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Mapping the global value and distribution of coral reef tourism

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ABSTRACT

Global coral reef related tourism is one of the most significant examples of nature-based tourism from a single ecosystem. Coral reefs attract foreign and domestic visitors and generate revenues, including foreign exchange earnings, in over 100 countries and territories. Understanding the full value of coral reefs to tourism, and the spatial distribution of these values, provides an important incentive for sustainable reef management. In the current work, global data from multiple sources, including social media and crowd-sourced datasets, were used to estimate and map two distinct components of reef value. The first component is local "reef-adjacent" value, an overarching term used to capture a range of indirect benefits from coral reefs, including provision of sandy beaches, sheltered water, food, and attractive views. The second component is "on-reef" value, directly associated with in-water activities such diving and snorkelling. Tourism values were estimated as a proportion of the total visits and spending by coastal tourists within 30 km of reefs (excluding urban areas). Reef-adjacent values were set as a fixed proportion of 10% of this expenditure. On-reef values were based on the relative abundance of dive-shops and underwater photos in different countries and territories. Maps of value assigned to specific coral reef locations show considerable spatial variability across distances of just a few kilometres. Some 30% of the world's reefs are of value in the tourism sector, with a total value estimated at nearly US$36 billion, or over 9% of all coastal tourism value in the world's coral reef countries.

1. Introduction

Coral reef related tourism is an important and still fast-growing industry, providing employment and income to over 100 jurisdictions world-wide, and often generating much-needed foreign earnings [1–6]. Coastal tourism in the vicinity of coral reefs is not always benign: negative impacts can include degradation and loss of marine life through activities such as diving and snorkelling [7–9], as well as indirect impacts arising from poorly planned coastal development, including dredging, building on intertidal spaces, and increases in pollution and solid waste [10–12]. Despite these risks, tourism may be a less significant threat than fishing, land-based run-off or coral bleaching [13], and may even help to reduce some threats, notably over-fishing, by offering financial or social incentives for sustainable management [14–17]. Many visitors to coral reefs already have heightened environmental awareness [18] and reef visitation can both help to fund [19] and to encourage [20] coral reef conservation.

Much of the focus on the value and impacts of coral reef tourism has focused on the direct use of coral reefs for in-water activities. The indirect value of coral reefs in driving coastal tourism remains less well quantified, but is also important. Studies have shown the considerable importance of clear water and beach characteristics such as fine sand in influencing tourist preferences [21–23]. There is also a sizeable literature on the multiple ecosystem functions provided by coral reefs which may support tourism benefits, including the generation of fine sand beaches [24], the maintenance and building of islands [25,26], protection from wave erosion and storm damage [27], and the production of seafood [28]. Coral reef imagery also plays an important

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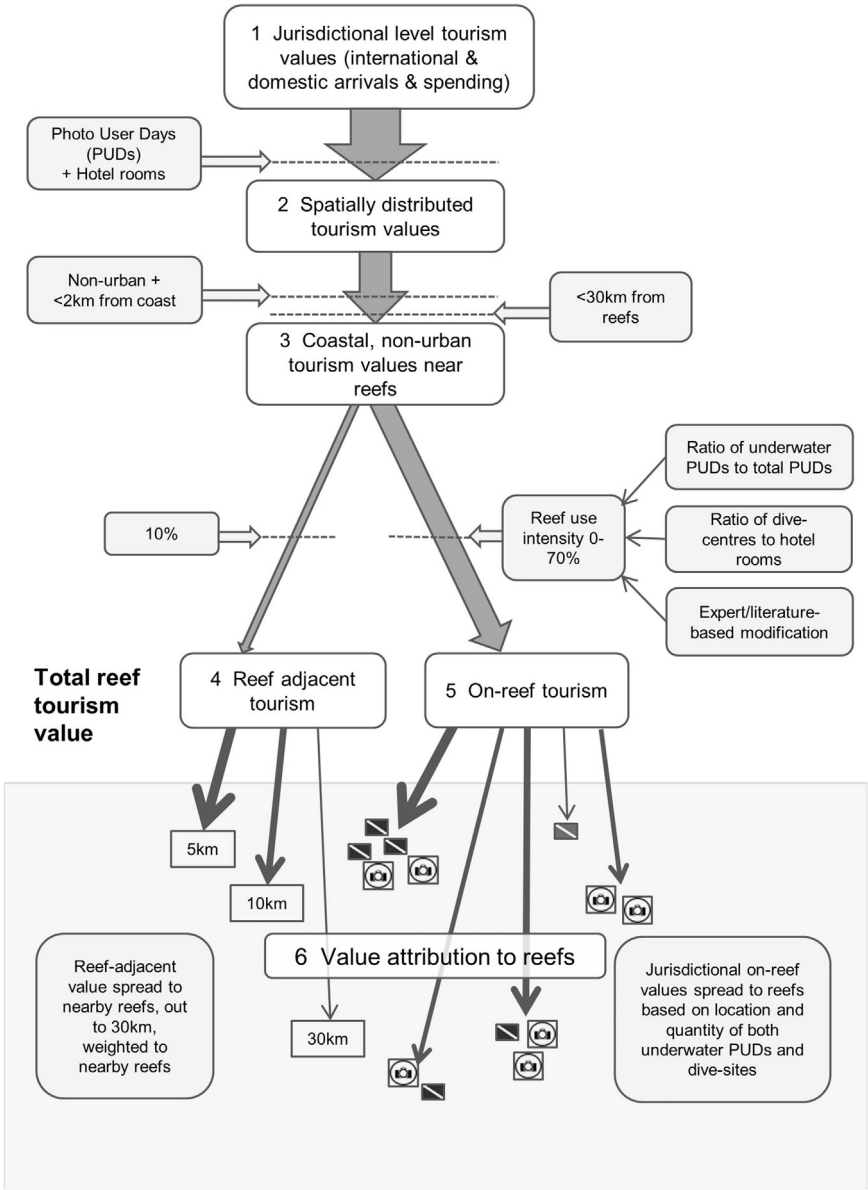

Fig. 1. A schematic representation of the methods employed to filter and spatially distribute components of national tourism statistics to coral reefs. Numbered stages are set out in detailed text description. Photo User Days (PUDs) give a measure of the intensity of photography in specified locations, they are more fully explained below.

role in marketing [29], while the perception of reef proximity, even for non-reef users, may be an important draw [23,30]. Finally, the health benefits associated with proximity to nature and to marine environments more generally are now increasingly realised [31,32], and are also likely to be played out in coral reef settings.

