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Worldwide increase in Artificial Light At Night around protected areas and within biodiversity hotspots

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ABSTRACT

Artificial Light At Night (ALAN) has several adverse impacts on biodiversity, and it has been recently used as a proxy to monitor human encroachment on landscapes at large spatial scales. The extent to which ALAN affects protected areas (PAs) and biodiversity hotspots (BHs) remains however untested at large spatial scales. We used this proxy to assess the spatial and temporal trends in the anthropization at a global scale within and around PAs and BHs. We found that ALAN is low and stable over time within PAs, but is the highest in a first outer belt (< 25 km) around PAs, and tends to increase in a second outer belt (25–75 km). In the meantime, ALAN is higher within BHs than outside, and is even the highest and increasing over time in an inner belt, close to their periphery. Our results suggest that although PAs are creating safety zones in terms of ALAN, they tend to be more and more isolated from each other by a concentric human encroachment. In contrast, BHs are submitted to an increasing human pressure, especially in their inner periphery. Overall, we suggest integrating ALAN in large-scale conservation policies.

1. Introduction

Artificial Light At Night (ALAN) is a pervasive phenomenon leading to an increasing light pollution across the globe (Hölker et al., 2010), and its study has become a major concern in conservation biology for two reasons.

First, because the adverse impacts of ALAN on biodiversity are now more and more documented. It impacts several taxa, including mammals, birds, reptiles, amphibians, fish, invertebrates and plants, both in terrestrial and aquatic ecosystems (see Gaston et al., 2014; Gaston and Bennie, 2014; Longcore and Rich, 2004 for detailed reviews). ALAN has for example significant impacts on individual movements (e.g. Polak et al., 2011; Stone et al., 2009), phenology (e.g. Bennie et al., 2016), and may lead to dramatic changes in interspecific interactions (e.g. Underwood et al., 2017), in community structures (e.g. Meyer and Sullivan, 2013), and in essential ecological processes such as pollination (Knop et al., 2017).

The second point of conservation interest is that ALAN can be used as a relevant proxy to monitor human encroachment at large (e.g. regional, national, or global) spatial scales. Since the 1990s, the monitoring of ALAN has received a large attention thanks to satellite data from the Defense Meteorological Satellite Program - Operational Linescan System (DMSP-OLS) observations (Elvidge et al., 1997) and more recently from the Visible Infrared Imaging Radiometer Suite (VIIRS) Day/Night Band (DNB) (see Falchi et al., 2016; Kyba et al., 2017). Between 1992 and 2013, no fewer than 144 articles using nightlight data were published in 61 different journals (Huang et al., 2014). In addition to several methodological studies dealing with the way to use such data (e.g. Hsu et al., 2015; Li et al., 2013), different regional (e.g. Bennie et al., 2014; de Freitas et al., 2017; Liu et al., 2012), continental (e.g. Bennie et al., 2014; Small and Elvidge, 2011) and global (e.g. Bennie et al., 2015; Davies et al., 2016; Falchi et al., 2016) maps of ALAN have been generated. It thus rapidly became a proxy of urban extent (see the review of Li and Zhou, 2017), human demography, urban land dynamics and socioeconomic parameters (30, 28 and 27 publications, respectively, reviewed by Huang et al., 2014 for these applications). Recently, ALAN was also used as a component of the human footprint (Venter et al., 2016) because it can both be monitored at a global scale and at a fine temporal and spatial scale, whereas many other components of global human pressure are only available at either low spatial or low temporal resolutions, and are spatially heterogeneous (Geldmann et al., 2014).

However, the literature explicitly linking the spatial distribution of ALAN with areas of special importance for biodiversity remains scarce. To our knowledge, there is for example no studies linking ALAN distribution with biodiversity hotspots (BHs), and only three studies linked ALAN distribution with the location of Protected Areas (PAs). For

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instance, Geldmann et al. (2014) used nightlight data together with human population density and land transformation to compute a Temporal Human Pressure Index (THPI), which was compared between the different IUCN protected area categories. However, as they reported, for several technical reasons (particularly the need for homogeneity between the different datasets used), this first and promising study used rather low spatial resolution data (10 km^2), only took into account the largest protected areas (> 200 km^2), did not compare artificial nightlight levels within and outside PAs, and only used a difference in artificial nightlight level between the two extreme dates of the dataset (1995 and 2010). Gaston et al. (2015), using two decades of ALAN recording data, compared the mean ALAN and its temporal trend in and out of the PAs at a global scale. They found that PAs tended to be darker at night than non-protected areas. The third study was conducted by Davies et al. (2016). Following the methods of Gaston et al. (2015), they focused on marine PAs and found that artificial light is widespread and increasing in a large percentage of marine PAs.

However, as for any human perturbation, ALAN not only has a direct influence at the exact place where it is located, but may also lead to the spatial fragmentation of "dark areas" (i.e. the areas which are not submitted to ALAN). Both PAs and BHs cannot be viewed as isolated islands, but rather as patches included in a larger landscape matrix. Therefore, it is crucial to assess whether ALAN is increasing not only *in* but also *around* (along a continuous spatial gradient) PAs and BHs. Indeed, beyond the situation within a particular zone, the continuous spatial distribution of a given pressure is highly informative in conservation biogeography (Whittaker et al., 2005). A given amount of ALAN can lead to very contrasted spatial dynamics depending on the fragmentation of impacted patches.

