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A global inventory of coral reef stressors based on satellite observed nighttime lights

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In this article, we present a satellite-based approach to gather information about the threat to coral reefs worldwide. Three chosen reef stressors – development, gas flaring and heavily lit fishing boat activity – are analysed using nighttime lights data derived from the Defense Meteorological Satellite Program (DMSP) produced at the National Oceanic & Atmospheric Administration, National Geophysical Data Center (NOAA/NGDC). Nighttime lights represent a direct threat to coral reef ecosystems and are an excellent proxy measure for associated human-caused stressors. A lights proximity index (LPI) is calculated, measuring the distance of coral reef sites to each of the stressors and incorporating the stressor's intensity. Colourized maps visualize the results on a global scale. Area rankings clarify the effects of artificial night lighting on coral reefs on a regional scale. The results should be very useful for reef managers and for state administrations to implement coral reef conservation projects and for the scientific world to conduct further research.

Keywords: coral reef stressors; artificial night lighting; DMSP; lights proximity index

1. Introduction

Coral reefs are of great importance for a number of reasons: they are areas with remarkable biodiversity; they are important for coastal protection; they provide people with seafood and new medicines; and they have a great recreational value. Corals and coral reefs are extremely sensitive; slight changes in the reef environment may have detrimental effects on the health of entire coral colonies. A variety of natural and anthropogenic reef stressors have been identified. Natural disturbances include hurricanes, which can break down reef structures (Hughes and Connell 1999), and changes in seawater temperatures, which can induce reef bleaching (West and Salm 2003). Anthropogenic disturbances have been linked to most decreases in coral cover and decline in general colony health when coral reefs and humans appear together (Edinger *et al.* 1998, Fabricius 2005). The impact of multiple stressors, both natural and anthropogenic, can have multiplicative effects on coral reef ecosystems (Hughes and Connell 1999). The interactions of the stressors are yet unknown, but evidence suggests that human-damaged

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reefs may be more vulnerable to some types of natural disturbances and take longer to recover after disturbance (Hughes and Connell 1999).

Because of the widespread distribution of coral reefs and their occurrence in remote locations, the most practical approach to the global survey of reef stressors and the monitoring of conditions that affect reefs is through the use of remotely sensed data. NOAA has established a global sea surface temperature tracking system focused on coral reefs (Nalli *et al.* 2004, NOAA/NESDIS/OSDPD 2006a). This programme, known as Coral Reef Watch, tracks sea surface temperatures using meteorological satellite data. The system automatically detects prolonged periods of high sea surface temperatures in coral reef locations to issue alerts for coral bleaching events (NOAA/NESDIS/OSDPD 2006b). A growing body of literature indicates that it is possible to detect coral bleaching events using high spatial resolution multi-spectral satellite imagery (Elvidge *et al.* 2004a).

To date, there has only been a single global survey of anthropogenic stressors on coral reefs. This is the Reefs at Risk survey conducted by Bryant *et al.* (1998), which assessed the potential for human impacts on reefs in four primary categories: (1) coastal development, (2) marine pollution, (3) overexploitation and destructive fishing, and (4) inland pollution and erosion. The authors assembled a global set of reef locations with more than 10,000 points, each with a latitude and longitude. The reefs at these points were rated at high risk if the rating for any one of the four categories was high risk. The ratings were assessed based on the proximity of the reef locations to specific map features, plus expert assessments on sewage treatment and destructive fishing practices occurring in certain parts of the world.

Reefs at Risk used four primary sources of geospatial information on reef stressors. The Digital Chart of the World (DCW) was used as the source for locations of cities and human settlements, airports and military bases, mines, oil wells, and oil tanks. This is a digital database produced by the US Defense Mapping Agency through digitization of navigation charts from the 1960s and 1970s. DCW is widely available through sources such as ESRI and others. Population data were drawn from the World Cities Database from Birbeck College and the 10 km resolution population grid of the Global Demography Project (Tobler *et al.* 1995). Locations of ports were drawn from the World Port Index of the US Defence Mapping Agency (NGIA 2005). The land cover database used in the modelling of erosion potential was the 14 class International Geosphere-Biosphere Programme (IGBP) 1 km product derived from NOAA Advanced Very High Resolution Radiometer (AVHRR) data (Belward *et al.* 1999).

