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Stemming the tide of light pollution encroaching into Marine Protected Areas

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Abstract

Many marine ecosystems are shaped by regimes of natural light guiding the behaviour of their constituent species. As evidenced from terrestrial systems, the global introduction of nighttime lighting is likely influencing these behaviours, restructuring marine ecosystems, and compromising the services they provide. Yet the extent to which marine habitats are exposed to artificial light at night is unknown. We quantified nightime artificial light across the world's network of Marine Protected Areas (MPAs). Artificial light is widespread and increasing in a large percentage of MPAs. While increases are more common among MPAs associated with human activity, artificial light is encroaching into a large proportion of even those marine habitats protected with the strongest legislative designations. Given the current lack of statutory tools, we propose that allocating 'marine dark sky park' status to MPAs will help incentivize responsible authorities to hold back the advance of artificial light.

Introduction

The United Nations has proclaimed 2015 '*The International Year of Light*', celebrating light science and its applications, including the global introduction of white artificial lighting. Yet, the spread of artificial light is increasingly recognized as a threat to biodiversity, human health and scientific endeavour (Longcore & Rich 2004, Hölker *et al*. 2010, Falchi *et al*. 2011, Gaston *et al.* 2012).

Nighttime lighting can affect biological systems in a myriad of ways, although research has primarily focused on terrestrial ecosystems, where such lighting causes habitat displacement (Stone *et al.* 2009), modulates reproductive development (Dominoni *et al.* 2013), disrupts navigation (Frank 1988), shifts daily activity patterns (Kempenaers *et al.* 2010), restructures communities (Davies *et al.* 2012), and affects ecosystem service provisioning (Lewanzik & Voigt 2014). Despite light being intrinsic to the life history of many marine species, its impacts in marine ecosystems are less well explored. Known examples include the disorientation and mortality of birds (Merkel 2010) and sea turtle hatchlings (Witherington & Bjorndal 1991), the aggregation and exploitation of fish and squid (Kiyofuji & Saitoh 2004, Becker *et al.* 2012), changing patterns of foraging by wading birds (Santos *et al.* 2009), and altering the composition of sessile invertebrate communities (Davies *et al*. 2015). A number of additional impacts on marine ecosystems are anticipated, since they are home to a plethora of species guided by natural light cues in many behaviours (Thorson 1964, Tanner 1996, Mundy & Babcock 1998, Naylor 1999, Cohen & Forward 2009). A number of marine invertebrate species synchronise broadcast spawning events using lunar light intensity (Naylor 1999), corals being the most notable example (Tanner 1996); zooplankton are guided by changing light intensity as they migrate towards the sea surface at night (Cohen & Forward 2009), a behaviour that is suppressed by artificially brightened skies in freshwater systems (Moore *et al.* 2000); and the introduction of whiter lighting will likely affect prey location and bioluminescent communication (Davies *et al.* 2014).

Coastal development, offshore infrastructure, shipping and fishing lights all contribute sources of artificial light to both offshore and nearshore marine ecosystems. It has been estimated that in

2010, 22% of the world's coastal regions (excluding Antarctica) were experiencing some degree of artificial light at night (Davies *et al.* 2014), a level that is increasing as the economies of developing countries grow. Given the variety of ways in which marine species could be affected, marine ecosystems are almost certainly being shaped by anthropogenic modifications to the natural light regimes they evolved with. Light pollution is, however, novel among global anthropogenic stressors (e.g. temperature, carbon dioxide, ocean acidification), in that changes to natural light regimes are comparatively instantaneous to reverse. Although a limited number of conservation tools are available to mitigate against its impacts, quantifying the extent of nighttime lighting in regions protected for cultural, aesthetic, biodiversity and socio-economic value is a crucial step towards identifying where preventative measures should be enforced (Davies *et al.* 2014). Gaston *et al*. (2015) found that 7-42% of terrestrial protected areas experienced increases in artificial light between 1992-2010. While previous studies highlighted the spatial extent of nighttime lighting across the world's coastlines (Davies *et al*. 2014), and in marine regions inhabited by light sensitive species (Aubrecht *et al.* 2008, Kamrowski *et al*. 2012, 2014a, Mazor *et al.* 2013), its extent in and encroachment into Marine Protected Areas (MPAs) is unknown. These regions represent the ecological marine assets most valued by humanity, hence determining the nighttime lighting they are experiencing is central to justifying future protective measures.