Given the broad array of economic and social benefits that coral reefs provide, there are growing attempts to build more sustainable approaches to reef-related tourism [33–37]. In large part, however, such efforts remain the target of individual operators, a few small island nations or some operators in the diving sector. The wider call for corporate social responsibility (CSR) has been slow to influence the tourism sector in general, with biodiversity conservation remaining low on the agenda even among those corporations who are engaging in CSR more broadly [38]. Against this background, a clear, quantified and reliable understanding of the value of coral reefs for tourism in specific settings could help, by raising awareness and highlighting opportunities for strengthening coral reef conservation, both in the public sphere and in the tourism sector.

Previous efforts to quantify the value and to describe the spatial distribution of reef-related tourism at large scales have been limited. Without mapping, de Groot et al. [39] generated a mean value for coral reef recreation of US$96,302 ha^{-1} yr^{-1}. This figure was derived from 29 studies, with a median value of US$1562 ha^{-1} yr^{-1}, but ranging from zero to almost US$1.5 million ha^{-1} yr^{-1}. The large mean value from this study was used in preference to the median value in a direct benefit transfer approach to all coral reefs, generating a global estimate of value of US$2.7 trillion per year, or 2.2% of all global ecosystem service values [derived from supplementary materials in 40], a figure that seems impossibly high given the spatially restricted nature of coral reef tourism. Elsewhere, Brander *et al.* [1] had already drawn attention to the challenges of such extrapolation: with data from 100 separate reef recreation studies, they conducted out-of-sample value transfer tests and estimated average transfer errors of 186%, a figure they deemed "unlikely to be acceptable in most policy-making scenarios" (pg 215).

Given the challenges of developing value transfer approaches, alongside the acknowledged benefits of developing an understanding not only of global values but of the spatial distribution of such value, this work presents a novel approach to accurately quantify global reef values and to distribute these values to specific reefs at local scales. The

work draws on a variety of data-sources including national-level visitor and expenditure statistics, together with locally accurate data from industry, social media and crowd-sourced datasets to support the spatial modelling of value distribution.

2. Framework and methods

In this work, coral reef related tourism is defined as the combined tourism and recreation activities that can be attributed to the presence of coral reefs. The value of such tourism is explored here using metrics of monetary value and tourist trip equivalents (a term used to account for the fact that many of the statistics are built up from fractions of total arrivals, acknowledging that reefs are only part of most destination choices). Two components of coral reef tourism are distinguished: on-reef or in situ values are derived from direct non-extractive reef uses including diving, snorkelling and glass-bottom boat tours [41]; reef-adjacent or *ex situ* values are not derived from in-water activities, but are indirectly linked to the presence of nearby reefs. The latter may include the role of reefs in generating clear calm waters and beach sand, outstanding views, fresh seafood and even their widespread use in advertising, all of which help to draw people to coral reef regions. Recreational fishing may represent an important additional value which we were unable to incorporate into our model, in large part due to the highly variable nature of reef dependency: much recreational fishing in coral reef countries targets non-reef fish in offshore waters.

Tourism was examined in the over 100 jurisdictions (countries and territories) around the world which have coral reefs. Statistics on travel and tourism to each jurisdiction were used as initial inputs. “Big data” from commercial, crowd-sourced, and social-media platforms were then used to make predictions of tourism expenditure and visitation to non-urban areas that could reasonably be linked to coral reefs. Paired, independent datasets were used to strengthen the robustness of the model, and the outputs were cross-referenced to existing studies. Finally, these tourism values were linked back and assigned to the reefs that were considered to be generating these values. Fig. 1 gives a schematic of this work, while details of the datasets and the methodological process are described below.

