LETTER

Global mismatch between research effort and conservation needs of tropical coral reefs

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Abstract

Tropical coral reefs are highly diverse and globally threatened. Management to ensure their persistence requires sound biological knowledge in regions where coral reef biodiversity and/or the threats to it are greatest. This paper uses a novel text analysis approach and Google Maps™ to examine the spatial coverage of scientific papers on coral reefs listed in *Web of Science*®. Results show that research is highly clumped spatially, positively related to per capita gross domestic product, negatively related to coral species richness, and unrelated to threats to coral reefs globally; indicating a serious mismatch between conservation needs and the knowledge required for effective management. Greater research effort alone cannot guarantee better conservation outcomes, but given some regions of the world (e.g., Central Indo-Pacific) remain severely understudied, priority allocation of resources to fill such knowledge gaps should support greater adaptive management capacity through the development of an improved knowledge base for reef managers.

Introduction

Coral reefs provide critical ecosystem goods and services (Moberg & Folke 1999; Conservation International 2008), yet their ability to supply these on a sustained basis continues to decline (Wilkinson 1999; Hughes *et al.* 2003; Pandolfi *et al.* 2003) in the face of multiple threats including overexploitation, poor water quality, invasive species, sedimentation, global warming, and ocean acidification (Bryant *et al.* 1998; Knowlton 2001; Sheppard 2003; Donner *et al.* 2005; Hoegh-Guldberg *et al.* 2007; Veron *et al.* 2009b). A comprehensive analysis of global risks across a range of marine habitats indicates that coral reefs have few areas remaining that are at low risk from human impacts: almost half of all coral reefs experience medium–high to very-high impact (Halpern *et al.* 2008). Moreover, the spatial distributions of many local threats to coral reefs (human populations, nutrient runoff and artisanal fishing) are heterogeneous (Bryant *et al.* 1998; Bruno & Selig 2007; Halpern *et al.* 2008) as are projected global climate effects, both in terms of elevated sea surface temperatures (Donner *et al.* 2005) and ocean acidification (Hoegh-Guldberg *et al.* 2007). Given limited global research resources, research effort should be targeted where it will be most effective, and the needs are greatest; in the broadest sense, toward those regions likely to face the greatest threat of degradation and number of possible extinctions. The requirement for knowledge increases further where the number and/or severity of hazards faced increases.

Because the conservation of species richness is one of the top global conservation priorities (Myers *et al.* 2000), areas hosting the greatest number of species should be afforded the greatest protection, all other things being equal. Where biodiversity is greater, more knowledge is required to understand the responses of these species, either singularly or in combination, to changing environments. For some taxonomic groups, the geographic distribution of species richness among the world's coral reefs is well known with maximum richness occurring in the Coral Triangle (Roberts *et al.* 2002; Veron *et al.* 2009a), making this province the world's highest conservation priority.

If current and projected knowledge are to adequately support management, rehabilitation, and long-term conservation of coral reefs, the geographic distribution of research should be proportional to the biodiversity of an area, or even biased in favor of high biodiversity regions and/or regions facing the greatest threats. Here we use a novel text analysis approach and Google Maps™ geocoding to compare the spatial coverage of scientific papers on coral reefs listed in Thomson Reuters *Web of Science*® to the distribution of coral species richness and threats to coral reefs globally. These analyses demonstrate that the global distribution of knowledge is not adequately aligned with conservation needs, and redressing this imbalance should be a priority.

Methods

We selected research papers on coral reefs and using data exported from *Web of Science*® (WoS), screened these for biological relevance using the World Registry of Marine Species (WoRMS) and assigned them to a geographical location using Google Maps™. These papers were then compared to a geo-referenced proxy for research capacity (GDP corrected for purchasing power parity), an estimate of coral species richness, and conservation needs based on risks faced (sea temperature, artisanal fishing, human impact, and nutrient level). Details are as follows (see supporting information for further details).

