LETTER

Global priority areas for incorporating land–sea connections in marine conservation

Benjamin S. Halpern[1], Colin M. Ebert[1], Carrie V. Kappel[1], Elizabeth M.P. Madin[2], Fiorenza Micheli[3], Matthew Perry[1], Kimberly A. Selkoe[1,4], & Shaun Walbridge[1]

[1] National Center for Ecological Analysis and Synthesis, 735 State Street, Santa Barbara, CA 93101, USA
[2] Department of Ecology, Evolution, and Marine Biology, University of California, Santa Barbara, CA 93106, USA
[3] Hopkins Marine Station, Stanford University, Oceanview Boulevard, Pacific Grove, CA 93950-3094, USA
[4] Hawaii Institute of Marine Biology, University of Hawaii, Kaneohe, HI 97644, USA

Keywords
Hotspots; nutrient runoff; land-based pollution; watersheds; ecosystem-based management.

Correspondence
Benjamin S. Halpern, National Center for Ecological Analysis and Synthesis, 735 State Street, Santa Barbara, CA 93101, USA. Tel: +805-892-2531; fax: +805-892-2510. E-mail: halpern@nceas.ucsb.edu

Received: 14 November 2008; accepted 5 March 2009

doi: 10.1111/j.1755-263X.2009.00060.x

Abstract

Coastal marine ecosystems rank among the most productive ecosystems on earth but are also highly threatened by the exposure to both ocean- and land-based human activities. Spatially explicit information on the distributions of land-based impacts is critical for managers to identify where the effects of land-based activities on ecosystem condition are greatest and, therefore, where they should prioritize mitigation of land-based impacts. Here, we quantify the global cumulative impact of four of the most pervasive land-based impacts on coastal ecosystems—nutrient input, organic and inorganic pollution, and the direct impact of coastal populations (e.g., coastal engineering and trampling)—and identify hotspots of land-based impact using a variety of metrics. These threat hotspots were primarily in Europe and Asia, with the top three adjacent to the Mississippi, Ganges, and Mekong rivers. We found that 95% of coastal and shelf areas (<200 m depth) and 40% of the global coastline experience little to no impact from land-based human activities, suggesting that marine conservation and resource management in these areas can focus on managing current ocean activities and preventing future spread of land-based stressors. These results provide guidance on where coordination between marine and terrestrial management is most critical and where a focus on ocean-based impacts is instead needed.

Introduction

Coastal marine ecosystems provide valuable services to humans, including seafood, coastal protection, water filtration, and recreation (M.E.A. 2005). These ecosystems are also some of the most at-risk areas, as human activities on land and at sea can directly or indirectly impact their species and communities (Halpern *et al.* 2008). Given the diversity of potential impacts to coastal marine ecosystems, resource managers and conservationists must prioritize which human activities and associated impacts to mitigate. Examples of distant land-based activities driving marine ecological condition, such as the persistent anoxic dead zone at the mouth of the Mississippi River attributed to nutrient runoff from upstream farms (Rabalais *et al.* 2002) or algal overgrowth of coral reefs from land-based nutrient pollution (Fabricius 2005), have increased the interest in considering such land-based drivers in coastal marine conservation globally. Yet, these examples are not necessarily the norm. There are many places where rainfall is extremely low, limiting the input of land-based drivers in coastal waters, for example, the desert coastline of Namibia and the Peruvian and Chilean Atacama coastal plains. In most cases, in between these extremes, discerning where land-based input plays a dominant or minor role in the ecological condition of a coastal area is difficult but is needed for efficient allocation of limited resources (Stoms *et al.* 2005; Tallis *et al.* 2008).

Past efforts have estimated global patterns of human changes to sediment regimes and nutrient input into coastal waters (Kroeze & Seitzinger 1998; Seitzinger & Kroeze 1998; Caraco & Cole 1999; Smith *et al.* 2003; Vorosmarty *et al.* 2003; Green *et al.* 2004; Dumont *et al.* 2005; Harrison *et al.* 2005; Seitzinger *et al.* 2005; Van Drecht *et al.* 2005; Boyer *et al.* 2006; Galloway *et al.* 2008). The resulting models are powerful but primarily apply to large watersheds. One study also evaluated smaller watersheds (Smith *et al.* 2003), but at a relatively coarse scale. Furthermore, patterns of change in nutrient loads do not necessarily capture potential or realized impact on marine ecosystems and, more importantly, do not account for cumulative impacts from multiple drivers of change. Finally, these models typically require input data that do not exist for many parts of the world and so cannot be applied everywhere. The research presented here makes substantial improvement on these issues using simple, but accurate, global models of land-based impacts.