Here we use remotely-sensed data in a broad-scale analysis to examine the extent of and trends in nighttime lighting across the global MPA network. Our results suggest that artificial lighting should not only be considered a threat to marine ecosystems, but also to regions that humanity has declared a vested interest in protecting.

Methods

We followed the methods of Gaston *et al.* (2015), with the exception that we extracted data for marine rather than terrestrial protected areas. All data handling and extraction were performed in R, GDAL tools (http://www.gdal.org/gdal_utilities.html) and ArcGIS 10 using a Behrmann equal-area projection. A map of the world's MPAs was extracted from the full World Database on Protected

Areas (WDPA) downloaded on 6/10/14 from http://www.protectedplanet.net/ (IUCN & UNEP 2014). Terrestrial protected areas adjacent to coastlines that had been classified as marine were removed by clipping out MPAs occurring within the coastal boundaries of a full resolution level 1 (global coastline) dataset downloaded from the Global Self-consistent, Hierarchical, High-resolution Geography (GSHHS) database (http://www.ngdc.noaa.gov/mgg/shorelines/gshhs.html). This provided 11,333 MPAs that were used to generate two datasets. First, the boundaries of adjacent MPAs were dissolved providing a map of the world's contiguous MPAs. This allowed estimates of the number and percentage of contiguous MPAs exposed to nighttime lighting to be derived without multiple overlapping designations over the same region. Second, the original data were subsetted to provide a map of MPAs for which IUCN categories have been designated (3,479 MPAs). Each IUCN category (I to VI) describes areas protected for contrasting levels of nature conservation versus human activity, hence we anticipated that areas protected as pristine natural habitats would be less exposed to artificial light at night than areas where human intervention is more prevalent, because the latter are more likely to be found in closer proximity to human population centres. We also calculated the distance of each IUCN categorized MPA to the coast to ascertain whether trends in artificial light intensity were driven by coastal or offshore development. For each IUCN categorized MPA, this was quantified as the average distance (in km) between the centre of each of its constituent pixels (lit and unlit) and the nearest polyline of coast.

The light pollution metrics for MPAs in both datasets were extracted from 21 intercalibrated DMSP/OLS stable nighttime lights images (nominal 1km resolution) from 1992 to 2012 (Baugh *et al.* 2010). Each image is composed from multiple images taken on cloud free nights throughout the year with the amount of artificial light in each pixel given by a digital number (D.N.) between 0 (no artificial light) and 63 (value at which sensors saturate). Prior to analysis, we employed the methods of Bennie *et al.* (2014) to address geo-location drift of up to 3 pixels, and lack of intercalibration between images collected on different successive satellites. Geo-location drift was rectified by shifting images in consecutive years by + or -5 pixels in x (latitude) and y (longitude) directions and correlating the resulting pixel intensities to the median (2002) image in time. The x and y offset of the resulting 121 combinations that provided the highest Pearson correlation coefficient was selected for analysis. Images were intercalibrated to the 1994 image using quantile regression on the median (CRAN: quantreg). This technique relates median pixel intensities to one another so that it is insensitive to pixels that increase or decrease in intensity between years. Provided with a calibration region in which a minority of pixels have undergone changes in artificial lighting between time steps, quantile regression on the median gives robust estimates of parameters. We selected the same calibration region as Gaston *et al.* (2015), a subset of the global map that contained most of the UK, because changes in the street lighting stock in the region are localised in extent between 1992 and 2012 and affect a minority of pixels (Bennie *et al.* 2014). 1994 was chosen as a reference to which all other images were calibrated because it displayed the highest proportion of pixels with digital numbers of both 0 and 63, the darkest and brightest measurements at which the satellite sensors saturate. By intercalibrating all images to this year, we ensured that estimates of trends in artificial light were calculated only from pixels that experienced a quantifiable change in intensity between years.

