Light pollution near Tenerife, Canary Islands

GLOBAL ASSESSMENT OF LIGHT POLLUTION

IMPACT ON PROTECTED AREAS

CIESIN Center for International Earth Science Information Network
The Earth Institute at Columbia University

AIT Austrian Institute of Technology

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WORKING PAPER

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This working paper is a contribution to the Dark Skies Advisory Group of the Cities and Protected Areas Specialist Group of IUCN's World Commission on Protected Areas.

IUCN, the International Union for Conservation of Nature, is the world's oldest and largest global environmental network - a democratic membership union with more than 1,000 government and NGO member organizations, and almost 11,000 volunteer scientists in more than 160 countries.
www.iucn.org

IUCN's World Commission on Protected Areas is the world's premier network of protected area expertise. WCPA has over 1,400 members, spanning 140 countries. Its mission is to promote the establishment and effective management of a worldwide representative network of terrestrial and marine protected areas as an integral contribution to IUCN's mission.
www.iucn.org/wcpa

WCPA's Cities and Protected Areas Specialist Group works to improve the lives of city dwellers while strengthening protection of nature – broadly defined – within cities and in larger ecosystems. It has some 100 members from over 35 countries.
www.citiesandconservation.org

The Dark Skies Advisory Group of the Specialist Group works to reduce light pollution and protect a natural night sky. While it focuses primarily on protected areas and sites, the group is also concerned with appropriate design and land development control policies.
www.interenvironment.org/pa/dark.htm

ABSTRACT

In this paper we present a novel global assessment of light pollution impact on protected areas. A set of spatial indicators was developed based on joint analysis of satellite observed nighttime lights as acquired by the U.S. Air Force Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS) and protected area distribution information provided by UNEP's World Conservation Monitoring Centre (WCMC). Following a global assessment of the degree to which each country's total land area is legally protected, light pollution impact and approximated human influence were calculated. Two new indices resulted from combining the global protected area distribution data and nighttime lights data: a Protected Area Light Pollution Index (PALI) and a Protected Area Human Impact Index (PAHI).

Results indicate that regions in Europe and Asia Minor, the Caribbean, South and East Asia as well as in the Eastern part of the United States are most affected. Introducing aggregated data on biomes reveals that temperate broadleaf and mixed forests suffer the biggest impact both in terms of general light pollution as well as lighting in protected areas. The presented risk assessment underscores the need for accurate and consistent spatial data on a global scale and can help to indicate which protected areas globally and nationally are at greatest risk of human activities. It is also an important step towards public communication and raising general awareness on the topic of light pollution.

1) INTRODUCTION

A major objective of the analysis leading to this working paper is to respond to recent interest in the ecological impacts of light pollution and its implications for conservation activities. In early 2009 the Dark Skies Advisory Group was set up within the Task Force on Cities and Protected Areas (now Cities and Protected Areas Specialist Group) of IUCN's (International Union for Conservation of Nature) World Commission on Protected Areas (WCPA). As stated on the specialist group's web site, protected areas are often connected to urban settlements in various ways. Protected areas provide important societal benefits such as education, recreation, tourist activities, and water supply. Notwithstanding the societal benefits, which are many, protected areas are also important to species conservation, and often provide a last refuge for species that have been extirpated from surrounding areas.

There is a growing body of literature related to research on the ecological consequences of artificial night lighting (e.g. book of the same title edited by Rich & Longcore 2006). This research has attracted the attention of both scientists and journalists (e.g. a featured article in *National Geographic magazine*, Klinkenborg 2008; an article in *The Wall Street Journal*, Hotz 2008; and an Op-Ed in *The New York Times*, Cheney & Bolevice 2008). There is also a series of Dark Sky conference events organized by the International Dark Sky Association.

However, most applications related to ecological impacts of artificial night lighting focus on adverse effects on light-sensitive ecosystems or species, such as coral reefs (Aubrecht et al. 2008a, 2009), sea turtles (Ziskin et al. 2008, Lorne & Salmon 2007, Witherington 1992), and migrating birds (Montevecchi 2006). This paper takes a more general approach by examining the proportion of protected areas and biomes in each country that are affected by artificial night lighting (ANL). We implicitly assume, for the purposes of this analysis, that much of the most important biodiversity in a country is located in protected areas, though we understand that this is not always the case.

2) DATA SOURCES

This section gives a brief overview of the data used for the presented study. The two main data sets which will be described in more detail are related to protected areas (PAs) on the one hand and artificial night lighting on the other hand. Ancillary data include country boundaries (CIESIN & CIAT 2005) and a map of terrestrial biomes (Olson et al. 2001). Biomes are described as broad terrestrial ecological regions that are composed of finer-scale 'ecoregions' being sensitive to more specific ecological patterns[1]. The list of biomes includes (1) Tropical and Subtropical Moist Broadleaf Forests, (2) Tropical and Subtropical Dry Broadleaf Forests, (3) Tropical and Subtropical Coniferous Forests, (4) Temperate Broadleaf and Mixed Forests, (5) Temperate Coniferous Forests, (6) Boreal Forests/Taiga, (7) Tropical and Subtropical Grasslands, Savannas, and Shrublands, (8) Temperate Grasslands, Savannas, and Shrublands, (9) Flooded Grasslands and Savannas, (10) Montane Grasslands and Shrublands, (11) Tundra, (12) Mediterranean Forests, Woodlands, and Scrub, (13) Deserts and Xeric Shrublands, (14) Mangroves, and two additional categories for (98) Lakes and (99) Rock and Ice. Biome and country data are used for statistical reporting regarding ratios of protected areas impacted by light pollution and human influence.

a. Protected areas

For delineation of protected areas worldwide data from the 2007 Annual Release of the World Database on Protected Areas (WDPA) provided by UNEP-WCMC (United Nations Environment Programme-World Conservation Monitoring Centre) was used. Through its Protected Areas Programme UNEP-WCMC has been compiling this information since 1981 and making it available to the global community. The WDPA is a joint project of UNEP and IUCN, being prepared by UNEP-WCMC in collaboration with the IUCN World Commission on Protected Areas (WCPA), governments and NGOs. According to the official data description of UNEP-WCMC (2009) the World Database on Protected Areas is the most comprehensive global spatial dataset on marine and terrestrial protected areas available.

Although the 2009 WDPA Annual Release (status of February 2009) had been made available at the time of this study, it was decided to use the 2007 version (status of December 2007) because the data for the United Kingdom were completely omitted from the latest release of 2009. This study has its focus on terrestrial areas, so marine protected areas are not considered for the analysis. Furthermore protected areas that were listed as historical, archaeological, or cultural sites, or that were listed as proposed but not yet designated were excluded. PAs with an 'international' designation were not included if they did not simultaneously have some kind of national status; since PAs without a national designation cannot be considered to have adequate legal protection. This decision is supported by the common practice of many studies utilizing the WDPA to assess the protected status of a nation's territory.

In order to keep the analysis simple and to be able to communicate the basic message to a broad public it was decided not to consider the IUCN 6-class system of protected area definitions inherent in the WDPA at this stage of the project. For future work it is planned to discriminate between these management categories which range from Ia '*strictly protected*' to VI '*areas conserving ecosystems and habitats, together with associated cultural values*' (Dudley 2008). Splitting up the overall protected land area in such a manner will then give a better and more detailed idea on the concrete global protected area status in relation to artificial night lighting.

The WDPA data are provided online for download as ESRI shapefiles and consist of both polygon and point features. Point features depict center point locations for protected areas where area boundaries have not been mapped or boundary files are not available. The WDPA provides information on the total protected area extent (in hectares) as defined in governmental declarations/decrees or management plans, so it was possible to create a spatial approximation for those PAs by creating a circular buffer around the points in accordance with the spatial extent. To avoid over-counting overlapping PAs, the dissolve command in ArcMap (ESRI ArcGIS) was used to create a consolidated set of polygons that distinguishes areas being under protected status from those that are not.

[1] As explained by CIESIN (2009) such ecoregions are probably more appropriate as policy targets, since they identify areas based on factors that affect biodiversity on the ground more precisely than biomes. Given the scale and resulting computational requirements of the present study (global 1-km grids) it was not possible to use such fine-scale regions as basic reference units of the analysis.

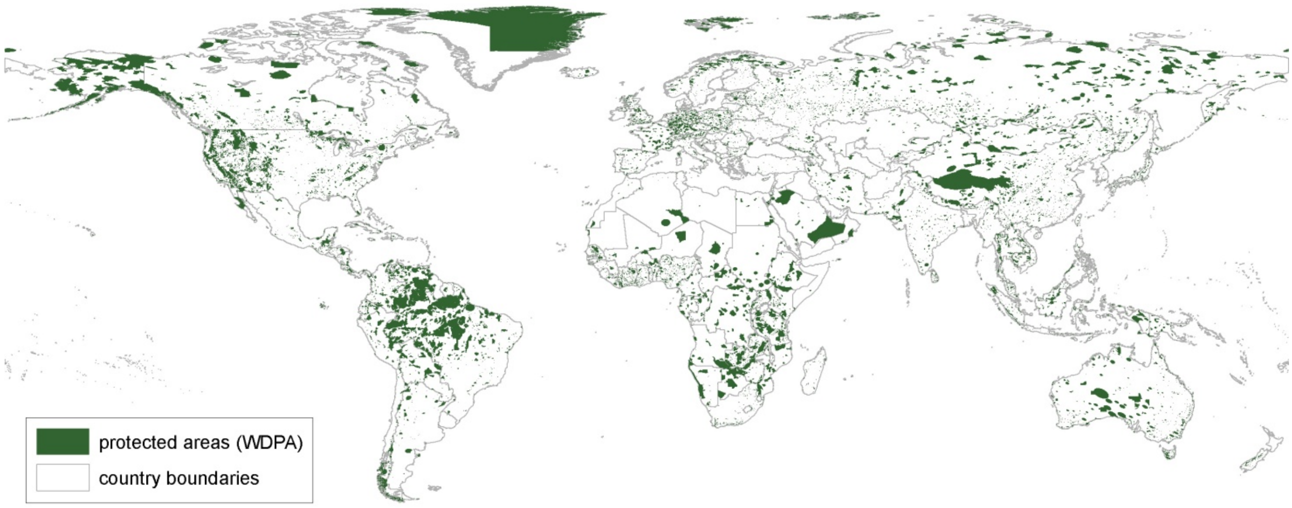

Figure 1: Modified WDPA data (point features buffered according to documented areal extent).

b. Artificial night lighting – light pollution

The footprint of human occupation is uniquely visible from space in the form of artificial night lighting – ranging from the burning of the rainforest to massive offshore fisheries to the omnipresent lights of cities and towns and related connecting road networks (Aubrecht et al. 2008b, Doll 2008). The National Oceanic and Atmospheric Administration, National Geophysical Data Center (NOAA-NGDC) processes and archives nighttime lights data acquired by the U.S. Air Force Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS) which was initially designed to monitor the global distribution of clouds using visible and thermal infrared spectral bands. The DMSP satellites are in a sun-synchronous, low altitude polar orbit. With 14 orbits collected per day and a 3,000 km swath width, each OLS is capable of collecting a complete set of images of the earth every 24 hours. At night the visible band signal is intensified with a photomultiplier tube (PMT) to enable the detection of moonlit clouds. The boost in gain enables the unique capability of observing lights present at the earth's surface at night. Most of the lights are from human settlements (Elvidge et al. 1997) and ephemeral fires (Elvidge et al. 2001a). Furthermore gas flares and offshore platforms as well as heavily lit fishing boats can be identified.

