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Quantifying the erosion of natural darkness in the global protected area system

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Abstract: *The nighttime light environment of much of the earth has been transformed by the introduction of electric lighting. This impact continues to spread with growth in the human population and extent of urbanization. This has profound consequences for organismal physiology and behavior and affects abundances and distributions of species, community structure, and likely ecosystem functions and processes. Protected areas play key roles in buffering biodiversity from a wide range of anthropogenic pressures. We used a calibration of a global satellite data set of nighttime lights to determine how well they are fulfilling this role with regard to artificial nighttime lighting. Globally, areas that are protected tend to be darker at night than those that are not, and, with the exception of Europe, recent regional declines in the proportion of the area that is protected and remains dark have been small. However, much of these effects result from the major contribution to overall protected area coverage by the small proportion of individual protected areas that are very large. Thus, in Europe and North America high proportions of individual protected areas (>17%) have exhibited high levels of nighttime lighting in all recent years, and in several regions (Europe, Asia, South and Central America) high proportions of protected areas (32–42%) have had recent significant increases in nighttime lighting. Limiting and reversing the erosion of nighttime darkness in protected areas will require routine consideration of nighttime conditions when designating and establishing new protected areas; establishment of appropriate buffer zones around protected areas where lighting is prohibited; and landscape level reductions in artificial nighttime lighting, which is being called for in general to reduce energy use and economic costs.*

Keywords: light, management, pollution, reserves, sky glow, threats

Cuantificación de la Erosión de la Oscuridad Natural en el Sistema Global de Áreas Protegidas

Resumen: *El ambiente de luz nocturna de la mayor parte de la Tierra se ha transformado por la introducción de la luz eléctrica. Este impacto continúa esparciéndose con el crecimiento de la población humana y de la extensión de la urbanización. Esto tiene consecuencias profundas sobre la fisiología y el comportamiento de los organismos y afecta a la abundancia y la distribución de especies, a la estructura de la comunidad y probablemente a los procesos y funciones de los ecosistemas. Las áreas protegidas juegan un papel importante en el amortiguamiento de una amplia gama de presiones antropogénicas para la biodiversidad. Usamos una calibración de un conjunto de datos satelitales globales de luces nocturnas para determinar que tan bien desempeñan este papel con respecto a la iluminación nocturna artificial. En un nivel global, las áreas que están protegidas tienden a ser más oscuras en la noche que aquellas que no lo están, y además, con la excepción de Europa, las declinaciones regionales recientes en la proporción del área que está protegida y permanece oscura han sido menores. Sin embargo, muchos de estos efectos resultan de una mayor contribución a la cobertura total del área protegida por parte de la pequeña proporción de áreas protegidas individuales que son muy grandes. Por esto en Europa y América del Norte, una alta proporción de áreas protegidas individuales (>17%) ha exhibido niveles altos de iluminación nocturna en todos los años recientes y en varias regiones (Europa, Asia, América Central y América del Sur) proporciones altas de áreas protegidas (32-42%) han tenido incrementos significativos de iluminación nocturna. Limitar y revertir la erosión de la oscuridad nocturna en las áreas protegidas requerirá una consideración rutinaria de las condiciones nocturnas cuando se designen*

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y establezcan nuevas áreas protegidas; un establecimiento de zonas de amortiguamiento apropiadas donde se prohíba la iluminación alrededor de las áreas protegidas; y una reducción de los niveles de paisaje en la iluminación nocturna artificial, la cual se pide en general para reducir el uso de energía y los costos económicos.

Palabras Clave: amenazas, brillo celestial, contaminación, luz, manejo, reservas

Introduction

Humans have transformed the nighttime light environment across much of the earth. Natural intensities, spectra, and cycles of light have been modified by lighting from public street lighting, advertising, public and private buildings, and vehicles and by sky glow, which is produced by upwardly emitted and reflected electric light being scattered by water, dust, and gas molecules in the atmosphere. These impacts continue to spread as the human population grows and becomes more urbanized (Cinzano et al. 2001; Hölker et al. 2010*a*) and as lighting technology changes (especially the move to "white light" lamps). The biological consequences of these changes to nighttime lighting are profound (Longcore & Rich 2004; Rich & Longcore 2006; Perkin et al. 2011; Gaston et al. 2012, 2013, 2014). At the organismal level they can influence physiology, behavior, reproduction, and movements (e.g., Witherington & Bjorndal 1991; Ugolini et al. 2005; Miller 2006; Lorne & Salmon 2007; Stone et al. 2009, 2012; Kempenaers et al. 2010; Warrant & Dacke 2010; Dominoni et al. 2013). In turn, these effects can alter the abundances and distributions of species, community structure, and likely ecosystem functions and processes (e.g., Davies et al. 2012; Mazor et al. 2013; Meyer & Sullivan 2013). The breadth of biological effects and the diversity of taxa for which these effects are documented continue to grow very rapidly (Gaston et al. 2013). Whilst attention has focused foremost on the direct effects, it is also clear there are strong synergies and interactions between nighttime lighting and other pressures on biodiversity, including habitat fragmentation and climate change (Gaston et al. 2014).

