

Stemming the tide of light pollution encroaching into Marine Protected Areas

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Complete List of Authors:	Davies, Thomas; University of Exeter, Environment and Sustainability Institute Duffy, James; University of Exeter, Environment and Sustainability Institute Bennie, Jonathan; University of Exeter, Environment and Sustainability Institute Gaston, Kevin; University of Exeter, Environment and Sustainability Institute
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1 **Stemming the tide of light pollution encroaching into Marine Protected Areas**

2 Thomas W. Davies, James P. Duffy, Jon Bennie & Kevin J. Gaston

3 Environment and Sustainability Institute, University of Exeter, Cornwall, UK

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5 Author emails: Thomas.Davies@exeter.ac.uk james.philip.duffy@gmail.com

6 J.J.Bennie@exeter.ac.uk K.J.Gaston@exeter.ac.uk

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14 Corresponding author: Thomas W. Davies (Thomas.Davies@exeter.ac.uk), University of Exeter,

15 Penryn Campus, Penryn, Cornwall TR10 9FE, UK

16

17 **Abstract**

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

29

30 Introduction

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

35 Nighttime lighting can affect biological systems in a myriad of ways, although research has primarily
36 focused on terrestrial ecosystems, where such lighting causes habitat displacement (Stone *et al.*
37 2009), modulates reproductive development (Dominoni *et al.* 2013), disrupts navigation (Frank
38 1988), shifts daily activity patterns (Kempnaers *et al.* 2010), restructures communities (Davies *et al.*
39 2012), and affects ecosystem service provisioning (Lewanzik & Voigt 2014). Despite light being
40 intrinsic to the life history of many marine species, its impacts in marine ecosystems are less well
41 explored. Known examples include the disorientation and mortality of birds (Merkel 2010) and sea
42 turtle hatchlings (Witherington & Bjorndal 1991), the aggregation and exploitation of fish and squid
43 (Kiyofuji & Saitoh 2004, Becker *et al.* 2012), changing patterns of foraging by wading birds (Santos *et*
44 *al.* 2009), and altering the composition of sessile invertebrate communities (Davies *et al.* 2015). A
45 number of additional impacts on marine ecosystems are anticipated, since they are home to a
46 plethora of species guided by natural light cues in many behaviours (Thorson 1964, Tanner 1996,
47 Mundy & Babcock 1998, Naylor 1999, Cohen & Forward 2009). A number of marine invertebrate
48 species synchronise broadcast spawning events using lunar light intensity (Naylor 1999), corals being
49 the most notable example (Tanner 1996); zooplankton are guided by changing light intensity as they
50 migrate towards the sea surface at night (Cohen & Forward 2009), a behaviour that is suppressed by
51 artificially brightened skies in freshwater systems (Moore *et al.* 2000); and the introduction of whiter
52 lighting will likely affect prey location and bioluminescent communication (Davies *et al.* 2014).

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

55 2010, 22% of the world's coastal regions (excluding Antarctica) were experiencing some degree of
56 artificial light at night (Davies *et al.* 2014), a level that is increasing as the economies of developing
57 countries grow. Given the variety of ways in which marine species could be affected, marine
58 ecosystems are almost certainly being shaped by anthropogenic modifications to the natural light
59 regimes they evolved with. Light pollution is, however, novel among global anthropogenic stressors
60 (e.g. temperature, carbon dioxide, ocean acidification), in that changes to natural light regimes are
61 comparatively instantaneous to reverse. Although a limited number of conservation tools are
62 available to mitigate against its impacts, quantifying the extent of nighttime lighting in regions
63 protected for cultural, aesthetic, biodiversity and socio-economic value is a crucial step towards
64 identifying where preventative measures should be enforced (Davies *et al.* 2014). Gaston *et al.*
65 (2015) found that 7-42% of terrestrial protected areas experienced increases in artificial light
66 between 1992-2010. While previous studies highlighted the spatial extent of nighttime lighting
67 across the world's coastlines (Davies *et al.* 2014), and in marine regions inhabited by light sensitive
68 species (Aubrecht *et al.* 2008, Kamrowski *et al.* 2012, 2014a, Mazor *et al.* 2013), its extent in and
69 encroachment into Marine Protected Areas (MPAs) is unknown. These regions represent the
70 ecological marine assets most valued by humanity, hence determining the nighttime lighting they
71 are experiencing is central to justifying future protective measures.

