point. Second-order MSP can be applied to integrate other important factors such as details of ecological connectivity (Cowen and Sponaugle, 2009; Jones et al., 2009; Harrison et al., 2012) and locations of critical spawning grounds or high-value but sparse habitat, and to optimize the uses of natural assets while assuring equity and the grounds for stewardship. Within each zone, best practice and continued investments in research and development are essential to (1) maximize the desired benefits, (2) limit negative interactions between the main uses, (3) capitalize on potential synergies between different activities, and (4) alter the spatial zoning as environmental conditions change over time due to climate change, population growth and other factors (Table 2). Best practices comprise, inter alia, the conventional, site-specific management of pollution, coastal development and tourism, fisheries and aquaculture, and biodiversity conservation.

The present state of the art of applied marine science is such that we have the ability to efficiently harness scientific information to (1) identify those areas critically important for ecosystem functioning and continued delivery of goods and services, and (2) guide adaptation to changing environmental conditions (including climate-mediated effects). Our knowledge may be imperfect, and significant uncertainties remain, but the necessary focusing of the management spotlight on key areas is now doable. Science has matured to where systems analysis is usually possible, although additional time-series of data can bolster understanding of system structure and function, can elucidate trends in condition

Table 3
Principles guiding management success for tropical coastal seas. Our MSP-based approach integrates national- or regional-scale planning using a suite of local interventions to implement the desired changes. Success of a new management regime will vary depending on the societal and governance context and on the nature of management processes introduced. Successful management outcomes characteristically take full account of socio-political context as well as ecological context.