Although much remains to be discovered, there is growing evidence that the biological effects of artificial light are not limited to the direct vicinity of the lit area and may spread over much larger extents via several mechanisms. First, individual lights may be visible many kilometers from their source, and can disrupt navigation in migrating species (e.g., Rodriguez & Rodriguez 2009). Second, sky glow may illuminate areas at levels equivalent to high elevation moonlight and at low, but detectable, levels sufficient for many species to use at a considerable distance from urban areas (Kyba & Hölker 2013). Third, sky glow may obscure natural patterns of starlight or polarized light in the night sky used by species for orientation (Kyba et al. 2011; Dacke et al. 2013). Finally, lit features such as towns, cities, and roads may act as population sinks for species attracted to light or barriers to movement for nocturnal species reluctant to cross illuminated areas (Threlfall et al. 2013). Hence, artificial lighting may have an effect on natural ecosystems even when the source of lighting lies many kilometers away.

The designation, establishment, and maintenance of protected areas is widely considered key to buffering biodiversity from a diverse range of, often intense, anthropogenic pressures (Margules & Pressey 2000; Gaston et al. 2002). For those pressures that derive at least proximally from activity within the bounds of a given protected area (e.g., habitat loss, overexploitation), this is principally achieved through appropriate local management actions (Gaston et al. 2008). For pressures, such as artificial nighttime lighting, that derive predominantly (but not necessarily exclusively) from outside a given protected area, their influence is primarily determined by where that area is situated and by management actions beyond its bounds that are usually shaped by environmental legislation and regulation. Protected areas are seldom, if ever, designated with low levels of light pollution as an explicit criterion, although initiatives such as the International Dark Sky Park movement have led to an increase in recognition of dark skies as a management goal for some protected areas (Welch & Dick 2012; International Dark-Sky Association 2013). However, protected areas are known to be established on areas of steeper slopes, low productivity, low economic worth, and low human density (e.g., Pressey 1994; Armesto et al. 1998; Scott et al. 2001; Cantú et al. 2004; García et al. 2005), and are therefore frequently likely to be located in sites with relatively dark skies. For this reason, protected areas can be considered key benchmarks of night skies in natural and seminatural environments, which in turn is vital to understanding the nature and intensity of artificial light. Thus questions arise as to whether protected areas have lower levels of such lighting than might otherwise be expected and how those levels are changing. In other words, how well are protected areas buffering biodiversity from artificial nighttime lighting?

We used a calibration of a global satellite data set of nighttime lights (Defense Meteorological Satellite Program's Operational Linescan System [DMSP/OLS]) to address these questions and tested the specific hypotheses that protected areas remain darker than unprotected lands; protected areas are increasing in artificial nighttime lighting; and protected areas that have International Union for Conservation of Nature (IUCN) categories have varying levels of change in nighttime lighting depending on the objectives of their category (i.e., more areas associated with human activity have significant increases in nighttime lighting than areas that are not associated with human activity).

Methods

Data

The full World Database of Protected Areas (WDPA) data set was downloaded in October 2012 (IUCN & UNEP 2012). It contained data on 173,275 unique protected areas across the globe in vector format.

We downloaded 19 yearly (1992–2010) nighttime stable lights composite images from http://ngdc.noaa.gov/eog/dmsp/downloadV4composites.html which have been created with data from the DMSP/OLS. The distribution of artificial light from these images has been used as a proxy for urbanization (Sutton 2003; Li et al. 2013), population density (Amaral et al. 2006), and economic activity (Chen & Nordhaus 2011), as well as to assess the spatial extent of light pollution itself (Cinzano et al. 2001; Butt 2012). The images are nominally at 1-km resolution but are resampled from data at 2.7-km resolution, and each pixel is represented by a digital number (DN) from 0 to 63. Zero represents darkness, whereas very brightly lit urban areas typically saturate at values of 63. Composites for each year have been created with data from the same satellite (the most recently launched) and for the years where 2 light data sets were available. At the time of download, the 2009 and 2010 rasters had a half pixel offset. We corrected this prior to analysis.