Approaches for linking ocean- and land-based management and conservation for specific cases at fine scales have been described elsewhere (Bryant *et al.* 1998; Stoms *et al.* 2005; Tallis *et al.* 2008). Here, we provide the first integrated analysis for all coastal areas of the world with a database that assesses the cumulative impact of four key land-based drivers of ecological change with global coverage: (1) nutrient input from agriculture and urban settings, (2) organic pollutants derived from pesticides, (3) inorganic pollutants from urban runoff, and (4) the direct impact of human populations on coastal marine habitats. We then use results from these analyses to identify hotspots of cumulative effects ("threat hotspots") using a number of different approaches: "cluster," "source," and "percent" threat hotspots. The three methods are designed to help address different types of management needs and questions. Cluster threat hotspots are areas with high cumulative impact from land-based drivers, often influenced by multiple watersheds or complex coastlines. Where these hotspots exist, both threat intensity and ecosystem vulnerability play a key role in producing high values. Source threat hotspots indicate where input of land-based drivers is high before it is dispersed into the ocean and translated into ecosystem impacts; these should primarily be at mouths of large, heavily populated watersheds. Source threat hotspots do not account for ecosystem vulnerability. They are useful in cases in which ecosystem distribution data are sparse and/or when management is focused on key species or other conservation targets below the ecosystem level. Finally, percent threat hotspots indicate where land-based impacts overwhelmingly drive total cumulative impacts (from 17 total land and sea drivers analyzed in (Halpern *et al.* 2008)). These hotspots are particularly important for efforts to prioritize where land-based threats need to be addressed regardless of the intensity of ocean-based threats. Where all three threat hotspots co-occur, land-based stressors affect the most vulnerable ecosystems, have the highest recorded input, and constitute a much larger source of impact than ocean-based drivers.

Our aim here is to inform several key management and conservation prioritization needs at local, regional, and global scales. Land-based threat hotspots help identify global priority areas for addressing land-based sources of stress, while also highlighting the need for local-scale management efforts to direct their attention to land-based activities. Similarly, country-level analyses help identify which countries are most in need of addressing land-based management, in turn guiding the prioritization of limited time and funds of international and federal agencies and conservation organizations in their efforts to mitigate land-based impacts to oceans. Finally, the analyses help put land-based impacts into a global context relative to the full suite of threats facing ocean ecosystems.

Methods

Cumulative impact model

The four drivers of land-based impact on marine ecosystems used here represent the two main ways in which land-based activities affect marine ecosystems: directly, generally mediated by local human population size, and indirectly through watershed dynamics. Direct human impact was derived from the proximity to human populations, while the other stressors were derived by modeling the distribution of relevant human activities on land, aggregating values to watersheds, and pluming this aggregate into adjacent oceans (see Supporting Information for details). We used a cumulative impact model (Halpern *et al.* 2008) to combine these four data sets into a single metric of ecological impact ("land-based" impact score) that accounts for differential ecosystem vulnerability to each driver (Halpern *et al.* 2007) for 20 different marine ecosystems. Briefly, log-transformed values of the intensity of each human activity (or driver) were rescaled 0–1 (D_i) and multiplied by an ecosystem vulnerability score (μ_{ij}) for each pixel (see Table S1) where the ecosystem(s)

(E_j) occurs and then averaged for each pixel such that cumulative impact ($\bar{I}_C$) is calculated as

$$\bar{I}_C = \frac{\left[\sum_{i=1}^{n}\sum_{j=1}^{m} D_i \times E_j \times \mu_{ij}\right]}{m}. \quad (1)$$