NOAA-NGDC archives the long-term DMSP data from 1992 to present. For this project individual orbits were processed with automatic algorithms (described in Elvidge et al. 1997, 2001b) identifying image features (such as lights and clouds) and quality of the nighttime data. A cloud-free composite of nighttime lights was produced for 2003 using data from DMSP satellite F-15 (see figure 2).

To identify the best nighttime lights data for creating an annual composite we adhered to the following standards:

- Only the center half of the orbital swath was used (best geolocation and sharpest features)
- Sunlight and moonlight were not present
- No solar glare contamination was allowed
- Only cloud-free images were used (based on thermal detection of clouds)

Nighttime image data from individual orbits meeting these criteria are the basis for a global latitude-longitude grid with 30 arc second resolution cells. This grid cell size corresponds to approximately 1 kilometer at the equator. In order to estimate the frequency with which lighting was present the total number of coverages and number of cloud-free coverages are tallied. The nighttime lights product used in the presented analysis is the average digital number in the visible band of cloud-free light detections multiplied by the percent frequency of light detection. The inclusion of the percent frequency of detection term normalizes the resulting digital values for variations in the persistence of flaring. For instance the value for a gas flare only detected half the time is discounted by 50 %. Background noise and land based fires were filtered out.

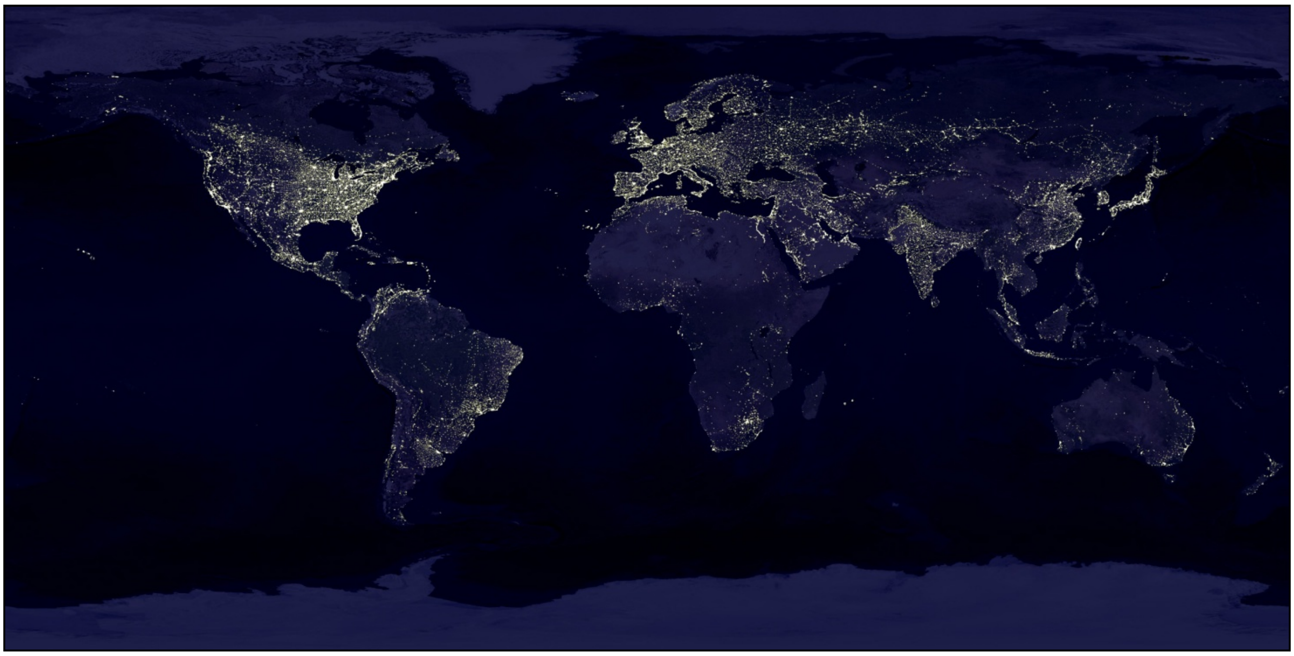

Figure 2: Data from DMSP-OLS, nighttime lights of the world, sample figure.

One important issue with observing artificial night lighting from space that needs to be addressed is a phenomenon known as skyglow. Even in its pristine state the night sky is not completely dark. Some light comes from the stars, some from sunlight scattered by space dust in the plane of the solar system, and some from atmospheric gases subject to radiation and particle fluxes mostly from the sun (Clark 2008). This is called **natural skyglow**. Light emitted from human settlements in the atmosphere is refracted or scattered by air and water molecules and suspended particles (atmospheric aerosol) caused by dust, pollen, salt from sea spray, and waste products from industry (House of Commons 2003). Artificially illuminating the sky over great distances this is called **artificial skyglow**.

In particular in the field of astronomy skyglow obscuring the night sky is an issue of utmost importance with extensive scientific research being conducted in recent years. Baddiley's guide 'Towards Understanding Skyglow' (2007a) lists different sources contributing to skyglow in urban and rural areas. Furthermore a mathematical model of skyglow is presented considering different skyglow mechanisms (i.e. directly radiated light above the horizontal; reflected light from the road, ground and other surfaces; light scattered by air molecules; light scattered by aerosols) and different types of luminaires. According to Clark (2008) the total artificial light flux emitted by a city tends to be proportional to the product of two quantities, (1) the number of light sources and (2) their mean output of light. Related to a growing economy and urban population growth typically both of these quantities increase over time.

Considering artificial skyglow entails that the DMSP satellite sensors record much larger areas than just the immediate location of the lighting sources. Using satellite observed nighttime lights for delineating urban areas (Small et al. 2005) and approximating impervious surfaces (Elvidge et al. 2007) requires eliminating skyglow from the data, i.e. by applying thresholds to the digital number values. When dealing with ecological issues skyglow is a significant factor of light pollution as already very low light intensities alter the natural environment. Following recent approaches of modeling ecological impact of artificial night lighting (Aubrecht et al. 2008a) for the present analysis skyglow is thus not modeled out but rather considered as important contribution.

3) METHODOLOGY

Two different approaches were used to relate the areal distribution of artificial night lighting to the areas under protected status. First, the direct impact of lighting is evaluated, hence referred to as light pollution, i.e. the direct spatial overlap between satellite observed nighttime lights as derived from DMSP-OLS and protected areas as delineated in the WDPA. In the second approach, we consider that DMSP nighttime lights data are an excellent proxy measure for human activities that impact neighboring areas. To account for this, the immediate vicinity of lighting sources is considered by applying a focal neighborhood function to the initial lights data set (see figure 3). This results in having pixels within a 5 pixel radius (about 5 km at the equator) of the actual lit area identified as being potentially at risk.

Before further analysis regarding the lights data was carried out the available protected areas data were associated with country boundary (CIESIN & CIAT 2005) and biome (Olson et al. 2001) delineation. A Protected Area Index (PAI) was calculated describing the ratio of terrestrial protected areas (cp. chapter 2) in relation to the total area per country and per biome. This was done using grid operations in ESRI ArcGIS. In order to have a consistent process chain grid operations were used throughout the project rather than doing parts of the analysis in vector format. The PAI is related to the Eco-Region Protection Indicator for the Natural Resources Management Index (NRMI) described in a CIESIN 2009 working paper[2]. This Eco-Region Protection Indicator measures the degree to which a country achieves the target of protecting at least 10% of each terrestrial biome within its borders. I.e. if the area protected is equal or greater than 10% of the biome, then the country receives a score of 1 for that biome. The global ratios for each biome are then averaged using a simple arithmetic average. The 10% target was adopted because that is the target most faithful to the existing international consensus (e.g. Convention on Biological Diversity 2004). Compared to the Eco-Region Protection Indicator, the PAI does not consider any threshold or weighting, but rather describes the direct ratio of areas under protection status to the total land area.

In addition to calculating the legally protected proportion of each biome, we applied the DMSP nighttime lights data to assess the degree to which each biome is affected by light pollution (LI, Light Pollution Indicator) and human influence (HI, Human Impact Indicator) respectively. Pivot tables were used to calculate corresponding index values on basis of the grid operations output. The main objective of this analysis is however to assess the spatial relation of artificial night lighting and protected areas. Corresponding indicators and underlying methodology are described in the following section.

