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To cite this article: Katie K Arkema *et al* 2014 *Environ. Res. Lett.* **9** 114016

OPEN ACCESS
IOP Publishing
Environmental Research Letters
Environ. Res. Lett. 9 (2014) 114016 (11pp)
doi:10.1088/1748-9326/9/11/114016

Assessing habitat risk from human activities to inform coastal and marine spatial planning: a demonstration in Belize

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Received 2 July 2014, revised 7 October 2014
Accepted for publication 21 October 2014
Published 18 November 2014

Abstract

Integrated coastal and ocean management requires transparent and accessible approaches for understanding the influence of human activities on marine environments. Here we introduce a model for assessing the combined risk to habitats from multiple ocean uses. We apply the model to coral reefs, mangrove forests and seagrass beds in Belize to inform the design of the country's first Integrated Coastal Zone Management (ICZM) Plan. Based on extensive stakeholder engagement, review of existing legislation and data collected from diverse sources, we map the current distribution of coastal and ocean activities and develop three scenarios for zoning these activities in the future. We then estimate ecosystem risk under the current and three future scenarios. Current levels of risk vary spatially among the nine coastal planning regions in Belize. Empirical tests of the model are strong—three-quarters of the measured data for coral reef health lie within the 95% confidence interval of interpolated model data and 79% of the predicted mangrove occurrences are associated with observed responses. The future scenario that harmonizes conservation and development goals results in a 20% reduction in the area of high-risk habitat compared to the current scenario, while increasing the extent of several ocean uses. Our results are a component of the ICZM Plan for Belize that will undergo review by the national legislature in 2015. This application of our model to marine spatial planning in Belize illustrates an approach that can be used broadly by coastal and ocean planners to assess risk to habitats under current and future management scenarios.

S Online supplementary data available from stacks.iop.org/ERL/9/114016/mmedia

Keywords: risk assessment, habitats, coastal zone management, coastal and marine planning, stressors, Belize, cumulative impacts

1. Introduction

Globally, the growing diversity and expansion of coastal and ocean uses are posing risks to ecosystems that provide habitat for species and benefits to people (Millennium Ecosystem Assessment 2005, Halpern *et al* 2008, Worm *et al* 2009). To address this problem, policy-makers and institutions around the world are pursuing cross-sectoral management for multiple uses and the long-term sustainability of marine ecosystems (Douvere 2008, McLeod and Leslie 2009). In the past year, the United States and the European Commission issued policies and proposed legislation for integrated management of ocean and coastal uses (Lubchenco and Sutley 2010, European Commission (2013), National Ocean Council 2013). Similar efforts are underway in many countries—from the Americas to Africa and Asia.

Over the past decade, the scientific community has risen to the challenge of developing science and tools for ecosystem-based management of the ocean (Arkema *et al* 2006, Ruckelshaus *et al* 2008, Klein *et al* 2009, Levin *et al* 2009, Sanchirico and Mumby 2009, Watts *et al* 2009, Lester *et al* 2010, Fulton *et al* 2011, White *et al* 2012, Ecosystem-Based Management Tools Network at www.ebmtools.org/). In particular, efforts to understand the effects people have on habitats and species have exploded, spawning two parallel avenues of work: cumulative impact mapping (Halpern *et al* 2008, Selkoe *et al* 2009, Ban *et al* 2010) and ecosystem risk assessment (Patrick *et al* 2010, Hobday *et al* 2011, Samhouri and Levin 2012, Williams *et al* 2011). Global and regional studies that map cumulative impacts of stressors on ocean ecosystems reveal the footprint of anthropogenic pressures worldwide (Halpern *et al* 2008), regional variation among stressors and species (Selkoe *et al* 2009, Ban *et al* 2010, Klein *et al* 2012) and most recently, effects of ocean activities on top predators (Maxwell *et al* 2013). With a similar goal in mind, scientists supporting marine resource management in the US and Australia adapted and applied a classic risk assessment framework to understand risk to important fishery species (Patrick *et al* 2010, Hobday *et al* 2011, Williams *et al* 2011) and a suite of ecosystem components (Samhouri and Levin 2012) from various types of stressors. From this extensive body of research comes useful approaches and improved understanding of relationships between multiple human activities and coastal and ocean ecosystems. Yet three important gaps preclude the ready uptake of these approaches into policy-making: (1) methods for estimating how habitats will change under future management scenarios, (2) better understanding of the degree to which estimated risk reflects observed environmental degradation, and (3) accessible and transparent tools for incorporating estimated risk into coastal and ocean planning.

Our collaboration between practitioners and scientists tackled these three impediments to uptake of risk assessments in coastal management. Here we present a model and open-source software for assessing risk of various types of stressors associated with human activities to the condition of coastal and marine habitats. The model integrates and builds on many of the approaches developed in the last several years, providing flexibility within its structure to adapt it to local conditions. Transparent software makes the model accessible to a wide variety of users (Guerry *et al* 2012, Sharp *et al* 2014). To demonstrate its use, we apply and test the model in Belize to assess current risk to three important coastal and marine habitats and to understand how risk would change under several feasible future management scenarios. The results from our analysis were used to inform the development of Belize's first Integrated Coastal Zone Management (ICZM) Plan that will be reviewed by the national legislature in 2015 (Clarke *et al* 2013, McKenzie *et al* 2014).

2. Methodology and tool for risk assessment

2.1. Overview of risk assessment model

Our approach focuses on habitats that provide a suite of benefits to people. We develop new criteria for estimating risk that are tailored to the life history characteristics of the main taxa comprising these habitats (see section 2.2 *Estimating habitat risk*) and allow us to assess risk to both habitat presence and function. When used in conjunction with models that estimate habitat-induced changes in ecosystem services, such as storm protection or tourism revenue, our habitat risk assessment (HRA) can help to evaluate trade-offs among human activities and benefits that ecosystems provide to people (Guerry *et al* 2012, Clarke *et al* 2013).

Essentially, our approach is a risk ranking method designed for coastal and marine habitats (Burgman 2005). Similar to previous studies, we use two dimensions of information to calculate risk or impact to ecosystem components (figure 1; Halpern *et al* 2008, Patrick *et al* 2010, Samhouri and Levin 2012). We refer to these dimensions as 'exposure' and 'consequence', where exposure represents the degree to which a habitat experiences stressors due to a specific human activity, given the effectiveness of management practices. Consequence reflects the habitat-specific response to stressors associated with different human activities (see supplementary material for additional details).