1. **Jurisdictional-level tourism.** Expenditure statistics were largely taken from the World Travel and Tourism Council [42] and represent spending for tourist and business trips, including travel and accommodation. Jurisdictions were largely countries and territories, although, due to the strong geographical differences, the US states of Hawaii and Florida were considered as distinct jurisdictions. Arrivals, largely derived from the UN World Travel Organisation (UNTWO) [43], include recorded overnight stays by international, cruise ship, and domestic visitors; they do not incorporate length of stay. The decision to include all travel in this initial step was driven by a desire to ensure a more complete and consistent dataset. Non-relevant travel was filtered out as outlined in the subsequent steps (below). Gaps in these data were filled from other international or national, sources (see Appendix A). Where possible, data were gathered for all years from 2008 to 2012. Local currency data were converted to historic US dollar values for 30 June of the relevant year. These values were then converted to 2013 values using the Consumer Price Index (CPI) price deflator (data.worldbank.org).
2. **Distribution of national tourism.** In order to develop an estimate of the geographic distribution of national tourism and expenditures, two independent data sources were used: the distribution of hotel rooms, and the distribution and frequency of geo-located photographs from the popular image-sharing website Flickr. Hotel rooms give an approximate measure of overnight visitor intensity. The Global Accommodation Reference Database (GARD), a commercial database, was generously made available (http://www.delta-check.de) for the coral reef nations of the world. This provided location and size (number of rooms) data for 125,498 hotels in coral reef jurisdictions. Publicly sourced photographs from Flickr include large quantities of geo-located photographs world-wide – an estimated 40–50 million have been uploaded to www.flickr.com annually since 2010. The geographic distribution of photos gives an indication of human activity and particularly leisure-based activities, and the spread and density of such photos have already been developed as a metric to quantify tourist activity [44]. Following the same approach as that work, a consistent spatial metric of the intensity of photography was utilised. Known as photo-user-days (PUD), these represent the total number of days, across all users, that at least one photograph was taken in a given area [44]. Average annual PUD per ~1 km gridded cell was computed for all coral reef nations and territories, including offshore waters, for the years 2005–2012.
   Wood et al. [44] and subsequent authors [45,46] have recognised possibilities of biases in the spatial distribution of Flickr images, based on who is uploading photographs and the numbers of photographs being taken of different recreational activities. With the hotels layer the present authors were not aware of any biases, however reporting may be better for some locations than others. Both layers were independently derived, but on comparison they tracked one another relatively well ($N = 103$ coastal states with hotels and PUDs, Pearson's $r = 0.899$, $p < 0.001$). Using each layer, a weighted distribution map was generated, showing the national tourism values assigned to locations based on the numbers of PUDs and, independently at this step, hotel rooms for each country or territory.
3. **Coastal non-urban tourism near reefs.** It was then necessary to filter out the tourism values that were unlikely to be reef-related from the national totals. Using weighted distribution maps described above, values were removed from three broad geographic extents: a) Non-coastal areas, defined as any areas beyond 2 km landwards and seawards of the coastline, b) Urban areas, defined as towns and cities of greater than 10,000 people [47], and c) Non-reef areas, defined as areas over 30 km from reefs that are unlikely to be benefitting in any substantial way from the presence of reefs [48]. The influence of business travel, deliberately included in the initial input statistics (1, above), is likely to be considerably reduced in this stage, as a large proportion will be urban and non-coastal. For the remainder, it was considered likely that business travel to coastal resorts near coral reefs will in part be driven by the attraction that reefs provide, and therefore that it was important to include such travel.
   The resulting two maps of coastal non-urban PUD and hotel-rooms were then aggregated into a single statistic for coastal non-urban tourism within 30 km of a coral reef (hereafter termed reef-coast tourism) for each country. While the correspondence between PUDs and hotel rooms was reassuring, it was felt that both layers, in different places, showed varying levels of completeness, and further that by combining both sources of information any unseen biases, or more local effects, could be reduced. To achieve this, the two layers were combined with a weighting of 2:1 towards the use of PUDs, which gave a more detailed spatial portrayal of visitor use than hotel rooms. This layer showed that 44% of coastal tourism in coral reef jurisdictions occurs within 30 km of reefs. If the distance was reduced to 10 km, that figure only dropped to 36%, suggesting that most tourism is in fact much closer to coral reefs than 30 km. Clearly not all tourism in this zone is attributable to coral reefs (see following steps), but this initial step provided a clear starting point for understanding the proportion of coastal tourism potentially attributable to coral reefs.
4. **Reef-adjacent values.** Many tourists do not take part in on-reef activities such as diving, snorkelling and boat-trips, but coral reefs may still play a critical role in attracting them to particular locations. While such reef-adjacent benefits are widely agreed to be key drivers of tourism in many locations, the authors were

unaware of any existing models which would enable the prediction of such values across multiple jurisdictions. Many existing reef valuation studies look only at on-reef values (reef visitation, diver numbers, etc.), while others provide total values for "reef regions", with the implicit assumption that all tourism can somehow be related to the presence of the reef. Given that the on-reef values were disaggregated separately (below), the approach taken here for these reef-adjacent values was to assign a simple estimate of 10% of the value of all reef-coast tourism to coral reefs. This is likely to be conservative: some other studies have assigned higher values, but these could also be more easily disputed. For example, Sarkis et al. [4] suggest that visiting the beach was a prime motivation for some 16% of visitors in Bermuda, while arguing that the beaches themselves are formed by the reefs and thus entirely coral reef dependent.

5. **On-reef tourism values.** Some of the highest tourism values from individual reefs are linked to direct, in-water uses, notably scuba diving, snorkelling and boat tours. The magnitude of on-reef tourism is influenced by a suite of natural, social and economic factors including biodiversity and reef health, ease of access to reefs, available infrastructure, history, and culture. Existing efforts to quantify on-reef tourism cover few jurisdictions and there is little consistency in methods. A novel approach was therefore devised to quantify the relative importance of on-reef tourism as a proportion of total reef-coast tourism, with help from existing studies to help calibrate these efforts (see Appendix A). This approach used two proxy measures: abundance of dive shops relative to hotel rooms and abundance of underwater photographs relative to all photographs shared on Flickr. For the first metric, data on the locations of more than 4000 dive shops world-wide were obtained from a crowd-sourced database, generously provided by www.diveboard.com. These were used to generate statistics on the number of dive shops per 1000 hotel rooms within the reef-coast region of each country. For the second metric, the collection of geo-located photographs shared on Flickr (see Method 2 above) were used to obtain a subset of images that were tagged with a keyword related to underwater recreation. Multiple search terms in eight languages were used to maximise the reach of this subset (see Appendix A). In total, the search identified over 14,500 PUDs according to the underwater images within 30 km of a coral reef. The ratio of underwater PUDs to total PUDs were then generated in the reef-coast regions of each country.
   These two ratios gave independent estimates of national on-reef use intensity. Ignoring values where either dataset held zero data there was a significant positive correlation between the rank-orders of jurisdictions developed from each dataset ($n = 89$ jurisdictions with both datasets, Pearson's $r = 0.632$, $p < 0.001$).
   While the authors felt the overall approach was strong, they were also aware of gaps or weaknesses in some of these datasets. For example, there were four jurisdictions where the (limited) dive tourism was not represented by any dive shops. Given these concerns it was felt appropriate to use both datasets, alongside some further expert intervention. Both datasets were scaled between 1 and 100 to produce relative measures. These numbers were then compared against each other and against several external sources (see Appendix A). Overall, underwater PUDS were the more spatially detailed and sensitive of the two datasets, and were also likely to represent the full range of in-water activities, including snorkelling and glass-bottom boat tourism alongside diving. Thus, a single on-reef use intensity statistic was generated, weighted 2:1 in favour of underwater PUDs over the dive shop metric. Where the two on-reef tourism metrics were well correlated, and where there was no evidence for errors (86 of the 102 jurisdictions with tourism) this single weighted number was used, capped at 70%, as the preferred metric for the proportion of remaining reef-coast tourism which could be assigned to on-reef value.
   For the remaining 16 territories known to have reef tourism, but with limited data or showing disagreement among the underwater PUD and dive-shop metrics, an equivalent number was generated through the following process (see Appendix A for further details). Where data were missing or very limited from either one of the two metrics (i.e. there were few or no underwater PUDs or dive shops), a new score was developed that was weighted towards the other metric, or used that metric alone (three territories). Where data were considered poor and were clearly divergent from a recent and comparable literature source, the numbers were replaced with that alternative (four territories). Where there was evidence, based on expert-knowledge and/or available references, that both metrics were under- or over-reporting, scores were altered to the best approximation of the authors (nine territories).
   Finally, the remaining 90% of reef-coast tourism (excluding the 10% assigned to reef-adjacent values) for each jurisdiction was multiplied by the estimate for on-reef tourism estimates described above (ranging from 0% to 70%) to give an estimate of on-reef value for each jurisdiction.
6. **Value attribution to reefs.** The final stage of this work was to separately assign the reef-adjacent and the on-reef values to the reefs that are likely to be generating those values. To ascribe reef-adjacent tourism expenditures, the national dollar and tourist trip equivalent values were distributed separately following PUD densities and hotel rooms within 30 km of a coral reef. The two layers were then combined with a 2:1 weighting as above, and the values from this combined layer were then attributed to nearby reefs (up to 30 km distant), using a series of steps (see Appendix A) with a weighting to assign the greatest proportion of these values to the nearest reefs (within 5 km).