Over the years, there have been advances in geospatial databases available for coral reef risk assessment derived from satellite data. For instance, the US Department of Energy has released a global population count grid at 30 arc second resolution known as Landscan that combines data from four satellite data sources. Another satellite observation directly related to human activity is nighttime lights. NOAA has produced global nighttime lights products from data acquired by the US Air Force DMSP Operational Linescan System (OLS) that provides up-to-date information on the location and impact zone of oil and gas producing and processing facilities, heavily lit fishing boats, plus the artificial night sky brightness that can extend many kilometres out from major urban centres. In addition, the nighttime lights data have been used to model the spatial distribution and density of constructed impervious surfaces (Elvidge *et al.* 2004b), a major factor contributing to the pollution of near-shore waters.

In this article, we develop a remote sensing index derived from nighttime lights for three types of anthropogenic activities known to have adverse effects on coral reefs: urbanization, offshore gas flaring and heavily lit fishing boats activity. This index measures a direct effect, that of artificial night lighting on coral reef communities, and serves as a proxy measure of the intensity the better known influences of urbanization (Fischelson 1973, Fabricius 2005), oil platforms and associated chronic oil pollution (Loya and Rinkevich 1980) and fishing (Edinger *et al.* 1998, Roberts 2005).

1.1 *Effects of artificial night lighting on coral reef communities*

Artificial night lighting from cities, flares and light-induced fisheries can have direct and indirect effects on marine organisms, including birds (Montevecchi 2006) and fish (Nightingale *et al.* 2006). A number of adverse effects are likely to occur in the biodiverse communities of coral reefs.

Corals are highly photosensitive – many species synchronize their spawning through detection of low light intensity from moonlight (Gorbunov and Falkowski 2002; Jokiel *et al.* 1985) and coral reef structure is strongly influenced by illumination (Wellington 1982). Seaweeds in coral reefs, signalled by lighting levels, can grow at night to reduce herbivory (Hay *et al.* 1988). Many coral reef anthozoans (e.g. corals, gorgonians, sea anemones and sea pens) expand and contract on a daily basis to conserve nutrients (Sebens and DeRiemer 1977, Levy *et al.* 2001). Other marine invertebrates in coral communities synchronise reproduction by monthly patterns of lunar illumination (Bentley *et al.* 2001).

Zooplankton in coral reefs undergoes diel vertical migration upwards at night to forage and downwards at dawn to avoid predation (Yahel *et al.* 2005a,b). Planktivorous coral reef fishes also exhibit diel vertical migration. For fish larvae, the direction and timing of these migrations differ between species and larvae age (Leis 1986). Such extensive structuring of this community by light is undoubtedly disrupted by artificial lighting, which has no ecological analogue – moonlight, starlight and bioluminescence are the only sources of light to which marine organisms are adapted (Hobson *et al.* 1981).

The synchrony of coral spawning breaks down under artificially simulated continuous full moon conditions (Jokiel *et al.* 1985). Because corals can detect illumination in the ranges caused by the moon, they are sensitive to even minor increases in nocturnal illumination, especially in the shorter wavelengths (Gorbunov and Falkowski 2002). Streetlights and other dim photopollution are sufficient to disrupt the spawning cycles of polychaete worms (Franke 1990, 1999).

The diel vertical migration of zooplankton has been shown in freshwater systems to be suppressed by sky glow from distant cities (Moore *et al.* 2000, 2006). Zooplankton in coral reef communities are almost certainly similarly affected, which would influence overall community structure (Wellington 1982, Yahel *et al.* 2005b).

Many coral reef fishes are highly phototropic (Choat *et al.* 1993) and lights can be used to attract fish to new reefs (Munday *et al.* 1998). Introduction of light to these environments would alter natural distribution patterns. Furthermore, some species are nocturnal specialists that forage efficiently in the dark (Holzman and Genin 2003, 2005) and could be adversely affected by increased lighting. Settlement of coral reefs by larvae of some species of fish is maximized at night and during the new moon. Increased settlement under dark conditions is interpreted to be a mechanism to minimize predation (Victor 1986, Kingsford 2001). Artificial light at night presumably removes this protective niche for colonization.