We searched WoS for all scientific papers containing the term "coral reef" or "coral reefs" in the field "topic." The resulting 8,246 papers were exported to EndNote®, transferred to Microsoft Access® and further limited to those papers containing "coral reef" or "coral reefs" in the title, keywords or abstract fields (5,768 papers). Using a semi-automated approach, text from the title, keywords and abstracts was matched against scientific names in WoRMS (Appeltans *et al.* 2010) in order to limit research articles to those of biological relevance (2,889 papers). Following this biological screening, text from the title, abstract and author keyword fields were used to construct a list of unique single, double and triple-word search terms that were assigned to a geographic location using Google Maps JavaScript API V2 (2009). This automated geocoding yielded many false matches, and results were cleaned by: (1) restricting accuracy codes to > 0 (unknown location) and < 5 (post code or street level), (2) removal of common but geographically meaningless terms, (3) restricting marine locations to within 100 km of coral reefs, and terrestrial locations to within 50 km of a coastline, and (4) manual screening of the 500 most commonly occurring locations. Following this we performed a manual check of 100 randomly selected papers identified as biologically relevant (contained a match to WoRMS), regardless of whether they had been successfully assigned to a geographic location. Of these, 54% were successfully assigned to the appropriate region and 28% were appropriately assigned to no region (they contained no useful geographic information), making a combined total success rate of 82%. Of the remainder, ~5% were assigned to the wrong region due to various geocoding errors and ~13% missed being geocoded even though they did contain valid geographic information. The region most often missed was the U.S. Caribbean and Gulf of Mexico (~4%), followed by the East Pacific (~2%). Missed papers were 1% or less in the other regions. Because one of our goals was to develop a new semi-automated approach to text analysis in a conservation context, no attempt was made to correct regional assignments or add missed papers back in. We chose instead to consider how these errors might affect the utility of this approach.

Successfully geocoded papers (2,336 in total) were used to generate a world map of coral reef research effort, using Esri ArcGIS® 9.3 spatial-analysis software. Summary statistics were calculated for 20 discrete global regions, modified from the 17 regions of Wilkinson (2008). After accounting for coral reef area (extracted from the global coral reef atlas (Spalding *et al.* (2001), version 7.0 of the global 1 km raster dataset compiled by the UNEP World Conservation Monitoring Centre (UNEP-WCMC) 2003), regional research effort was examined with respect to the weighted mean per capita gross domestic product (GDP) (World Economic Outlook Database of the International Monetary Fund 2009), the spatially weighted mean species richness of corals using data from

Coral Geographic (Veron 2010), and four of the most important anthropogenic threats to coral reefs: elevated sea surface temperatures, artisanal fishing, direct human pressure (estimated by population density) and nutrient inputs (Halpern *et al.* 2008) using simple linear models. Models examined included 7 single-predictor models, 6 two-predictor models (GDP + each single predictor representing conservation need), and a further 6 models including the interaction with GDP (19 models in total, see Table 1). Assumptions of a Gaussian error distribution, linearity, and co-linearity of predictors were satisfied in all cases (see the Supplementary Information for more details).

Results

Global coral reef research was strongly clumped, with much of the effort concentrated on the Great Barrier Reef (Australia), the Caribbean, Hawaii, southern Japan, and Polynesia, but with at least some research in all regions containing tropical coral reefs (Figure 1A). When aggregated by region, and adjusted for coral-reef area, research effort was highest in Eastern Australia, the three Caribbean regions, the tropical western Atlantic, the Northwest Pacific and Polynesia, and lowest in the Central Indo-Pacific region (Figure 1B).

Only GDP and coral species richness (or a combination thereof) showed any indication of a relationship with relative research effort (Table 1, Figure 2). There was a positive effect of GDP, with high GDP regions having greater research effort and a negative effect of coral species richness, particularly among low GPD regions (Figure 2 and Table 1). Either singly or in aggregate, there was no evidence for a relationship between relative research effort and any of the threat factors considered (Figures 1D, 2C–G, and Table 1).

Discussion

Currently, global coral reef research is strongly clumped relative to regional reef area. The over-representation of research effort in Eastern Australia, the wider Caribbean, and the U.S. Pacific is likely due in large part to these regions being within easy reach of leading tropical research centers. Indeed, six of the top 20 research institutes are based on the east coast of Australia and several similar American institutions are situated in close proximity to Caribbean and Hawaiian coral reefs (ISI 2004). Under-representation of research relative to reef area appears to arise though a combination of difficult access in remote areas such as the Central Indo-Pacific, Eastern Africa, Red Sea and the Gulf of Oman, Indian Ocean Islands, Micronesia, Western and Northern Australia, and South-west Pacific and extensive reef area in the Central Indo-Pacific. Relative research effort apparent in some regions may be biased downward if more research effort in these regions is reported in journals or monographs not indexed by WoS (discussed later). Acknowledging this potential bias, under-representation was associated with low GDP and therefore presumably less research capacity, as well as possible permitting issues in these areas. Protection of nature, at least in South East Asia where these analyses indicate the most severe under-representation, has remained a predominantly foreign concern (Henley & Osseweijer 2005). It is not possible to know, using the present methods, where the researchers producing this knowledge are based, but a predominance of foreign researchers in such areas may indicate an even greater imbalance of domestic capacity to deal with conservation issues.