Bennie *et al*. (2014) demonstrated that when using this calibration approach 94% of increases, and 93% of decreases in pixel intensity by 3 digital numbers, can be attributed to changes in artificial lighting on the ground (i.e. declining industry, urban expansion). MPAs were therefore classified as currently exposed to nighttime lighting if they contained any pixels where the intercalibrated digital number exceeded 5.5 (Davies *et al*. 2014, Gaston *et al.* 2015) in the 2012 image. The number and percentage of MPAs exposed or not were calculated, along with the area and percentage area of the global MPA network exposed. Temporal trends in artificial light (increasing, decreasing or neutral) were determined for each MPA using Mann Kendall tests of the monotonic trend in mean pixel intensity through time derived from DMSP images from 1992 to 2012 (Fig. 1). MPAs for which the direction of the trend could not be established with 95% confidence were classified as having experienced no change in artificial light (neutral).

Results

In 2012 4,051 (35%) of the world's 11,442 contiguous MPAs were experiencing artificial light (at least one pixel >5.5 digital number) at night (Fig. 2A). Of those MPAs 57% (2,293) were exposed to widespread light present in 100% of pixels, and 72% (2,901) across more than 50% of their pixels(Table 1). Hence, not only is the presence of artificial light common in MPAs, but its extent within those MPAs exposed is typically widespread. Regions in which a large proportion of MPAs were exposed to artificial light include the North West Atlantic and Mediterranean Sea (Fig. 2B), the Gulf of Mexico and Caribbean Sea (Fig. 2C), the eastern coast of South America (Fig. 2D), and coastal bounded MPAs of Australia (Fig. 2A). The area of the world's MPA network experiencing nighttime lighting in 2012 (based on total number of lit pixels across all MPAs) encompassed 60,452 km^2, however, because a limited number of protected area designations cover vast areas of ocean with little human habitation, while the majority are small and coastal bounded (Fig. 2), this equates to 0.7% of the world's total MPA area coverage (lit pixels expressed as a proportion of total pixels across all MPAs). Between 1992 and 2012, 1,687 (14.7%) of the world's contiguous MPAs experienced significant increases in mean artificial light intensity, 305 (2.7%) experienced significant decreases, and 9,450 (82.6%) experienced no change (Fig. 3A) (although the above results mean that nighttime lighting is present in many no change areas).

Categories with high levels of human interaction contained a higher fraction of MPAs in which mean artificial light intensity significantly increased between 1992 and 2012 (Table 2). Category I areas encompass strict nature reserves or wilderness regions, hence it is unsurprising that these contained the lowest percentage (9%, Table 2) of MPAs experiencing increases in average light intensity. Categories II, IV and VI (national parks, habitat/species management areas, and regions where sustainable resource use occurs) may be accessed for recreation, are managed using human intervention or associated with previous human land use. A higher proportion (18% for II, 17% for IV and 16% for VI, Table 2) of these MPAs experienced an increase in mean artificial light intensity over the period. Landmarks protected for their monument status (category III) and protected seascapes (category V) represent areas protected specifically for their associated cultural or aesthetic value, and in the last case have been created through human-landscape interaction. It is unsurprising then that the fraction of MPAs experiencing increases in mean artificial light intensity was highest (20% for III and 25% for V, Table 2), since many of them are located close to human population centres. Indeed, MPAs experiencing positive or negative trends in artificial light intensity were generally closer (<3km) to the coast than those where light intensity did not change (Table 2) suggesting that the observed trends were driven by coastal development.

Discussion

A large fraction of the world's MPAs are experiencing nighttime lighting, the amount of which is also increasing in many of these areas. Of those MPAs designated even with the highest status of protection (IUCN Category I), 9% are experiencing increases in mean artificial light intensity.

2.7% of contiguous MPAs experienced decreases in artificial light. Declines have also been observed in some European nations and attributed to changes in prevailing lighting technologies, legislation, and declining economic/industrial activity (Bennie *et al*. 2014). It seems plausible that these drivers are equally likely to be the cause of decreasing artificial light in coastal and offshore regions. For example, changes in rig lighting are expected as oil and gas prices fluctuate, wells run dry, and new wells become established.

Given the importance of light in guiding the behaviours of many marine species (Thorson 1964, Tanner 1996, Mundy & Babcock 1998, Naylor 1999, Cohen & Forward 2009), these results suggest that nighttime lighting may influence the ecology of many of the most valued regions of the ocean.