Because the nocturnal responses to light in coral reef communities are to levels of light at moonlight intensities and lower, any artificial alteration of this environment is likely to influence community structure, species interactions and ultimately reduce biodiversity by homogenizing the light environment (Longcore and Rich 2004, Rich and Longcore 2006).

Oceans are flat, open environments with no barriers for light outside of the curvature of the earth and marine organisms are consequently highly adapted to respond to light such as bioluminescence (Montevecchi 2006). Inasmuch as gas flares, light-induced fisheries and nearby terrestrial settlements provide illumination that is brighter than the full moon, especially at shorter wavelengths, an impact can be expected in coral reefs. This effect may be greater or smaller than the impact of the activities themselves, but together they represent significant stressors on vulnerable coral reef ecosystems.

2. Methods

2.1 *Data sources*

2.1.1 *DMSP nighttime lights 2003*

The DMSP OLS was designed to collect global cloud imagery using a pair of visible and thermal spectral bands. The DMSP satellites are flown in polar orbits and each collects 14 orbits per day. With a 3000 km swath width, each OLS is capable of collecting a complete set of images of the earth twice a day. At night the visible band signal is intensified with a photomultiplier tube (PMT) to enable the detection of moonlit clouds. The boost in gain enables the detection of lights present at the earth's surface. Most of the lights are from human settlements (cities and towns) and fires, which are ephemeral. Gas flares are also detected and can easily be identified when they are offshore.

NOAA/NGDC archives the long-term DMSP data from 1992 to present. The archive is organized as individual orbits that are labelled to indicate the year, month, data and start time. For this project, the individual orbits were processed with automatic algorithms that identify image features (such as lights and clouds) and the quality of the nighttime data. These algorithms have been described in Elvidge *et al.* (1997, 2001). A cloud-free composite of nighttime lights was produced for year 2003 using data from DMSP satellite F-15. The following criteria were used to identify the best nighttime lights data to create a composite:

(1) centre half of orbital swath (best geolocation and sharpest features);
(2) no sunlight present;
(3) no moonlight present;
(4) no solar glare contamination;
(5) cloud-free (based on thermal detection of clouds).

Nighttime image data from individual orbits that meet the above criteria are added into a global latitude–longitude grid (Platte Carree projection) having 30 arc second resolution cells. This grid cell size is approximately a square kilometre at the equator. The total number of coverages and number of cloud-free coverages are also tallied in order to estimate the frequency with which lighting was present. The nighttime lights product used in this analysis is the average digital number in the visible band of cloud-free light detections multiplied by the per cent frequency of light detection. The inclusion of the per cent frequency of detection term normalizes the resulting digital values for variations in the persistence of flaring. For instance the value for a gas flare only detected half the time is discounted by 50%. The resulting value is referred to as the 'lights index'. Background noise and land based fires were filtered out. The remaining lights were divided into three thematic categories: (1) electric lighting from cities, human settlements and lit facilities on land, (2) gas flares, and (3) heavily lit fishing boats (Figure 1).

2.1.2 *Reef data*

The second database used in this project is a global compilation of coral reef locations (Figure 2). The data were obtained from Reefs at Risk, World Resources Institute (WRI), 1998. The dataset originates from the United Nations Environment Programme–World Conservation Monitoring Centre. WRI converted it into raster format at 1 km resolution and then converted this grid into a point dataset. In this project a list of reef locations in text format was used. Each record represents one coral reef point location with its geographic position (longitude/latitude) and a location code attached to it. It consists of 330,490 globally distributed point locations of coral reefs.

The location code attached to each reef location in the original data assigned each reef point to a country. The corresponding country for each code value had to be found and a new attribute table was built. To be able to create reasonable reports for the results based on geographic regions, the original location code had to be modified. The primarily country-based structure was kept and enhanced. Often one country had several different location codes with attached reef locations. The Bermuda Islands serve as an example with 465 reef locations assigned to five different location codes following no apparent pattern. Nearly all of these 465 reef points (97%, 450 points) were attached to one location code and just 15 points (3%) were portioned to the other four codes. To identify The Bermuda Islands as one unique geographic region, these five location codes were merged to a single code.