The nature of the raw nighttime light data meant that in some parts of the images there was also an element of geolocation error. To reduce this, we used 2001 as a base year, the image to correlate other years against, because it was at the center of our time series. Using the statistical package R (R Core Team 2013) with the packages rgdal (Bivand et al. 2013) and raster (Hijmans & van Etten 2013), each of the 19 images were split into 200 tiles of equal size (2157 × 1709 pixels). Each tile was consecutively shifted by -5 to $+5$ pixels in both the x (longitude) and y (latitude) directions. A Pearson correlation of the DN values of all pixels in each of the 121 shifted tiles and the original 2001 corresponding tile was calculated. The x and y offset with the maximum correlation of all 121 was applied to the tile and it was adjusted accordingly to maximize the matching of spatial pattern between images. This process was repeated for all tiles containing land masses ($n = 114$) and for all years (excluding the base year). They were then stitched back together to create an adjusted global image for each year. The mean number of tiles corrected per year across all years was 74; 2000 had the fewest corrected tiles ($n = 14$) and 2010 had the most ($n = 113$). For drift corrected tiles, 95% of r^2 values were above 0.57 and the average was 0.83. The maximum shift was 4 pixels.

No onboard calibration of the nighttime lights sensors exists, and the time series include data from 6 different satellites with different sensors, so the DNs within the images must be cross-calibrated carefully in order to assess accurately changes in brightness over time (Elvidge et al. 2009). Li et al. (2013) addressed this problem using robust regression techniques to map changes in lighting in rapidly developing regions of Asia. We used a similar robust regression technique, quantile regression through the median (as described in Bennie et al. [2014]), using the quantreg package (Koenker 2013) in R to calibrate the DMSP/OLS data.

Quantile regression through the median allows for a proportion of pixels within the calibration set to increase (or decrease) in brightness between images without exerting excessive leverage on the calibration. However, it is likely to be a conservative estimate of the global increase in artificial light intensity for 2 reasons. First, signal saturation in brightly lit urban areas means that further increases in light intensity in these areas cannot be detected. Second, although efforts were taken to calibrate images in a region with relatively stable levels of nighttime lighting, increases in brightness are more likely than decreases and so it is likely that any drift in calibration will lead to underestimation of relative light intensities toward the end of the study period. The year 1994 was chosen as a base reference because the image for this year had a high proportion of pixels with DNs of both zero and 63. Calibrations of the data set within an assumed no-change region have been used to quantify change (Elvidge et al. 2005, 2009).

Using robust regression techniques relaxes the requirement for a calibration area that has no absolute change in brightness throughout the calibration period and allows for a proportion of pixels within each time step to increase or decrease in brightness without affecting the calibration coefficients. Eight potential terrestrial training areas were investigated to find the one with least variation between 1992 and 2010. Training areas as opposed to whole images were used because this would have been excessively computationally intensive. Each was approximately 1000 × 1000 pixels in size and incorporated a different part of Earth's surface. A subset of the global image that contained most of the United Kingdom had the most stable data and was used for calibration. Each consecutive year from 1992 to 2010 was then calibrated against this base year using this area.

Bennie et al. (2014) showed that over 94% of observed increases in DN of more than 3 units and over 93% of observed decreases of the same magnitude could be attributed to a known change on the ground consistent with the direction of change (i.e., urban expansion, industrial closure). We defined a threshold for darkness of <5.5 DN. By using a threshold effectively twice the detection limit for change, we defined a conservative estimate of lit area and limited the extent to which dark sites may be classified as lit due to noise in the data set or calibration errors.

Processing

The following operations were performed in ArcMap 10 (ESRI 2011) unless stated otherwise. First, all marine or partially marine protected areas were removed using an attribute table filter that left just terrestrial protected areas ($n = 165{,}794$). The terrestrial polygons were then split into 6 broad geographical regions (Africa, Asia, Australia and New Zealand, Europe, North America, and South and Central America). All of the WDPA and DMSP/OLS data were projected to the Behrmann equal area projection. This projection meant that every pixel in the nighttime lights imagery was 810.87 × 810.87 m. Some protected areas consisted of more than 1 discrete polygon, yet for this analysis each spatial polygon was handled separately. To achieve this, each of the 6 regional shapefiles was dissolved and every resulting self-contained polygon was defined as a unique feature class within a shapefile with the multipart to singlepart tool. GDAL/OGR (GDAL 2012) tools were then used to extract all qualifying pixels for each of the polygon features. Qualifying pixels were those with center points that fell within the boundaries of a protected area network polygon. This was repeated for every self-contained polygon for all 19 years of nighttime lights data. Some protected areas were designated after the start of this time series. It is not possible to control for this given the inconsistent nature of the available designation data and the form of the analyses, but this is unlikely to have a significant impact on the results reported, given the nature of those findings.