These scores ranged from 0 to 6.3 and were binned into five categories for comparison: high ($\bar{I}_C > 3.5$), medium-high ($\bar{I}_C = 2.5$–3.5), medium ($\bar{I}_C = 1.5$–2.5), low ($\bar{I}_C = 0.5$–1.5), and very low ($\bar{I}_C < 0.5$). We used the $\bar{I}_C$ values averaged across ecosystems instead of the sum (Halpern *et al.* 2008) because we had to assume that four intertidal ecosystems that are poorly mapped at the global scale (beach, rocky intertidal, intertidal mud, and salt marsh) exist in all coastline pixels. The sum model would inappropriately overweight impact to these pixels. Currently, no empirical data on coastal ecosystem response to the full suite of land-based threats exist, precluding the ability to translate our land-based impact scores into actual measures of ecosystem degradation. Consequently, these categories represent relative impact scores. Data processing and validation, analysis, and constraints and methods for modeling cumulative impact scores are described elsewhere (Supporting Information).

Calculating threat hotspots

Using these scores, we conducted three types of analyses to determine where land-based stressors are having the greatest impact. First, we used a 25-km-radius moving window function to smooth the spatial distribution of the cumulative impact (I_C) scores and help identify clusters (>25 km^2) of high values (>60% of global maximum value). We then calculated the size (km^2) of each of these "cluster" threat hotspots. The moving window function smoothes across potentially discontinuous high-value cells, allowing for a quick identification of clusters of high values. We found similar results using a 12- and 18-km-radius moving windows, most notably the rank order of the top 30 hotspots. We chose the 25-km radius because: (1) it merged neighboring discontinuous clusters that clearly stemmed from the same land-based source, and (2) it produced a manageable number of threat hotspots (the exact number is arbitrary and dependent on the size of the moving window). Because the moving window function can "jump" across land barriers, we clipped away regions of a cluster that were disconnected from the main cluster by these land barriers (necessary for only five threat hotspots).

To calculate high sources of stressors ("source" threat hotspots), we summed the value of each stressor within each watershed and then transformed these summed values to the range 0–1 (the D_i values before they are plumed into the ocean). We then summed the transformed values into a single metric of land-based pollution and arbitrarily selected the top 30 sources (values decline exponentially, with a leveling off beginning at rank 20 such that source threat hotspots with rank >20 differ little from each other; see Table S2). Source threat hotspots represent the footprint of land-based activities' impacts and do not take into account ecosystem vulnerability (μ_{ij}). Finally, to calculate the relative contribution of land-based stressors to total cumulative impact (from 17 stressors; termed "percent" threat hotspots), we divided land-based cumulative scores by the total cumulative impact scores (Halpern *et al.* 2008) to produce a fraction (or percent) ranging from 0 to 1. Groups of pixels >25 km^2 with values >75% were considered percent threat hotspots. There were many isolated or small clusters of coastline pixels, particularly in the Canadian Arctic, which had high percent values because ocean-based impacts were extremely low (or zero); we excluded these from this threat hotspots analysis but addressed them in the coastline length analysis explained below.

Global and national results

We calculated the amount of coastal and shelf area (<200 m deep) and coastline (first 1 km of ocean adjacent to land) affected by land-based stressors globally and within each country's exclusive economic zone (EEZ). Total cumulative impact scores ranged from 0.1 to 90 (Halpern *et al.* 2008) and land-based impact scores ranged from 0 to 6.3; we assumed that land-based scores <1.0 represent coastal areas with little influence from land-based stressors. We also provide results for land-based impact scores <0.5 as a more conservative estimate of areas little affected by land-based drivers.

Predicting locations of high impact

We evaluated whether and how well several ancillary but related variables can predict the intensity of land-based impact and the location and attributes of threat hotspots. We expect human population size within a country and the length of a country's coastline to be related to the total amount of coastal waters impacted by land-based stressors; we used multivariate linear regression to test this relationship, with Canada removed from the analyses because it was an extreme outlier (with the longest coastline and one of the lowest population densities in the world). We also used linear regression to test how well several watershed-scale variables, including watershed size, human population size, land-class coverage, and the amount of area in different levels of protection,