Previous studies differ in how they combine information from these two dimensions of risk. Cumulative impact mapping studies tend to use a multiplicative approach to estimate risk (Halpern *et al* 2008, Selkoe *et al* 2009, Ban *et al* 2010) whereas ecosystem risk assessment studies tend to estimate risk as the Euclidean distance for a specific habitat-activity combination in risk plots (Patrick *et al* 2010, Hobday

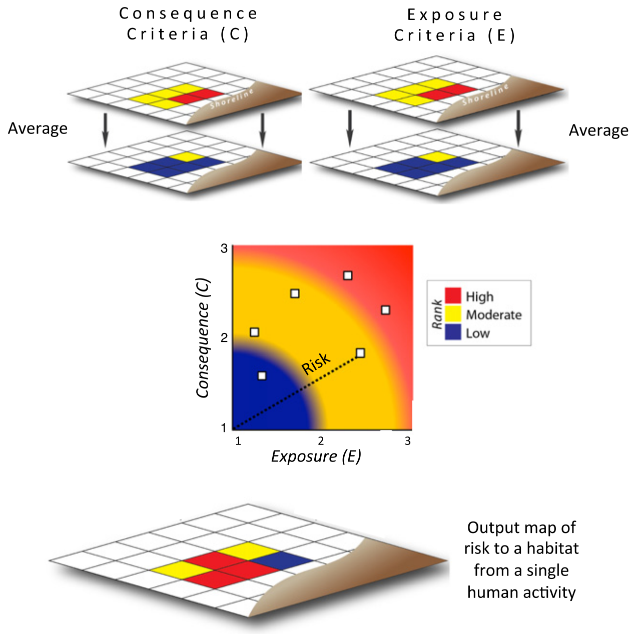

Figure 1. Conceptual diagram depicting how exposure and consequence criteria (table 1) are combined to estimate risk as the Euclidean distance in each grid cell for a particular habitat-activity combination. Colored bands in risk plot are numerically determined and based on the range of exposure and consequence scores (1–3 in this assessment) and the high, medium and low classification scheme described in the methods.

et al 2011, Samhouri and Levin 2012). Initial sensitivity testing suggests that overall the two approaches agree on the highest and lowest risk habitats or regions, although intermediate risk results may differ (Samhouri *per. communication*). Our model can accommodate either function.

A particular challenge in estimating risk is quantifying the habitat-specific effect of different human activities (i.e., consequence). Cumulative impact mapping studies generally elicit consequence information from expert opinion (Halpern *et al* 2008, Teck *et al* 2010, Maxwell *et al* 2013). Although much of the input data required for the model we present could be compiled from expert opinion, we instead estimate consequence based on a set of criteria for which information can be readily found in the peer-reviewed literature (after Patrick *et al* 2010, Hobday *et al* 2011, Samhouri and Levin 2012). For many policy-making processes, results based on scientific literature, rather than expert opinion, are preferred for objectivity, repeatability, and transparency.

We integrate and build on these approaches to develop a model that can be tailored to a variety of ecosystems and policy needs. We call it the HRA model, and it has been implemented in the Natural Capital Project's InVEST toolbox (Guerry *et al* 2012, Sharp *et al* 2014). Because the model is freely available in open-source software, the analysis can be repeated by government planners, NGOs, or other stakeholders to assess future scenarios for managing coastal and marine ecosystems.

2.2. Estimating habitat risk

Our model includes two options for estimating risk posed to habitats from multiple stressors; either the multiplicative approach in which risk to habitat i caused by stressor j is calculated as the product of exposure and consequence

$$R_{ij} = E \cdot C \tag{1}$$

or the Euclidean approach in which risk to habitat i caused by stressor j is the distance to the origin for a particular habitat-stressor combination in a plot with exposure and consequence axes (figure 1).

$$R_{ij} = \sqrt{(E-1)^2 + (C-1)^2}\ . \tag{2}$$

Using the Euclidean framework, the risk to species increases with distance from the origin and exposure and consequence exert equal influence on risk (figure 1; Patrick *et al* 2010, Hobday *et al* 2011, Samhouri and Levin 2012).

To estimate exposure and consequence for habitats, we developed several new criteria based on the cumulative impact and risk assessment literature for ecosystem components. These include four criteria for quantifying exposure and four for consequence (table 1). To estimate exposure of habitats to human activities, the model requires information on (1) spatial and (2) temporal overlap between habitats and activities, (3) intensity of the activity and (4) effectiveness of management strategies for reducing exposure (table 1; see supplementary material, available at stacks.iop.org/ERL/9/114016/mmedia for further details).

To estimate the consequence of exposure to human activities, the model requires information about habitat-specific sensitivity to different activities and life history characteristics of the different taxa. For example, consequence criteria from risk assessments for fisheries and ecosystem components include fecundity and breeding and reproductive strategies (Patrick *et al* 2010, Hobday *et al* 2011, Samhouri and Levin 2012). We developed new criteria that are relevant for biogenic and abiotic habitats: (1) change in area, (2) change in structure, (3) frequency of natural disturbance and (4) resilience (table 1). For biogenic habitats the resilience criterion encompasses the natural mortality rate, recruitment rate, dispersal potential and recovery time of the habitat-forming species. For non-living habitats, whose resilience cannot be captured through demographic rates, resilience is evaluated through estimates of recovery time to pre-disturbed conditions.

The model produces exposure and consequence scores on a scale of 1 (lowest) to 3 (greatest) risk, but the approach is flexible and can be adapted to a range of habitat risk categories most appropriate to the local context (e.g., 1, 2, 3…n).

Exposure and consequence are weighted averages of the exposure values e_i and consequence values c_i for each criterion i as

$$E = \frac{\sum_{i=1}^{N} \dfrac{e_i}{d_i \cdot w_i}}{\sum_{i=1}^{N} \dfrac{1}{d_i \cdot w_i}}, \tag{3}$$

Table 1. Definitions and scoring bins for the exposure and consequence criteria (see supplementary material for more details).