	Defining feature		
Context	Explanation	Management principles	Citation
Perceived crisis	Community members have greater interest in stewardship when they are aware that environmental conditions have deteriorated and/or provision of goods and services is reduced	Use public interest in stewardship as one criterion guiding site selection	Pollnac et al., 2001; Christie et al., 2009
Small community	Small communities without major influx of migrants tend to exhibit simpler structure, greater social homogeneity, and clear leadership	Seek out communities with stable societal structure as initial sites for intervention	Pollnac et al., 2001
Market access	Overexploitation of fishery resources is often associated with greater market access. International trade benefits coastal communities only if based on sustainable fisheries	Control or reduction in catch is more difficult in communities with good access to global markets; directly limiting export markets may be required	Berkes et al., 2006, Cinner et al., 2012, Kurien, 2005; Sadovy, 2005
Resource dependence	Overexploitation of fishery resources is associated with greater resource dependence. Access to coastal fisheries may be critical for food security in poorer communities	Control or reduction in catch is more difficult in communities strongly dependent on these resources. Diversify livelihoods to increase socio-ecological resilience and stewardship	Allison and Ellis, 2001; Cinner et al., 2012, Hall et al., 2013
Sense of trust and cohesion at implementation level	Elevated social capital improves the likelihood of resource management success	Institutional governance capacity must match contextual complexity. Invest in social capital creation (e.g. leadership development, education) as a cost effective strategy	Gutiérrez et al., 2011; Cinner et al., 2012
Process			
Stakeholder group entitlements	Legal rights to resource, dependency on resource for subsistence and livelihood, or historical and cultural relationship to an area influence role in policy process	Conduct stakeholder analysis as an early step to policy creation. Understand and use entitlements to underpin policy	Pomeroy and Rivera-Guieb, 2005
Transparent and participatory planning	Genuine participation strengthens legitimacy of management, mitigates against negative impacts on vulnerable groups and fosters sense of ownership among communities	Employ transparent and participatory planning to build policy ownership, support and compliance. How and why decisions are made should be apparent to key stakeholders, so they need to be engaged early and continuously. Creation of a broad-based and inclusive constituency of diverse economic, gender, ethnic, social groups is needed. Legal recognition of the rights of various social groups should influence policy development and implementation	Pollnac et al., 2001, Pomeroy and Rivera-Guieb, 2005; Christie and White, 2007; Lorenzen et al., 2010b; Gutiérrez et al., 2011
Education	Support and compliance depend on individuals understanding the principles guiding policy. Educational programs raise awareness of ocean conditions and costs and benefits of resource use patterns and policies	Raise awareness of stakeholders about environmental principles, and resource condition. Build informed compliance with management goals	Pietri et al., 2009; Pollnac et al., 2001
Social ecological monitoring and evaluation	Planned and unexpected societal and ecosystem changes are likely, and can be measured by multi-disciplinary evaluation processes. Resulting data inform adaptive planning processes	Utilize appropriate monitoring techniques to quantify societal and ecosystem change, and inform adaptive planning. Regularly conduct policy evaluation to encourage accountability	Margoluis and Salafsky, 1998; Ostrom, 2009
Capacity and leadership development	Human and institutional capital created through formal and informal education are essential for success. Existing local leaders can be valuable tools for success	Assess leadership potential and management capacity. Investing in creation of social capital is essential and cost effective for success	Christie et al., 2009; Pietri et al., 2009; Gutiérrez et al., 2011
Context-appropriate conflict resolution mechanisms	Mechanisms to resolve conflicts between resource user groups and constituencies will only be effective if they are appropriate to the societal, cultural, and governance patterns in place	Use socio-political understanding to ensure context-appropriate conflict resolution mechanisms are in place early. Address conflict quickly and appropriately. Use policies to partition resource uses fairly, and create stewardship incentives	Olsen and Christie, 2000; Christie et al., 2009; Allen, 2013
Adaptive planning	Policy should adapt in response to environmental and social change. Clear outcome-based objectives and monitoring information can shape iterative policy implementation	Institutionalize process and outcome monitoring to encourage adaptation and policy refinement	Cinner et al., 2012; Margoluis and Salafsky, 1998; Olsen and Christie, 2000
Sustainable finance	Use local and non-local, private and public sector resources to ensure long-term financing over decades and at a scale which ensures basic management processes are covered	Finance must be adequate to task. Create self-sustaining and diverse finance sources that are matched to institutional capacity to effectively use financial resources	Christie et al., 2005; Margoluis and Salafsky, 1998
Output			
Policies address social and ecological objectives	Policies balance social (e.g., economic development) and ecological (e.g., biodiversity conservation) objectives. Policies address objectives at ecologically meaningful scale but within institutional capacity to implement	Define social and ecological objectives and necessary trade-offs. Assess institutional capacity. Scale implementation to balance ecological function and institutional capacity. Monitor progress	Aswani et al., 2012; Cinner et al., 2012; Gutiérrez et al., 2011; Ostrom, 2009; Pollnac et al., 2010

Zoning establishes appropriate boundaries around resources and those allowed to use them	Appropriate boundaries enable separation of incompatible uses and emergence of governance systems that effectively address the commons dilemma	Define boundaries appropriate to the scales of resources and their users. This may require multiple or nested boundaries for different resources	Ostrom, 1990, 2009; Lorenzen et al., 2010a; Sanchirico et al., 2010
Context-appropriate policy encourages stewardship	Policies tailored to local social ecological context while considering external drivers and processes. Culture, business, law, public opinion, and other considerations incorporated. Incentives created to encourage sustainable ecosystem and resource stewardship	Scale policies to governance capacity and social ecological issues. Incrementally adapt frameworks and management tools to build from existing facilitating conditions and successful policies	Aswani et al., 2012; Christie et al., 2009; Cinner et al., 2012; Gutiérrez et al., 2011; Pollnac et al., 2010
Equitable policies	Policies equitably distribute rights and responsibilities, benefits and costs among stakeholders. Graduated sanctions well enforced. Environmental policy balanced with economic development needs	Create equitable policy making process that is information rich, transparent, and participatory	Cinner et al., 2012; Gutiérrez et al., 2011; Ostrom, 1990; Pollnac et al., 2001
Nested institutional design	Coordination is needed between institutions at different governance levels, and across regulatory/jurisdictional boundaries. Rights and responsibilities of each institution are understood across governance levels. Institutions coordinate to facilitate information sharing, harmonized work plans and budgets, and integrated planning and implementation. Lead institution clearly designated to facilitate coordination	Create institutional coordination mechanisms appropriate for complex and multi-sectoral challenges. Foster upwards and downwards accountability and incentive systems within governance hierarchies	Ostrom, 1990; Pomeroy and Rivera-Guieb, 2005; Cinner et al., 2012; Haque, 2012