Irrespective of the causes and potential biases, geographic patterns in research effort on coral reefs has been highly non-representative with respect to reef area, but has effort been proportional to, or otherwise biased against, areas that support the greatest biodiversity and/or face the greatest threats? We detected a negative relationship between research effort and coral species richness, largely driven by the most diverse coral region of the globe being in the central Indo-Pacific (Veron *et al.* 2009a), the region most under-represented by research. This pattern is likely consistent for other taxonomic groups as well (Roberts *et al.* 2002). Furthermore, because discovered species richness is likely to increase with research effort, especially in regions with large amounts of reef area, the slope of the negative relationship between species richness and research effort reported here may be underestimated. Therefore, overall the distribution of research effort appears to be driven primarily by proximity to top ranking coral reef ecology research institutions and wealthy nations, while being unrelated to species richness.

The lack of any relationship between regional research effort and the risks faced by coral reefs indicates that better targeting of research effort toward high-risk regions, especially those with high species richness, is required. Prioritization of such effort, however, may need to be adjusted through time. For example, although some areas (e.g., Australia) currently appear to be at lower risk of human induced impacts, climate projections suggest there may be substantial impacts in the future (Hoegh-Guldberg *et al.* 2007). In the meantime, spatially disparate patterns in the threats to reefs suggest it may be necessary to tailor research effort toward filling knowledge gaps relevant to specific threats faced by reefs in any given region of the world. Moreover, research in one region may not

Table 1 Coral reef area corrected research effort as a function of national per capita GDP, species richness (N.coral), aggregated threat status (Agg.Threat) and four threats: changes in sea surface temperature (SST), artisanal fishing (Art.Fish.), direct human impact estimated by population density (Dir.Human) and nutrient inputs (Nut.). Linear models were constructed with area-corrected number of research papers as the dependent variable. Competing models were compared using the variance explained by the model (as measured by adjusted R^2), Akaike Information Criterion (AIC_c) and Akaike weights (wi). Shown are standardized regression coefficients for the predictors entered in each model. Model averaged standardized regression coefficients (Johnson & Omland 2004) were also computed based on Akaike weights (bold).

	Predictor variables							Interaction terms									
Model	GDP	N.coral	Agg.Threat	Art.Fish.	Nut.	Dir.Human	SST	N.coral : GDP	Agg.Threat : GDP	Art.Fish. : GDP	Nut. : GDP	Dir.Human : GDP	SST : GDP	Intercept	R^2	AIC_c	wi
1	0.36	−0.36						0.37						0.02	0.35	58.10	0.24
2	0.36	−0.42												0.00	0.24	58.60	0.19
3		−0.44												0.00	0.15	58.90	0.16
4	0.38													0.00	0.10	60.10	0.09
5							0.34							0.00	0.07	60.70	0.07
6	0.26		0.82						−0.80					0.11	0.20	62.00	0.03
7	0.29						0.23							0.00	0.09	62.30	0.03
8			0.21											0.00	−0.01	62.30	0.03
9	0.36		0.16											0.00	0.07	62.80	0.02
10	0.40				0.16									0.00	0.07	62.80	0.02
11					0.11									0.00	−0.04	63.00	0.02
12	0.38			0.09										0.00	0.05	63.10	0.02
13				0.09										0.00	−0.05	63.10	0.02
14						−0.03								0.00	−0.05	63.20	0.02
15	0.38					−0.02								0.00	0.04	63.30	0.02
16	0.32						0.14						−0.34	0.13	0.14	63.60	0.02
17	0.40				0.21						−0.16			−0.02	0.03	65.90	0.01
18	0.38			−0.12						0.25				0.00	0.01	66.40	0.00
19	0.37					−0.11						0.20		0.01	0.02	66.20	0.00
Average	0.25	−0.24	0.04	0.00	0.01	0.00	0.03	0.09	−0.03	0.00	0.00	0.00	−0.01	0.01			