A second set of analyses were undertaken with just those protected areas with designated IUCN categories ($n = 56{,}226$). Protected areas have been classified by the IUCN on a I–VI scale on the basis of their respective management objectives (IUCN 2012). The terrestrial polygons used in the prior global network analysis which had a category assigned were split into 6 shapefiles by IUCN category with an attribute filter (ESRI 2011). To avoid replication of data due to overlap, once pixels had been extracted for 1 protected area they were treated as no longer available for extraction by another. In light of this decision, each of the 6 category shapefiles were extracted in ascending order; the protected area features within the shapes were extracted in descending order by size. For example, the largest protected area in category I was used as a mask, those pixels were then turned to NULL in the raster, and the second largest protected area in category I was used as a mask, etc. Once all category I protected areas had been processed, category II protected areas were used as masks, again in descending size order but with the nighttime lights rasters inclusive of the NULL data from the prior category (i.e., excluding areas assigned as category I). This was repeated for all 6 categories, ensuring that all pixels were used only once. All data extraction and modification of raster files was performed with GDAL/OGR tools (GDAL 2012).

A global landmass vector was obtained from http://www.gadm.org/ (Global Administrative Areas 2012). In ArcMap 10 (ESRI 2011), countries from each of the 6 aforementioned geographical regions were selected and exported as new shapefiles. Using the extract by mask tool in ArcMap, clipped images were created for each of the 6 regions for all 19 years. Frequency counts were then calculated indicating the distribution of the DNs for each year in order to compare results for protected areas with overall changes in nighttime lighting.

Analyses

All analysis was performed in the statistical package R (R Core Team 2013). For both the protected area network polygons and protected areas as individual units, the Mann-Kendall trend test was used to identify any significant trends in nighttime light values. The mean of all calibrated pixels within each area for each of the 19 years was used in the test. This analysis was performed using the Kendall package (McLeod 2011). Kendall's tau (τ) was also calculated for individual protected areas in all 6 IUCN categories.

The uniformity of the nighttime light image within individual protected areas was measured by looking at the proportion of total pixels that contributed to 95% of the cumulative DN found within them (Σ DNs).

Results

Across the land masses of the world the majority of areas remained dark at night. We estimated that at least 86% of the terrestrial surface (excluding Antarctica) was in relative darkness ($DN \leq 5.5$) in any 1 year between 1992 and 2010 (Fig. 1a). The average for all 19 years was 92%. For all 6 major terrestrial regions, areas that were protected tended to have lower nighttime light levels than those that were not protected (Table 1). The difference was small in Africa and in Australia and New Zealand but more marked in Asia, Europe, North America, and South and Central America (Table 1).

Based on the average calibrated data, the proportion of dark pixels declined between 1992–1995 and 2007–2010 in both protected and unprotected areas across all regions (Fig. 2). Generally these declines were small. For protected areas it was only in Europe that a substantial decline (−15.6%) in the total protected area classified as dark occurred. However, with regards to unprotected areas Europe saw a marked decline, and there were also