more precisely, and can give greater confidence in predicted outcomes. We can readily identify areas of significant biodiversity, presumed resilience, and particular value in the delivery of ecosystem goods and services (including the regulatory and supporting services upon which the entire planet depends). These priority areas must be the base layer in the blueprint moving spatial planning and zoning forward – they are key to linking conservation with sustainable use and development, and minimizing risk.

In second order MSP, information about habitat coverage and extent, biodiversity, ecological processes, and human uses of the area can thus be synthesized to prioritize areas for the strictest possible protection. The management of these areas must reflect the full suite of threats these ecosystems and human communities face – an off-the-shelf, universally applicable protected area designation will not suffice. Flagging and protecting critical areas allows us to safeguard the base upon which future prosperity depends. Without prioritization and subsequent spatial protections, we speed up a vicious cycle: loss of services, increasing conflicts and costs, and systems being driven toward thresholds from which recovery or restoration is neither economically feasible in theory nor possible in practice.

The first and second order MSP we propose should not be confused with initiatives to establish MPA networks or the use of area closures in fisheries management. MSP paints on a larger canvas (Lorenzen et al., 2010a; Agardy et al., 2012) and is more akin to land management predicated on allocation of space for food production, industry and nature conservation based on soil type, water availability, terrain, population density, etc. Nations will need to undertake a significant administrative reorientation to be able to embrace this more holistic approach, but failing to change is not really an option. Indeed, because coastal biological production is often driven by complex patterns of connectivity over broad scales, MSP should ideally be practiced at the scale of LMEs or regional seas. Meeting this ideal will require astute integration among the plans of neighboring countries to be fully effective. This is a major challenge.

Using MSP to implement zoning does not absolve management agencies from the need to continue targeted regulation of pollution and habitat destruction or management of fisheries and regulation of international trade in fishery products. These activities must continue (as the best practice mentioned above), but under an MSP umbrella that will help force the integration of management effort across agencies, sectors, and jurisdictions. Ultimately, MSP will also entail development of rights to use space in specific zones. Among other benefits, this will incentivize the aquaculture enterprises needed to fill the growing gap between the fish required for a nation's food security and the fish available from its capture fisheries.

5. Improving the likelihood of success

When policies intended to protect tropical ecosystem function are introduced in ways that do not attend adequately to social dynamics or governance feasibility, they tend to fail (Ostrom, 2009; Cinner et al., 2012). We are proposing a substantial reinvigoration of management, and we would be naïve to imply that success will come easily. It will not. To be successful, the application of holistic MSP at the scale we propose will require very careful attention to socio-economic and governance dynamics. This is a major challenge for governments, for NGOs, for the multinational sector, and for coastal communities. Long-term and comparative studies have demonstrated that there is no panacea: success of management requires that appropriate technical knowledge be applied in a context-sensitive way that builds ownership and compliance (Christie and White, 2007). Fortunately, there now exist detailed guides for using specific management approaches (Christie et al., 2009; Tallis et al., 2010; Agardy et al., 2012), and a growing consensus regarding best management practices based on evaluations of success in particular instances (Pollnac et al., 2010, Gutiérrez et al., 2011, Cinner et al., 2012).