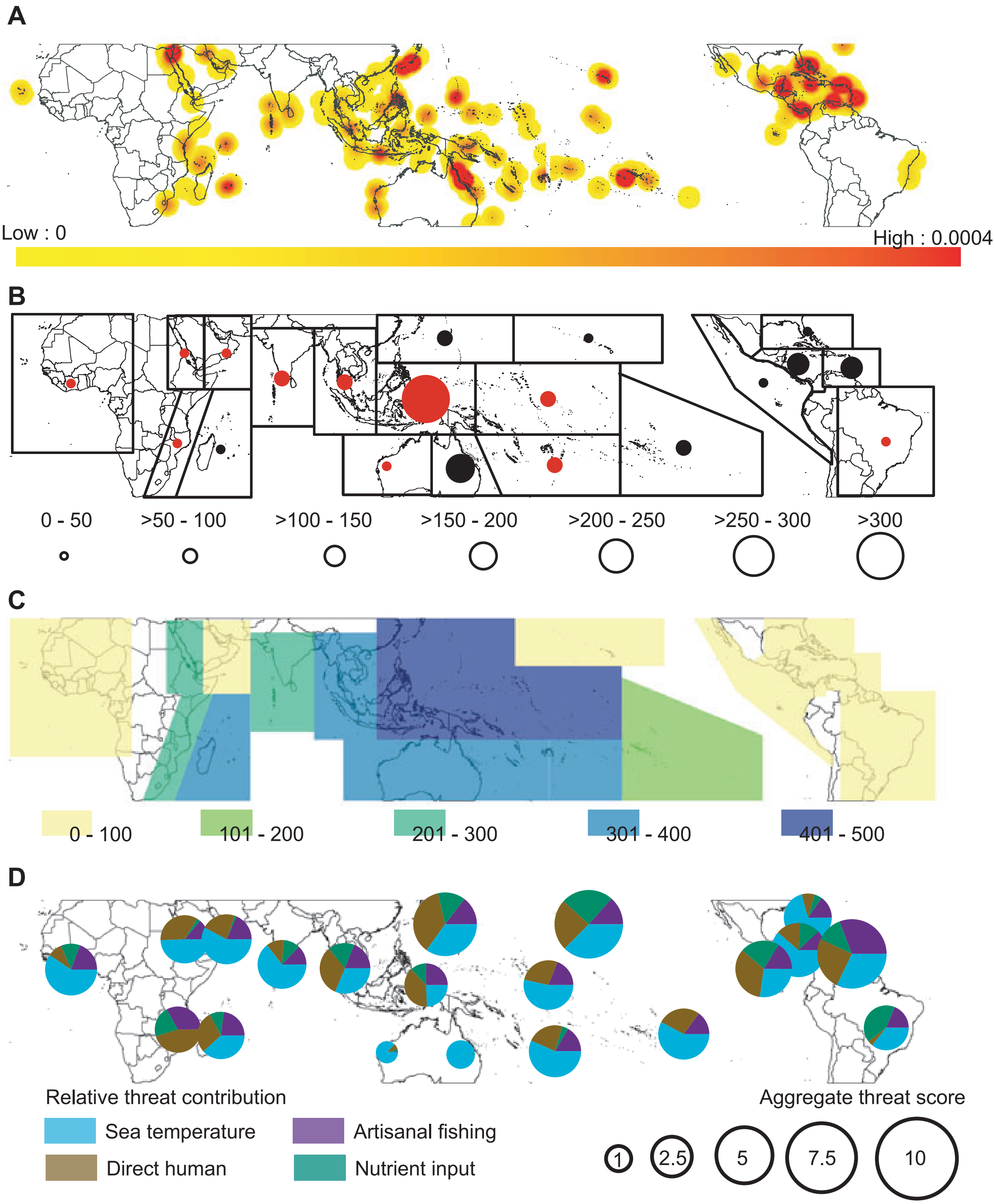

Figure 1 Coral reefs: global distributions of research effort, species richness and threats. We prepared a kernel density map of research papers showing the $\log_{10}(x + 1)$ mean density of papers within a 500 km neighborhood (A). We then corrected the number of papers for the area of coral reef contained within regions (magnitude of deviation from expected is indicated by size of circle, colored red for lower than expected and black for higher than expected). The 20 regions (starting from the Westernmost margin coordinate) are Western Africa, Eastern Africa, Red Sea and Gulf of Aden Region, South West Indian Ocean, Persian Gulf, Gulf of Oman and Arabian Sea, South Central Asia, South East Asia, Western Australia, North West Pacific (upper), Central Indo-Pacific (lower), Eastern Australia, Central Pacific, Southern Pacific, Hawaii and North Pacific, South East Pacific, East Pacific, Meso American Region, US Caribbean and Gulf of Mexico, Lesser Antilles and Southern Tropical America (B). We show the regional polygons color coded according to their weighted mean coral species richness (Veron *et al.* 2009a) (C). Finally, we mapped the aggregated threat status (indicated by pie chart size), and the relative contribution of the four different threat factors (Halpern *et al.* 2008) (D).