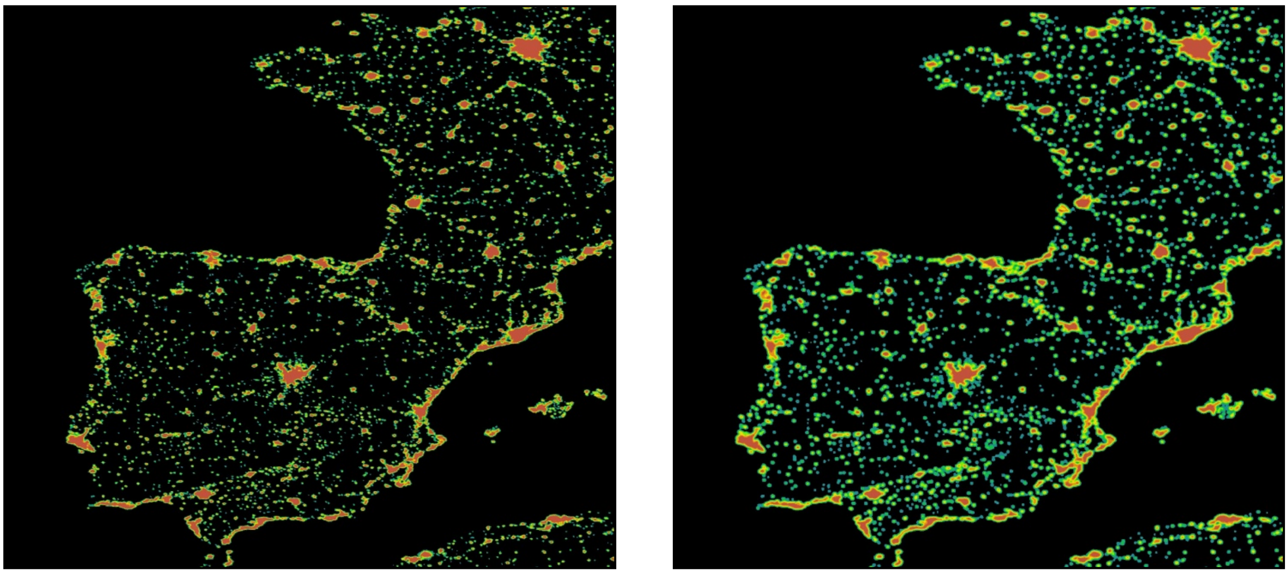

Figure 3: Direct lighting impact (DMSP) vs. indirect impact (DMSP as proxy measure for human activities); detail: SW Europe.

[2] http://sedac.ciesin.columbia.edu/es/mcc.html (last accessed: 09/23/2009)

a. Direct impact of artificial night lighting on protected areas

In a first step we created a new lights file based on the original DMSP data but featuring just those areas that spatially overlap with protected areas. Thus a previously generated binary protected areas raster data set (i.e. featuring 1-values for PAs and 0-values for all other areas) was multiplied with the DMSP data eliminating all DMSP pixels but those located within a dedicated PA. For the first assessment of lighting impact a binary approach was also chosen for the lights data, i.e. deriving a binary lights data set showing whether areas are lit at night or not regardless of lighting intensity. We purposefully include the overglow (i.e. outer regions of lit areas with low DN values) which is recorded by the DMSP-OLS sensor, since low lighting intensities can be sufficient to alter natural environment conditions.

Next, we linked the new binary lights data with the country-protected areas file. This enables reporting the proportion of protected areas per country being directly affected by light pollution. The outcome will hence be entitled as Protected Area Light Pollution Indicator (PALI).

b. Artificial night lighting as a proxy measure for human impact on protected areas

In addition to measuring the direct impact of ANL, as discussed above we buffered the DMSP data by 5 pixels to create a measure of anthropogenic influence on protected areas. We derived a binary lights data set in which the focal neighborhood operator assigned the value 1 to each pixel within a 5px radius circle around a lighting source, whereas all pixels further away we classified as 0 (not affected). This new binary grid file was linked with the country-protected area as described above. The result is referred to as Protected Area Human Impact Indicator (PAHI).

4) RESULTS

All indicators were calculated on country and global level. Joint analysis of the various input data (i.e. national boundaries, biomes, protected areas, and nighttime lights) in a GIS environment requires large computational capacities. First runs in vector format included tiling data to regions/countries and scripting various procedures of the analysis using a stepwise rather than a global approach. However, due to geographic projections and data format conversions (raster to vector), this introduced rather large errors in terms of areal object description. Therefore the final analysis was conducted entirely in raster format including a previously created global area grid (originating from CIESIN's GRUMP data set) accurately describing pixel extents even in high latitudes.

a. Protected Area Index (PAI)

The first indicator measures the degree to which each reference area is under protection status. First, protected areas from the WDPA were analyzed on country level, with the Protected Area Index (PAI) describing the protected proportion of each country (see figure 4). Introducing the biome data into the analysis resulted in a PAI similar to the Eco-Region Protection Indicator described by CIESIN (2009). For each country it measures the ratio of protected areas related to the total area of each of the 14+2 biomes. Table 1 shows the list of biomes with their absolute land area as well as their corresponding relative proportion when seen in a global context (second to last column). Associated calculated PAI values are provided in the last column.

Reference	**Description**	**Area** (absolute/relative) [km²]	[%]	**PAI**[g] [%]
World*	–	129,980,271.5	100.0	**12.7**
Biome 1	Tropical and Subtropical Moist Broadleaf Forests	19,788,016.1	15.2	20.6
Biome 2	Tropical and Subtropical Dry Broadleaf Forests	2,985,963.9	2.3	8.0
Biome 3	Tropical and Subtropical Coniferous Forests	706,855.5	0.5	**6.9**
Biome 4	Temperate Broadleaf and Mixed Forests	12,560,815.3	9.7	11.0
Biome 5	Temperate Coniferous Forests	4,005,253.2	3.1	**24.7**
Biome 6	Boreal Forests/Taiga	14,552,773.6	11.2	8.9
Biome 7	Tropical and Subtropical Grasslands, Savannas, and Shrublands	20,116,133.7	15.5	12.5
Biome 8	Temperate Grasslands, Savannas, and Shrublands	9,958,627.8	7.7	**3.7**
Biome 9	Flooded Grasslands and Savannas	1,052,857.8	0.8	19.2
Biome 10	Montane Grasslands and Shrublands	4,877,074.5	3.8	**24.9**
Biome 11	Tundra	7,765,962.7	6.0	16.7
Biome 12	Mediterranean Forests, Woodlands, and Scrub	3,186,732.3	2.5	**6.9**
Biome 13	Deserts and Xeric Shrublands	27,782,793.3	21.4	9.2
Biome 14	Mangroves	317,533.2	0.2	20.0
Biome 98	Lakes	51,577.4	0.0	24.1
Biome 99	Rock and Ice	254,835.9	0.2	**29.9**

Table colors: Black - 3 largest biomes; Red - 3 most negative PAI values; Green - 3 most positive PAI values

g This table shows the global values of the PAI

* The first line ('World') shows the PAI for the total land area, the other lines show the PAI for biomes 1-99

Table 1: The global perspective of the PAI.

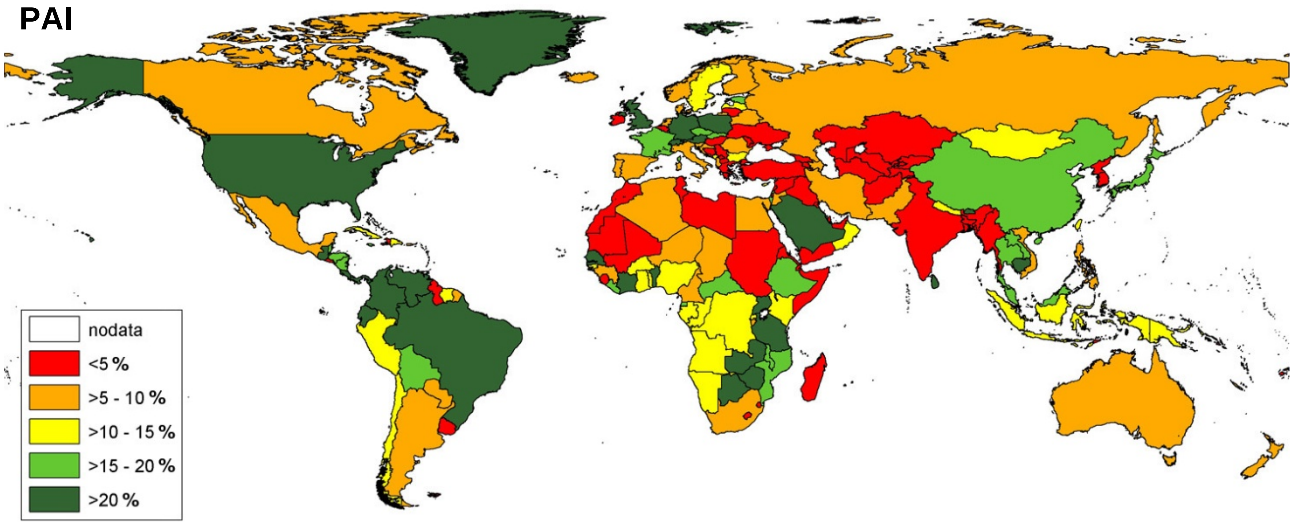

Figure 4: PAI classified on country level and visualized using a bipolar color scale (red: negative; green: positive).

Table 1 lists the results of the **Protected Area Index (PAI)** calculation for the total land area and for each biome on a global scale. The three biomes featuring the largest total area are highlighted in black color in the left-most column, i.e. that is biome 13 *'Deserts and Xeric Shrublands'* covering 21.4% of the global land area, biome 7 *'Tropical and Subtropical Grasslands, Savannas, and Shrublands'* covering 15.5% and biome 1 *'Tropical and Subtropical Moist Broadleaf Forests'* covering 15.2%.

Regarding notable PAI values biome 99 *'Rock and Ice'* tops the list with approximately 30% of its total area being legally protected, followed by biome 10 *'Montane Grasslands and Shrublands'* and biome 5 *'Temperate Coniferous Forests'* both having nearly 25% of protected area. It has to be mentioned though that these three biomes all just cover a minor part of the total global land area (just 7% altogether). On a global scale 12.7% of this total land area is protected. Out of the 'big three' biomes covering the largest proportion of land area (altogether more than 50%) just biome 1 *'Tropical and Subtropical Moist Broadleaf Forests'* features an above-average protection value (20.6%). On the lower end of the list featuring general biome protection status stands biome 8 *'Temperate Grasslands, Savannas, and Shrublands'* (after all covering approximately 8% of the global land area) with less than 4% of its area being protected, preceded by biomes 12 *'Mediterranean Forests, Woodlands, and Scrub'* and 3 *'Tropical and Subtropical Coniferous Forests'* both having less than 7% of protected area.