The aim of our study is to analyze the spatial distribution and the temporal trend in ALAN according to the spatial distribution of PAs and BHs. More precisely, we address the two following objectives:

(i) to draw a global map of the mean ALAN and its temporal trend between 1993 and 2012.

Although several static maps of the mean ALAN are available, it is still much more difficult to find maps of its temporal trend at a global scale. Trends were provided by country, by city, and even PAs (Elvidge et al., 2014; Gaston et al., 2015; Hsu et al., 2015). Huang et al. (2014) provided a map of the trends for China between 1992 and 2008 (including 1996, 2000 and 2004), Bennie et al. (2014) proposed a map of temporal trends in Europe (including 1995–2000 and 2005–2010) and artificial nightlight data at only two different dates were used to map temporal trends in "human pressure" (Geldmann et al., 2014) or in "human footprint" (Venter et al., 2016) at a worldwide scale. But the spatial distribution of high-resolution and long-term trend in ALAN is missing at a global scale. Here, we aim at proposing a continuous global map of two decades ALAN trend made from the recent inter-calibrated DMSP-OLS NTL time series data (Zhang et al., 2016) and computed by a cell by cell regression analysis.

(ii) to analyse the spatial distribution of the mean ALAN and its temporal trend along a continuous spatial gradient from the core of the PAs and the BHs to their peripheries.

Protected areas are meant to protect biodiversity from major human pressures. We thus expect them to prevent any increase in ALAN or, at least, to be located where ALAN is the lowest. Biodiversity hotspots (BHs) are considered to be areas hosting the highest biological diversity, which have to be conserved first. However, they are also among the most densely populated areas (Williams, 2013), and we expect them to be located where ALAN is both high and increasing.

2. Material and methods

2.1. Nightlight data

The Defense Meteorological Satellite Program - Operational Linescane System (DMSP-OLS) Night-Time Light (NTL) archive is one of the most comprehensive datasets for monitoring, characterizing an understanding global human activities at a global scale and with such a long time lag. Although noise removal and other corrective processing are applied to the NTL imagery by the National Oceanic and Atmospheric Administration (NOAA), the time series cannot be directly used for quantitative change analysis because of the presence of systematic biases (Elvidge et al., 2014). One of the key issues is the lack of inter- and intra-annual calibration between satellites. Few models have been developed to improve the consistency of the data at global scale (e.g. Elvidge et al., 2014; Hsu et al., 2015; Zhang et al., 2016).

In this study, we used the freely available global inter-calibrated nighttime lights series (hereafter "NTL") from Zhang et al. (2016) (http://urban.yale.edu/data). The dataset is a calibrated version using the "Ridgeline Sampling and Regression" method, generated from the stable DMSP-OLS NTL annual composite cloud-free product (version 4). At country and regional scales and among the different calibration methods, the systematic bias minimization of Zhang et al. (2016) appears to be superior (Pandey et al., 2017). The dataset includes the data from six satellites: F10, F12, F14, F15, F16, and F18 spanning over 20 years from 1993 to 2012 and quantifies the yearly average of stable light, ranging in brightness Digital Number (hereafter "DN") from 0 (no artificial light) to 63 (value at which sensors saturate). Areas contaminated by sunlight, moonlight, fires and other ephemeral lights were removed (see Baugh et al., 2010) for a description of the methodology used to develop the Stable Light Product). In this study, we used the data acquired by the most recent satellite when several data were available the same year.

The final products have a spatial resolution of 30 arc *sec* (i.e. 1-km spatial resolution at the equator), spanning −180 to 180 degrees longitude and − 65 to 75 degrees latitude. For this study, all the raster data were projected using the Mollweide equal area projection, which accurate representation of areas takes precedence over the shape and angles.

2.2. Protected areas (PAs)

We used the World Database on Protected Areas (WDPA) of December 2016. All the PAs smaller than the spatial resolution of the nightlight data (1 km^2), marine PAs as well as PAs created after 1993 were removed from our analyses. Thus, 40,701 protected areas were analyzed from a total of 211,723 which covered 10,733,883 km^2.

2.3. Biodiversity hotspots (BHs)

We used the freely available Biodiversity Hotspots database version 2016.1 from the Critical Ecosystem Partnership Fund, (http://www.cepf.net/resources/hotspots/Pages/default.aspx). We removed non-terrestrial hotspots. Our analyses include 36 different biodiversity hotspots (listed in Appendix 1).

2.4. Biogeographical regions

Because both ALAN on the one hand and PAs and BHs on the other are unevenly distributed across the globe (in terms of number and coverage), we also disentangle our results according to the 6 main biogeographical realms following the typology of Olson et al. (2001): Palearctic (PA), Neotropic (NT), Indo-Malay (IM), Nearctic (NA), Australasian (AA), and Afrotropic (AT). The Antarctic biogeographical realm was not considered because of the poor coverage of nightlight data in this area. All the results by biogeographical realms are given in Appendix 2.

2.5. Distance from PAs and BHs borders

To study the spatial distribution of ALAN according to PAs and BHs, two distance maps from (i) PAs and (ii) BHs borders were generated.