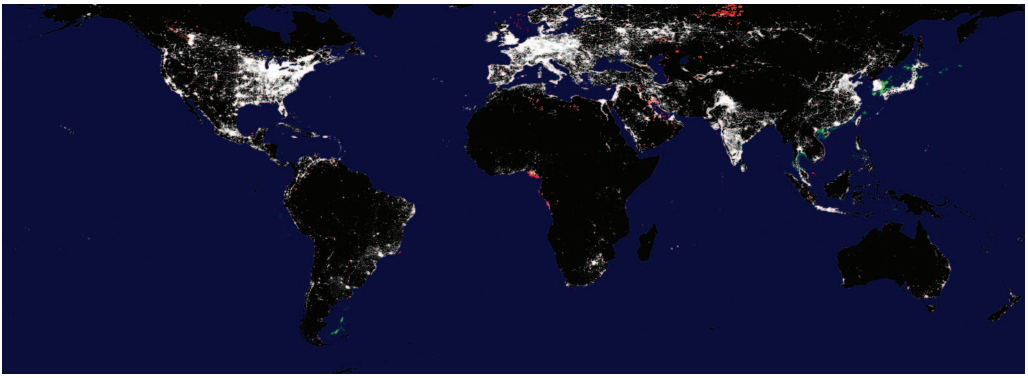

Figure 1. The categories of the global dataset of nighttime lights in 2003 are as follows: (1) cities, white; (2) gas flares, red; (3) boats, green.

Figure 2. (a) The global distribution is shown with the reef locations marked in white. (b) An overlay of the nighttime lights dataset colourized by light intensity and the coral reefs dataset.

In addition to merging location codes, sometimes codes were split when (1) two countries had the same location code in the original data and were better separated, or (2) a unique code value was assigned to several islands, separating them from the corresponding country to better differentiate report areas. The original 241 location codes were transformed to 146 usable geographic regions.

The second important enhancement of the reef dataset was to correct non-systematic displacements relative to the DCW and the nighttime lights dataset. Because the displacements were not consistent, no systematic adjustment could fix these problems. Some points had to be moved towards West, some towards North, others towards East and South. Errors were found for both small and large islands (e.g. Puerto Rico and Guadeloupe). Correction of theses displacements was essential to avoid reefs being located on land and to allow further use of the data.

2.2 *Analysis*

Three reef stressors were included in the index calculation using the satellite observed nighttime lights data: (1) cities and towns, (2) gas flares, and (3) heavily lit fishing boats. For each of these three reef stressors a lights proximity index (LPI) was calculated. We assumed that the nearer a coral reef is located to an artificial night lighting source the greater is its potential endangerment from direct and indirect impacts. This process was computed using Interactive Data Language (IDL).

We set a threshold value of 5 km for gas flares and heavily lit fishing boats and 25 km for cities and towns and summed the value of lit pixels within this radius for each reef point (Figure 3).

The script calculating the LPI was run for each of the three reef stressors. Computing the index for proximity of cities and towns to coral reefs was most time consuming. Because these lights are distributed globally, all of the reef points had to be considered for the calculation.

The calculation time for the LPI considering heavily lit fishing boats could be decreased considerably because of the geographically limited occurrence of these light sources. The reef points were reduced to just those points located in a specified geographic region in Southeast Asia/Indonesia where heavily lit fishing boats had been detected in the pre-analysis of the nighttime lights data. The second factor reducing computation time is the smaller radius of the circle included in the calculation.

The LPI script for gas flares was enhanced in a similar way. The only difference is that there is not just one geographic region where gas flaring occurs, but rather several small regions widely distributed over the whole globe. So the list of global reef location points had to be reduced to several lists of the respective regions. These new lists of potentially affected reef areas were then accumulated to one single list including all the coral reef points in potential proximity to gas flares.

3. Results

LPI values were calculated in three runs for each coral reef location; one run for cities and towns, generally referred to as development, one for gas flares and one for heavily lit fishing boats. The output was three ENVI raster files with corresponding text files for each of the chosen reef stressors. The text files have the same structure as the original reef data list (longitude, latitude, reef location code) with an additional column for the LPI values. The raster files refer to these text files having the value of one point location assigned to one grid cell with an area of one square kilometre.