Rising human population densities within coastal regions (Small & Nicholls, 2003), coupled with improving per capita income in developing countries, will inevitably see further encroachment of nighttime artificial light into near-shore marine environments. Artificial lighting from offshore infrastructure is also set to rise, with oil and gas supplies increasingly reliant on offshore extraction, and continued growth of offshore wind power generation. New technologies are increasingly allowing such developments to take place in deeper waters, raising the prospect of further introducing nighttime lighting into regions that have remained unexposed, and in some cases (e.g. Arctic Ocean) are home to species known to be vulnerable to bright lights (Merkel, 2010).

There has been great emphasis on managing fisheries, pollution, offshore development, and mineral extraction in our oceans (Halpern & Warner 2002, Lester *et al*. 2009), and MPAs have proven a useful tool for achieving these goals. Our work has shown that nighttime lighting is common in these regions, and its effects warrant investigation both compared to and in combination with previously recognized disturbances so that proportionate mitigation measures can be sought. Reducing levels of artificial light in marine environments is challenging as it is often perceived as beneficial for economic growth, security, operational safety and aesthetics in marine developments. Marinas use artificial light for security and aesthetic purposes, while curbing its use in dockyards or on ships and oil platforms could violate standards set for operational safety. Legal frameworks to curtail use of artificial light in marine environments are yet to be developed because understanding of how nighttime lighting affects marine ecosystems is limited, and has not warranted compromising continued use for these activities. Despite light being recognized as a pollutant under the European Commission Marine Strategy Framework Directive (Commission decision 2010/477/EU; MFSD 2010), it states that there is currently insufficient information available to define limits of good environmental status for its use. Artificial lighting is also seen as a symbol of modernity in many developing nations, while in developed nations its use is often perceived as the norm (Lyytimaki 2013). Changing public perceptions of nighttime lighting towards avoiding its use is therefore a major challenge. Combined with a lack of legislative options, conservation managers are left to seek voluntary incentives to curb its use, by working with local communities to foster a healthy balance between the benefits and environmental impacts (e.g. Kamrowski *et al*. 2014b).

Switching off, dimming or shielding lights, preserving naturally dark landscapes and limiting the use of spectra known to cause ecological impacts have all been suggested as potential approaches conservation managers can use to reduce the prevalence of artificial light (Falchi *et al*. 2011, Gaston *et al.* 2012, Davies *et al*. 2014). In cases where ecologically less damaging lighting can be installed or existing installations modified without any noticeable interference with human activity, for example seaward shielding of lights illuminating piers, mitigation may be as simple as improved managerial awareness of artificial light as an environmental issue. Reducing the ecological impacts of artificial light in marine environments via manipulation of spectral output may offer further benefits. The deeper penetration of blue light in seawater suggests that avoiding short wavelengths could help minimize ecological impacts. Voluntary incentives exist through programmes that seek to preserve naturally dark areas, and benefit from the touristic value this brings (Rodrigues *et al*. 2014), such as those through the International Dark-Sky Association (IDSA; www.darkskyparks.org). The IDSA has certified 28 dark sky parks and reserves as of 2014, although none has been designated specifically to preserve dark skies in marine habitats and few in coastal regions. 'Marine Dark Sky Parks' would be an important first step towards preventing further encroachment of artificial light into marine ecosystems that are recognized for their aesthetic, cultural, biodiversity and resource value.

Artificial light is prevalent and increasing in large proportions of the global MPA network. Given the expectedly pervasive impacts of nighttime lighting on marine ecosystems, improved understanding of its ecological effects is urgently needed to inform and justify proportionate mitigation strategies. The current paucity of information available to support legal frameworks for mitigation suggests conservation managers should seek dark sky status for their reserves as a means of effectively stemming the advance of light pollution into regions that are currently naturally lit, if not individual MPAs in their entirety.

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Table 1. The extent of artificial light at night within lit MPAs. The number (*n*) and percentage (%) of MPAs classified as lit that contain the percentage of lit pixels given in the left hand column. For 2295 (57%) of MPAs classified as lit, the proportion of pixels lit within each MPA was equal to 100.