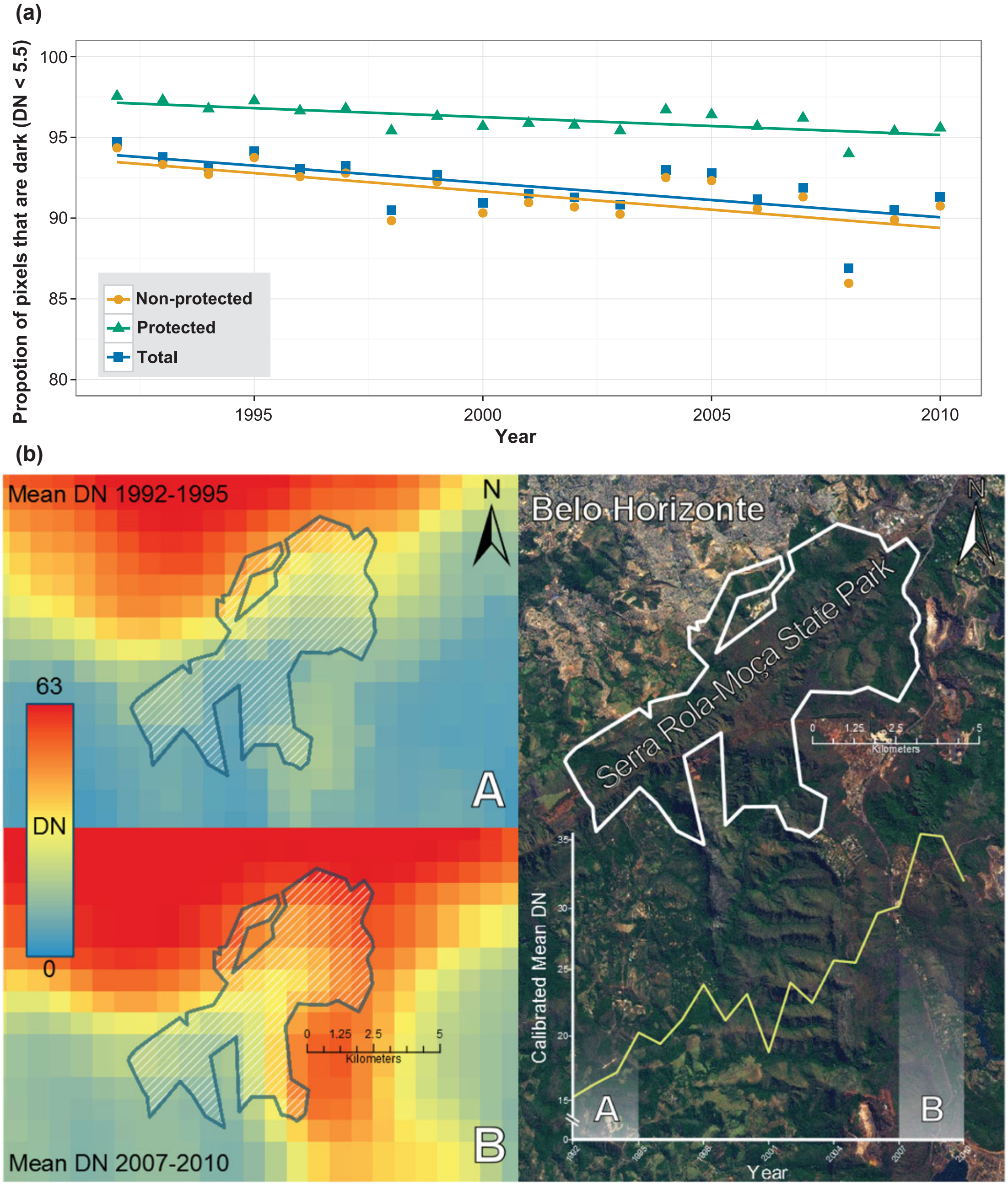

Figure 1. (a) Change in the global proportion of pixels that are dark (DN <5.5, where DN is an index of pixel brightness) in protected and unprotected areas over time and (b) nighttime lighting in Serra Rola-Moça State Park (near Belo Horizonte, Brazil) in 1992–1995 (A) and 2007–2010 (B). Satellite imagery courtesy of ESRI imagery basemap (ESRI 2013).

moderate decreases in Asia, North America, and South and Central America (Fig. 2). A chi-square test showed that in all regions the average count of lit (DN > 5.5) pixels was significantly less in protected areas than unprotected areas when compared to unlit pixels ($p < 0.001$). Similarly a chi-square test showed that in all regions there was a greater proportion of unprotected area with increased brightness (>5.5 change in DN over the 19 years) than protected area ($p < 0.001$).

Between 1992 and 2010 there were widespread increases in the average nighttime light in many protected areas (Table 2). Particularly notable are the 32–42% ($n = 13{,}061$) of protected areas in Europe, Asia, and South and Central America that have had significant increases. Across all regions very few protected areas had significant decreases (Table 2). Protected areas in Australia and New Zealand, Europe, and North America tended to be smaller in size than in Africa, Asia, and

Table 1. The percentages of total pixels in protected and unprotected areas in different regions grouped by the level of nighttime lighting, as measured by digital number (DN) values split into 8 bins.*

			Bin							
Region	*Area type*	*Total size of area (km^2)*	*0-5.5*	*5.5-9.5*	*9.5-19.5*	*19.5-29.5*	*29.5-39.5*	*39.5-49.5*	*49.5-59.5*	*59.5-63*
Africa	protected	3,339,504	99.62	0.17	0.12	0.03	0.02	0.02	0.01	0.01
	unprotected	29,566,290	98.36	0.67	0.5	0.16	0.10	0.08	0.07	0.06
Asia	protected	4,340,200	98.34	0.9	0.5	0.12	0.06	0.04	0.03	0.02
	unprotected	44,089,577	91.08	4.33	2.8	0.68	0.37	0.29	0.23	0.22
Australia and New Zealand	protected	1,002,642	99.66	0.16	0.11	0.03	0.02	0.01	0.01	0
	unprotected	6,955,705	99.05	0.35	0.29	0.09	0.05	0.04	0.04	0.07
Europe	protected	1,132,546	64.78	15.6	13.14	3.25	1.52	0.95	0.55	0.21
	unprotected	4,748,280	57.73	16.65	14.73	4.22	2.37	1.79	1.44	1.07
North America	protected	1,601,856	96.93	1.49	0.97	0.25	0.14	0.10	0.06	0.06
	unprotected	18,540,066	85.51	5.82	4.65	1.30	0.75	0.61	0.54	0.82
South and Central America	protected	3,830,032	98.66	0.62	0.42	0.12	0.07	0.05	0.04	0.04
	unprotected	16,581,421	94.31	2.58	1.76	0.48	0.27	0.21	0.17	0.21