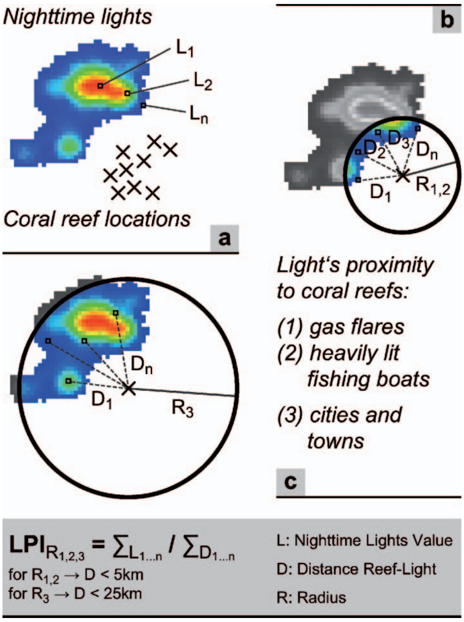

Figure 3. (a) A set of coral reefs in proximity to an area with artificial night lighting is shown. During the LPI calculation a circle with a defined radius according to the respective reef stressor is computed around each coral reef location. Only the nighttime lights falling inside the circle are used for the index calculation. As cities and towns are considered to have a much larger influence, the radius was set to 25 km (R_3 in part c) compared to a radius of 5 km used for the index calculation for reefs in proximity to gas flares and heavily lit fishing boats ($R_{1,2}$ in part b). The values of all relevant nighttime lights raster cells are summed up ($\Sigma L_{1\,\ldots\,n}$). This sum is divided by the sum of all distances ($\Sigma D_{1\,\ldots\,n}$) from the coral reef point location to each of the relevant raster cells. The potential reef endangerment grows with smaller distance values and stronger nighttime lights. The index value increases on a continuous numeric scale.

A complete list of reefs and associated LPI values for each stressor is available in the 'Data Download Section' of the NOAA/NGDC/EOG website (http://ngdc.noaa.gov/dmsp).

3.1 *Colourized images*

To visualize the LPI values, colourized images were created using a modified rainbow colour ramp. Reef locations in no close proximity to an artificial night lighting source have an LPI value of zero and are marked in white. Reefs with low LPI values are visualized in blue colours. When the index values get larger the colour turns via green, yellow and orange to red. A land-sea-mask is used as basis for orientation. Figure 4 shows one geographic region significant for reef stress caused by development – Puerto Rico.

3.2 *Area ranking*

To describe the regional status of the influence of artificial night lighting and associated stressors on coral reefs, the previously adapted location code was used and several rankings of potentially endangered coral reef areas were created.

The first approach was to use the summed LPI values of all coral reefs in one geographic area (cf. Table 1). The geographic areas differ greatly in size and accordingly also in the number of related reef points. 'Indonesia' serves as an example for an area with a large geographic extent and accordingly a high number of points. Without a doubt the results could be enhanced if large areas were split and smaller areas were defined.

To account for the variation in the number of reef points the list was normalized using the average point value of each area (cf. Table 2). This way, areas like 'Singapore', with a small number of points and with all of them having a particularly high LPI value, stand on top of the table. Nonetheless also 'Puerto Rico' with a larger number of points shows an extremely high average point value.

The LPI values for heavily lit fishing boats and gas flares were divided by the number of points in the region to produce average values (cf. Table 3). The scripts for these stressors were implemented only for those areas within predefined regions near boats or gas flares. For example 'Oman' had just 12 of its 615 reef points located inside the 'flares calculation area' and all of those 12 points had very high LPI values. As a result also the average LPI value of those cells was very high (299), if just the 12 reef points were considered. After assigning the full number of points, the average flares LPI value for 'Oman' drops to six.