% of total MPA area lit	*n* lit MPAs	% lit MPAs	Mean MPA area (km^2)
= 100	2295	57	5.6
90 to 99	104	3	42.6
80 to 89	106	3	48.2
70 to 79	101	2	55.9
60 to 69	122	3	63.3
50 to 59	173	4	28.7
40 to 49	123	3	153.3
30 to 39	151	4	78.5
20 to 29	197	5	165.8
10 to 19	204	5	373.0
1 to 9	386	10	3097.0
<1	89	2	63815.8
Total	**4051**		

Table 2. The number (n) and percentage (%) of Marine Protected Areas designated under each IUCN category that experienced significant increases, decreases or no significant trends (neutral) in artificial light intensity between 1992 and 2012. The amount of artificial light within each MPA was classified as significantly increasing or decreasing with 95% confidence using Mann Kendall tests of the monotonic trend in mean pixel intensity (digital number).

IUCN category	**Total**	**Increasing light**			**Decreasing light**			**No change**		
		n	*%*	*Mean distance to coast (km)*[*]	*n*	*%*	*Mean distance to coast (km)*[*]	*n*	*%*	*Mean distance to coast (km)*[*]
I	560	52	9	1.7 ± 1.0	5	1	1.0 ± 0.5	503	90	5.4 ± 1.4
II	486	89	18	1.5 ± 0.2	11	2	2.7 ± 1.3	386	79	5.4 ± 1.3
III	66	13	20	0.8 ± 0.4	2	3	0.2 ± 0.1	51	77	1.8 ± 1.0
IV	852	148	17	1.2 ± 0.2	39	5	0.5 ± 0.1	665	78	6.4 ± 1.8
V	597	151	25	2.0 ± 0.7	27	5	1.0 ± 0.6	419	70	3.2 ± 1.6
VI	918	146	16	2.1 ± 0.4	44	5	1.5 ± 0.6	728	79	19.5 ± 2.5
Total	3479	599	17	-	128	4	-	2752	79	-

[*] Means ± standard errors calculated from the average distance of all pixels within each MPA to the nearest pixel on land.

Figure 1. Terrestrial light pollution encroaching into the Taean Coast National Marine Park, South Korea between (A) 1992 and (B) 2012. Inset below displays the trend in mean pixel intensity derived from DMSP/OLS nighttime satellite images inter-calibrated using quantile regression on the median (Bennie *et al.* 2014a).

Figure 2. The distribution of artificially lit (containing at least one pixel with a digital number >5.5, Red) and unlit (where no pixels had a digital number >5.5, blue) contiguous Marine Protected Areas (A) around the world, and in (B) North West Atlantic and Mediterranean, (C) Gulf of Mexico and Caribbean, and (D) eastern coast of South America. Note that lit or unlit refers to any region within an MPA experiencing artificial light at night.

Figure 3. The distribution of contiguous Marine Protected Areas that experienced a significant increase (red), decrease (blue) or no change (purple) in artificial light at night (A) around the world, and in (B) North West Atlantic and Mediterranean, (C) Gulf of Mexico and Caribbean, and (D) eastern coast of South America. The amount of artificial light within each MPA was classified as significantly increasing or decreasing with 95% confidence using Mann Kendall tests of the monotonic trend in mean pixel intensity (digital number).