**Averages of all 19 years studied. The lowest bin (DN = 0-5.5) represents relative darkness, whereas the highest bin (DN = 59.5-63) indicates the brightest pixels.*

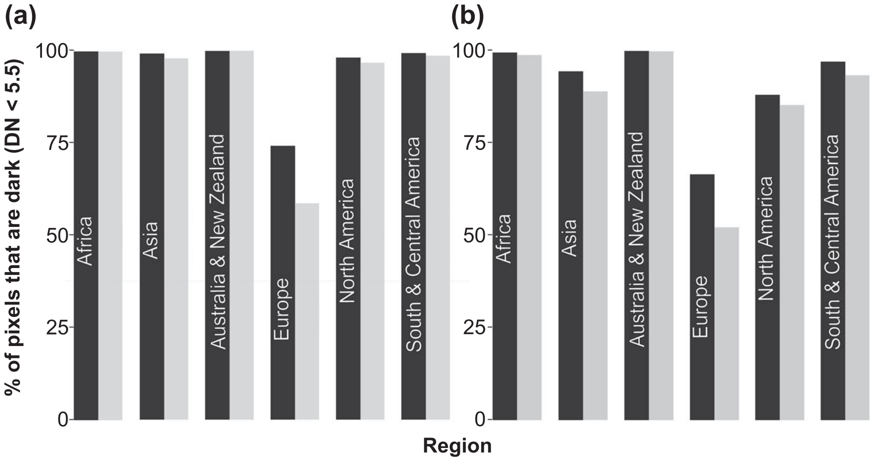

Figure 2. Percentage of pixels classified as dark (DN < 5.5) averaged over the first (dark bars) and last (light bars) 4 years in the time series across 6 regions for (a) protected and (b) unprotected areas.

Table 2. Results of Mann-Kendall trend test of changes in mean nighttime lighting in protected areas across 6 regions ($p < 0.05$).

Region	*Mean protected area size (km^2)*	*Protected area size SE*	*Total number of areas*	*Significant increase (%)*	*Significant decrease (%)*	*Nonsignificant light trend**
Australia and New Zealand	76.30	14.38	13,140	6.80	0.43	2.14
North America	57.47	7.87	27,874	8.89	3.40	17.37
Africa	847.59	121.28	3,940	13.15	1.09	1.90
Europe	34.80	3.35	32,540	32.12	2.15	24.28
South and Central America	1257.81	284.89	3,045	38.52	0.62	7.36
Asia	1,273.533	278.47	3,408	42.14	0.85	2.00

**Protected areas with a mean digital number ≥5.5 for all years that did not show a significant trend in nighttime lighting. Digital number is defined in Table 1's footnote.*

South and Central America. However, in Africa, Asia, and Australia and New Zealand those showing an increase in light tended to be significantly smaller. In Europe and North America, they were significantly larger (Supporting Information). Many large protected areas remained dark; over 95% of protected pixels fell within dark (mean DN < 5.5 for all 19 years) protected areas apart from in Europe, where only 49.5% of protected pixels did. In Europe a substantial number of protected areas (24.3%) exhibited high levels of nighttime lighting (DN ≥ 5.5) in all years, but there was no significant directional temporal change in that lighting. This was also true of North America (17.4%), but not of other regions (Table 2).

For the majority of protected areas throughout all 6 regions, a greater proportion of total pixels contributed to 95% of total brightness averaged over the last 4 years of the time series compared with the first 4 (Fig. 3).