For on-reef values two layers were employed to assign reef use-intensity: underwater PUDs, as described above, and a global dataset of dive-sites provided from diveboard.com. The dive-sites dataset is a crowd-sourced dataset, and required some cleaning to remove duplicate sites (based on identical geographic locations). The final layer held 8938 sites for the coral reef jurisdictions used in this study.

Both dive sites and underwater PUDs were buffered to a circle of 5 km radius to allow for the possible alignment errors between these and the coral reef layer. Similar numbers of dive sites and underwater PUDs were found in coral reef regions and so the two were simply combined (unweighted) to develop a map of in situ use intensity, and this map was intersected with the global coral reef map, giving every 500 m reef cell a measure of use-intensity.

The national on-reef tourism values were then distributed based on this use-intensity map. This was irrespective of distance from hotels or proximity to cities as it was felt that the underwater PUDs and dive-sites were reliable metrics and were further enabling the model to account for the highly variable distances that are travelled in different jurisdictions, as well as to capture those reefs supporting multi-day "liveaboard" reef tourism.

Reef-adjacent and on-reef tourism values were summed to arrive at a final estimate and map of tourism value on coral reefs.

Summary statistics were generated from the various stages of this work, enabling us to give an indication of the value of coastal tourism, coastal tourism near reefs, and finally reef value, both combined and separately for the two components. The maps were also used to generate a better understanding of the patterns and to overlay national and territorial boundaries in order to derive politically relevant summary statistics.

3. Results

Of the 117 jurisdictions in this study, 102 registered at least some tourism value (the remainder including many uninhabited territories as well as jurisdictions with ongoing conflicts, see Appendix A). The global