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

76 **Methods**

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

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

99

100 The light pollution metrics for MPAs in both datasets were extracted from 21 intercalibrated
101 DMSP/OLS stable nighttime lights images (nominal 1km resolution) from 1992 to 2012 (Baugh *et al.*
102 2010). Each image is composed from multiple images taken on cloud free nights throughout the
103 year with the amount of artificial light in each pixel given by a digital number (D.N.) between 0 (no
104 artificial light) and 63 (value at which sensors saturate). Prior to analysis, we employed the methods
105 of Bennie *et al.* (2014) to address geo-location drift of up to 3 pixels, and lack of intercalibration
106 between images collected on different successive satellites. Geo-location drift was rectified by

1107 shifting images in consecutive years by + or -5 pixels in x (latitude) and y (longitude) directions and
1108 correlating the resulting pixel intensities to the median (2002) image in time. The x and y offset of
1109 the resulting 121 combinations that provided the highest Pearson correlation coefficient was
1110 selected for analysis. Images were intercalibrated to the 1994 image using quantile regression on
1111 the median (CRAN: quantreg). This technique relates median pixel intensities to one another so that
1112 it is insensitive to pixels that increase or decrease in intensity between years. Provided with a
1113 calibration region in which a minority of pixels have undergone changes in artificial lighting between
1114 time steps, quantile regression on the median gives robust estimates of parameters. We selected
1115 the same calibration region as Gaston *et al.* (2015), a subset of the global map that contained most
1116 of the UK, because changes in the street lighting stock in the region are localised in extent between
1117 1992 and 2012 and affect a minority of pixels (Bennie *et al.* 2014). 1994 was chosen as a reference
1118 to which all other images were calibrated because it displayed the highest proportion of pixels with
1119 digital numbers of both 0 and 63, the darkest and brightest measurements at which the satellite
1120 sensors saturate. By intercalibrating all images to this year, we ensured that estimates of trends in
1121 artificial light were calculated only from pixels that experienced a quantifiable change in intensity
1122 between years.

1123

1124 Bennie *et al.* (2014) demonstrated that when using this calibration approach 94% of increases, and
1125 93% of decreases in pixel intensity by 3 digital numbers, can be attributed to changes in artificial
1126 lighting on the ground (i.e. declining industry, urban expansion). MPAs were therefore classified as
1127 currently exposed to nighttime lighting if they contained any pixels where the intercalibrated digital
1128 number exceeded 5.5 (Davies *et al.* 2014, Gaston *et al.* 2015) in the 2012 image. The number and
1129 percentage of MPAs exposed or not were calculated, along with the area and percentage area of the
1130 global MPA network exposed. Temporal trends in artificial light (increasing, decreasing or neutral)
1131 were determined for each MPA using Mann Kendall tests of the monotonic trend in mean pixel
1132 intensity through time derived from DMSP images from 1992 to 2012 (Fig. 1). MPAs for which the

133 direction of the trend could not be established with 95% confidence were classified as having
134 experienced no change in artificial light (neutral).

135

136 **Results**

137 In 2012 4,051 (35%) of the world's 11,442 contiguous MPAs were experiencing artificial light (at least
138 one pixel >5.5 digital number) at night (Fig. 2A). Of those MPAs 57% (2,293) were exposed to
139 widespread light present in 100% of pixels, and 72% (2,901) across more than 50% of their
140 pixels (Table 1). Hence, not only is the presence of artificial light common in MPAs, but its extent
141 within those MPAs exposed is typically widespread. Regions in which a large proportion of MPAs
142 were exposed to artificial light include the North West Atlantic and Mediterranean Sea (Fig. 2B), the
143 Gulf of Mexico and Caribbean Sea (Fig. 2C), the eastern coast of South America (Fig. 2D), and coastal
144 bounded MPAs of Australia (Fig. 2A). The area of the world's MPA network experiencing nighttime
145 lighting in 2012 (based on total number of lit pixels across all MPAs) encompassed 60,452 km²,
146 however, because a limited number of protected area designations cover vast areas of ocean with
147 little human habitation, while the majority are small and coastal bounded (Fig. 2), this equates to
148 0.7% of the world's total MPA area coverage (lit pixels expressed as a proportion of total pixels
149 across all MPAs). Between 1992 and 2012, 1,687 (14.7%) of the world's contiguous MPAs
150 experienced significant increases in mean artificial light intensity, 305 (2.7%) experienced significant
151 decreases, and 9,450 (82.6%) experienced no change (Fig. 3A) (although the above results mean that
152 nighttime lighting is present in many no change areas).