Criteria	Low risk (1)	Medium risk (2)	High risk (3)	Description of criteria
Exposure criteria				
Spatial overlap	<10% of Habitat overlaps with stressor	10–30% of Habitat overlaps with stressor	>30% of Habitat overlaps with stressor	The model uses maps of habitats and stressors associated with human activities to calculate the percentage of each habitat type that overlaps with each stressor and its zone of influence.
Temporal overlap	Habitat and stressor co-occur for 0–4 months a year	Habitat and stressor co-occur for 4–8 months a year	Habitat and stressor co-occur for 8–12 months a year	The duration of time that the habitat and the stressor associated with human activities experience spatial overlap.
Intensity	Low	Medium	High	The exposure of a habitat to a human activity depends not only on whether the habitat and activity overlap in space and time, but also on the intensity of the activity, for example, number of cruise ship trips per year.
Management effectiveness	Very effective	Somewhat effective	Poorly managed	Management can limit the negative impacts of human activities on habitats, thus reducing exposure even where and when the activities interact with habitats.
Consequence criteria—sensitivity				
Change in area	Low loss in area (<20%)	Medium loss in area (20–50%)	High loss in area (50–100%)	The percent change in extent of a habitat when exposed to a given stressor. Habitats that lose a high percentage of their coverage area when exposed to a given stressor are highly sensitive, while those habitats that lose little area are less sensitive and more resistant.
Change in structure	Low loss in structure (<20% loss in density)	Medium loss in structure (20–50% loss in density)	High loss in structure (50–100% loss in density)	The percentage change in structural density of the habitat when exposed to a given stressor.
Frequency of disturbance	Daily to weekly	Several times a year	Less often	If a habitat is naturally perturbed in a way similar to the anthropogenic stressor, it may be more resistant to additional stress.
Consequence criteria—resilience				
Natural mortality	High mortality (80% or higher)	Moderate mortality (20–50%)	Low mortality (<20%)	Habitats with high natural mortality rates are generally more productive and more capable of recovery.
Recruitment	Annually or more often	Every 1–2 years	Every 2+ years	Frequent recruitment increases the chance that incoming propagules can re-establish a population in a disturbed area.
Connectivity	High dispersal (>100 km)	Medium dispersal (10–100 km)	Low dispersal (<10 km)	Larval dispersal and close spacing of habitat patches increases the recovery potential of a habitat by increasing the chance that incoming propagules can re-establish a population in a disturbed area.
Recovery time	Less than 1 year	1–10 years	More than 10 years	Habitats that reach maturity earlier may be able to recover more quickly from disturbance. Here we refer to maturity of the habitat as a whole (i.e., a mature reef) rather than reproductive maturity of individuals.

$$C = \frac{\sum_{i=1}^{N} \frac{c_i}{d_i \cdot w_i}}{\sum_{i=1}^{N} \frac{1}{d_i \cdot w_i}}. \tag{4}$$

where d_i represents the data quality rating for criterion i, w_i represents the importance weighting for criterion i and N is the number of criteria evaluated for each habitat. After Patrick *et al* (2010) and Samhouri and Levin (2012), the model includes parameters for data quality, as well as weighting, such that higher data quality and higher importance result in a larger influence on the overall risk score. These data quality and weighting options emphasize transparency, so scoring is repeatable and understandable within a decision-making process. Our approach to averaging across criterion scores follows the precedent of previous studies (Patrick *et al* 2010, Samhouri and Levin 2012, Hobday *et al* 2011) since we lack definitive science about how to combine criteria. Note, however, that averaging can result in a dilution effect where criteria that could lead to high risk of habitat degradation (e.g., large change in habitat area) are diluted by low risk values for criteria such as infrequent temporal overlap. In contexts where it's clear that averaging misrepresents reality, our open source software is flexible and allows criteria to be dropped from the analysis altogether (but see Patrick *et al* 2010 for discussion of skewed results with too few criteria).

Our approach also addresses the overlap of stressors and habitat by incorporating spatial estimates of zones of influence for each human activity. For example, coastal development may occupy a specific footprint along the shoreline, but its impacts, such as chemical leaching or sedimentation, may extend into the nearshore environment. The model buffers the footprint of the human activity to include the distance of influence (as documented in the literature) and decays exposure over this expanded area. Again, our approach is flexible and can accommodate three possible decay functions: 'no decay' applies the exposure to the stressor footprint plus buffer. 'Linear' and 'exponential' use these forms to decay exposure before it enters into the risk equation.

To assess the influence of multiple activities, we quantify the cumulative risk of all stressors on each habitat i as the sum of all risk scores for each combination of habitat and activity j as R_{ij}

$$R_i = \sum_{j=1}^{J} R_{ij}. \tag{5}$$

Lastly, to make the results more accessible to a policy audience, we classify areas of habitat as high, medium or low risk based on the risk posed by any individual activity or the risk posed by the cumulative effects of multiple activities. We assign high risk to grid cells with a cumulative risk of >66% of the maximum score for any individual stressor-habitat combination (i.e., 2.8 for the Euclidean distance equation) or >66% of the maximum cumulative risk, which is a function of the number of human activities. We classify cells as medium if they have individual or cumulative risk scores between 33%–66% of the total possible cumulative score and as low if they have individual or cumulative risk scores of 0–33% of the total possible score for a single or multiple activities. The colored bands in figure 1 reflect this classification scheme for a single stressor and habitat.

3. HRA for coastal and marine planning in Belize

Home to the largest barrier reef in the western hemisphere, an extensive system of mangrove forests and over 300 cayes, Belize's coastal and marine ecosystems provide habitat to a diversity of species and numerous benefits to the country and its people. Over 40% of the Belizean population lives and works in the coastal zone. World-renowned snorkeling and diving draw more than 800 000 tourists to the region annually, and several commercial, recreational and subsistence fisheries support livelihoods and provide sustenance (Cooper *et al* 2009).

The broad suite of ocean-related activities underpins the Belizean economy, but also poses risks to the coastal and marine ecosystems that support these sectors. In 1998, the national government passed visionary legislation (Belize Coastal Zone Management Act 2000) requiring government agencies to address the rapid coastal development, overfishing and many other uses that were putting pressure on the natural environment. The Act establishes the Coastal Zone Management Authority and Institute (CZMAI) as the regulatory body, and calls explicitly for an ICZM Plan that supports cross-sector management, employs science and local knowledge in its design, and includes spatially explicit recommendations for coastal development, transportation, extractive and non-extractive uses and conservation areas. The draft ICZM Plan is national in scope, but incorporates social, economic and ecological differences among the nine coastal planning regions (figure S1).