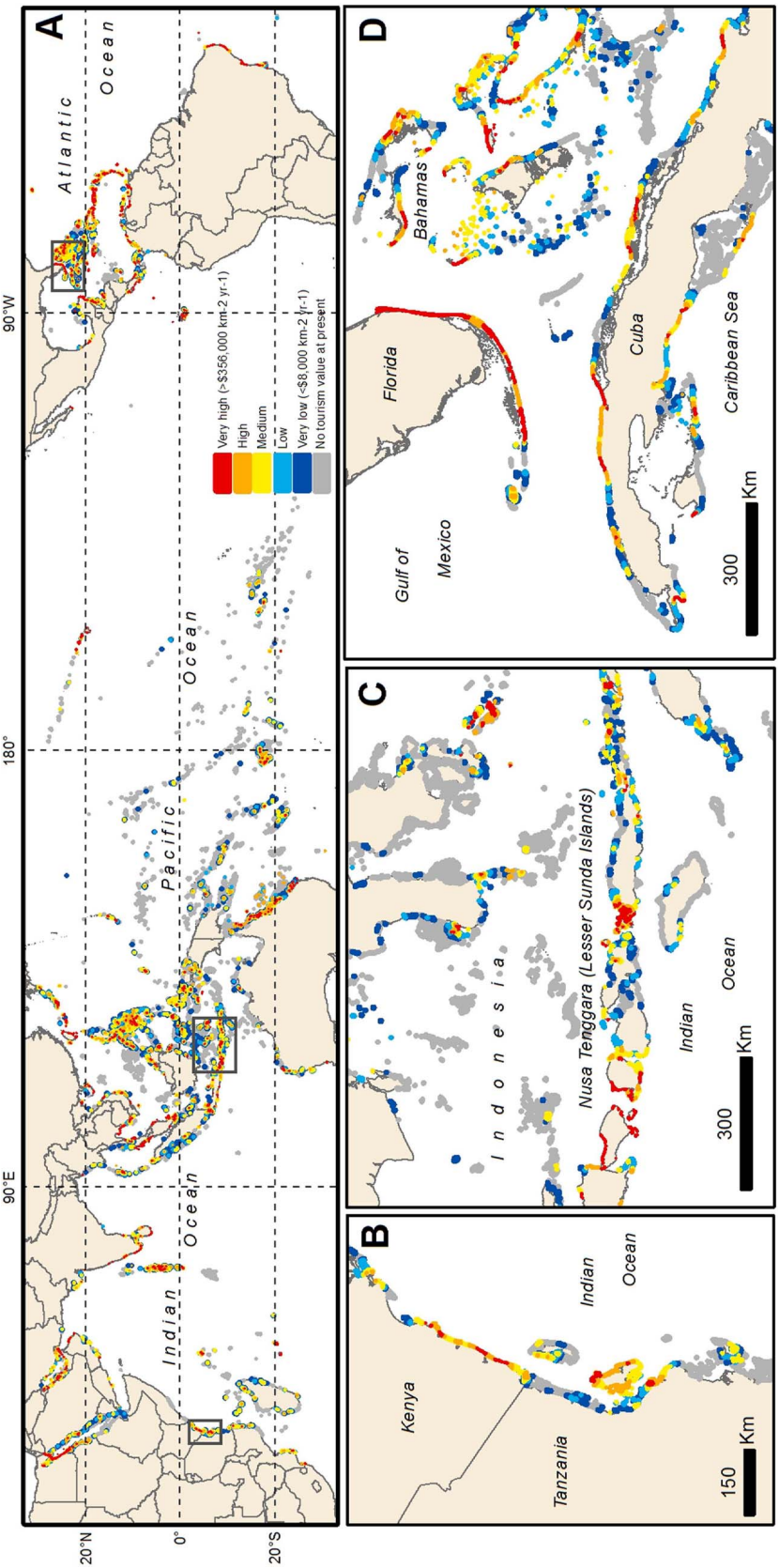

Fig. 2. Economic value of coral reefs for tourism (A). This figure summarises the combined dollar values of expenditures for on-reef and reef-adjacent tourism. Reefs without assigned tourism value are grey; all other reefs present values binned into quintiles. Lower panels show Kenya and Tanzania (B), South-central Indonesia (C), and Northern Caribbean, with part of Florida, Cuba and the Bahamas (D). (Further maps can be seen in Appendix A and online at maps.oceanwealth.org).

Table 1
Total values associated with the various steps of the methods chain.

	Spending (US$ million)	Proportion of total	Proportion of coastal	Tourist trip equivalents (thousands)	Proportion of total	Proportion of coastal
Total for all coral reef nations	2,371,967	100%		5,650,099	100%	
Coastal non-urban tourism	378,737	16.0%	100%	814,406	14.4%	100%
Coastal non-urban within 30 km of coral reefs	163,213	6.9%	43.1%	323,707	5.7%	39.7%
Reef-adjacent tourism	16,321	0.7%	4.3%	32,371	0.6%	4.0%
On-reef tourism	19,459	0.8%	5.1%	37,524	0.7%	4.6%
Total adjacent and on-reef value	35,780	1.5%	9.4%	69,895	1.2%	8.6%

spread of these values is presented in Fig. 2, while summary statistics are presented in Table 1.

Reef tourism is calculated to be worth some US$35.8 billion dollars globally every year, representing the total of within-country expenditure by international and domestic visitors that the authors believe can be assigned to the presence of coral reefs. This is about 1.51% of all visitor spending (a number which includes domestic and international visitor spending, including local travel and accommodation) in coral reef jurisdictions. Visitor numbers equate to some 70 million tourist trip equivalents, or 1.24% of all visitors to coral reef jurisdictions, where visits include only overnight and multiple night stays by international, cruise-ship, and domestic visitors (but do not account for the length of stay). These are likely to be conservative estimates, but it should also be noted that tourism is a very large industry in several of the countries in the study (such as USA, Brazil, China and Australia), with coral reefs being only a minor component. Across the world's coral reef jurisdictions some 40% of coastal, non-urban tourist arrivals and 43% of expenditures were made within 30 km of coral reefs. Well over 20% of these values are attributed directly to the presence of coral reefs (Table 1).

Global statistics hide the considerable variability in the value of coral reef tourism captured in this work, as shown in the global map (Fig. 2). In dollar terms 70.4% of reefs are recorded as having zero tourism value, with the remainder reaching values of millions of international dollars per square kilometre per year. This high variability, already noted by previous authors [1,39], is an important feature: the mean value of all cells with any tourism value is US $482,428 km^{-2} yr^{-1}, while the median value is only US $48,000 km^{-2} yr^{-1}. The top 1% of cells are recording values greater than US$7,248,000 km^{-2} yr^{-1} and their combined value makes up some 33% of the global total values. Such high value reefs are nonetheless broadly distributed – over 70% of jurisdictions with reef tourism have at least some of their reef estate generating values greater than $1,000,000 km^{-2} yr^{-1}. National summaries (Tables 2, 3 and Appendix A) capture a portion of this variety, however, even within nations there is large variation from reef to reef (Fig. 2).

While the models and data enable many different approaches for exploration (see also http://maps.oceanwealth.org), national level summaries provide valuable information at a policy-relevant scale. Tables 2, 3 give the findings for the 10 jurisdictions with the highest levels of tourism expenditure and tourist trip equivalents, presenting both the combined values and the separated values for reef-adjacent and on-reef contributions to these values. The dominant position of Egypt in these statistics was likely correct at the time of the input data, but this value has most likely since fallen sharply due to changes in tourism caused by geopolitics and regional instability. It is interesting to draw attention to the significant variance in the contribution of on-reef versus reef-adjacent tourism.

From the national-scale summary data provided in Appendix A it is possible to investigate the relative importance of coral reef tourism, both as a proportion of all tourism, or indeed as a proportion of GDP. Such numbers show the particular importance of reef tourism in small island jurisdictions. In each of the Maldives, Palau, Bonaire, the Turks and Caicos Islands, and the British Virgin Islands, coral reefs support over one third of all tourism value and 10% or more of the entire GDP.

Table 2
Estimated expenditures by tourists within the ten jurisdictions with the highest total values. Note that due to the strong geographical differences, the US states of Hawaii and Florida have been treated independently.