Figure 4 shows a map visualizing the results of the **PAI** calculation on country level using a bipolar color scheme with red standing for low protection status and green standing for high protection status. In order to get an idea of regional disparities a couple of country samples are provided. Countries featuring a high proportion of protected areas include Venezuela (53.4%) and Germany (49.9%) while countries such as Libya, Iraq, Aruba and Anguilla have less than 0.1% of its total land area under legal protection status.

b. Light Pollution Indicator (LI) and Human Impact Indicator (HI)

After showing the proportion of each country and biome being legally protected using the WDPA data set, the next step was to calculate indicators of light pollution and human impact per country and biome. The **Light Pollution Indicator (LI)** hence considers lighting as detected by DMSP-OLS as a potential stress factor to the natural environment in general. Adding the immediate neighborhood of lighting sources to the concept gives a more general idea of potentially adverse human influence reaching out from settlement centers (**HI, Human Impact Indicator**).

Table 2 provides the biome list with corresponding LI and HI values in adjacent columns giving a good impression of the varying increase of affected areas as a result of the 5px neighborhood inclusion. The two biomes being most affected both in exclusive consideration of direct lighting impact and in taking lighting as proxy measure for human influence are biome 4 *'Temperate Broadleaf and Mixed Forests'* and biome 12 *'Mediterranean Forests, Woodlands, and Scrub'*. In particular biome 4 should be highlighted as it covers almost 10% of the global land area. Out of the 'big three biomes' (again marked in black in the left-most column) biome 7 *'Tropical and Subtropical Grasslands, Savannas, and Shrublands'* is amongst the least affected areas featuring both very low LI (0.5%) and HI values (3%). Also biomes 1 *'Tropical and Subtropical Moist Broadleaf Forests'* and 13 *'Deserts and Xeric Shrublands'* are below average regarding light pollution and potential anthropogenic stress. In a global perspective 4% of the total land area is to some extent affected by light pollution (lighting intensity not being considered). Extending the area of direct lighting influence and taking this as proxy measure for human influence increases the proportion of area at potential risk to more than 10%.

Reference	**Description**	**Area** (absolute/relative) [km^2]	[%]	**LI**[g] [%]	**HI**[g] [%]
World*	–	129,980,271.5	100.0	**4.0**	**10.1**
Biome 1	Tropical and Subtropical Moist Broadleaf Forests	19,788,016.1	15.2	1.8	8.5
Biome 2	Tropical and Subtropical Dry Broadleaf Forests	2,985,963.9	2.3	5.4	**19.9**
Biome 3	Tropical and Subtropical Coniferous Forests	706,855.5	0.5	3.7	14.1
Biome 4	Temperate Broadleaf and Mixed Forests	12,560,815.3	9.7	**18.7**	**31.0**
Biome 5	Temperate Coniferous Forests	4,005,253.2	3.1	7.5	17.6
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Biome 99	Rock and Ice	254,835.9	0.2	**0.0**	**0.2**

Table colors: Black - 3 largest biomes; Red - 3 most negative LI and HI values; Green - 3 most positive LI and HI values
[g] This table shows the global values of LI and HI
* The first line ('World') shows the LI and HI for the total land area, the other lines show the LI and HI for biomes 1-99

Table 2: The global perspective of LI and HI.

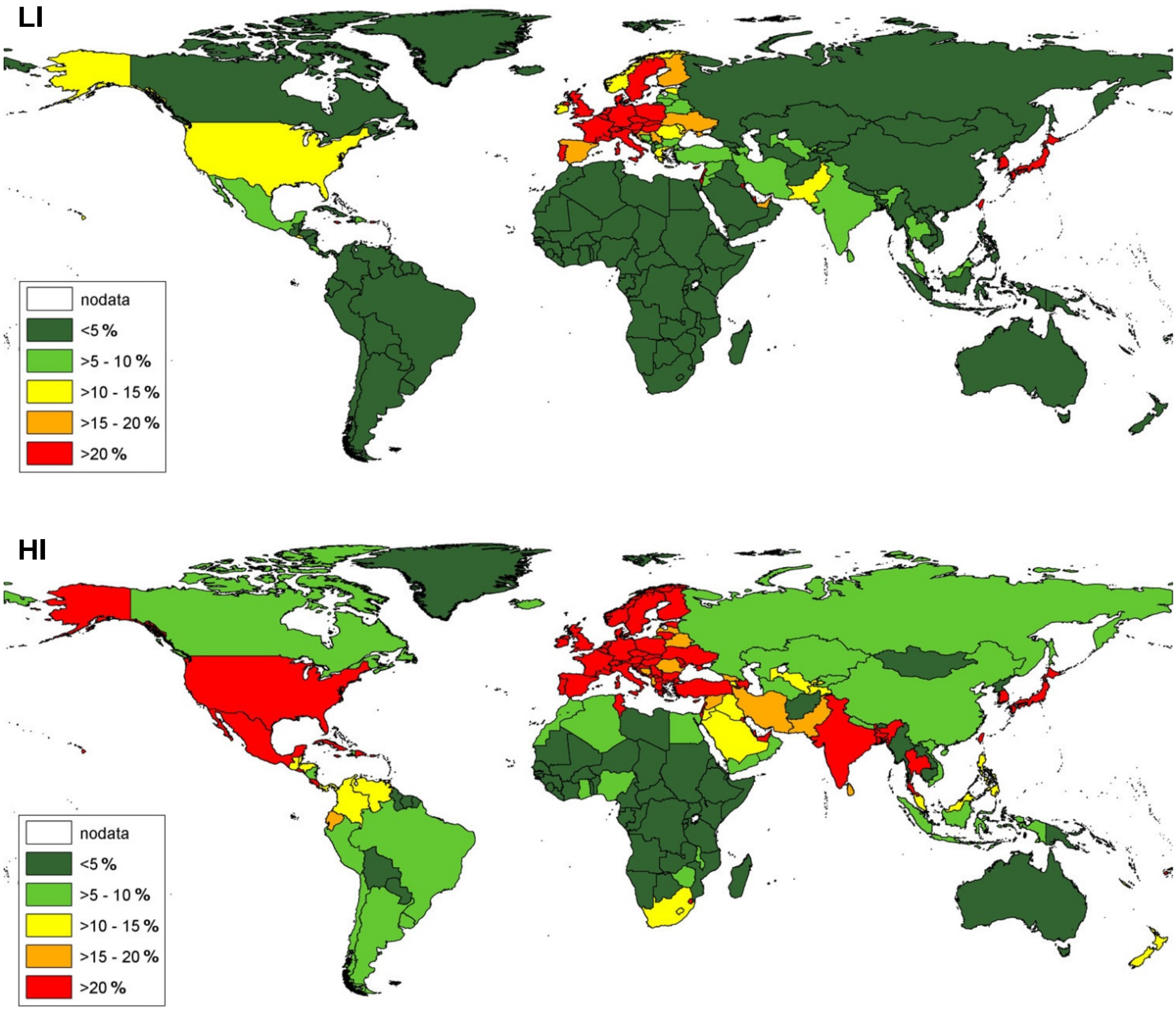

Figure 5: LI and HI classified on country level and visualized using a bipolar color scale (red: negative; green: positive).

When looking at the **LI** map on country level (see figure 5, top), it is obvious that Europe is the region most affected with countries such as Germany and Italy featuring index values of around 50% and the BeNeLux countries (Belgium, Netherlands, Luxemburg) having up to 95% of its total land area affected by light pollution. In the United States artificial night lighting has an impact on almost 15% of its total land area. Puerto Rico even has more than 80% directly affected and Japan comes up with a number of 40%. On the other side of the ranking most African countries feature very low LI values (e.g. Mozambique, Namibia, Niger, all 0.1%) and also Brazil and Argentina have just approximately 1% of its land area affected by light pollution.

An additional consideration of the immediate vicinity of lighting sources as a proxy measure for human influence on the natural environment (e.g. air and water pollution) in most cases results in a rather strong increase of the index values (see figure 5, bottom). The USA for example feature an **HI** value of nearly 30% and Puerto Rico of 95%. Large differences between LI and HI values in a given country can point to the existence of large numbers of small and widely distributed individual lighting sources rather than few bigger light accumulations (in terms of areal extent).

c. Protected Area Light Pollution Indicator (PALI) and Protected Area Human Impact Indicator (PAHI)

The final index calculations now combine information on protected area delineation and sources of artificial night lighting, hence measuring the degree to which each country's protected areas are affected by direct light pollution impact and potential human influence respectively. Again, the assessment is further broken down to a higher spatial level of detail by additionally considering biome distribution within country boundaries. Figure 6 shows Germany as an example to illustrate the methodology. Protected areas are colored in grey, and on the left we show the effects of direct light pollution and on the right we show the extent of the broader human influence (lights visualized according to their intensity using a bipolar color scale with yellow standing for high and blue for low intensities). For the final index calculations binary version of both lights files were used, i.e. not considering lighting intensity but mere areal extent.

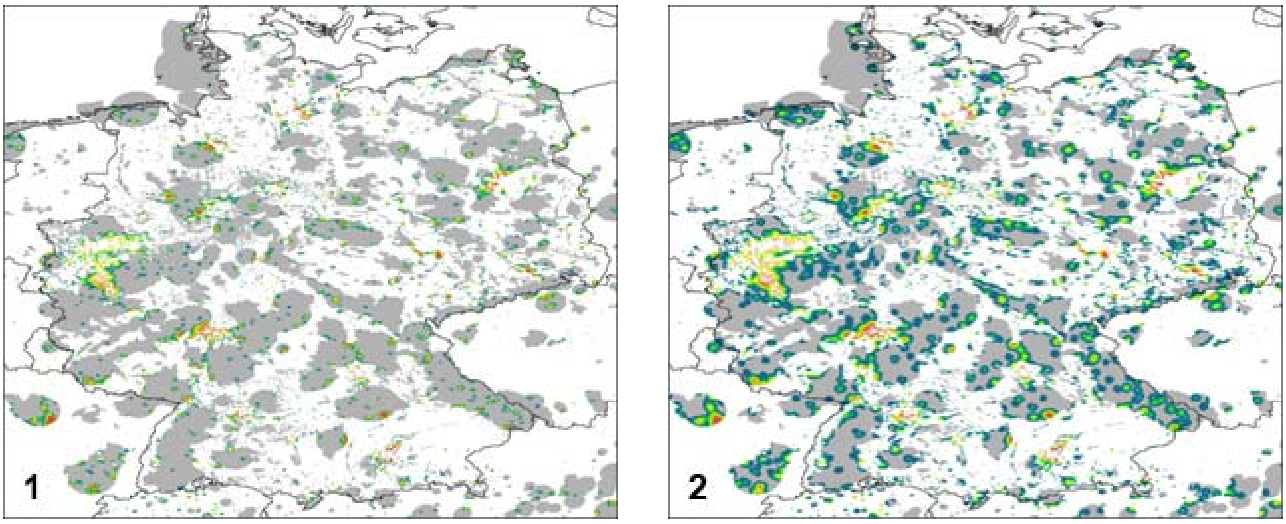

Figure 6: Artificial night lighting in protected areas - Germany:
(1) direct light pollution vs. (2) spatially extended lights taken as proxy measure for potentially adverse human influence.