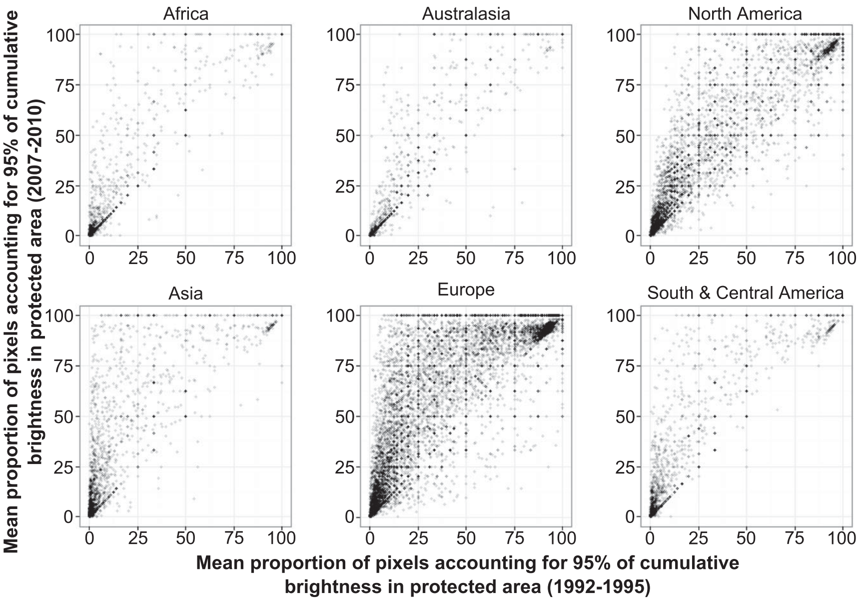

Figure 3. Mean proportion of pixels accounting for 95% of cumulative brightness in protected areas from 1992 to 1995 relative to that from 2007 to 2010.

Especially in North America and Europe, some protected areas displayed uniform nighttime light spread within protected areas at both the beginning and end of the study period.

With regards to IUCN categories, a lower proportion of category I protected areas had increased nighttime lighting than any other category. This was also the case when considering the proportion of the total area covered by each category (Fig. 4). Category V protected areas were the most heavily affected; over 30% of individual areas and approximately 50% of their total coverage exhibited significant increases in nighttime lighting.

Discussion

Artificial nighttime lighting is increasingly widely recognized as posing a substantial threat to biodiversity through its restructuring of the ecological and evolutionary night (e.g., Rich & Longcore 2006; Hölker et al. 2010*a*, 2010*b*; Perkin et al. 2011; Gaston et al. 2013). In particular, it is evident that alongside the more obvious lethal effects (e.g., collisions with light towers, enhanced likelihood of predation), there is a wide range of nonlethal biological effects of artificial nighttime lighting (e.g., changes to time available for foraging and to circadian rhythms [Gaston et al. 2013]). A variety of approaches have been suggested to limit the impact of artificial nighttime lighting, including preventing areas from being artificially lit; limiting the duration of lighting; reducing the trespass of lighting into areas that are not intended to be lit (including the night sky); reducing the intensity of lighting; and changing the spectral composition of lighting (Gaston et al. 2012). Of these arguably the simplest and the most important is the retention of existing darker areas. Protected areas are obvious priorities for such action.

At a global scale, our results show that organisms within protected areas are indeed often relatively well buffered from the effects of artificial nighttime lighting. Even in more intensely lit regions such as Europe, protected areas tend to be darker than those that are not protected (Table 1). In the main, this situation was maintained throughout the study period of 1992–2010; the proportion of the overall protected area that was dark underwent a substantial decline only in Europe (Fig. 2). This is not to say, however, that natural lighting conditions within protected areas are not coming under pressure. The overall picture is strongly influenced by the frequency distribution of the sizes of protected areas. A relatively few large ones contribute a high proportion of the overall coverage by protected areas, and the vast majority of protected areas are small (Gaston et al. 2008). The larger protected areas have been better buffered from increases in nighttime lighting (Supporting Information). This is likely a direct result of their large size, which means that much of their extent will be displaced far from potential sources of artificial nighttime lighting (e.g., towns, cities, transport infrastructure), and of the designation and establishment of larger protected areas in more remote regions, where competition with other forms of land use is typically lessened (Cantú-Salazar & Gaston 2010). Smaller protected areas have a much greater likelihood of experiencing increases in nighttime lighting. Because areas of such sizes predominate, the overall proportions of protected areas with these increases have been marked (32–43%) in several regions (Table 2). Notably in Asia, despite the large average size of protected areas, 43% have had significant increases in lighting. This trend is likely to continue, given the rapid growth in electric lighting in the emerging economies of China, India, and Southeast Asia (Small & Elvidge 2013). This provides an additional argument to many others

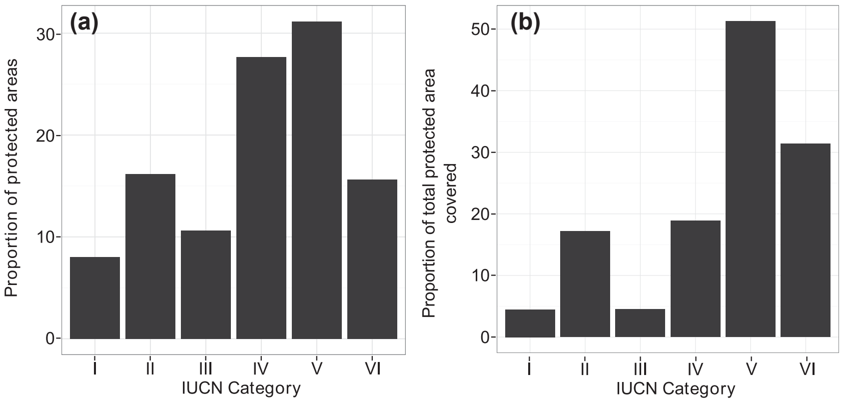

Figure 4. The proportion of (a) individual protected areas and (b) total protected area with significant increases in nighttime lighting by International Union for Conservation of Nature (IUCN 2012) category (I, strict nature reserve or wilderness area; II, national park; III, natural monument or feature; IV, habitat or species management area; V, protected landscape; VI, protected area with sustainable use of natural resources).