153

154 Categories with high levels of human interaction contained a higher fraction of MPAs in which mean
155 artificial light intensity significantly increased between 1992 and 2012 (Table 2). Category I areas
156 encompass strict nature reserves or wilderness regions, hence it is unsurprising that these contained
157 the lowest percentage (9%, Table 2) of MPAs experiencing increases in average light intensity.

158 Categories II, IV and VI (national parks, habitat/species management areas, and regions where

159 sustainable resource use occurs) may be accessed for recreation, are managed using human
160 intervention or associated with previous human land use. A higher proportion (18% for II, 17% for IV
161 and 16% for VI, Table 2) of these MPAs experienced an increase in mean artificial light intensity over
162 the period. Landmarks protected for their monument status (category III) and protected seascapes
163 (category V) represent areas protected specifically for their associated cultural or aesthetic value,
164 and in the last case have been created through human-landscape interaction. It is unsurprising then
165 that the fraction of MPAs experiencing increases in mean artificial light intensity was highest (20%
166 for III and 25% for V, Table 2), since many of them are located close to human population centres.
167 Indeed, MPAs experiencing positive or negative trends in artificial light intensity were generally
168 closer (<3km) to the coast than those where light intensity did not change (Table 2) suggesting that
169 the observed trends were driven by coastal development.

170 Discussion

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

174 2.7% of contiguous MPAs experienced decreases in artificial light. Declines have also been observed
175 in some European nations and attributed to changes in prevailing lighting technologies, legislation,
176 and declining economic/industrial activity (Bennie *et al.* 2014). It seems plausible that these drivers
177 are equally likely to be the cause of decreasing artificial light in coastal and offshore regions. For
178 example, changes in rig lighting are expected as oil and gas prices fluctuate, wells run dry, and new
179 wells become established.

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

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

191

192 There has been great emphasis on managing fisheries, pollution, offshore development, and mineral
193 extraction in our oceans (Halpern & Warner 2002, Lester *et al.* 2009), and MPAs have proven a
194 useful tool for achieving these goals. Our work has shown that nighttime lighting is common in
195 these regions, and its effects warrant investigation both compared to and in combination with
196 previously recognized disturbances so that proportionate mitigation measures can be sought.

197 Reducing levels of artificial light in marine environments is challenging as it is often perceived as
198 beneficial for economic growth, security, operational safety and aesthetics in marine developments.
199 Marinas use artificial light for security and aesthetic purposes, while curbing its use in dockyards or
200 on ships and oil platforms could violate standards set for operational safety. Legal frameworks to
201 curtail use of artificial light in marine environments are yet to be developed because understanding
202 of how nighttime lighting affects marine ecosystems is limited, and has not warranted compromising
203 continued use for these activities. Despite light being recognized as a pollutant under the European
204 Commission Marine Strategy Framework Directive (Commission decision 2010/477/EU; MFSF 2010),
205 it states that there is currently insufficient information available to define limits of good
206 environmental status for its use. Artificial lighting is also seen as a symbol of modernity in many
207 developing nations, while in developed nations its use is often perceived as the norm (Lyytimaki
208 2013). Changing public perceptions of nighttime lighting towards avoiding its use is therefore a

209 major challenge. Combined with a lack of legislative options, conservation managers are left to seek
210 voluntary incentives to curb its use, by working with local communities to foster a healthy balance
211 between the benefits and environmental impacts (e.g. Kamrowski *et al.* 2014b).

212

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

229

230 Artificial light is prevalent and increasing in large proportions of the global MPA network. Given the
231 expectedly pervasive impacts of nighttime lighting on marine ecosystems, improved understanding
232 of its ecological effects is urgently needed to inform and justify proportionate mitigation strategies.
233 The current paucity of information available to support legal frameworks for mitigation suggests
234 conservation managers should seek dark sky status for their reserves as a means of effectively

235 stemming the advance of light pollution into regions that are currently naturally lit, if not individual
236 MPAs in their entirety.

237

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242

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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	<i>n</i> lit MPAs	% lit MPAs	Mean MPA area (km²)
= 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		
		<i>n</i>	%	<i>Mean distance to coast (km)*</i>	<i>n</i>	%	<i>Mean distance to coast (km)*</i>	<i>n</i>	%	<i>Mean distance to coast (km)*</i>
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).