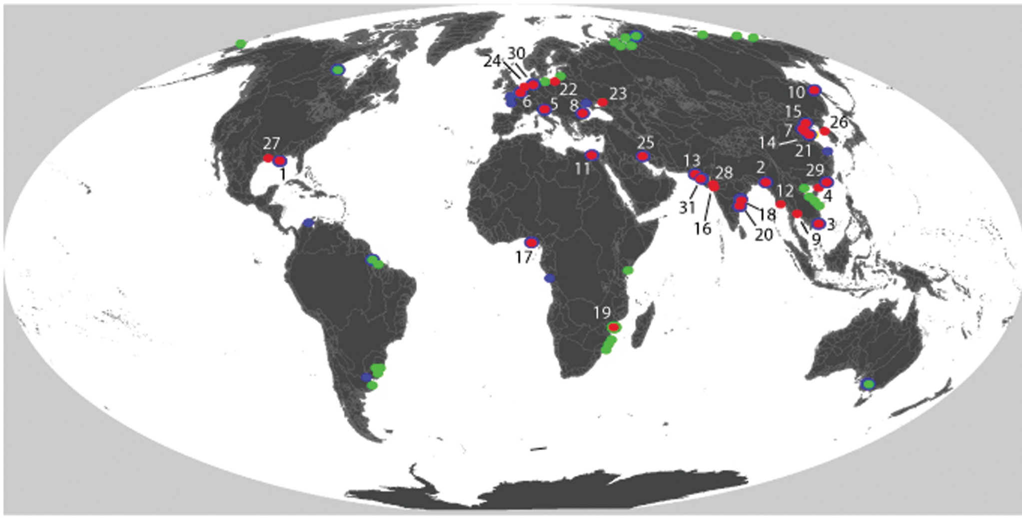

Figure 1 Global threat hotspots of land-based impacts on marine ecosystems. Threat hotspots were derived in three ways (see also Methods): (1) by assigning each cell the sum of all values within a 25-km-radius moving window and then selecting clusters of cells >25 km^2 with summed values exceeding 60% of the global maximum (cluster threat hotspots, red), (2) by the sum of the transformed land-based input of stressors at watershed mouths before the values are plumed into the ocean (source threat hotspots, blue), and (3) by calculating the percentage of total human impact on each pixel contributed by land-based sources and then identifying clusters >25 km^2 with values $>75\%$ (percent threat hotspots, green). Numbers reference the rank order of the 31 cluster threat hotspot locations (red) detailed in Table 1. Where threat hotspots overlap, the colors overlap in concentric rings. White lines on land are watershed boundaries.

predict cluster threat hotspot size (see Supporting Information for details). A high correlation would allow for these easier-to-measure variables to be used in future efforts to identify threat hotspots.

All open-access data and analytical code used in this project can be downloaded at http://www.nceas.ucsb.edu/GlobalMarine.

Results and discussion

We found 31 "cluster," 30 "source," and 28 "percent" threat hotspots globally, primarily in Europe and Asia (Figure 1; Table 1). Countries with the highest number of all three threat hotspots included Russia, China, and India. More than three-quarters of cluster threat hotspots and most source threat hotspots were in India, China, and Europe, and two-thirds of percent threat hotspots were in Russia, Vietnam, Mozambique, and Brazil. Cluster and source threat hotspots often overlapped, but percent threat hotspots rarely overlapped with either (Tables 1 and S2). Only one threat hotspot was identified by both cluster and percent threat hotspot approaches, at the Zambezi River mouth in Mozambique, and none was identified by all three methods. Cluster threat hotspots without source threat hotspots had highly vulnerable ecosystems, while source threat hotspots without cluster threat hotspots had less vulnerable ecosystems. Source threat hotspots in data-poor areas require caution because better data might identify patches of vulnerable ecosystems or species important for community or ecosystem function that were not identified in our global-scale habitat data. Percent threat hotspots represent the proportion of land-based impacts relative to total impacts and their locations diverged greatly from the other two types, as they were not necessarily tied to river mouths and could have low cumulative impact scores. In particular, high-latitude percent threat hotspots (Figure 1) had a low total cumulative impact, indicating that management in these regions should focus on land-based sources of stress. In contrast, percent threat hotspots in South America, East Africa, and southeast Asia (Figure 1) had a relatively high total cumulative impact (Halpern *et al.* 2008), indicating that management will need to address both land- and ocean-based stressors. In sum, our three threat hotspot types highlight that the importance of land-based impacts vary greatly depending on the extent and distribution of input sources, the vulnerability of ecosystems affected, and the extent of ocean-based stressors simultaneously affecting those ecosystems.