	Proportion of tourism which is coastal, non-urban	Reef-adjacent tourism value (Million US$ per year)	Proportion of reef-coast tourism assigned as on-reef	On-reef tourism value (Million US$ per year)	Total tourism value (Million US$ per year)
Egypt	44%	947.5	53%	4519.8	5467.3
Indonesia	29%	1106.2	20%	1991.2	3097.5
Mexico	27%	1657.4	9%	1342.5	2999.9
Thailand	34%	1331.6	9%	1078.6	2410.2
Australia	24%	473.1	40%	1703.0	2176.1
China	13%	1348.1	2%	88.1	1435.1
Philippines	30%	451.2	23%	934.0	1385.1
USA (Hawaii)	58%	680.1	9%	550.8	1230.9
Japan	10%	542.6	13%	634.9	1177.5
USA (Florida)	11%	850.6	4%	306.2	1156.8

Although a quantitative evaluation of accuracy has not been made, the spatial distribution and relative importance of tourism appears to match well with both expert opinion and other datasets. For example, Fig. 3 shows the current map alongside the map of day visits plotted by the Great Barrier Reef Marine Park Authority. Setting aside the higher resolution of the current map, the approximate locations of reef use correspond well with on-reef use data derived in the present work. Given the differences in units it not possible to directly compare numbers, but total visitor numbers also suggest a broad agreement: the current work estimates a total of 1.45 million trip equivalents for on-reef tourism the Great Barrier Reef. This number lies between the estimates, based on industry reporting, of 1.1 million “people visiting coral sites” [49] and the estimate of 1.8 million “visits” to the Great Barrier Reef Marine Park in 2013 [50]. Separately, our maps also show a close visual correlation with a variety of on-reef uses that were mapped at very high resolution using aerial surveys for the Ningaloo reef system in Australia [51], further increasing our confidence in the reliability of our method.

In comparing the geographic distribution of on-reef values with reef-adjacent values it is noteworthy that on-reef use is more spatially restricted, recording values from only about 15% of the world's coral reefs. Given that on-reef tourism counts for a little over half of the total estimated economic values this clearly represents a much higher value per unit area for many reefs (average US$512,650 km^{-2} yr^{-1}, median US$128,000 km^{-2} yr^{-1}). There are very few places where on-reef tourism occurs with no reef-adjacent values – these largely represent remote reefs being visited by liveaboard dive vessels such as the reefs of the Coral Sea and parts of Eastern Indonesia. Reef-adjacent tourism is more widespread, covering 26% of the world's reefs, with typically

Table 3
Estimates of visitation by tourists within the ten jurisdictions with the highest total values. Note that the numbers are "tourist trip equivalents" represent numbers of trips that could be directly assigned to the presence of reefs, allowing for proportional inclusion of arrival statistics where the reef was only a part of the reason for the visit. Total numbers visiting or otherwise benefiting from the coral reefs would be much higher.

	Proportion of visitors that are coastal, non-urban	Reef-adjacent tourism value (1000 visitor trip equivalents)	Proportion of reef-coast tourism assigned as on-reef	On-reef tourism value (1000 visitor trip equivalents)	Total tourism value (1000 visitor trip equivalents)
Indonesia	29%	6722.3	20%	12,100.1	18,822.4
Philippines	30%	3406.5	23%	7051.4	10,457.9
China	13%	8462.6	2%	1523.3	9985.9
Egypt	44%	818.7	53%	3905.4	4719.0
USA (Florida)	11%	2377.8	4%	856.0	3233.8
Mexico	27%	1544.7	9%	1251.2	2795.9
Malaysia	19%	780.7	20%	1405.2	2185.9
Australia	24%	408.2	40%	1469.4	1877.5
Japan	10%	840.5	13%	983.4	1823.9
Cayman Islands	99%	175.7	55%	869.8	1045.6

lower values (average US$250,612 $km^{-2}\,yr^{-1}$, median US $20,000 $km^{-2}\,yr^{-1}$). It is worth noting that some of the locations identified as solely important for reef-adjacent benefits may not be generating on-reef tourism, either because they are degraded, or because they are naturally occurring in turbulent or turbid waters and do not offer accessible, attractive features to divers and snorkelers. These might include many Persian Gulf reefs, and those off the mainland coasts of India and China. In most places, however, on-reef and reef-adjacent values are broadly co-located, with differences expressed in different levels of value and more subtle difference in spatial extent, as shown in Fig. 4.

4. Discussion and conclusions

The current work quantifies, for the first time, both the global value of coral reefs for tourism and recreation, and the spatial variability of