To design a spatial plan for the sustainable use of the coastal and marine environment for the benefit of Belizeans and the global community, CZMAI worked with the Natural Capital Project to use an ecosystem services approach (Daily *et al* 2009, Tallis and Polasky 2009, Guerry *et al* 2012, McKenzie *et al* 2014, Ruckelshaus *et al* in press). A key component of this approach is to balance benefits of development—based on national and sectoral development goals and policies (Clarke *et al* 2013) —with concomitant risk from human activities to ecosystems that provide benefits to people, both now and in the future (Guerry *et al* 2012). In this context we use the InVEST HRA model presented here to assess risk to coral reefs, mangrove forests and seagrass beds, under the current distribution of uses and under three alternative scenarios designed during the planning process (Clarke *et al* 2013). We ask three questions: (1) what is the current risk from human uses and how does this vary spatially and among habitats? (2) To what extent does estimated risk reflect observed measures of habitat quality? (3) How will risk to habitats change under three future management scenarios? Our risk results are incorporated into the ICZM Plan as a metric for evaluating alternative management scenarios and to

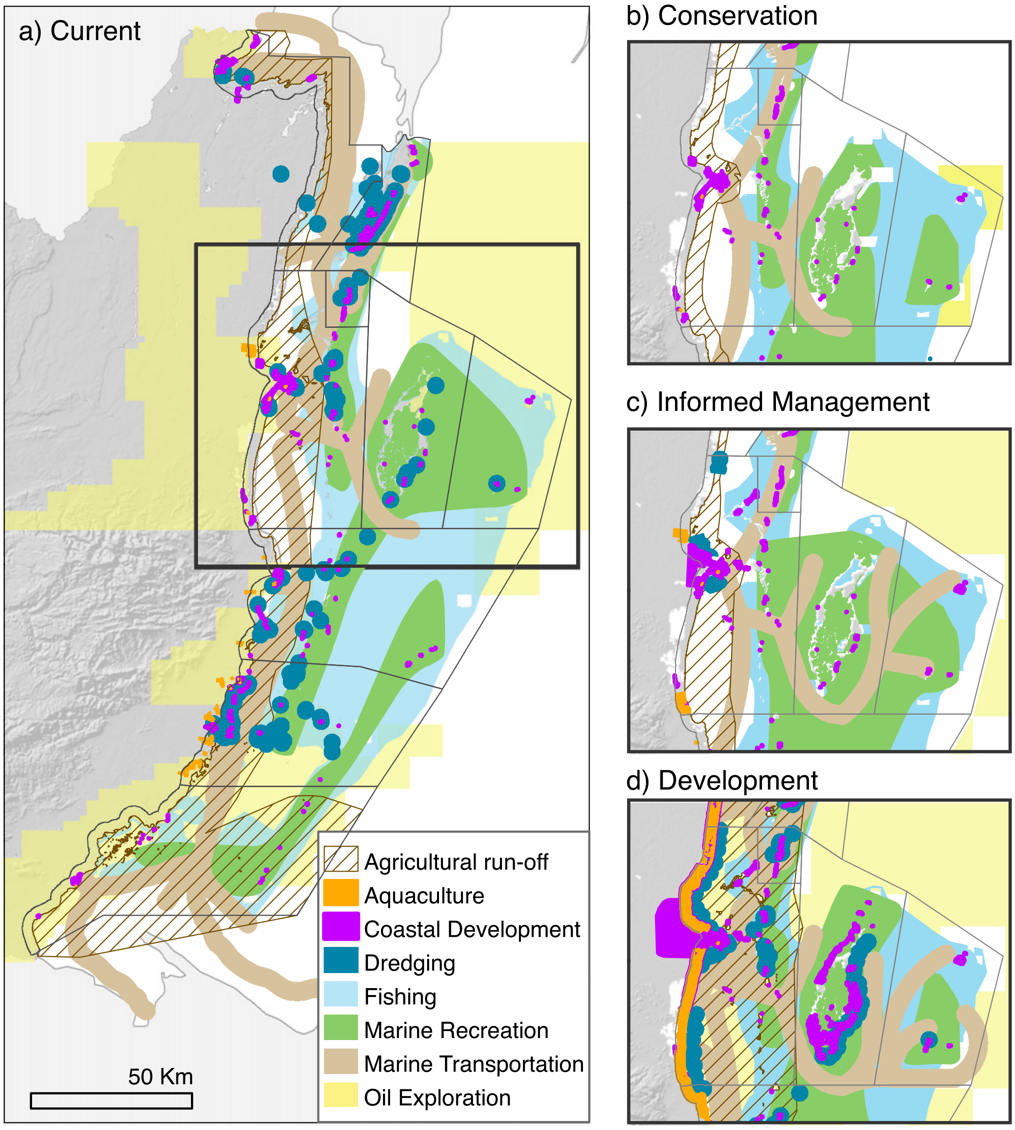

Figure 2. Current (a) and three future zoning scenarios for human activities—(b) conservation, (c) Informed Management, and (d) Development. See supplementary materials for individual maps of the human activities included in the Current scenario.

estimate future values of ecosystem services (Clarke *et al* 2013).

3.1. Risk to habitats from the current distribution of human activities

We focus on risk to three habitat types—coral reefs, mangrove forests and seagrass beds (figure S2)—as these provide the primary habitat for numerous ecologically and economically important species and a suite of benefits for people (Cooper *et al* 2009, Clarke *et al* 2013). Based on extensive stakeholder engagement and communication with relevant government agencies (Clarke *et al* 2013), CZMAI identified 11 categories of human activities to include in the spatial zoning scheme. Of these, eight activities—coastal development, marine transportation, dredging, oil exploration, fishing, recreation, agricultural run-off and aquaculture—pose potential stress to the habitats of interest (figures 2(a), 3, S2, S3). Several of these activities occur on land, yet can influence corals and seagrass through 'zones of influence' (see section 2.2 *Estimating habitat risk*). The boundaries for the planning process and risk assessment extend from 3 km inland to the edge of the territorial sea (18 000 km^2; figure S1).

To estimate risk, we use information on (1) exposure of corals, mangroves and seagrass in Belize to the eight activities and (2) the consequence of this exposure (table 1). First, we estimate spatial overlap using data layers for the three habitats (figure S2) and each of the eight activities (figure 2(a), figure S3 and supplementary material). We score the remaining exposure criteria based on information from the scientific and gray literature, stakeholders and government officials (see supplementary material). We rank consequence criteria using the peer-reviewed literature (table 1, supplementary material) and apply the model at a 500-meter resolution.

We find a similar range in cumulative risk among corals (0.88–8.3), mangroves (0.6–7.4) and seagrasses (1.2–9.7),