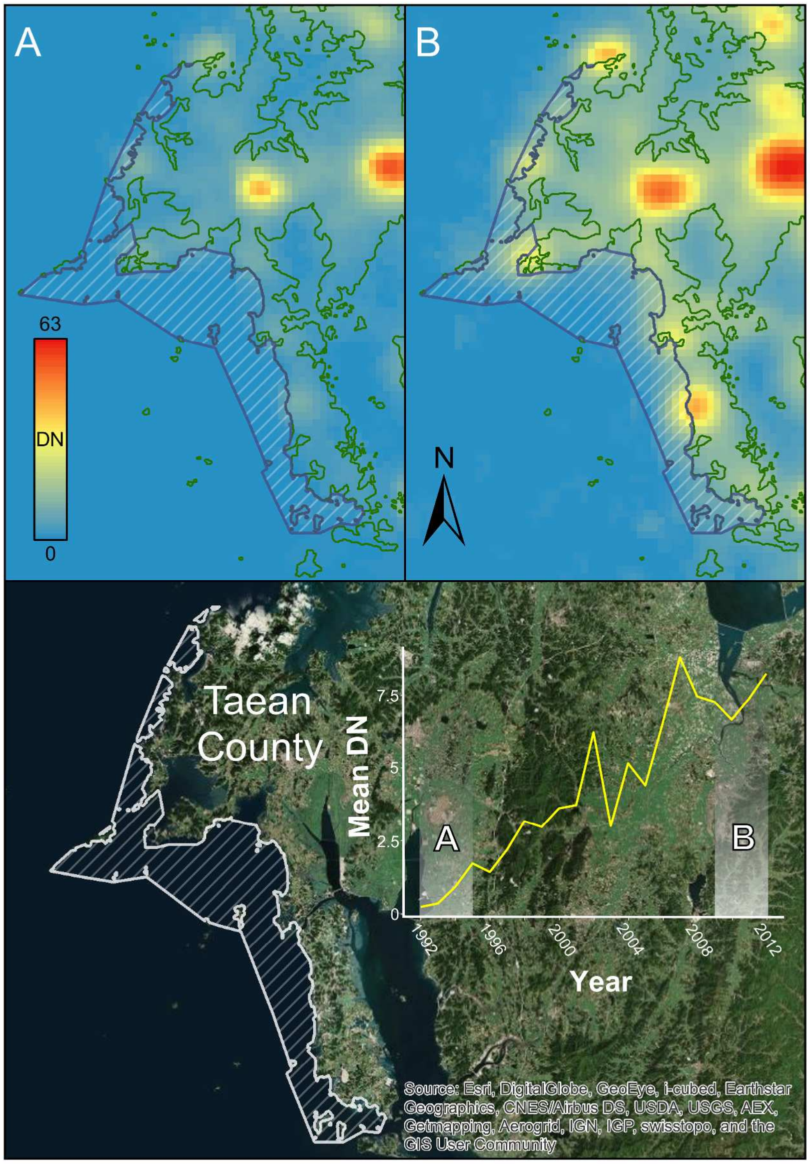

Figure 1. Terrestrial light pollution encroaching into the Taean Coast National Marine Park, South Korea between (A) 1992 and (B) 2012. Inset below displays the trend in mean pixel intensity derived from DMSP/OLS nighttime satellite images inter-calibrated using quantile regression on the median (Bennie et al. 2014a).