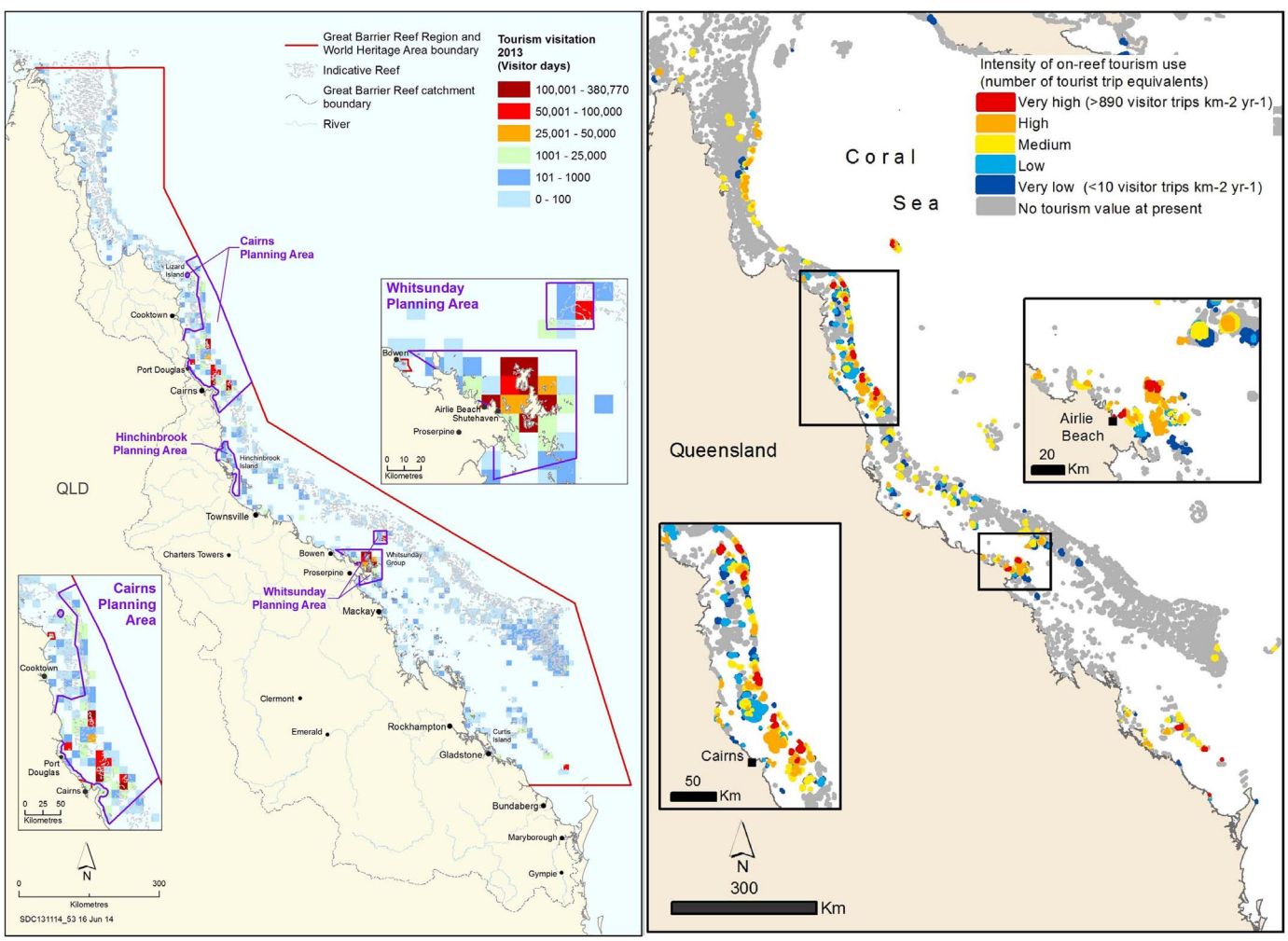

Fig. 3. Coral reef tourism in the Great Barrier Reef. Left: day visits to the Marine Park – the Great Barrier Reef Marine Park Authority estimates over 80% of tourism takes place in only 7% of the region [50, p112]. Right: on-reef tourism from the current work for the same areas. The maps, derived from independent sources, appear to be well correlated with both the location and the intensity of use.

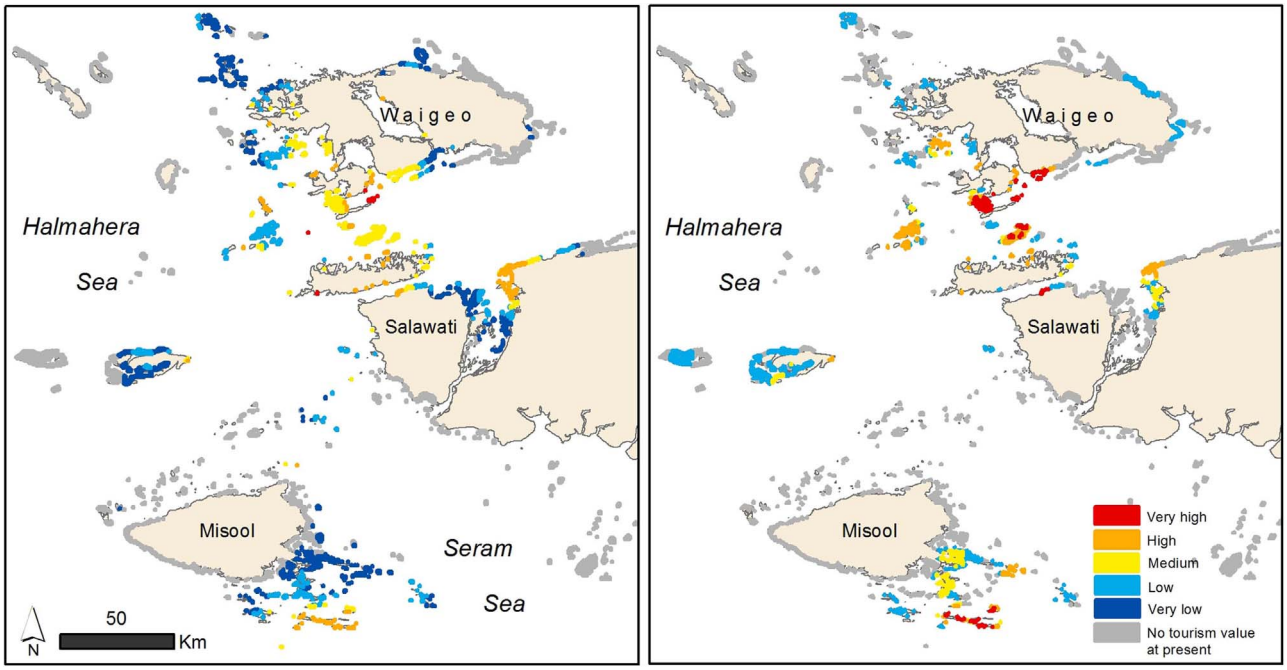

Fig. 4. Relative economic value of coral reefs for tourism in Raja Ampat, Indonesia, separated into reef-adjacent values (left) and on-reef values (right). The lack of local infrastructure and hotels probably explains the low values of the former, while the methods used here of linking value directly to dive-sites and underwater photographs ensures that the values of reefs that are distant from built tourist infrastructure are still recorded in the model for on-reef values.

this value. The estimated US$35.8 billion generated annually by coral reefs is probably conservative, but nonetheless an important sum. The spatial distribution of this value is highly variable: seventy percent of the world's coral reefs have no value in the current model, but even among the remainder the range is considerable, from just a few thousands of dollars up to several millions of dollars per square kilometre of reef per year. The summary values from this work (mean US$482,428 km^{-2} yr^{-1}, median US$48,000 km^{-2} yr^{-1}) are far lower than those of de Groot et al. [39] (US$9,630,200 km^{-2} yr^{-1} and US $156,200 km^{-2} yr^{-1}), a difference that likely reflects both the conservative nature of the current model and the likelihood that any numbers generated from a synthesis of field studies like de Groot would be biased towards higher value sites. The authors believe the current work to provide a more accurate estimate.