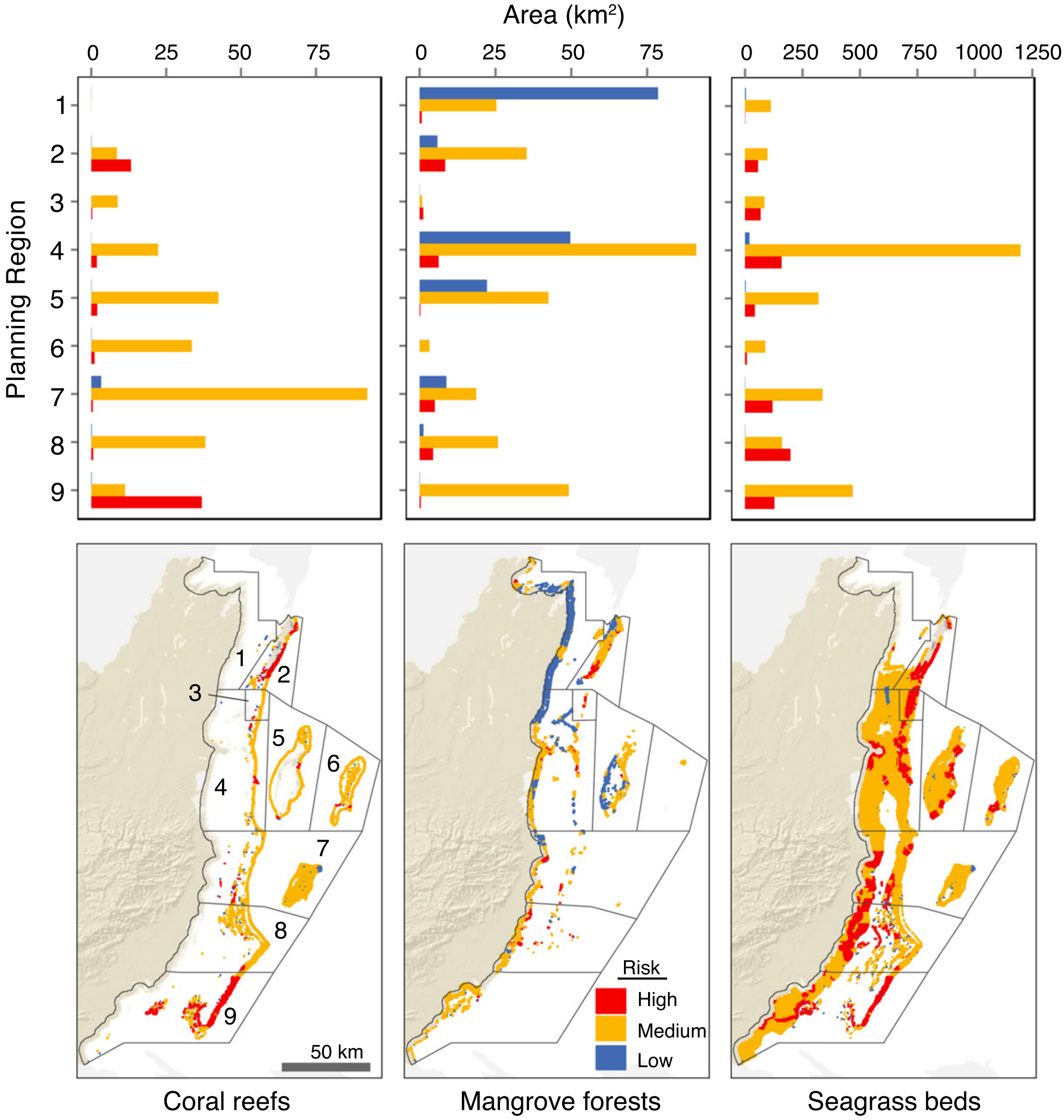

Figure 3. Full extent of coral reefs, mangrove forests and seagrass beds classified as high, medium and low risk from current human activity. Top panels show total area of habitat in each risk category per planning region: (1) Northern Region, (2) Ambergris Caye, (3) Caye Caulker, (4) Central Region, (5) Turneffe Atoll, (6) Lighthouse Reef Atoll, (7) South Northern Region, (8) South Central Region, and (9) Southern Region.

with the exception of a few high values for seagrass (figure S4 (a)–(c)). To inform the ICZM Plan, we classify the results for each habitat as high, medium or low based on the categorization scheme described at the end of section 2.2 *Estimating risk*, and assume a maximum cumulative risk of eight for the three habitats (figure S4). Model results suggest large differences in risk to habitats among regions. Broad sections of mangrove forests are at low risk in the Northern, Central and Turneffe Atoll planning regions, whereas only small, isolated patches of seagrass and coral are at low risk throughout the study area (figure 3). All three habitats are at particularly high risk of degradation around Ambergris Caye (figure 3), likely due to the occurrence of nearly all eight stressors in this region (figures 2, S3). Inspection of the exposure-consequence risk plot for seagrass around Ambergris Caye reveals that under the current scenario dredging poses greater risk to seagrass than development or transportation, due to a combination of high exposure and high habitat-specific consequence of that exposure (figure 4(c)). For corals, exposure to dredging is similar to seagrass but a lower habitat-specific consequence score results in overall lower risk (figure 4(a)).

3.2. Model testing: estimated habitat risk compared to observed habitat quality

Recent studies in marine systems rarely address whether modeled risk and cumulative impact results compare to

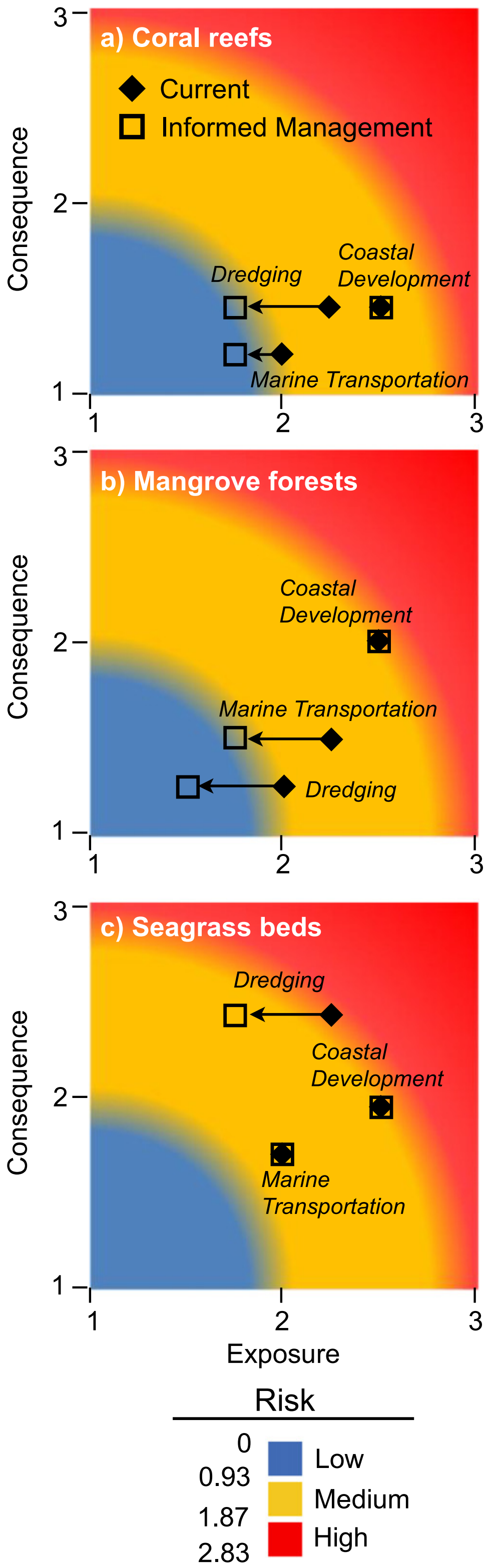

Figure 4. Risk plots showing average consequence and exposure scores for (a) coral reefs, (b) mangrove forests and (c) seagrass beds in Ambergris Caye for three stressors (marine transportation, coastal development and dredging). Arrows indicate shifts in risk from the Current (diamonds) to Informed Management (squares) scenario. This plot mirrors the conceptual diagram in figure 1.