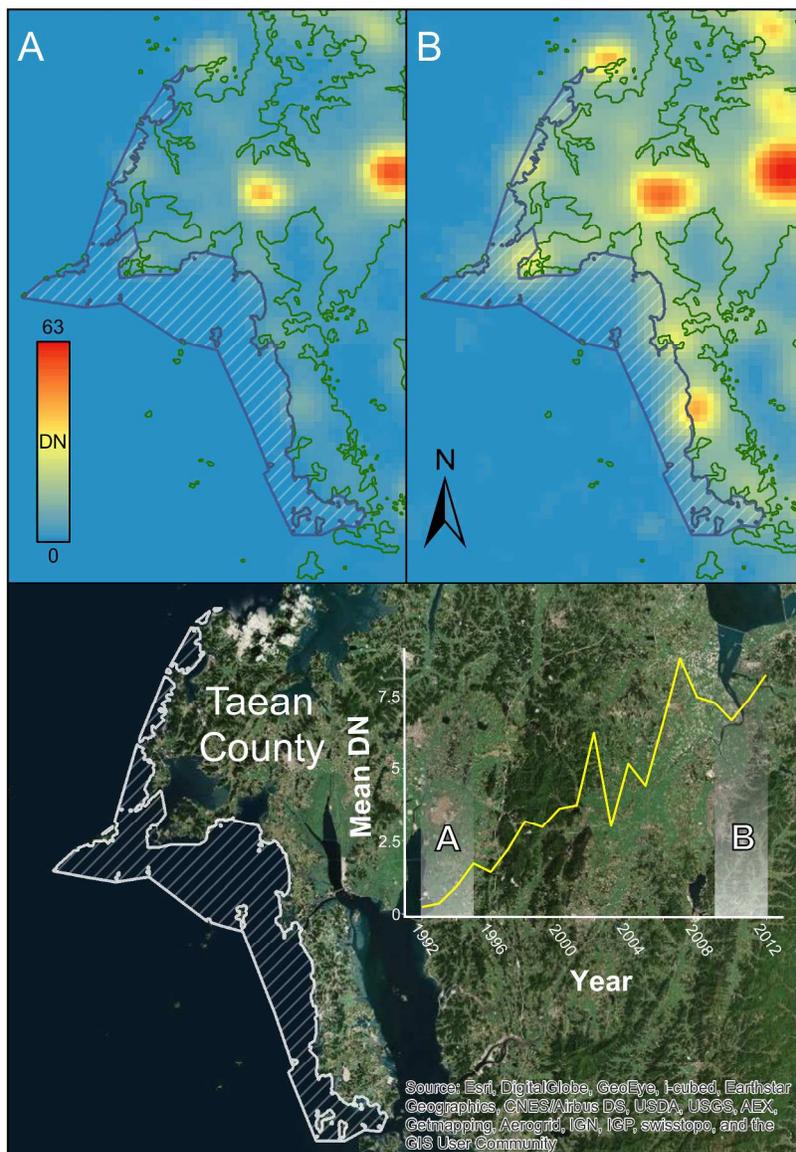


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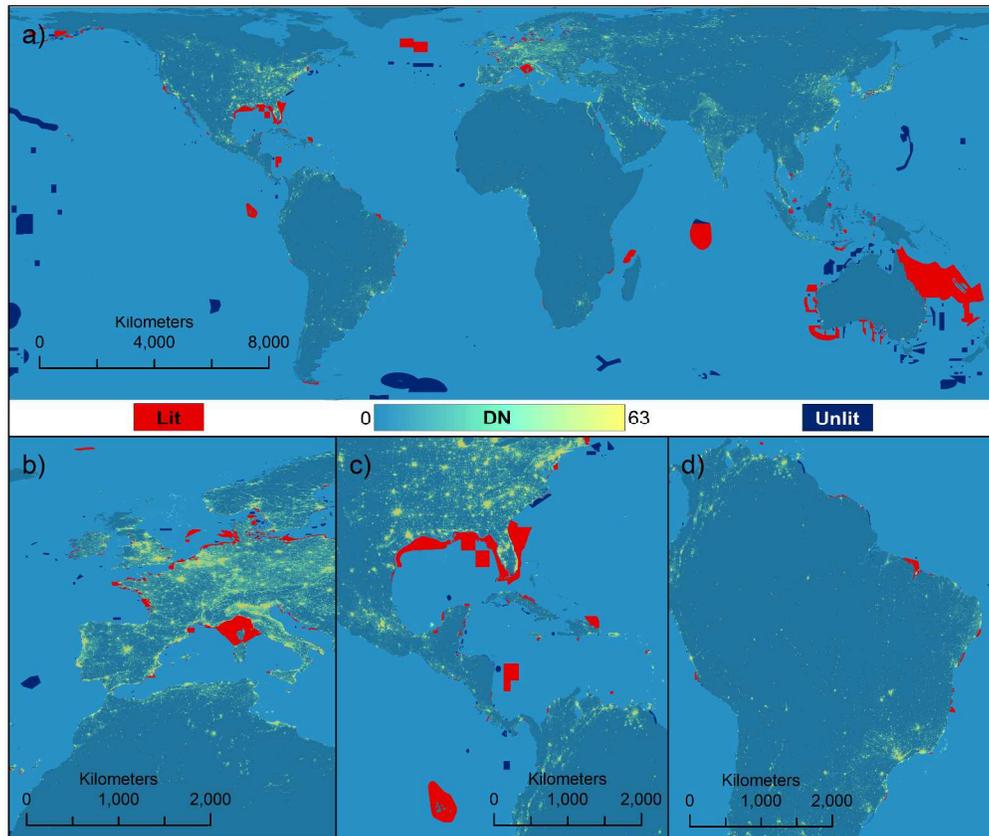