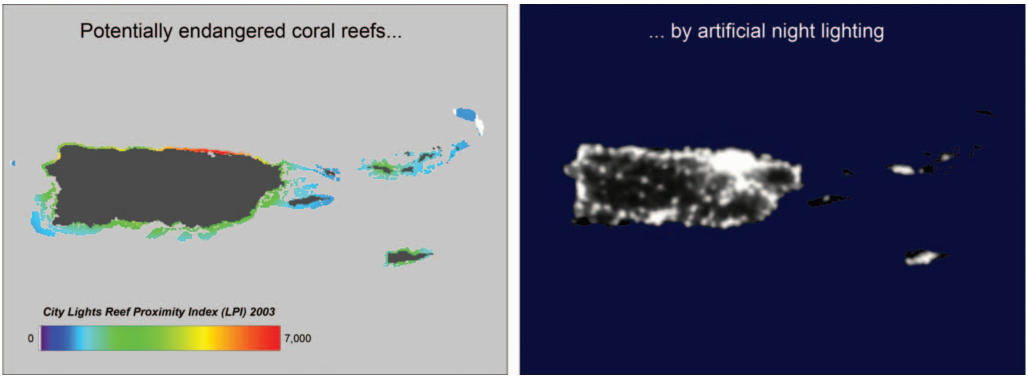

Figure 4. The area of Puerto Rico was chosen to show coral reefs being at high risk by artificial night lighting caused by development (left part). There are many reefs within a 25 km radius of cities and towns having high LPI values due to their close proximity to the lighting sources (which are shown as reference on the right). Reefs in regions around big cities such as the capital, San Juan, especially show particularly high LPI values and the corresponding red colour in the image.

Table 1. Ranking by aggregated sum.

Development			
Area code	Area name	Sum value	Number of points
71	Puerto Rico	4,131,317	2626
17	Red Sea: Saudi Arabia & Yemen	3,087,648	7712
20	Japan	2,524,594	3283
161	Indonesia	2,114,357	54,851
10	Red Sea: Egypt	1,904,668	6018

The five highest ranked regions according to the 'aggregated sum approach', regarding the development-LPI values. 'Puerto Rico' is designated to be most endangered.

Table 2. Ranking by average point value.

Development				
Area code	Area name	Sum value	Number of points	Avg
175	Singapore	298,613	61	4895
11	Red Sea: Israel & Jordan	49,666	16	3104
115	Barbados	216,103	124	1743
71	Puerto Rico	4,131,317	2626	1573
27	Bahrain	982,804	653	1505

The five highest ranked regions according to the 'average point value approach', regarding the development-LPI values. 'Singapore' is designated to be most endangered.

Table 3. Ranking of boats- and flares-areas.

Area code	Area name	Sum value	Number of points	Avg
Heavily lit fishing boats				
131	Thailand: Gulf of Thailand	92,099	1180	78
117	Thailand West	24,994	1126	22
18	China	17,790	1726	10
52	Vietnam	3243	1098	3
37	Taiwan	2581	1024	3
Gas flares				
27	Bahrain	229,565	653	352
8	Iran: Persian Gulf	183,261	691	265
31	Qatar	61,449	808	76
168	Brunei	9515	223	43
33	United Arab Emirates	57,036	1367	42

The five highest ranked regions regarding the LPI values of reefs in proximity to heavily lit fishing boats and gas flares. The 'Gulf of Thailand' is designated to be the area by far most endangered through fishing activities, while 'Bahrain' and 'Iran: Persian Gulf' are at highest risk through gas flaring.

3.3 *Coincidence of multiple factors*

There are several geographic areas where multiple reef stressors coincide (cf. Table 4). That means that either two or all three of the investigated artificial night lighting sources appear together in one region near coral reefs.

'Bahrain' and 'Iran: Persian Gulf' – two areas where reefs with high LPI values considering gas flaring as well as with quite high values considering development are located – have to be emphasized. Regarding the collective occurrence of the two stressors development and heavily lit fishing boats, especially 'Gulf of Thailand' and 'Thailand West', stand out. The reefs in both areas have extremely high average LPI values for fishing boats.

Three regions show a coincidence of all three reef stressors: 'Indonesia', 'Malaysia' and 'Philippines'. All three areas are large, which increases the probability of multiple stressors occurring, and none of the average LPI values regarding either development or boats or gas flares is particularly high. Smaller units of study would have produced more informative results for these areas.

Although many coral reefs are affected by multiple stressors, some reefs remain relatively undisturbed. Regions such as the 'Cargados-Carajos-Islands' near Mauritius are completely unaffected. Also much larger islands (cf. number of points in Table 5) such as

Table 4. Coincidence of multiple factors.