Looking at the values for the **Protected Area Light Pollution Indicator (PALI)** on a global scale (table 3) we see that protected areas are comparatively most affected by light pollution in areas assigned to either biome 4 *'Temperate Broadleaf and Mixed Forests'*, 12 *'Mediterranean Forests, Woodlands, and Scrub'*, or 14 *'Mangroves'*. As expected it is however notable that the proportion of affected PA in general is quite low (1.8%) with all but two biomes featuring index values below 5%. This is mainly due to smoothing effects when calculating global values. Spatial outliers cannot be seen on this level of detail, but will be shown on country level.

A closer look at the results of the **Protected Area Human Impact Indicator (PAHI)** shows that this 'spatial extension' in most cases leads to immense index value increases from the original PALI. For example biome 4 features a PAHI value of 44.2%, i.e. nearly half of the protected areas in *'Temperate Broadleaf and Mixed Forests'* are to some extent exposed to human activities. There are a couple more biomes featuring far higher values than the PAHI global average of 8.6% (e.g. biomes 12, 98 and 8). On the other hand biomes such as 10 *'Montane Grasslands and Shrublands'* and 11 *'Tundra'* have just slightly more than 1% of its total PA affected even with considering the immediate vicinity of lighting sources.

Reference	Description	PA Area (abs./rel.) [km^2]	[%]	PALI[g] [%]	PAHI[g] [%]
World*	–	16,537,314.6	100.0	**1.8**	**8.6**
Biome 1	Tropical and Subtropical Moist Broadleaf Forests	4,069,947.3	24.6	0.8	3.4
Biome 2	Tropical and Subtropical Dry Broadleaf Forests	238,390.0	1.4	2.9	12.1
Biome 3	Tropical and Subtropical Coniferous Forests	48,769.0	0.3	3.0	16.2
Biome 4	Temperate Broadleaf and Mixed Forests	1,379,677.8	8.3	**8.6**	**44.2**
Biome 5	Temperate Coniferous Forests	990,566.6	6.0	3.1	16.9
Biome 6	Boreal Forests/Taiga	1,290,543.4	7.8	0.6	4.2
Biome 7	Tropical and Subtropical Grasslands, Savannas, and Shrublands	2,519,228.8	15.2	0.5	2.2
Biome 8	Temperate Grasslands, Savannas, and Shrublands	363,746.7	2.2	3.9	20.8
Biome 9	Flooded Grasslands and Savannas	202,415.8	1.2	1.1	5.0
Biome 10	Montane Grasslands and Shrublands	1,213,418.6	7.3	**0.2**	**1.2**
Biome 11	Tundra	1,296,096.9	7.8	**0.2**	**1.4**
Biome 12	Mediterranean Forests, Woodlands, and Scrub	218,361.7	1.3	**8.8**	**34.8**
Biome 13	Deserts and Xeric Shrublands	2,552,205.8	15.4	1.4	5.7
Biome 14	Mangroves	63,489.9	0.4	**4.2**	14.3
Biome 98	Lakes	12,430.9	0.1	3.2	**33.1**
Biome 99	Rock and Ice	76,259.7	0.5	**0.1**	**1.1**

Table colors: Black - 3 largest biomes; Red - 3 most negative PALI and PAHI values; Green - 3 most positive PALI and PAHI values

g This table shows the global values of PALI and PAHI

* The first line ('World') shows the PAL and PAHII for the total land area, the other lines show the PALI and PAHI for biomes 1-99

Table 3: The global perspective of PALI and PAHI.

Looking at the index values of **PALI** and **PAHI** mapped on country level (figure 7), Europe in general, Japan, and some Caribbean islands show a significant incursion of nighttime lights into protected areas (colored in red). Puerto Rico has more than 60% of its total protected area directly affected by artificial lighting at night, while Martinique even reaches a value of 98%. European countries such as Belgium (21.1%), Germany (16.1%), France (14.6%) and Italy (13.9%) all feature a PALI higher than 10%. Compared to that, the United States are on the rather low end of the list, having approximately 3% of its PAs impacted by light pollution. However, more than half of all countries (140 countries, 60%) show PALI values of even less than 3%.

Adding the immediate neighborhood of lighting sources increases the calculated index values significantly. 117 countries (about 50% of all countries) thus have more than 10% of their PAs exposed to human activities as approximated from satellite nighttime lights (compared to just 54 countries or 23% with matching PALI values). According to this method nearly all of Europe falls in the category of highest risk. Countries such as Puerto Rico and Martinique feature PAHI values of 100%, thus not even having a single region within their designated protected areas which is more than 5km away from settlements, i.e. the threshold for areas to be considered as potentially not influenced.

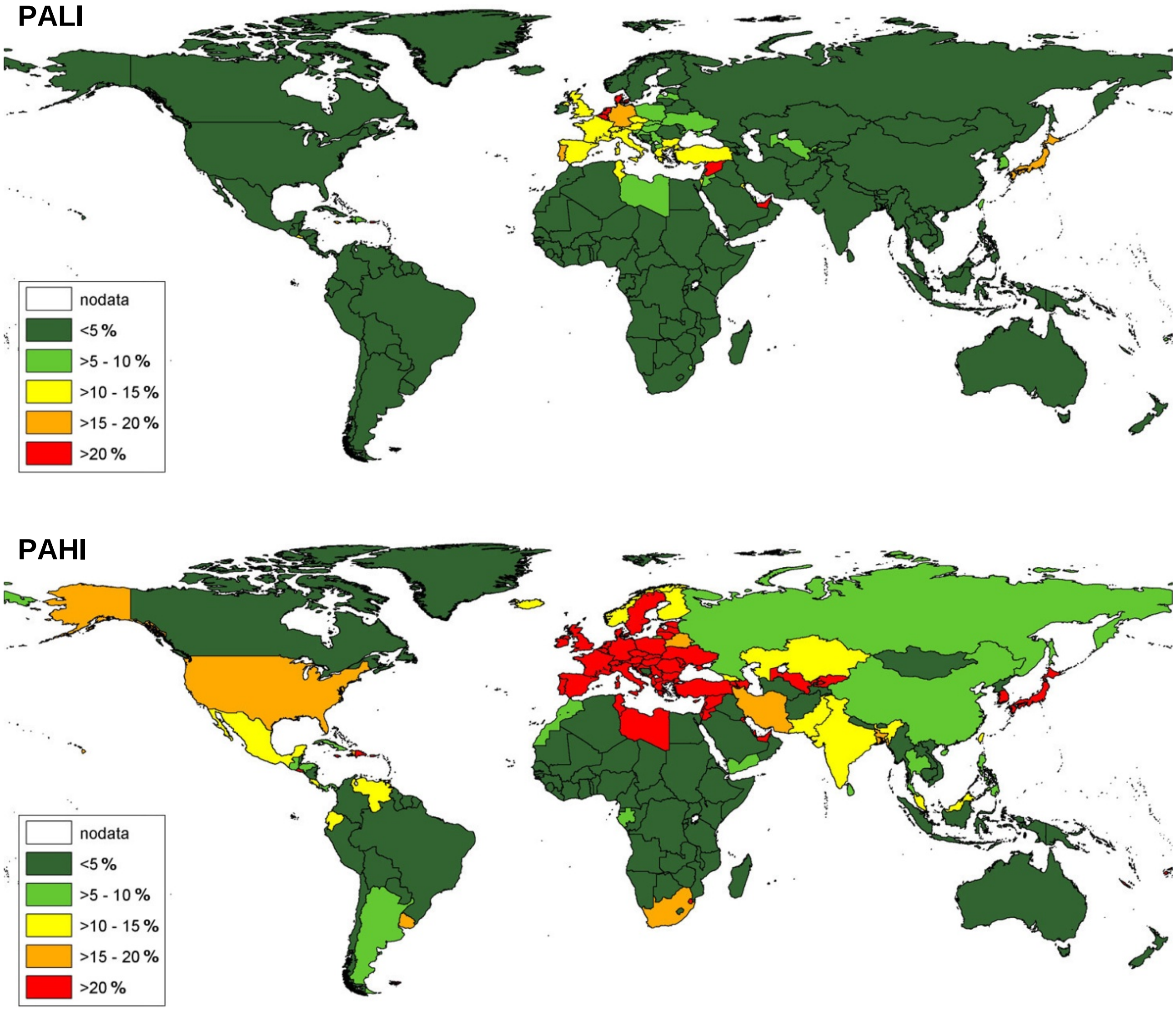

Figure 7: PALI and PAHI classified on country level and visualized using a bipolar color scale (red: negative; green: positive).

With the analyses carried out on a combined country-biome level it is possible to visualize results with greater spatial precision (see figure 8). This reveals patterns in particular in large countries such as the United States, China and Russia. In the U.S. the divergence of East and West becomes obvious. Large unaffected areas in China (e.g. Western China) and Russia (Siberia) can be identified in contrast to regions featuring very high values due to their high population density.