Large portions of coastal areas experience little to no impact from land-based stressors, as modeled here: 40% of the global coastline and nearly all (94.7%) of the world's coastal and shelf areas experience little

Table 1 Characteristics of threat hotspots of land-based impact on coastal marine ecosystems based on cluster methods (red spots in Figure 1), with overlapping source (by rank) and percent threat hotspots also shown for comparison. Percent hotspots are not ranked.** indicates the threat hotspot that is also a percent hotspot

Threat hotspot rank								
Cluster	Source	%	River/bay	Nearest city	Country	Size of cluster (km²)	Watershed size (km²)	No. of input watersheds
1	1		Mississippi River	New Orleans	United States	1,028	3,212,288	1
2	3		Ganges	Dhaka	Bangladesh	921	1,586,414	1
3	14		Mekong River	Saigon	Vietnam	844	807,915	2
4	7		Pearl River	Miacau (near Hong Kong)	China	802	449,392	1
5	28		Po River	Venice	Italy	789	89,267	2
6	11		Rhine and Meuse Rivers	Rotterdam	The Netherlands	731	198,378	2
7	30		Hai He River	Tianjin	China	721	192,873	2
8	6		Danube River	Galati	Romania	662	795,667	1
9			Chao Phraya River	Bangkok	Thailand	645	212,365	5
10	5		Volga	Nikolayevsk	Russia	634	2,026,992	1
11	10		Nile River	Cairo	Egypt	606	3,002,194	1
12			Irrawaddy River	Yangon (Rangoon)	Myanmar	591	390,287	1
13	8		Indus River	Karachi	Pakistan	552	754,261	1
14			Yellow River (west branch)	Cangzhou	China	538	84,438	2
15	21		Liao River	Anshan	China	532	232,133	3
16			Narmada	Surat	India	510	95,981	1
17	27		Niger River	Port Harcourt	Nigeria	430	2,163,994	1
18	15		Godavari River	Rajahmundry	India	387	308,907	1
19		**	Zambezi River	Tete	Mozambique	305	1,385,878	1
20	18		Krishna River	Vijayawada	India	271	253,918	1
21	13		Yellow River (east branch)	Binzhou	China	214	363,373	1
22			Vislinskiy Zaliv	Elblag	Poland	197	194,607	1
23			Don River	Rostov-on-Don	Russia	174	427,605	1
24			Ijsselmeer Lake/Wadden Sea	Kampen	The Netherlands	144	14,843	1
25	20		Euphrates and Tigris Rivers	Al Basrah	Iraq	141	873,715	1
26			Imjin and Han Rivers	Seoul	South Korea	121	37,514	3
27			Trinity River	Galveston	United States	72	56,933	2
28			Mahi and Sabarmati Rivers	Vadodara and Ahmedabad	India	70	53,154	2
29			Han, Rong, and Lian Rivers	Shantou	China	49	34,399	2
30	23		Elbe River	Bremen	Germany	37	43,810	1
31	16		Luni River	Gujarat	India	24	402,183	1

impact (cumulative impact <1.0; 19.7% and 87.1%, respectively, have impact <0.5). Only 2.3% (20,250 km) of global coastlines but as much as 42.6% (~3.2 million km^2) of coastal and shelf areas (at depths <200 m) experience no apparent effect of land-based stressors (cumulative impact = 0). The majority of global coastlines are distant from the major sources of potential impact, so these estimates should be robust to the model's inherent assumptions about plume sizes and positions. More realistic plume models would affect the size, shape, and alongshore spread of some threat hotspots but not their general locations or global- and national-level statistics on the intensity of land-based drivers.

Our quantification of land-based impacts along coastlines may be inflated as our model assumes presence in all coastal pixels of four intertidal ecosystems (Halpern *et al.* 2008). Beach ecosystems are much less vulnerable than the other three (Table S1) but are globally abundant. Consequently, even more of the global coastline than what we report here may experience little to no impact from land-based stressors, and this could affect the location and number of percent hotspots. However, the result that land-based impact to coastal and shelf areas is currently concentrated in small areas is likely robust, as is the location of source or cluster hotspots.