measures of observed ecosystem quality (but see Halpern *et al* 2008). To fill this gap, we examine how well our risk results from the HRA model align with empirical data on the quality of coral reef and mangrove habitat in Belize[7]. For mangroves, we compare modeled cumulative risk to observed forest fragmentation estimated from a dataset of satellite images spanning the years 1980 to 2010 along the entire coast of mainland Belize, atolls and cayes (Cherrington *et al* 2010). During this period less than 2% of the mangrove forest was further cleared beyond initial fragmentation so forest coverage remains fairly constant. We use fragmentation as a measure of ecosystem structure that indicates whether the areal extent of a patch has been altered by human activity. We assess the model's ability to distinguish between fragmented and non-fragmented forest pixels (500-meter resolution, figure S8) using receiver operating characteristic (ROC) curves (figure S9). ROC curves are a diagnostic tool for evaluating whether a logistic model discriminates between events (fragmented) and non-events (non-fragmented forests, see supplementary material). The area under our ROC curve for mangroves is 0.8 (area = 1 means that the model discriminates perfectly; figure S9b) and 79% of the predicted probabilities are associated with observed responses. These results suggest that our model for cumulative risk performs well at distinguishing between fragmented and intact forest ($N = 11\,369$, DF = 1, Wald Chi-square = 1508, $P < 0.001$).

To evaluate risk to corals estimated by the HRA model, we compare modeled risk to observed indicators of coral health at 134 sites throughout Belizean waters in 2006. The observed data on coral health include three separate datasets: percent cover of coral, percent cover of macroalgae and density of parrotfish and surgeonfish (HRI 2008). We assume that high coral cover, low macroalgal cover, and more fish grazing indicate lower human impact. To compare modeled coral risk estimates to observed coral health data, we use simple kriging, a tool from geospatial statistics that allows us to construct a confidence interval for the model estimate of coral risk at locations where direct model estimates are not available (Chiles and Delfiner 1999, Wackernagel 2003). To apply simple kriging to model estimates we first estimate the spatial dependence of modeled coral risk, using a so-called variogram (Wackernagel 2003; see supplementary materials for further details on estimated fit). After applying the appropriate standardization and conversion rates to the data, we average the observed datasets to generate a single indicator of coral health. We find that 74% of the observed data lie within the 95% C.I. of the kriged model data (figure S10). In particular, the model aligns well with data on coral reef health for much of the barrier reef, Turneffe and Lighthouse Reef atolls, but poorly for Glover's Reef. We used this information to better understand why the HRA model might perform poorly there, and found that several areas in Glover's Reef were designated as no-fishing zones in 2002. While the model uses this layer to attribute a relatively low risk to these places, the observed data suggest that by 2006 the coral ecosystems had not yet fully recovered. In reality, recovery of

[7] Unfortunately, observed data on seagrass quality are not available.

degraded ecosystems is often lengthy and risk assessments, which capture snapshots in time, may not account for these time lags.

3.3. Habitat risk under three future zoning scenarios for human activities

To understand the influence of human activities on coral reefs, mangrove forests and seagrass beds in the future, we assess habitat risk under three alternative scenarios (i.e., conservation, informed management and development) for coastal and ocean uses (figures 2(b)–(d), S5–7). These scenarios were developed through an extensive stakeholder engagement process and review of government reports and existing legislation (Clarke *et al* 2013, McKenzie *et al* 2014). Conceptually, the management scenarios are designed to reflect a range of stakeholder interests and alternative futures (see supplementary material). We use the stakeholder-generated visions for alternative futures to generate three sets of spatial zones depicting possible future locations of the eight human uses and a few changes to the exposure and consequence ratings (figures 2(b)–(d), supplementary tables, Clarke *et al* 2013).

We assess future habitat risk using the new activity layers for each scenario, maps of the current distribution of corals, mangroves and seagrass, and the risk assessment approach described in section 2.2 *Estimating habitat risk* and table 1. Results from our analysis suggest that the Informed Management scenario would reduce the area of mangroves, corals and seagrass at high risk to less than 20% of the area currently at high risk (figures 2(c), 5), while nearly tripling the area of coastal development, doubling the area of aquaculture and reducing the extent of oil exploration and dredging (Clarke *et al* 2013). Under the Development scenario (figure 2(d)) the area of mangroves at high risk would more than triple, and the area of seagrass and corals would be more than five times the area at high risk under the current scenario (figure 5). Of the three future scenarios, the Conservation option (figure 2(b)) would result in the greatest area of low-risk habitat and least amount at high risk, for all three habitats (figure 5). Figure 4 elucidates how we used our analysis to adjust the zones of human activities in the future scenarios. For example, the shift to the left on the exposure axis for the Informed Management scenario reflects a decision to reduce spatial overlap between dredging and seagrass in Ambergris Caye by reducing and relocating the extent of the dredging zone.

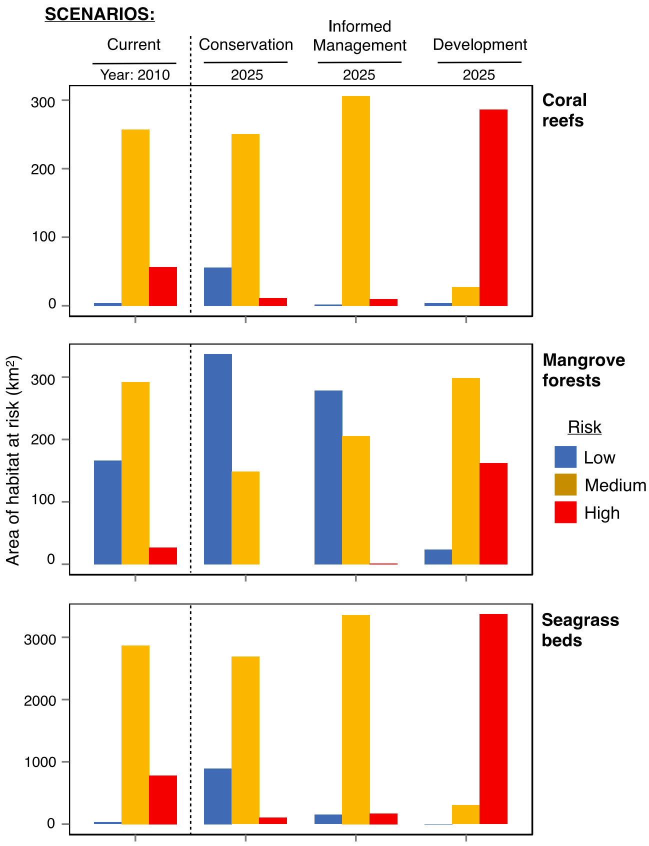

Figure 5. Area of coral reef, mangrove forests and seagrass beds at high, medium and low risk under the Current and three future scenarios of human activities.