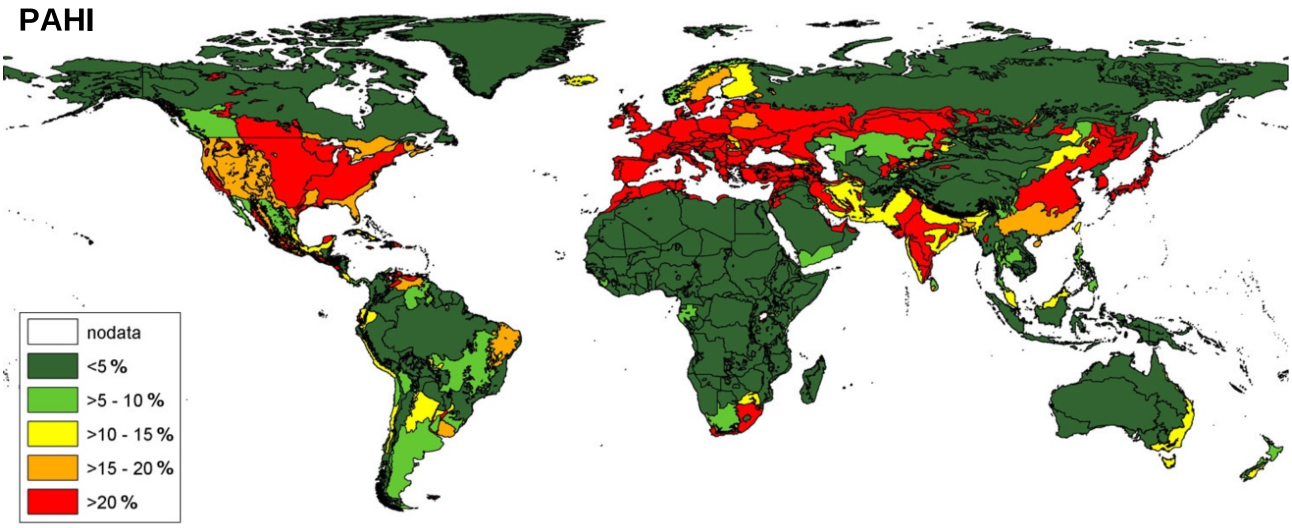

Figure 8: PAHI classified on the highest available level of spatial detail (country-biome combination).

Table 4 summarizes all calculated indicators and highlights the corresponding top 3 and bottom 3 in the order of the index values (negative: red; positive: green). This inter-comparison reveals interesting patterns and correlations, e.g. biome 12 '*Mediterranean Forests, Woodlands, and Scrub*' is identified as the overall number one in terms of potential risk. Regions assigned to this biome (3,186,732km^2; that is 2.5% of the global land area) are amongst the most affected by both direct light pollution and related approximated human activities. Less than 7% of these regions (218,361.7km^2) are legally protected, whereas in addition to that these few protected areas are also on the top of the list regarding both direct lighting impact and approximated anthropogenic influences.

Biome 4 '*Temperate Broadleaf and Mixed Forests*' (12,560,815km^2; 9.7% of the global land area) features even higher index values regarding impact of light pollution (LI: 18.7%) and related human activities (HI: 31.0%). With 11% of the regions assigned to biome 4 having legal protection status, at least the PAI value is slightly higher than the one of biome 12, even though it is still below the average of 12.7%. Featuring a value of 44.2% the corresponding PAHI (showing human impact on protected areas) is by far higher than all other biomes. The PALI which measures the direct light pollution impact on protected areas is about five times the average value (8.6%), just being topped by biome 12.

On the other hand there are a couple of biomes which should be mentioned as positive examples. First, there is the separately designated biome 99 '*Rock and Ice*' having approximately 30% of its land area protected. There is hardly any lighting observed in these regions, which results in all related indicators featuring very low values. Biome 99 however just covers 0.2% of the total land area. Around 6% of the global land area is assigned to biome 11 '*Tundra*' whereof after all 16.7% feature legal protection status. With very little artificial night lighting detected in regions of biome 11 as well, very low related indicator values are the logical result.

The three biomes covering more than half of the global land area (biome 1 '*Tropical and Subtropical Moist Broadleaf Forests*' – 15.2%, biome 7 '*Tropical and Subtropical Grasslands, Savannas, and Shrublands*' – 15.5%, biome 13 '*Deserts and Xeric Shrublands*' – 21.4%) feature light pollution related indicators which are all slightly below the average values. Biome 1 and biome 7 are around or even above the average regarding the degree to which they are protected (PAI), while for biome 13 a lower protection ratio is identified.

Reference	Description	PAI[g] [%]	LI[g] [%]	HI[g] [%]	PALI[g] [%]	PAHI[g] [%]
World*	–	**12.7**	**4.0**	**10.1**	**1.8**	**8.6**
Biome 1	Tropical and Subtropical Moist Broadleaf Forests	20.6	1.8	8.5	0.8	3.4
Biome 2	Tropical and Subtropical Dry Broadleaf Forests	8.0	5.4	**19.9**	2.9	12.1
Biome 3	Tropical and Subtropical Coniferous Forests	**6.9**	3.7	14.1	3.0	16.2
Biome 4	Temperate Broadleaf and Mixed Forests	11.0	**18.7**	**31.0**	**8.6**	**44.2**
Biome 5	Temperate Coniferous Forests	**24.7**	7.5	17.6	3.1	16.9
Biome 6	Boreal Forests/Taiga	8.9	1.8	4.6	0.6	4.2
Biome 7	Tropical and Subtropical Grasslands, Savannas, and Shrublands	12.5	**0.5**	**3.0**	0.5	2.2
Biome 8	Temperate Grasslands, Savannas, and Shrublands	**3.7**	6.1	17.9	3.9	20.8
Biome 9	Flooded Grasslands and Savannas	19.2	5.0	10.1	1.1	5.0
Biome 10	Montane Grasslands and Shrublands	**24.9**	1.1	4.7	**0.2**	**1.2**
Biome 11	Tundra	16.7	**0.4**	**1.0**	**0.2**	**1.4**
Biome 12	Mediterranean Forests, Woodlands, and Scrub	**6.9**	**10.7**	**28.3**	**8.8**	**34.8**
Biome 13	Deserts and Xeric Shrublands	9.2	2.0	6.1	1.4	5.7
Biome 14	Mangroves	20.0	**8.1**	17.5	**4.2**	14.3
Biome 98	Lakes	24.1	5.4	12.5	3.2	**33.1**
Biome 99	Rock and Ice	**29.9**	**0.0**	**0.2**	**0.1**	**1.1**

Table colors: Black - 3 largest biomes; Red - 3 most negative index values; Green - 3 most positive index values

[g] This table shows the global values of PAI, LI/HI, and PALI/PAHI

* The first line ('World') shows the index values for the total land area, the other lines show the index values for biomes 1-99

Table 4: The global perspective of all calculated indicators (PAI, LI/HI, PALI/PAHI).

5) DISCUSSION AND CONCLUSION

One limitation in this analysis is the inconsistent quality of the protected areas input data. For some countries no polygon boundaries for protected areas are available at all (e.g. see Austria in figure 9). Buffering the point features according to their legally stated areal extent allows for correctly assessing the degree to which a country's total area is protected (see PAI calculations). Yet, the fact that the actual delineation of the protected areas is unknown introduces some level of error when spatially intersecting the buffered points with ancillary data. Figure 9 shows the correct delineation of Austria's six National Parks as reference compared to the protected area approximations of the WDPA in order to clarify the problem. The authors support the efforts of UNEP-WCMC in collecting and compiling the WDPA data set, and issue an urgent invitation to the responsible agencies at the national level to contribute their data to the WDPA. Ultimately, countries will benefit more from these kinds of analyses if they are able to provide the best available data.

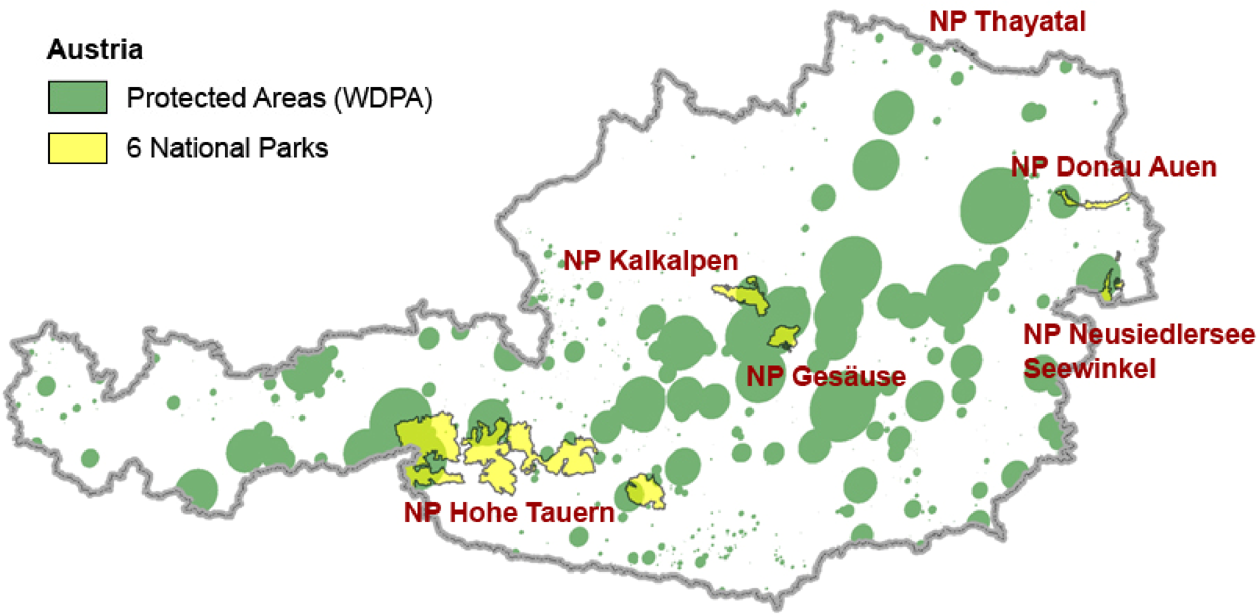

Figure 9: Protected Areas in Austria – Points derived from the WDPA buffered according to their stated extent (green) compared to polygon delineations of Austria's six National Parks (yellow).

In this paper a novel global assessment of light pollution impact on protected areas was presented. Satellite observed nighttime lights and spatial data on protected area distribution as derived from the WDPA were jointly analyzed and a set of spatial indicators was developed. First, an assessment of the legally protected proportion of each country's total land area was conducted (PAI). Introducing DMSP nighttime lights data ratios of both direct light pollution impact (LI) and approximated potential human influence (HI) were calculated on country level.

Combining the available data on global protected area distribution and nighttime lights we created two indices measuring the impact of artificial night lighting (PALI) and related human influences (PAHI) on protected areas. All spatial indicators were also calculated on the level of biomes, i.e. aggregations of eco-regions as defined by Olson et al. (2001), significantly increasing both thematic and spatial level of detail. Results indicate that regions in Europe and Asia Minor, the Caribbean, East Asia as well as in the Eastern part of the United States are most affected. On biome level '*Temperate Broadleaf and Mixed Forests*' suffer the biggest impact both in terms of general light pollution and lighting in designated protected areas.