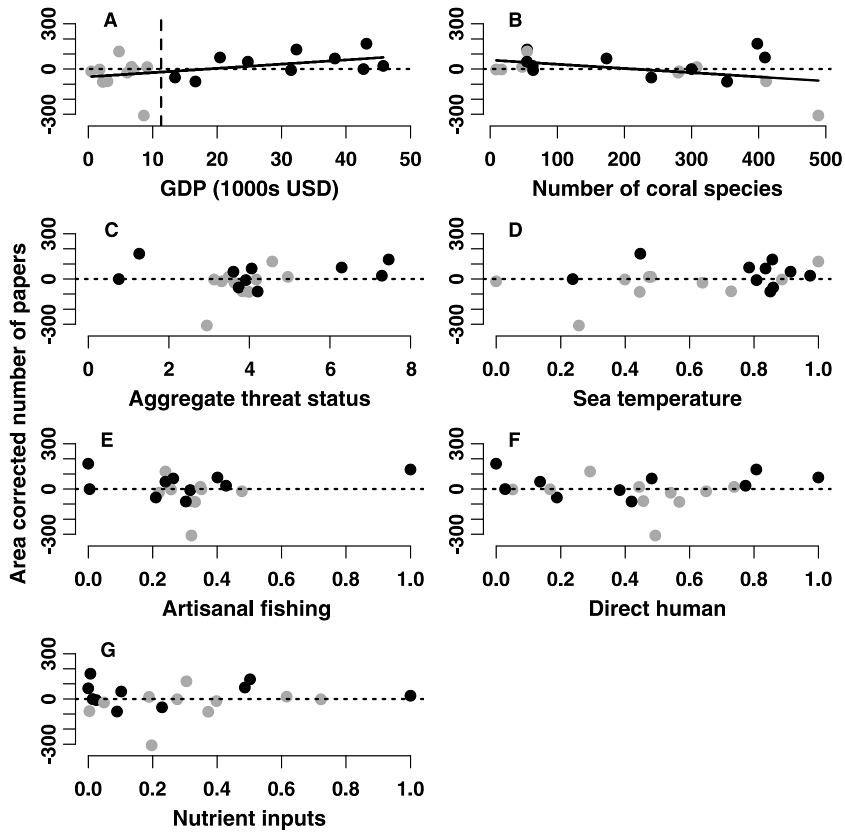

Figure 2. Coral reef research effort, by region, as a function of per capita GDP, species richness of zooxanthellate corals and threats. For each of the 20 regions, we compared the area corrected number of papers (deviations from the expected) with per capita GDP (vertical dashed line indicates median GDP) (A), weighted mean coral species richness (Veron *et al.* 2009a) (B), and aggregated threat status (Halpern *et al.* 2008) (C). Normalized values of threat factors (Halpern *et al.* 2008) are in D-G. Black circles indicate regions with a high (>median) GDP and gray circles indicate those with a low (<median) GDP.

be applicable to others, even when species richness and other metrics of community composition are similar, because the constituent species and drivers of change are likely to be region specific. We have also not considered here any potentially synergistic effects of chronic human impacts (e.g., overfishing) and natural disturbances (e.g., hurricanes), which have damaged coral reefs in some regions (Hughes *et al.* 2007). If such synergistic effects are widespread, the imperative to shift research to where impacts are most likely becomes even stronger.

Given that global resources for management-related coral reef research are limited, how best then to distribute these resources to maximize conservation outcomes? At a local scale, a small number of well-studied-reefs may be the most effective approach, especially if such sites are representative of others nearby. Such an approach will not, however, address the global mismatch identified here between information and conservation needs. Instead, research effort will need to be shifted if conservation needs are to be properly addressed at a regional scale. Regardless of whether conservation need is defined in terms of overall biodiversity or level or type of threat, more research effort should be targeted toward some of the more poorly studied geographic regions, particularly the central Indo-Pacific, an area which hosts the greatest coral biodiversity, is at risk, and is comparatively poorly known. More recently there have been some attempts to increase effort in this region, with ongoing initiatives including the Partnerships for International Research and Education (PIRE) of the National Science Foundation (NSF) (2010), in the United States; the *Coral Triangle Declaration on Coral Reefs, Fisheries and Food Security 2009*, through the Coral Triangle Initiative, with its Regional and National Plans, including marine protected areas (MPAs) as well as capacity building. A future initiative might consider providing resources for capacity building in informatics, including cataloguing of in-country museum collections and literature, and assistance with publication of gray literature, to allow globally distributed electronic resources to better reflect the total research effort, and to make such knowledge available to a broader audience.