A low land-based impact predominates worldwide primarily because most land (72%) is encompassed in only 663 large watersheds (Syvitski *et al.* 2005) (out of >140,000 globally) that drain to relatively small stretches of the coast. A vast portion (>99%) of global coastal area, therefore, is adjacent to small coastal watersheds with relatively small amounts of pollutant runoff. Furthermore,

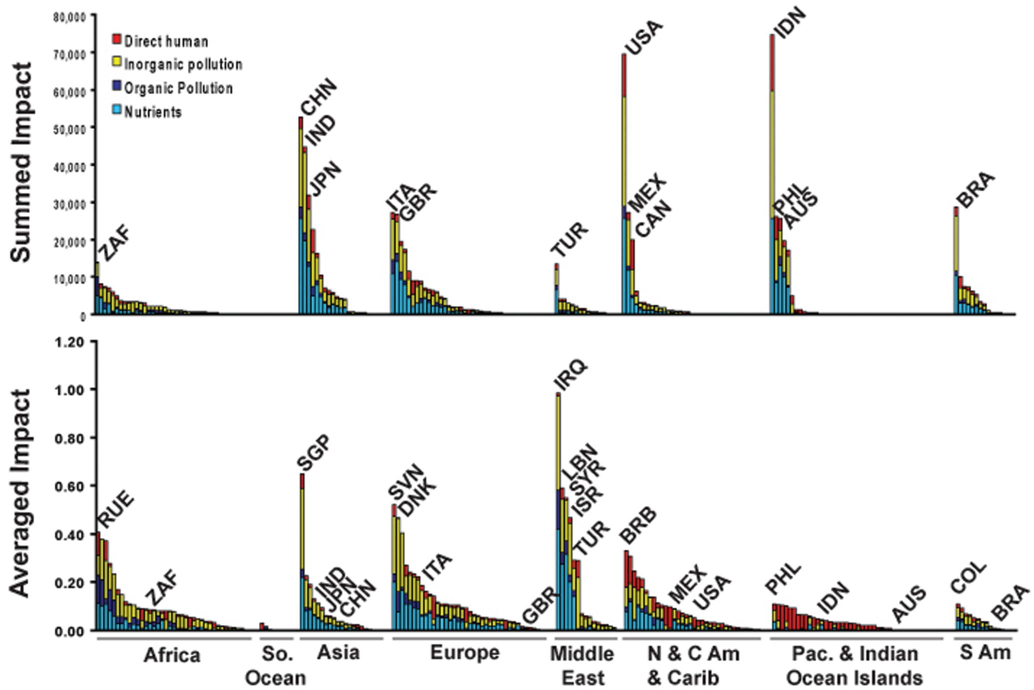

Figure 2 The (A) sum and (B) average cumulative impact scores for coastal (<200 m depth) regions of each country grouped by continents, derived from four land-based drivers of change. The average scores account for the differences in coastal area among countries. Human drivers are color-coded: nutrient input (green), organic pollution (blue), inorganic pollution (yellow), and direct human impact (red). Countries are labeled with standard 3-letter codes. See Table S3 for region labels and country-specific values. Countries in panel A are also labeled in panel B for reference.

many locations have low human population density in adjacent terrestrial areas and/or low levels of human activities such as farming within the watersheds.

Both global- and federal-level conservation and management prioritization efforts can benefit from identifying which countries are most in need of addressing land-based sources of impact to marine ecosystems. It is at the federal level that most land-use regulations are set. Identifying the top-priority countries can help motivate those countries, and the international bodies to which they belong (e.g., the United Nations or European Union), to take action and help inform the priorities of global-scale NGOs. Not surprisingly, the countries exacting the greatest total land-based impact on coastal marine ecosystems (Figure 2A) have some of the longest coastlines and largest coastal areas in the world (but not all, e.g., Italy and India) and large human populations. Indeed, population size and coastline length are correlated with the impact of land-based stressors (multivariate linear regression: $R^2 = 0.70$, $P < 0.001$). With results standardized by area (i.e., average per-pixel scores), heavily populated and developed countries with relatively small coastlines top the list (Figure 2B). Countries that have high values using either approach (e.g., Italy and Turkey; see Figure 2) most urgently need to address land-based stressors.