(e.g., Soulé & Terborgh 1999; Peres 2005) for establishing and maintaining large protected areas.

Information about artificial light thresholds for ecological impacts is largely absent from the literature, and because the available satellite data do not correspond directly to known light levels on the ground, it is not possible to determine how impacts differ over the range of light intensities detected in the satellite images. For this reason our approach was to assess the extent to which detectable light is present within the vicinity of protected areas, and we were cautious about attributing specific impacts. Similarly, it is not clear whether impacts are greater when a small proportion of an ecosystem is illuminated at a high intensity or a large proportion at a low one. However, given the range of biological effects reported at low light levels, we recommend a research effort into determining the impact of low levels of artificial light on biodiversity and ecosystem function.

With regards to the change in levels of artificial light at night, variation between IUCN categories was expected due to the differing objectives expressed in IUCN management guidelines (Dudley 2008). As would be expected, category I areas, which strictly preserve the natural environment and forbid permanent habitation were least affected (Fig. 4). A considerably higher proportion of category II areas showed significant increases, perhaps unsurprisingly because these may include tourist infrastructure and visitor facilities. A low proportion of category III areas also showed significantly positive trends. Category III areas protect natural monuments and are described as having high visitor value, so infrastructure and its associated lighting would be expected; however, we found little difference in lighting trend between these and the more strictly protected category I areas. Category IV areas are the most numerous and set out to protect particular species or habitats. It is perhaps the most striking result that nearly 30% of these are experiencing a significant increase in nighttime lighting (Fig. 3). Of all the IUCN categories, category V encompasses those areas that are likely to experience the most human interaction because it is through that very process that they have formed. The biggest proportion and coverage of these areas had significant increases in nighttime lighting, as would be expected according to the objectives set by the IUCN (Fig. 4). Lastly, category VI areas allow for the sustainable use of the habitat within them, so some increases in lighting would be expected and this is what we found.

The artificial nighttime lighting in protected areas can result from several sources. First, it may arise from within these areas as a consequence of permitted or illegal settlements and from transport and tourist infrastructure. In Europe, large protected areas frequently include human settlements and transport networks, and in North America they may include light sources from infrastructure for tourists. This may account for the observation that protected areas showing increases in lighting tend to be larger in size than average in these regions (Supporting Information). It is also likely to contribute to the finding that a greater proportion of protected areas in the lower IUCN categories, for which levels of regulation are less restrictive, have had significant increases in nighttime lighting (Fig. 4).

Second, protected areas can experience nighttime lighting from sources close to their boundaries. In some instances the growth in these sources may be attributable to the protected areas themselves, which can attract human settlements to their borders, and may be driven by those who are in search of employment and other benefits of protected areas (Wittemyer et al. 2008). More often, increases in lighting are likely due to general encroachment from urban expansion into the lands neighboring protected areas. Belo Horizonte in Brazil is a prime example; human settlement and industry having strangled Serra Rola-Moça State Park such that by the end of the study period the majority of the park was more brightly lit than at the beginning (Fig. 1b).

Third, protected areas can experience nighttime lighting as a consequence of sky glow from urbanization that may be some distance from their boundaries. This is doubtless a widespread occurrence, with the severity of the effect dependent not simply on the distance of a given protected area from urban development, but also the nature of the nighttime lighting of that development, the intervening topography, and prevailing weather conditions.

We suggest 3 courses of action to limit the influence of artificial nighttime lighting on the global protected area system. First, the artificial nighttime lighting that prevails locally and regionally, and how this is projected to change, should be a consideration when determining where to establish new protected areas. Second, buffer zones should be established around existing protected areas in which particular attention is paid to limiting future growth in, and where possible reducing, artificial nighttime lighting. This might include part-night switch offs, dimming, and careful attention to the spectra of the lights that are used (Gaston et al. 2012). Third, measures should be taken more widely to enable landscape level reductions in artificial nighttime lighting, which may be achievable in some parts of the world at the present time given the alignment between imperatives to reduce expenditure on public lighting in the wake of the global financial crisis and the environmental benefits to be gained (Gaston 2013).

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Supporting Information

A figure showing the size distributions of all protected areas and those with significant increases in nighttime lighting (Appendix S1) is available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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