Here we have assumed that the geographic distribution of coral reef research contained in WoS reflects our current knowledge of coral reefs. However, not all coral reef research will be captured by WoS. Research may be reported in gray literature, on websites, in languages other than English, in smaller journals and in technical reports, or other publications not indexed by WoS, or may use superseded place names. For example, Wilkinson (2008) tabulated the extent of data collection and an assessment of the reliability of methods used for coral reef monitoring, another proxy for research effort. Assignment to his highest category for monitoring quality usually involved monitoring by trained scientists and is the only one of his three categories that is likely to result in publication of peer-reviewed scientific papers, often with involvement of scientists from developed nations.

We also make the assumption that more research effort should result in better conservation outcomes. Beyond a certain point, this assumption may not be valid, particularly in the presence of any diminishing return on investment (e.g., terrestrial plants Grantham *et al.* 2008). We agree with the case made for conservation in pelagic ecosystems; that management action should be adaptive and begin as soon as possible based on the best information currently available (Game *et al.* 2009). Our advocacy for the identification of knowledge gaps and the priority allocation of resources to fill them will support this adaptive capacity.

While the semi-automated approach to text analysis developed here and used in our analyses can save substantial effort, it is not without limitations and potential pitfalls. By enumerating some of these here, we hope to support the future application of these methods to other research questions. WoS provides a KeyWords Plus® field that is merged with author keywords when exported into some bibliographic databases. This was unsuitable for mining location data because it removes geographical keywords where they appear in the title and adds those contained in the references (Garfield 1990). While this may not matter for some applications, for field-based research it is desirable to know the actual research locations. As new methods of citation analysis are under discussion (Butler 2008), inclusion of a standardized geographic keyword field should be considered for all publications of field-based research. A model for such an approach might be the United Nations Atlas of the Oceans (2010) which provides two keyword fields for each publication: one for subject and discipline based keywords and an additional field for geographic keywords at different scales. Adopting such a scheme could considerably enhance the ease and accuracy of geocoding the scientific literature.

A second challenge for the geocoding approach used here was the large number of successful matches that were unrelated to a location where coral reef research occurred, making it impossible to fully automate the geocoding process and necessitating cleaning of the geocoded output. Some of the more automated spatial methods of cleaning used here (e.g., removing points not within 100 km of a reef, or removing those on land not within 50km of the coast) may also incidentally exclude some useful terms (see Methods and Supplementary Methods for more details). Our manual check found that 13% of papers that could have been geocoded were missed, with the area most affected being the U.S. Caribbean and Gulf of Mexico. It is likely therefore that relative research effort in this region is even higher than we have estimated. The number of missed papers could be substantially reduced if more manual effort was allocated to assessing the validity of geographic terms. Although doing so may be useful in future studies, the patterns reported here would only have been reinforced. While it seems that Google Maps™ geocoding has considerable potential for further application in this area, the utility of the method will depend on a tradeoff between the level of accuracy required and the time available for manual screening of the original papers or the resultant geocoded terms.

Here, we have concentrated on knowledge and conservation needs specific to coral reefs. However, global patterns of human impact appear similar across a range of marine ecosystems (Halpern *et al.* 2008). Therefore, it seems likely that research effort in other marine and possibly terrestrial ecosystems would be similarly underrepresented in the Central Indo-Pacific. Indeed, this region also contains the greatest richness of a range of coastal and oceanic marine taxa beyond coral reefs (Tittensor *et al.* 2010) and threatened bird species (Orme *et al.* 2005). The destruction, in a single generation, of both the forests and marine resources in Indonesia (Fox 2005) highlights the broad range of ecosystems at risk in this region and the potential generality of the conservation issues we highlight here for tropical reefs. Overall, our results point to a serious mismatch between conservation needs and the knowledge required for the effective management of the world's coral reefs, and supports the case for re-focusing scientific effort to fill knowledge gaps to ensure better conservation and management outcomes.

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Supporting information

Additional Supporting Information may be found in the online version of this article, including Supplementary Methods and References.

Supplementary Methods
Figure S1 Research effort as a function of coral reef area and national per capita GDP.
Table S1 Google Maps™ accuracy code definitions.
Supplementary References

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