This analysis presents a kind of protected areas risk assessment, and can be used to identify protected areas that may require additional resources for management owing to their proximity to urban areas. The data set also points to countries (e.g. BeNeLux and Germany) and regions within countries (Eastern China) where lighting control measures near protected areas could limit the effects of light pollution on biodiversity (Deda et al. 2007). It is well known that certain types of outdoor lighting contribute disproportionately to the effects of light pollution (Baddiley 2007b, Cabello & Kirschbaum 2007, Pas 2007, Hollan 2008, Mt. Megantic Astro Lab 2009), and as countries invest in new developments or upgrade old lighting systems, it is important to consider the ecological effects of lighting as guided by the emerging field of scotobiology – the 'biological science of darkness'. The concept of scotobiology[3], developed in 2003 (Bidwell 2003), describes the study of biological systems that require nightly darkness for their effective performance; systems that are inhibited or prevented from operating by light (Bidwell et al. 2007, Dick 2008, Dick et al. 2009).

Nearly 15 years ago this topic was already highlighted in a leading article published in the Lighting Journal entitled 'Social Factors behind the Development of Outdoor Lighting' (Simpson 1995). The author then stated that '*We were learning that outdoor lighting is more than just filling the space with light; learning that it is more than just a way of making our roads visible to motorists; learning that sensitivity in design is equally as important outdoors as it is indoors; and learning to take care of our environment*'. There has been much debate on the control and directionality of lighting in the last two decades. One country which serves as a good example in this context is the Republic of Slovenia, where in August 2007 a Lighting Law was adopted, prohibiting light above the horizontal and requiring the use of shielding for most luminaires (Mizon & Morgan-Taylor 2008). Other countries have not yet reached a comparable level of official acknowledgment. However, 'rules for lighting' are proposed and related fights for legislative measures are going on in several countries such as the Czech Republic (Hollan 2003) and Switzerland (Righetti 2007). Besides shielding and controlling directionality of lighting, these proposed rules include 'not to use more light than necessary', 'to dim light after peak hours', and requiring 'limits for illuminated advertisements'. Improving conditions assumingly caused by law-enforced management activities against light pollution were observed on the island of Oahu in the Hawaiian archipelago in a satellite based analysis of trends of lighting impact on coral reefs (Aubrecht et al. 2009).

We consider that this analysis may help to raise awareness on the topic of light pollution among protected areas personnel, conservation and scientific communities, and the general public. The developed spatial indicators can easily be adapted to similar analyses. As a next step, the authors plan to monitor the ecological threat of artificial night lighting in areas of high species richness using species distribution grids developed by CIESIN's SEDAC Project.

[3] Scotobiology – The Biology of Darkness; http://www.muskokaheritage.org/ecology-night/scotobiology-article.asp

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LIST OF ABBREVIATIONS

AIT	Austrian Institute of Technology
ANL	Artificial Night Lighting
CIESIN	Center for International Earth Science Information Network
DMSP	Defense Meteorological Satellite Program
DN	Digital number
GIS	Geographic Information System
GPW	Gridded Population of the World
GRUMP	Global Rural-Urban Mapping Project
HI	Human Impact Indicator
IUCN	International Union for Conservation of Nature
LI	Light Pollution Indicator
NGDC	National Geophysical Data Center
NOAA	National Oceanic and Atmospheric Administration
NRMI	Natural Resources Management Index
OLS	Operational Linescan System
PA	Protected Area(s)
PAHI	Protected Area Human Impact Indicator
PAI	Protected Area Index
PALI	Protected Area Light Pollution Indicator
PMT	Photomultiplier Tube
SEDAC	Socioeconomic Data and Applications Center
UNEP	United Nations Environment Programme
WCMC	World Conservation Monitoring Centre
WCPA	World Commission on Protected Areas
WDPA	World Database on Protected Areas

APPENDIX

The following appendix table (table 5) lists PALI and PAHI index values along with numbers for the total land area and the percent area protected (PAI) on country level. For comparison the first line shows the corresponding values on global scale. Referring to the CIESIN Eco-Region Protection Indicator, countries which do not achieve the target of protecting at least 10% of each terrestrial biome within its borders (following the international consensus, Convention on Biological Diversity 2004) are highlighted in red in the PAI column. Countries having more than 20% of its total land area legally protected are marked in green pointing to positive examples. In the columns featuring the values for PALI and PAHI those countries are highlighted in red that have more than 10% of its protected areas impacted by artificial night lighting and associated human activities. On the other hand countries featuring index values lower than 1% (i.e. pristine protected areas in terms of light pollution) are marked in green.

Country	Code	Land area [km²]	PAI [%]	PALI [%]	PAHI [%]
World*		**129,980,271.5**	**12.7**	**1.8**	**8.6**
Afghanistan	AFG	635,956.6	0.4	0.0	0.0
Albania	ALB	27,979.0	8.9	3.1	26.5
Algeria	DZA	2,318,907.2	6.3	0.8	3.0
American Samoa	ASM	163.3	1.0	51.4	61.7
Andorra	AND	453.5	5.9	76.2	100.0
Angola	AGO	1,250,293.5	12.4	0.1	0.3
Anguilla	AIA	64.4	0.0	-	-
Antigua and Barbuda	ATG	396.7	7.2	95.6	100.0
Argentina	ARG	2,744,830.4	5.1	1.5	6.8
Armenia	ARM	28,245.2	4.1	2.1	35.4
Aruba	ABW	177.2	0.0	-	-
Australia	AUS	7,683,647.8	9.4	0.4	2.0
Austria	AUT	82,573.2	22.5	10.2	57.7
Azerbaijan	AZE	85,126.0	7.1	2.3	23.0
Bahamas	BHS	11,411.8	12.4	2.5	12.4
Bahrain	BHR	598.9	1.3	73.4	100.0
Bangladesh	BGD	131,402.6	1.2	2.0	16.0
Barbados	BRB	421.6	0.6	100.0	100.0
Belarus	BLR	206,050.5	6.9	2.5	19.8
Belgium	BEL	30,462.3	2.9	21.1	94.3
Belize	BLZ	21,915.8	17.3	0.3	2.1
Benin	BEN	115,720.6	23.7	0.0	0.0
Bermuda	BMU	41.0	2.7	59.5	100.0
Bhutan	BTN	37,872.4	26.9	0.0	0.0
Bolivia	BOL	1,073,664.5	18.5	0.3	1.8
Bosnia and Herzegovina	BIH	46,730.4	0.6	0.0	0.4
Botswana	BWA	579,029.6	30.9	0.1	0.4
Brazil	BRA	8,405,983.4	27.2	0.6	3.3
Brunei	BRN	5,710.1	43.2	6.4	12.9
Bulgaria	BGR	110,581.6	10.9	11.5	50.1

Burkina Faso	BFA	275,410.8	14.3	0.1	0.5
Burundi	BDI	25,040.8	5.7	0.0	0.2
Cambodia	KHM	177,458.4	24.1	0.0	0.2
Cameroon	CMR	463,481.5	9.1	0.0	0.0
Canada	CAN	9,201,347.2	8.0	0.7	4.4
Cape Verde	CPV	3,881.0	0.0	-	-
Cayman Islands	CYM	234.2	4.8	62.0	100.0
Central African Republic	CAF	622,305.3	17.8	0.0	0.0
Chad	TCD	1,263,316.2	9.5	0.0	0.1
Chile	CHL	709,557.6	14.2	0.1	1.0
China	CHN	9,287,110.1	16.4	1.3	5.3
Colombia	COL	1,127,135.5	20.4	0.2	1.3
Comoros	COM	1,608.0	0.0	-	-
Congo	COD	2,290,587.1	11.8	0.1	0.3
Cook Islands	COK	600.7	0.1	99.8	100.0
Costa Rica	CRI	50,334.9	30.0	2.6	14.2
Côte d'Ivoire (Ivory Coast)	CIV	318,968.6	22.8	0.2	1.4
Croatia	HRV	58,465.7	8.5	7.9	38.0
Cuba	CUB	108,352.9	13.8	1.4	7.9
Cyprus	CYP	9,106.5	11.1	10.3	42.9
Czech Republic	CZE	78,457.9	15.9	13.9	84.3
Denmark	DNK	41,125.3	5.5	20.9	100.0
Djibouti	DJI	21,528.8	0.0	-	-
Dominica	DMA	737.8	21.9	13.3	48.9
Dominican Republic	DOM	47,756.0	14.1	5.2	20.4
East Timor	TLS	14,682.4	1.4	0.0	0.0
Ecuador	ECU	253,745.5	24.6	4.1	12.6
Egypt	EGY	974,796.6	5.9	0.6	3.5
El Salvador	SLV	19,966.2	2.3	12.3	54.7
Equatorial Guinea	GNQ	26,778.3	18.5	0.0	0.0
Eritrea	ERI	121,662.7	4.8	0.0	0.0
Estonia	EST	42,621.8	18.1	2.7	24.9
Ethiopia	ETH	1,124,563.3	18.0	0.1	0.6
Falkland Islands	FLK	11,201.1	0.3	2.2	81.0
Faroe Islands	FRO	1,218.7	0.0	-	-
Fiji Islands	FJI	17,504.9	1.3	8.2	23.8
Finland	FIN	307,667.3	9.5	1.1	10.9
France	FRA	542,861.9	18.6	14.6	74.0
French Guiana	GUF	82,798.1	6.6	0.6	1.8
French Polynesia	PYF	2,975.4	0.8	0.0	0.0
Gabon	GAB	262,189.5	14.5	2.3	5.4
Gambia	GMB	10,415.4	2.1	0.0	0.5
Georgia	GEO	68,522.5	3.6	0.9	13.9