Given the amount of work required to map and evaluate threat hotspots, we tested how well a variety of easily measured metrics correlate with cluster hotspot size. Although watershed size, human population size, and land-use attributes were correlated in most cases, the explanatory power was low ($R^2 = 0.02$–0.26; Table S4). Akaike information criterion model selection procedures on all possible combinations of multivariate linear regressions produced a slightly better correlation ($R^2 = 0.46$, $F = 4.0$, $P = 0.006$) based on watershed size, urban and mixed land use, and area in the International Union for Conservation of Nature (IUCN) II, III, V, VI and unprotected status (Table S4).

Our analyses likely fall short in three ways. First, no globally comprehensive data exist for a number of important land-based stressors, including past habitat destruction (e.g., dredging and filling of estuaries), point-source pollution (e.g., sewage outfall and factories), altered sediment regimes (particularly increases), and garbage from terrestrial sources. Second, we do not explicitly include connectivity among sites via dispersal and migration such that the impact to some locations may be underestimated or misaligned. Third, past habitat conversion is unaccounted for; the loss of nursery habitats such as mangroves and salt marshes augments the stress of land-based activities on remaining intact areas. New hotspots might emerge with future inclusion of these data.

The general results are not likely to differ greatly with additional data, however, since land-based impact is primarily driven by watershed processes and coastal human population size, both of which are captured well by the model. Additional stressors are likely to be spatially concordant with the four included here; their inclusion would most likely accentuate the existing threat hotspots rather than add many new threat hotspots. For example, recently published data on the global distribution and extent of dead zones arising from land-based eutrophication (Diaz & Rosenberg 2008) align closely with the locations of our threat hotspots and the nations exacting the greatest impact on coastal ecosystems from the stressors that we considered. For regions identified as low impact because there is little water flow out of the watershed (e.g., Western Australia, southwestern Africa, northern Chile, and southern Argentina), our results are most robust because no mechanism exists to transport impact of any driver to the coast. Future changes in climate or coastal human population distribution could increase (or decrease) the risk depending on how runoff is affected. Finally, global patterns of threat hotspot location and the extent of coastal and shelf area and coastline impacted by land-based stressors should be accurate, while results at local scales may be sensitive to unknown patterns of dispersal and plume dynamics.

Regardless of these issues, this first global analysis of the influences of land-based stressors on coastal marine ecosystems highlights the regions, nations, and specific locations around the world where immediate coordination of land and ocean management and conservation is crucial. This need for coordinated management of land- and ocean-based activities, and of their impacts on the suite of coastal marine ecosystems, will only increase as human populations continue to grow.

Acknowledgments

Thanks to R. Watson, B. Steneck, R. Myers, D. Heinnemann, R. Fujita, H. Fox, and M. Spalding for initial input into the approach used in this project, J. Harrison for input and nutrient validation data from the Global-NEWS project, and J. Hutton at the United Nations Environment Programme (UNEP) for sharing ecosystem data layers. This work was funded by the National Center for Ecological Analysis and Synthesis (NCEAS), which is supported by the National Science Foundation, a grant from the David and Lucile Packard Foundation to the NCEAS to evaluate ecosystem-based management in coastal oceans (B.S.H., C.V.K., and S.W.), support from the National Marine Sanctuaries MOA 2005-008/66832 (K.A.S), and an National Science Foundation Graduate Research Fellowship (E.M.P.M.).

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1: Weighting factors used for each threat-by-ecosystem combination. Values were derived from expert opinion surveys

Table S2: Characteristics of source and percent threat hotspots

Table S3: Country-level statistics for the impact within EEZ waters of each land-based stressor

Table S4: Statistical results for linear regressions between watershed attributes and cluster threat hotspot size

Figure S1: Global map with the eight regions used for subglobal analyses indicated. These regions were used for most of the land-based threats calculations before the results were converted to a global projection. The regions include N. America (light green), S. America (light blue), Africa (green), Europe (orange), mainland Asia (dark blue), Asian Islands (pink), Australia (yellow), and Pacific Islands (red). The Lambert project was used for analyses within each subregion and then converted to the Mollweide projection shown here.

References

Boyer, E.W., Howarth R.W., Galloway J.N., Dentener F.J., Green P.A., Vorosmarty C.J. (2006) Riverine nitrogen export from the continents to the coasts. *Global Biogeochem Cycles* **20**, Gb1s91, doi: 10.1029/2005gb002537.

Bryant, D., Burke L., McManus J., Spalding M. (1998) *Reefs at risk: a map-based indicator of threats to the world's coral reefs*. World Resources Institute, Washington, D.C., p. 60.