In terms of visitor numbers, the estimated global total presented here – some 70 million tourist trip equivalents – can be most appropriately equated to visits that would not have been made to these places without the presence of reefs. The actual numbers of persons visiting reefs, or receiving some indirect benefits from them, would be far higher.

While visitor numbers and dollar values are broadly aligned, they do not follow identical patterns (Tables 2, 3, and Appendix A). By using both dollar and visitor numbers it is possible to explore the relative importance of tourism in different locations. Such approaches can be further helped by contextualising the numbers – while reef dependent tourism makes up 60% of total tourism revenues in the Maldives and 43% of GDP, the values for Australia are only 2.4% of all tourism and less than 0.2% of GDP (See Appendix A). Within jurisdictions the maps identify areas where coral reef tourism is particularly valuable – such values need to be seen and utilised, particularly where there may be pressures on coral reefs, competing uses, risks or trade-offs associated with other activities.

Tourism is highly aggregated in space. Visitation is likely driven by transport and infrastructure and perhaps reinforced through the selection of sites by reputation and previous use, and these undoubtedly help to explain the concentration of tourism benefits to only 30% of reefs, and indeed the even narrower concentration of on-reef tourism to only 15% of reefs. Given this concentration, one perhaps more surprising observation is that the reefs generating more than US$1 million km^{-2} per year (less than 3% of all reefs) are widely distributed across 71 jurisdictions, and across all continents and oceans.

While the actual numbers and maps are important, the current work also highlights a new and important approach to the mapping of tourism value. The use of “big data” from multiple sources including traditionally generated maps alongside social media and crowd-sourced datasets, offers a remarkably rich new frontier in terms of mapping and understanding previously unmappable natural processes and human interactions. While publicly-generated geospatial information could be further tested, and refined, the wise use of such data already offers a means to generate real field “observations” by non-experts at scales sufficient to capture real-world activities or phenomena in a manner that is currently unthinkable with expert-observation alone.

These approaches could be modified and improved in several ways by future studies. The current work deliberately downscaled PUD data to a 1 km grid in order to achieve more manageable processing times. While the model could be re-run with these same layers at finer resolutions, it is equally important to point out that the same process could be undertaken at smaller scales and with other input layers, such as national and sub-national level information on visitor numbers and spending, hotels, dive centres and dive-sites. Also, in the present work, a number of assumptions were made using expert judgement, including the 2 km coastal boundary, the 30 km distance for reef-related tourism, and the 10% reef-adjacent value. The authors believe that this approach is conservative, but other users could update and repeat this work with improved, or indeed more spatially nuanced parameterisation.

The existence of vast areas of coral reefs with zero value for tourism needs to be viewed in a broader context. Such reefs are clearly not value-less. They have values, both monetary and non-monetary, for fisheries, coastal protection, genetic diversity, and more [52,53]. Coral reefs everywhere have myriad non-use or existence values associated with their biodiversity, cultural, spiritual and inspirational worth [54,55]. Indeed, such values may be highest on less heavily used reefs. In addition, the current maps do not consider option or future use values for reef tourism, although managers and governments may still be interested to use these findings to help to inform them on potential tourism values of reefs in other areas.

It is further important to note that coral reef tourism is rarely environmentally neutral. As mentioned in the introduction, it has been held responsible for the deterioration of many reefs, but such impacts are not inevitable. Well-managed tourism can be highly sustainable, and may represent a preferred option for safeguarding biodiversity in places where local communities need income and employment from their reefs and want to balance multiple competing objectives [35].

Nature-dependent and nature-based tourism and recreation are of considerable social, cultural and economic importance, far beyond the example of coral reefs. Other ecosystems attract visitors for activities such as birdwatching, boating, recreational fishing, whale-watching, and more. Other studies have begun to explore some of these activities at different scales [56–61]. Beyond these nature-based activities, there is still a paucity of research around the value of *ex-situ*, ecosystem-adjacent, benefits such as views, water quality enhancement, food supply and so forth. Work is also limited on the value-flows away from critical ecosystems: this work maps the source of benefits (the reefs), however understanding the geographic flow of such value is also critically important [62]. While many benefits may remain in local communities, coral reefs and other ecosystems also contribute to wider tourism and tax revenues within individual jurisdictions. Reef tourism, in particular, is highly international, and benefits extend to remote beneficiaries via international hotel chains, airlines, tour operators and even the manufacturers of products from dive equipment to souvenirs. Such flows of benefits away from the locations where the coral reefs occur can be a source of concern to the host nations. At the same time, raising awareness of such values to reef-remote communities, for example in the countries of northern Europe or the USA, could increase the imperative for supporting coral reef conservation even among nations that do not have coral reefs.

The broad distribution of very high value reefs shown in this study should be used to highlight the widespread and critical importance of these ecosystems to the tourism industry, and further should be used by the same industry to ensure their facilities and activities do not have any negative impact on reefs. In a growing array of cases, industry players are already making advances towards reducing impacts and contributing to reef conservation [17,63,64], but the same players, and others, should further use this improved understanding to demand policy and management interventions, including protected areas and environmental improvements such as controls over land-based sources of pollution, to ensure continued or improved reef health.

While the approaches presented here could be improved and adapted for use in different settings, they already represent a powerful resource with which to support such changes. Coral reef dependent tourism goes beyond the well-known suite of in-water activities, and the combined values of reef tourism are significant to industry players, local communities and governments. Armed with improved information, it is hoped that sustainable management of coral reefs will become a higher priority in processes ranging from the management of individual resorts to the representation of coral reef dependent tourism in the rapid growth of marine spatial planning.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.marpol.2017.05.014.

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