4. Discussion

This paper describes a transparent and repeatable approach for estimating risk to habitats from cumulative effects of human activities. In collaboration with the government of Belize, we used this approach and the accompanying open-source software to inform the design of Belize's national ICZM Plan. Although previous studies have made great strides in developing the science needed to assess the impacts of multiple ocean uses, ours is the first to propose a risk assessment model for coastal and marine habitats that provide a suite of services to people and are often key biological targets in ocean planning. Further, our study is the first to estimate how scenarios that consider changes in the spatial extent of human activities influence the cumulative risk to habitats in the future.

Differences in risk among planning regions and ecosystems stem from variation in spatial and temporal overlap, intensity of uses, management effectiveness, habitat life history characteristics and differences in how corals, mangroves and seagrass respond to stressors posed by human activities (table 1). The power of our approach is that by explicitly decomposing risk into exposure and consequence, we can identify management options for reducing impacts. In general, management interventions have greater potential to reduce risk via shifts in exposure than changes in consequence. For example, shrinking and moving dredging zones from Ambergris to Central Region reduces risk to seagrass by lowering exposure, but further risk reduction options are limited due to a high consequence score. Management approaches are not as likely to reduce the consequence component of risk for seagrass because consequence is based on species-specific life history attributes that do not respond quickly to change in a pressure such as dredging (see results; figure 4). Several previous studies highlight the potential of this approach (Dawson *et al* 2011, Hobday *et al* 2011), yet none have tested it within a marine spatial planning process. Results from the HRA model identify planning regions where corals, mangroves and seagrass are at high risk and which activities contribute the most to risk. This information can be used in consultation with stakeholders and policy-makers to identify where the spatial extent (and thus exposure) of certain high-risk activities can be reduced, relocated and/or expanded to areas without sensitive habitats and to prioritize management plans accordingly.

One of the benefits of our approach is that it allows managers to prioritize locations for actions to reduce risk. However, because the risk scores are relative, it is possible that even low risk areas are not free from human degradation. Another limitation is that we do not explicitly account for the influence of past activities. For example, the impacts of fishing on coral health at Glover's Reef before its designation as a protected area are absent from our risk analysis (see section 3.3. *Model testing*), but comparison to empirical data suggests this effect persists. These caveats can and should be considered in decision-making. Our approach also assumes *a priori* that each stressor contributes equally to the final cumulative risk score. Currently, the balance of evidence for weighting and combining stressors is mixed and context dependent (Crain *et al* 2008) so we chose the simplest approach commonly used in the literature (Halpern *et al* 2008, Ban *et al* 2010, Maxwell *et al* 2013). Future studies that compare risk assessments in various contexts, and incorporate sensitivity analyses that test different combinations, weights and ranges for criteria and stressors, will improve our model and advance the science and management of cumulative impacts from human activities to ecosystems.

The Belizean government is putting forward the Informed Management scenario as the preferred spatial plan for zoning human activities. The government's recommendation stems in part from the estimated reduction in risk to coral reefs, mangrove forests and seagrass beds under this scenario. Our results suggest that this plan would lead to an increase in the area of coral, mangrove and seagrass at low risk of degradation from human activities and a decrease in the area of habitat at high risk, relative to the current configuration of human activities and the Development scenario. While the Conservation scenario provides the best outcome for habitats, it restricts expansion and relocation of several activities critical for the Belizean economy, including coastal development and marine transportation (figure 2). Considering multiple social and ecological goals is central to the vision of marine spatial planning. Risk to coastal and marine habitats provides a metric for evaluating conservation outcomes and can be used in conjunction with ecosystem service models to estimate potential change in social and economic outcomes under alternative management scenarios (Clarke *et al* 2013).

Our model and this story of its application within a real ocean planning process have the potential to fundamentally change marine and coastal management in Belize and around the world. In Belize, the development of an ICZM Plan is a political and scientific achievement that has taken years to come to fruition—in part because of the lack of a systematic approach to coastal planning when initial calls for a national plan began over a decade ago. The HRA framework helped to organize and add efficiency to an otherwise ad-hoc exercise of siting human activities. This approach is repeatable and transferable elsewhere. Ocean plans are in development in at least 25 other countries and on track for implementation by 2025 (Merrie and Olsson 2014). By identifying where cumulative risk from multiple activities is likely to degrade coastal and marine habitats, and how changing the location and extent of these activities reduces risk, our approach has the potential to inform multi-sectoral ocean processes underway in countries around the world.

Acknowledgements

We are grateful for support from Google Inc. Charitable Giving Fund of Tides Foundation, the Summit Foundation, and the Gordon and Betty Moore Foundation. We thank the staff at the Belize Coastal Zone Management Authority and Institute for facilitating site visits, time, expertise and vision for the coastal planning process. In addition, we thank the many government departments, non-governmental organizations and individuals in Belize that provided data, review and local knowledge, particularly Nadia Bood, Julie Robinson, Emil Cherrington and Leandra Cho-Ricketts. We are further indebted to David Fisher, Katherine Wyatt, Jameal Samhouri and Anne Guerry for their critical roles in helping this work reach the publication phase. Finally, we thank World Wildlife Fund for its commitment to our partnership and efforts to advance coastal zone planning in Belize.