	Area code	Area name	Sum value	Number of points	Avg	Lights
2 Coincidences	27	Bahrain	982,804	653	1505.1	Cities
			229,565		351.6	Flares
	8	Iran: Persian Gulf	415,489	691	601.3	Cities
			183,261		265.2	Flares
	31	Qatar	546,400	808	676.2	Cities
			61,449		76.1	Flares
	131	Thailand: Gulf of Thailand	375,370	1180	318.1	Cities
			92,099		78.1	Boats
	117	Thailand West	310,670	1126	275.9	Cities
			24,994		22.2	Boats
	18	China	449,751	1726	260.6	Cities
			17,790		10.3	Boats
3 Coincidences	161	Indonesia	2,114,357	54,851	38.6	Cities
			4489		0.1	Boats
			8682		0.2	Flares
	162	Malaysia	412,688	4061	101.6	Cities
			1287		0.3	Boats
			6709		1.7	Flares
	56	Philippines	1,627,927	31,029	52.5	Cities
			27,924		0.9	Boats
			20,733		0.7	Flares

The selected geographic regions where multiple reef stressors coincide are shown.

Table 5. Least affected areas.

Development				
Area code	Area name	Sum value	Number of points	Avg
175	Singapore	298,613	61	4895.3
203	Australia: Great Barrier Reef	280,147	43,112	6.5
109	Marshall Islands	39,802	6539	6.1
218	Madagascar	9512	2423	3.9
193	Solomon Islands	1278	6422	0.2
129	Spratly Islands	636	6607	0.1
86	Cargados Carajos	0	373	0.0

Selection of areas with very low average LPI values, thus as a whole not being heavily affected by nighttime lighting caused by development. For comparison, 'Singapore', the area with the highest average LPI value, is included.

the 'Spratly Islands' in the South China Sea or the 'Solomon Islands' east of Papua New Guinea have an average LPI value less than one. The 'Great Barrier Reef' is one of the largest defined areas with 43,112 reef points, but stands with an average LPI value of 6.5 at the lower end of the list as well. The same applies for the 'Marshall Islands' in the western Pacific Ocean and for 'Madagascar'.

4. Discussion

In this article, a global inventory of three reef stressors – development, gas flaring and heavily lit fishing boats – was presented. A satellite-based approach was used, developing an artificial nighttime lights proximity index. The results indicate that coral reefs in Puerto Rico and regions in the Red Sea and in the Persian Gulf are extremely endangered by cities and towns. The last two are also greatly affected by gas flaring, while fishing activities are most threatening in the Gulf of Thailand.

The methodology developed here provides an objective and easily repeatable approach to monitor threats to coral reefs. Although a much simpler approach, it yields results that are substantially similar to those in approaches requiring many more input variables (Bryant *et al.* 1998). In this way it is an efficient method to measure the impacts of several well-known stressors of coral reefs using the proxy measure of nighttime lights. The broad correlation between lights and urbanization is well established, but it is possible that specific conditions in cities can be remediated without reducing artificial lighting. Enforcement of laws such as the US Clean Water Act can reduce impacts from runoff of sediments, nutrients and other pollutants from urban areas. For example, the Puerto Rico Aqueduct and Sewage Authority were found guilty of violating the Clean Water Act for discharge of pollutants. It will pay a criminal fine of $9 million and invest $1.7 billion in capital improvement projects and other remedial measures to treat chemicals and remove phosphorus from water discharged into the ocean (EPA, 6/22/2006, Elias Rodriguez, rodriquez.elias@epa.gov). The benefits of such marginal changes are beyond the scope of this tool to detect. Despite this limitation, we are confident that at the global scale of the analysis nighttime lights correlate well with coral reef stressors.

Nighttime lights, in addition to serving as a proxy measure for other human activities, pose a unique threat to coral reef ecosystems that has not previously been identified or described. Despite the ample conceptual basis for this threat (cf. Section 1.1), researchers of tropical marine systems have recognized impacts from artificial night lighting only for sea turtles and their nesting beaches (Salmon 2006). Our identification of areas that are particularly subjected to lights at night should guide researchers seeking to investigate these impacts in the field. The results of this project should also be useful for reef managers around the world to identify sites that require aggressive restoration actions or to prioritize the protection of pristine reef areas.

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