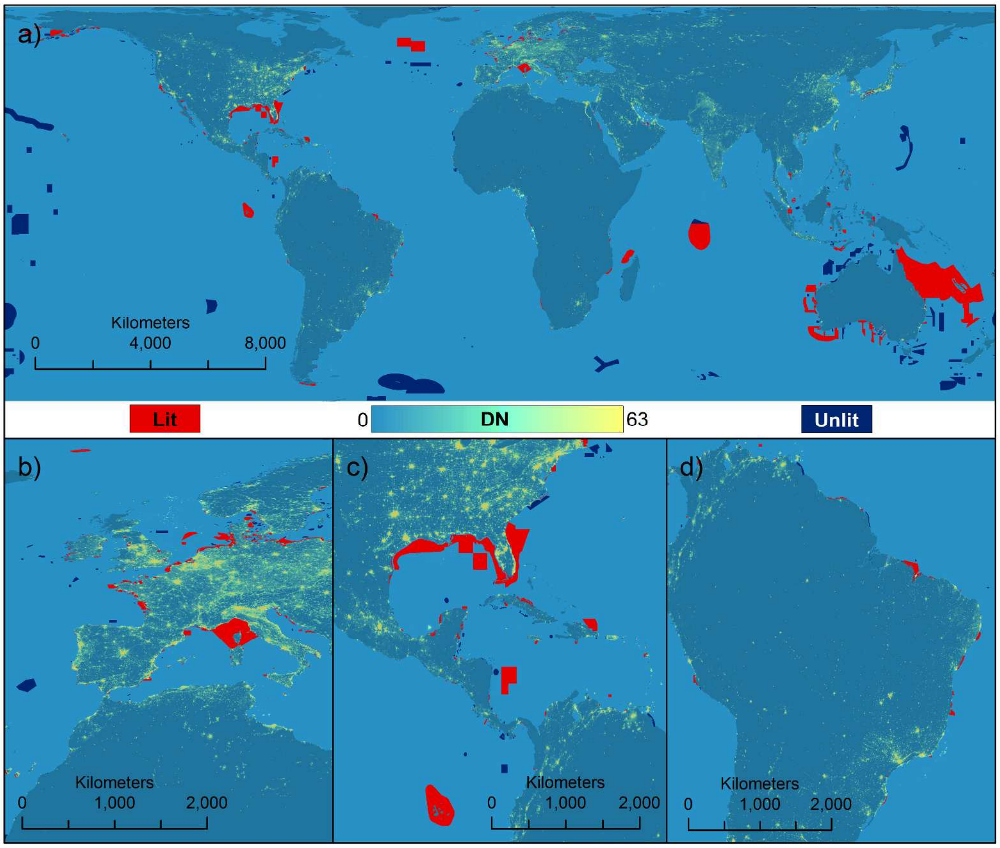

Figure 2. The distribution of artificially lit (containing at least one pixel with a digital number >5.5, Red) and unlit (where no pixels had a digital number >5.5, blue) contiguous Marine Protected Areas (A) around the world, and in (B) North West Atlantic and Mediterranean, (C) Gulf of Mexico and Caribbean, and (D) eastern coast of South America. Note that lit or unlit refers to any region within an MPA experiencing artificial light at night.

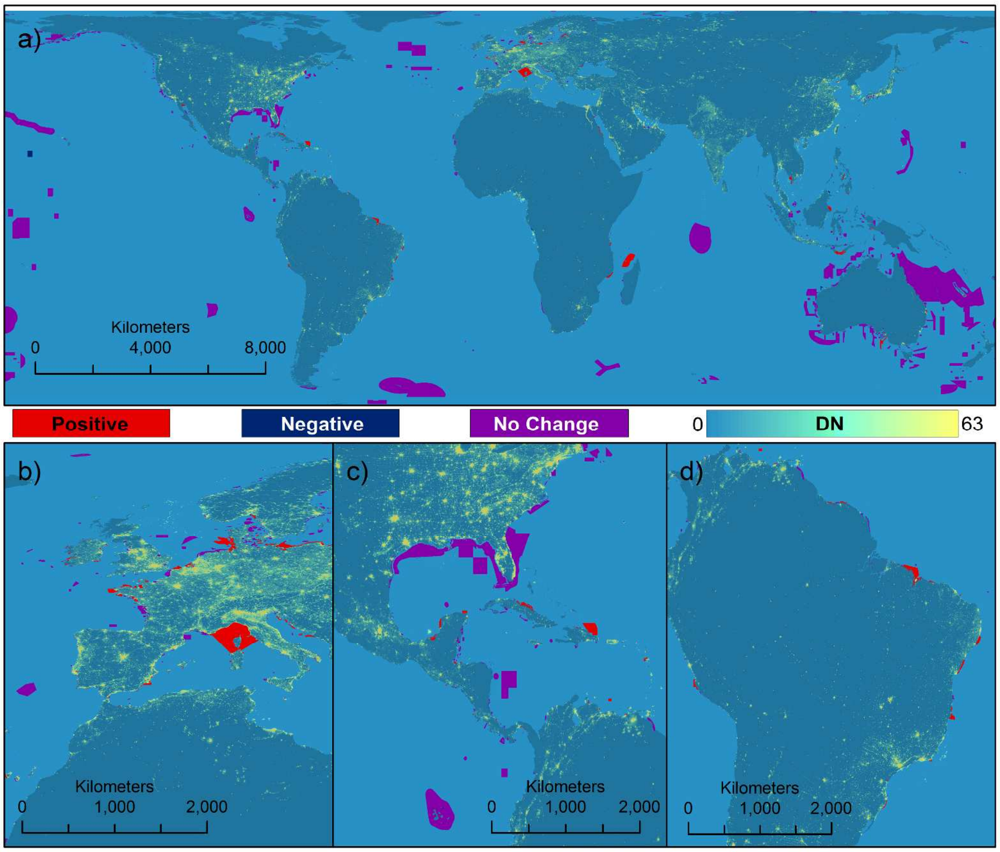

Figure 3. The distribution of contiguous Marine Protected Areas that experienced a significant increase (red), decrease (blue) or no change (purple) in artificial light at night (A) around the world, and in (B) North West Atlantic and Mediterranean, (C) Gulf of Mexico and Caribbean, and (D) eastern coast of South America. The amount of artificial light within each MPA was classified as significantly increasing or decreasing with 95% confidence using Mann Kendall tests of the monotonic trend in mean pixel intensity (digital number).