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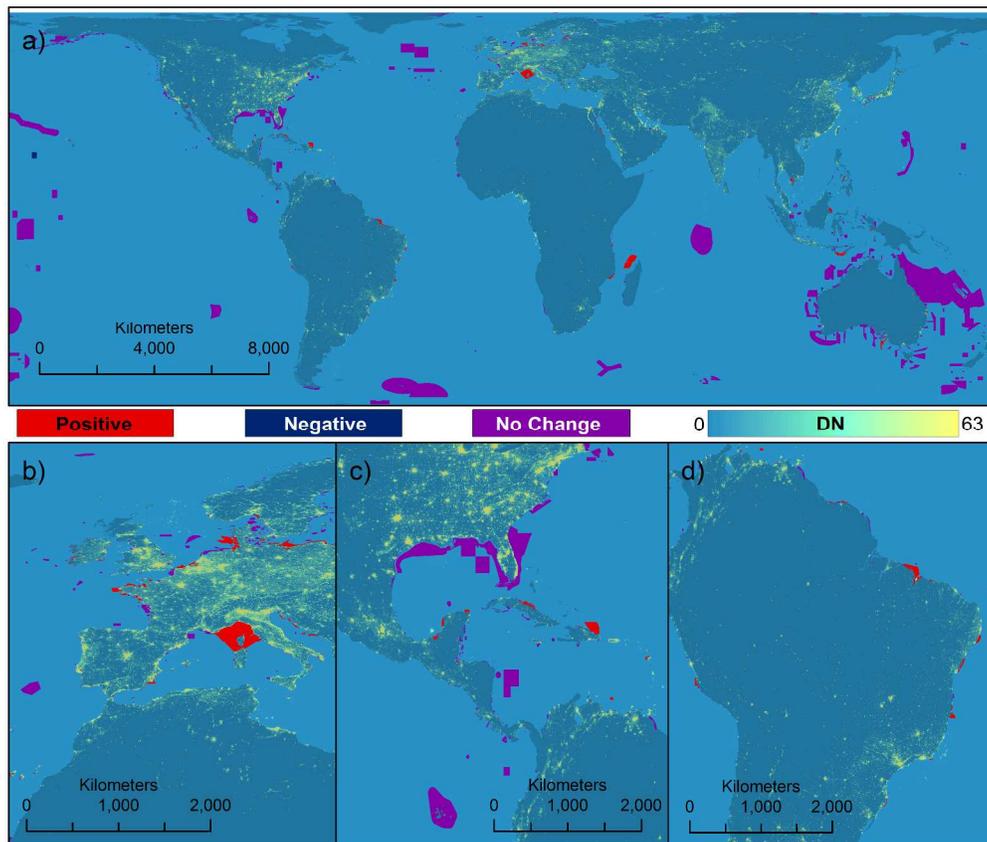


Figure 3. The distribution of contiguous Marine Protected Areas that experienced a significant increase (red), decrease (blue) or no change (purple) in artificial light at night (A) around the world, and in (B) North West Atlantic and Mediterranean, (C) Gulf of Mexico and Caribbean, and (D) eastern coast 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).