Communities are most receptive to new management when (1) the need is widely perceived to be critical, (2) the community is relatively small and closely dependent on local resources without the distortion caused by ready access to distant markets, (3) the society is cohesive and engenders a high level of trust, (4) business leaders display buy-in, and (5) there is reasonable transparency of governance (Ostrom, 2009). Management approaches that work best take due account of the existing entitlements of stakeholders, include culturally appropriate mechanisms for building capacity and leadership and resolving conflicts, have adaptive management inbuilt, and include a sound base of enabling legislation and sustainable finance (Gutiérrez et al., 2011). When such management is introduced to a receptive community, the resulting policies can be expected to be socially and ecologically appropriate, to be equitable, and to lead to sustained stewardship. Such an outcome at the local level can be nested sustainably into a regional, or an LME scale enterprise made cohesive by MSP. Table 3 provides more detail, setting out enabling societal and governance contexts, management processes, and outcome principles as derived from collective experience over hundreds of interventions in tropical coastal regions.

For success, it is vital that efforts to improve management are initially focused on local communities of appropriate societal, governance, and ecological context (McClanahan et al., 2009). However, these local successes are inadequate unless combined into a broader-scale change of practice. Since the ultimate goal is spatial planning on a national or regional LME scale, building real management effectiveness will best be done by using context to help choose among alternate local intervention nodes, and by making the effective integration of these local nodes a primary objective for higher (national) level management. The general principles described in Table 3 can inform a variety of management tools and frameworks.

Applying the principles outlined in Table 3 will be very challenging. Clear vision and a strong commitment to success will be needed. The establishment of novel management regimes is likely best done incrementally, building from existing sustainable practices (Christie et al., 2009), and nurturing numerous local, bottom-up efforts, while integrating them across a wider region in a way that is ecologically justifiable and societally defensible. This will require a long-term perspective, and use of an adaptive planning process, linked directly to social and ecological monitoring. Those leading this process will need to sustain a wider regional, national or LME-scale goal, and not be satisfied with achieving short-term improvement for single local communities. This is the case, despite the fact that their initial successes will be precisely these small-scale (frequently short-term) improvements in local communities. Until now, the spill-on effects of such successes have been felt at the local level only, lauded by those working with communities to build sustainable environmental management. The MSP approach we propose will help leaders make the leap towards more strategic, systematic and region-wide improvements in sustainability.

6. Conclusions

Over 1.3 billion people, mostly in developing countries, live in coastal communities bordering tropical seas. These seas include a wide array of ecosystems, subject to an equally diverse set of human impacts, provided by societies with different traditions, beliefs, expertise, and governance styles. The dependence of communities on coastal ecosystems for food and livelihoods is high because in many cases they lack the wealth that permits access to alternative food supplies.

The widespread aspirational goal of improved coastal management remains thwarted by fragmented, intermittent and unsuccessful approaches and practices, and, in some places, by a belief in simple technological 'fixes' without structural changes to management. Continuing to promote the same types of interventions and short-term development assistance is not going to result suddenly in success. Climate change and associated impacts between now and 2050 (Table 1, Fig. 2) will exacerbate the pervasive degradation of tropical seas, even as rapidly growing coastal communities increase demand for their goods and services.

Refocused MSP, based on a spatially integrated index of human impact and ocean zoning (Figs. 3 and 4), offers a means to reconcile the multiple demands for use of tropical coasts, allowing developing countries to fulfill their needs and aspirations for fishing, aquaculture, industry, trade, tourism and conservation. Provided this expanded MSP framework is applied in a way that suits the contexts of local and national societies and their governance systems, it will force a holistic, integrated approach to management at ecologically appropriate scales.

Long-term socially acceptable sustainability of tropical coastal seas based on expanded MSP will require effective adaptation to local societal, cultural and governance traditions, effective and sustained participation of all community groups, strong local and national political leadership, and vigorous support by development partners and NGOs. Urgent global efforts to reduce GHG emissions are also needed. Humanity has the capacity to substantially improve coastal management; the futures of millions of poor people living on tropical coasts depend on us collectively rising to that challenge.

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