Caraco, N.F., Cole J.J. (1999) Human impact on nitrate export: an analysis using major world rivers. *Ambio* **28**, 167–170.

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

Dumont, E., Harrison J.A., Kroeze C., Bakker E.J., Seitzinger S.P. (2005) Global distribution and sources of dissolved inorganic nitrogen export to the coastal zone: results from a spatially explicit, global model. *Global Biogeochem Cycles* **19**, Gb4s02, doi:10.1029/2005gb002488.

Fabricius, K.E. (2005) Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. *Mar Pollut Bull* **50**, 125–146.

Galloway, J.N., Townsend A.R., Erisman J.W. *et al*. (2008) Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. *Science* **320**, 889–892.

Green, P.A., Vorosmarty C.J., Meybeck M., Galloway J.N., Peterson B.J., Boyer E.W. (2004) Pre-industrial and contemporary fluxes of nitrogen through rivers: a global assessment based on typology. *Biogeochemistry* **68**, 71–105.

Halpern, B.S., Selkoe K.A., Micheli F., Kappel C.V. (2007) Evaluating and ranking global and regional threats to marine ecosystems. *Conserv Biol* **21**, 1301–1315.

Halpern, B.S., Walbridge S., Selkoe K.A. *et al*. (2008) A global map of human impact on marine ecosystems. *Science* **319**, 948–952.

Harrison, J.A., Seitzinger S.P., Bouwman A.F., Caraco N.F., Beusen A.H.W., Vorosmarty C.J. (2005) Dissolved inorganic phosphorus export to the coastal zone: results from a spatially explicit, global model. *Global Biogeochem Cycles* **19**, Gb4s03, doi:10.1029/2004gb002357.

Kroeze, C., Seitzinger S.P. (1998) Nitrogen inputs to rivers, estuaries and continental shelves and related nitrous oxide emissions in 1990 and 2050: a global model. *Nutrt Cycl Agroecosys* **52**, 195–212.

M.E.A. (2005) *Ecosystems and human well-being: synthesis report*. Millennium Ecosystem Assessment, Washington, D.C.

Rabalais, N.N., Turner R.E., Wiseman W.J. (2002) Gulf of Mexico hypoxia, aka "The dead zone". *Ann Rev Ecol Syst* **33**, 235–263.

Seitzinger, S.P., Kroeze C. (1998) Global distribution of nitrous oxide production and N inputs in freshwater and coastal marine ecosystems. *Global Biogeochem Cycles* **12**, 93–113.

Seitzinger, S.P., Harrison J.A., Dumont E., Beusen A.H.W., Bouwman A.F. (2005) Sources and delivery of carbon, nitrogen, and phosphorus to the coastal zone: an overview of global Nutrient Export from Watersheds (NEWS) models and their application. *Global Biogeochem Cycles* **19**, Gb4s01, doi:10.1029/2005gb002606.

Smith, S.V., Swaney D.P., Talaue-McManus L. *et al*. (2003) Humans, hydrology, and the distribution of inorganic nutrient loading to the ocean. *BioScience* **53**, 235–245.

Stoms, D.M., Davis F.W., Andelman S.J. *et al*. (2005) Integrated coastal reserve planning: making the land-sea connection. *Front Ecol Environ* **3**, 429–436.

Syvitski, J.P.M., Vorosmarty C.J., Kettner A.J., Green P. (2005) Impact of humans on the flux of terrestrial sediment to the global coastal ocean. *Science* **308**, 376–380.

Tallis, H., Ferdana Z., Gray E. (2008) Linking terrestrial and marine conservation planning and threats analysis. *Conserv Biol* **22**, 120–130.

Van Drecht, G., Bouwman A.F., Boyer E.W., Green P., Siebert S. (2005) A comparison of global spatial distributions of nitrogen inputs for nonpoint sources and effects on river nitrogen export. *Global Biogeochem Cycles* **19**, Gb4s06, doi:10.1029/2005gb002454.

Vorosmarty, C.J., Meybeck M., Fekete B., Sharma K., Green P., Syvitski J.P.M. (2003) Anthropogenic sediment retention: major global impact from registered river impoundments. *Global Planet Change* **39**, 169–190.

Editor: Dr. Amanda Lombard