Germany	DEU	353,703.0	49.9	16.1	87.1
Ghana	GHA	231,433.1	15.0	0.1	1.5
Gibraltar	GIB	4.3	0.0	-	-
Greece	GRC	127,477.8	3.5	11.1	62.5
Greenland	GRL	347,844.3	45.9	0.0	0.0
Grenada	GRD	301.5	2.5	44.5	100.0
Guadeloupe	GLP	1,661.8	13.7	41.4	100.0
Guam	GUM	511.5	10.8	79.4	100.0
Guatemala	GTM	107,903.9	31.0	1.3	6.6
Guernsey	GGY	157.6	0.0	-	-
Guinea	GIN	245,202.6	6.8	0.2	0.9
Guinea-Bissau	GNB	33,077.7	14.6	0.2	1.9
Guyana	GUY	207,821.7	3.2	0.0	0.0
Haiti	HTI	26,695.9	0.4	7.3	18.8
Honduras	HND	111,239.9	17.3	1.5	8.2
Hong Kong	HKG	939.8	38.5	88.2	100.0
Hungary	HUN	91,606.3	5.0	6.6	51.1
Iceland	ISL	89,126.5	8.7	1.4	13.7
India	IND	3,205,473.9	5.0	3.1	13.5
Indonesia	IDN	1,871,071.4	13.9	0.5	2.9
Iran	IRN	1,614,078.6	6.8	3.3	15.9
Iraq	IRQ	428,332.6	0.0	0.0	0.0
Ireland	IRL	67,789.8	0.9	4.2	42.8
Isle of Man	IMN	537.1	0.0	-	-
Israel	ISR	21,892.9	16.7	12.0	52.8
Italy	ITA	296,251.9	7.9	13.9	68.6
Jamaica	JAM	10,920.5	18.6	20.0	57.3
Japan	JPN	365,877.8	15.7	18.9	69.7
Jordan	JOR	89,686.2	9.0	6.1	22.2
Kazakhstan	KAZ	2,632,158.1	2.4	2.3	14.4
Kenya	KEN	579,655.0	11.4	0.4	3.0
Kiribati	KIR	756.0	16.9	0.0	0.0
Korea, North	PRK	121,147.3	2.2	0.1	1.0
Korea, South	KOR	96,783.0	4.0	8.5	40.7
Kosovo	KSV	196.0	0.0	-	-
Kuwait	KWT	17,216.7	1.6	11.6	54.1
Kyrgyzstan	KGZ	182,038.1	3.3	2.8	22.4
Lao Peoples Democratic Republic	LAO	229,196.3	15.4	0.0	0.2
Latvia	LVA	63,411.6	14.3	5.4	39.0
Lebanon	LBN	10,219.6	0.5	1.5	20.6
Lesotho	LSO	30,574.9	0.5	0.0	0.6
Liberia	LBR	95,973.0	18.2	0.0	0.0
Libyan Arab Jamahiriya	LBY	1,619,439.3	0.1	7.2	36.5

Liechtenstein	LIE	163.5	20.7	25.8	100.0
Lithuania	LTU	64,396.9	4.3	3.6	36.1
Luxembourg	LUX	2,585.7	15.5	31.2	100.0
Macau	MAC	11.7	0.0	-	-
Macedonia	MKD	24,662.0	3.5	8.3	67.3
Madagascar	MDG	589,315.9	3.0	0.0	0.0
Malawi	MWI	95,038.5	18.3	0.6	2.7
Malaysia	MYS	327,718.8	17.0	3.1	11.9
Maldives	MDV	13.5	0.0	-	-
Mali	MLI	1,247,885.3	2.4	0.0	0.0
Malta	MLT	274.9	8.9	0.0	0.0
Marshall Islands	MHL	53.5	0.0	-	-
Martinique	MTQ	1,091.1	34.3	97.8	100.0
Mauritania	MRT	1,042,488.3	0.5	0.0	0.0
Mauritius	MUS	1,919.7	4.6	14.6	83.7
Mayotte	MYT	339.5	2.1	0.0	0.0
Mexico	MEX	1,936,200.2	7.0	2.3	10.9
Micronesia	FSM	562.2	1.4	50.8	100.0
Moldova	MDA	33,286.3	1.2	0.6	25.8
Monaco	MCO	5.0	11.4	100.0	100.0
Mongolia	MNG	1,547,320.0	12.8	0.0	0.3
Montenegro	MNE	13,435.8	12.4	8.1	41.8
Montserrat	MSR	95.0	8.7	100.0	100.0
Morocco	MAR	672,230.6	3.1	1.6	6.6
Mozambique	MOZ	771,981.0	15.8	0.0	0.0
Myanmar	MMR	661,502.5	4.6	0.8	3.7
Namibia	NAM	826,004.4	14.0	0.1	0.6
Nauru	NRU	15.0	0.0	-	-
Nepal	NPL	138,086.7	14.6	0.2	2.1
Netherlands	NLD	33,821.8	8.4	24.0	100.0
Netherlands Antilles	ANT	747.8	12.7	59.4	100.0
New Caledonia	NCL	18,347.7	5.5	6.5	32.7
New Zealand	NZL	259,623.7	7.7	0.3	2.0
Nicaragua	NIC	117,854.5	18.1	0.4	2.9
Niger	NER	1,184,472.3	7.1	0.0	0.0
Nigeria	NGA	899,139.2	13.4	0.6	2.7
Niue	NIU	250.8	22.0	0.0	0.0
Norfolk Island	NFK	35.1	10.3	20.8	100.0
Northern Mariana Islands	MNP	393.3	0.1	0.0	0.0
Norway	NOR	305,297.5	5.9	0.5	10.6
Oman	OMN	313,255.4	10.5	0.1	0.6
Pakistan	PAK	788,320.4	10.0	2.2	12.8
Palau	PLW	401.3	1.1	0.0	0.0

Palestinian Territory	PSE	6,008.6	0.1	9.1	62.1
Panama	PAN	73,194.4	24.2	2.6	7.1
Papua New Guinea	PNG	458,149.7	10.7	0.3	1.3
Paraguay	PRY	395,107.3	5.3	0.5	1.6
Peru	PER	1,274,168.1	12.3	0.1	1.5
Philippines	PHL	289,287.2	9.5	1.0	6.4
Pitcairn Island	PCN	35.0	0.0	-	-
Poland	POL	309,261.8	21.7	8.2	53.0
Portugal	PRT	90,472.9	6.2	19.0	69.2
Puerto Rico	PRI	8,809.8	5.7	60.9	100.0
Qatar	QAT	11,075.3	0.3	7.7	69.3
Republic of Congo	COG	340,467.7	11.7	0.0	0.0
Reunion	REU	2,506.4	16.2	7.9	45.8
Romania	ROU	235,538.6	7.8	3.3	25.8
Russia	RUS	16,379,688.0	8.7	1.0	6.5
Rwanda	RWA	23,877.5	10.1	0.0	0.3
Saint Helena	SHN	329.4	10.6	24.3	31.4
Saint Kitts and Nevis	KNA	254.6	2.0	0.0	39.7
Saint Lucia	LCA	595.3	14.6	39.5	100.0
Samoa	WSM	2,798.1	2.6	1.2	26.6
San Marino	SMR	58.7	0.0	-	-
Sao Tome and Principe	STP	956.9	0.0	-	-
Saudi Arabia	SAU	1,955,635.0	30.4	1.0	3.4
Senegal	SEN	195,552.1	24.6	0.1	0.8
Serbia and Montenegro	SCG	87,396.7	2.1	7.3	44.1
Seychelles	SYC	173.3	16.9	26.3	100.0
Sierra Leone	SLE	71,839.0	5.0	0.7	4.3
Singapore	SGP	546.3	5.4	98.9	100.0
Slovakia	SVK	48,749.3	18.6	5.8	48.7
Slovenia	SVN	20,232.1	6.3	6.6	44.5
Solomon Islands	SLB	27,383.3	0.1	0.0	0.0
Somalia	SOM	635,490.0	0.6	0.0	0.1
South Africa	ZAF	1,217,886.7	6.8	3.1	16.9
Spain	ESP	501,117.2	8.5	13.1	53.0
Sri Lanka	LKA	64,649.5	21.1	2.1	10.0
St. Pierre and Miquelon	SPM	197.5	15.9	1.9	54.2
St. Vincent and Grenadines	VCT	397.8	11.6	0.0	82.7
Sudan	SDN	2,498,341.0	4.2	0.0	0.2
Suriname	SUR	140,430.9	11.6	0.5	2.7
Svalbard and Jan Mayen	SJM	25,776.6	56.1	0.0	0.0
Swaziland	SWZ	17,381.6	3.0	5.1	62.2
Sweden	SWE	418,652.8	10.1	2.9	22.1
Switzerland	CHE	38,146.3	21.5	11.5	73.3

Syrian Arab Republic	SYR	185,465.5	0.3	40.4	100.0
Taiwan	TWN	35,750.0	11.6	6.6	12.0
Tajikistan	TJK	126,413.6	3.5	0.3	3.1
Tanzania	TZA	888,824.1	33.1	0.1	0.7
Thailand	THA	510,716.8	19.8	1.3	7.4
Togo	TGO	57,215.4	11.2	0.5	3.0
Tokelau	TKL	3.4	0.0	-	-
Tonga	TON	546.5	8.1	7.1	13.5
Trinidad and Tobago	TTO	5,064.8	30.5	19.1	57.5
Tunisia	TUN	154,738.6	1.2	13.5	44.0
Turkey	TUR	767,476.7	1.8	12.6	48.2
Turkmenistan	TKM	484,568.3	2.9	0.3	3.9
Turks and Caicos Islands	TCA	425.2	17.3	1.6	10.9
Tuvalu	TUV	12.8	0.0	-	-
Uganda	UGA	206,201.5	28.3	0.2	0.6
Ukraine	UKR	586,136.5	3.3	6.6	39.9
United Arab Emirates	ARE	78,214.2	1.4	22.6	55.8
United Kingdom	GBR	243,544.3	24.5	13.1	72.7
United States	USA	9,145,728.1	22.0	3.4	16.8
Uruguay	URY	173,595.8	0.2	3.9	18.2
Uzbekistan	UZB	414,196.6	2.3	7.1	28.6
Vanuatu	VUT	11,676.1	4.2	5.3	30.4
Venezuela	VEN	899,451.1	53.4	4.5	13.8
Vietnam	VNM	325,602.9	5.6	0.3	1.2
Virgin Islands, British	VGB	116.8	4.6	22.4	55.4
Virgin Islands, U.S.	VIR	322.2	13.3	90.2	100.0
Wallis and Futuna Islands	WLF	153.9	0.0	-	-
Yemen	YEM	416,617.2	0.6	0.7	5.4
Zambia	ZMB	740,756.5	36.2	0.2	1.1
Zimbabwe	ZWE	388,019.5	27.0	0.3	1.9

Table colors: Red - negative index values (PAI<10, PALI>10, PAHI>10); Green - positive index values (PAI>20, PALI<1, PAHI<1)

* The first line ('World') shows the index values for the total land area, the other lines show the index values on country level

Table 5: List of PALI and PAHI along with numbers on total land area and percent area protected (PAI) on country level.