References

Arkema K, Abramson S C and Dewsbury B M 2006 Marine ecosystem-based management: from characterization to implementation *Front. Ecol. Environ.* **4** 525–32

Ban N C, Alidina H M and Ardron J A 2010 Cumulative impact mapping: advances, relevance and limitations to marine management and conservation, using Canada's Pacific waters as a case study *Mar. Policy* **34** 876–86

Belize Coastal Zone Management Act 2000 *Chapter 329 revised edition 2000 showing the law as at 31st December 2000* (Belmopan, Belize: The Government of Belize) p 29

Burgman M 2005 *Risks and Decisions for Conservation and Environmental Management* (Cambridge: Cambridge University Press) p 504

Cherrington E A, Hernandez B E, Trejos N A, Smith O A, Anderson E R, Flores A I and Garcia B C 2010 *Technical Report: Identification of Threatened and Resilient Mangroves in the Belize Barrier Reef System* (Water Center for the Humid Tropics of Latin America and the Caribbean (CATHALAC) and World Wildlife Fund (WWF)) **27**

Chiles J and Delfiner P 1999 *Geostatistics: modeling spatial uncertainty* (New York: Wiley) p 695

Clarke C, Canto M and Rosado S 2013 *Belize Integrated Coastal Zone Management Plan* (Belize City: Coastal Zone Management Authority and Institute) p 423

Cooper E, Burke L and Bood N 2009 *Coastal Capital: Belize* (Washington, DC: World Resources Institute) p 53

Crain C M, Kroeker K and Halpern B S 2008 Interactive and cumulative effects of multiple human stressors in marine systems *Ecol. Lett.* **11** 1304–15

Daily G C, Polasky S, Goldstein J, Kareiva P M, Mooney H A, Pejchar L, Rickets T H, Salzman J and Shallenberger R 2009 Ecosystem services in decision making: time to deliver *Front. Ecol. Environ.* **7** 21–8

Dawson T P, Jackson S T, House I C and Mace G M 2011 Beyond predictions: biodiversity conservation in a changing climate *Science* **332** 53–8

Douvere F 2008 The importance of marine spatial planning in advancing ecosystem-based sea use management *Mar. Policy* **32** 762–71

European Commission 2013 *Proposal for a Directive of the European Parliament and of the Council for Establishing a Framework for Maritime Spatial Planning and Integrated Coastal Management* European Commission 65

Fulton E A *et al* 2011 Lessons in modelling and management of marine ecosystems: the Atlantis experience *Fish Fish.* **12** 171–88

Guerry A D *et al* 2012 Modeling benefits from nature: using ecosystem services to inform coastal and marine spatial planning *Int. J. Biodivers. Sci., Ecosyst. Serv., Manage* **8** 107–21

Halpern B S *et al* 2008 A global map of human impact on marine ecosystems *Science* **319** 948–52

Hobday A J *et al* 2011 Ecological risk assessment for the effects of fishing *Fish. Res.* **108** 372–84

Klein C J, Jupiter S D, Selig E R, Watts M E, Halpern B S, Kamal M, Roelfsema C and Possingham H P 2012 Forest conservation delivers highly variable coral reef conservation outcomes *Ecol. Appl.* **22** 1246–56

Klein C J, Steinback C, Watts M, Scholz A J and Possingham H P 2009 Spatial marine zoning for fisheries and conservation *Front. Ecol. Environ.* **8** 349–53

Lester S E *et al* 2010 Science in support of ecosystem-based management for the US West Coast and beyond *Biol. Cons.* **143** 576–87

Levin P S, Fogarty M J, Murawski S A and Fluharty D 2009 Integrated ecosystem assessments: developing the scientific basis for ecosystem-based management of the ocean *PLoS Biol.* **7** e1000014

Lubchenco J and Sutley N 2010 Proposed US policy for ocean, coast, and Great Lakes stewardship *Science* **328** 1485–6

Maxwell S M *et al* 2013 Cumulative human impacts on marine predators *Nat. Commun.* **4** 2688–897

McKenzie E, Posner S, Tillmann P, Bernhardt J R, Howard K and Rosenthal A 2014 Understanding the use of ecosystem service knowledge in decision making: lessons from international experiences of spatial planning *Environ. Plann.* C **32** 320–40

McLeod K and Leslie H 2009 *Ecosystem-Based Management for the Oceans* (Washington, DC: Island Press) p 392

Merrie A and Olsson P 2014 An innovation and agency perspective on the emergence and spread of marine spatial planning *Mar. Policy* **44** 366–74

Millennium Ecosystem Assessment 2005 *Ecosystems and Human Well-Being: Current State and Trends* (Washington, DC: Island Press) p 23

National Ocean Council 2013 *National Ocean Policy Implementation Plan* (Washington, DC: Executive Office of the President) p 32

Patrick W S *et al* 2010 Using productivity and susceptibility indices to assess the vulnerability of United States fish stocks to overfishing *Fish. Bull.* **108** 305–22

Ruckelshaus M *et al* 2013 Notes from the field: lessons learned from using ecosystem service approaches to inform real-world decisions *Ecol. Econ.* in press

Ruckelshaus M, Klinger T, Knowlton N and DeMaster D P 2008 Marine ecosystem-based management in practice: scientific and governance challenges *Bioscience* **58** 53–63

Samhouri J F and Levin P S 2012 Linking land- and sea-based activities to risk in coastal ecosystems *Biol. Cons.* **145** 118–29

Sanchirico J N and Mumby P 2009 Mapping ecosystem functions to the valuation of ecosystem services: implications of species–habitat associations for coastal land-use decisions *Theor. Ecol.* **2** 67–77

Selkoe K A, Halpern B S, Ebert C M, Franklin E C, Selig E R, Casey K S, Bruno J and Toonen R J 2009 A map of human impacts to a 'pristine' coral reef ecosystem, the Papahānaumokuākea Marine National Monument *Coral Reefs* **28** 635–50

Sharp R *et al* 2014 *InVEST User's Guide: Integrated Valuation of Environmental Services and Tradeoffs* (Stanford, CA: The Natural Capital Project) p 321

Tallis H and Polasky S 2009 Mapping and valuing ecosystem services as an approach for conservation and natural-resource management *Ann. New York Acad. Sci.* **1162** 265–83

Teck S J *et al* 2010 Using expert judgment to estimate marine ecosystem vulnerability in the California Current *Ecol. Appl.* **20** 1402–16

Wackernagel H 2003 *Multivariate Geostatistics: An Introduction with Applications* 3rd edn (Berlin: Springer) p 387

Watts M E, Ball I R, Stewart R S, Klein C J, Wilson K, Steinback. C, Lourival R, Kircher L and Possingham H P 2009 Marxan with zones: software for optimal conservation based land- and sea-use zoning *Environ. Modell. Softw.* **24** 1513–21

White C, Halpern B S and Kappel C V 2012 Ecosystem service tradeoff analysis reveals the value of marine spatial planning for multiple ocean uses *Proc. Natl. Acad. Sci.* **12** 4696–701

Williams A, Dowdney J, Smith A D M, Hobday A J and Fuller M 2011 Evaluating impacts of fishing on benthic habitats: a risk assessment framework applied to Australian fisheries *Fish. Res.* **112** 154–67

Worm B *et al* 2009 Rebuilding global fisheries *Science* **325** 578–85