Artificially lit surface of Earth at night increasing in radiance and extent

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A central aim of the "lighting revolution" (the transition to solid-state lighting technology) is decreased energy consumption. This could be undermined by a rebound effect of increased use in response to lowered cost of light. Here we use the first-ever calibrated satellite radiometer designed for night lights to show that from 2012–2016, Earth's artificially lit outdoor area grew by 2.2% per year, with total radiance growth of 1.8% per year. Continuously lit areas brightened at a rate of 2.2% per year. Large differences in national growth rates were observed, with the lighting of few countries remaining stable or decreasing. These data are not consistent with global scale energy reductions, but rather indicate increased light pollution, with corresponding negative consequences for flora, fauna, and human wellbeing.

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One Sentence Summary: Earth's artificially lit area is expanding at 2.2% per year, with existing lit areas brightening by 2.2% per year.

Introduction

Continued improvement in the luminous efficacy of light sources and increases in GDP have resulted in tremendous growth in artificial light use over several centuries (*1*). Historically, lighting has been subject to a strong rebound effect, in which increases in luminous efficacy result in correspondingly greater light use rather than energy savings (*2*). Regardless of historical or geographical context, humans tend to use as much artificial light as they can buy for ∼0.7% of GDP (*3*). Outdoor lighting became commonplace with the introduction of electric light, and grew at an estimated rate of 3-6% per year during the second half of the 20$^{\text{th}}$ century (*4*). This has caused widespread "loss of the night", with half of Europe and a quarter of North America experiencing substantially modified light-dark cycles (*5*).

A critical question for sustainable development is whether the use of outdoor light will continue to grow exponentially, or whether developed countries are nearing saturation in demand (*3*). In addition to the possibility that the existing light levels are already sufficient for any desired visual task, factors that reduce demand include: greater public recognition of the unintended ecological (*6*) and astronomical (*5, 7*) impacts of outdoor light pollution, official warnings that overexposure to artificial light may be affecting human sleep and health (*8*), efforts to transition to a sustainable society with decreased electricity demand (*9*), the desire of local governments to reduce the costs of lighting (*10*), and the establishment of protected "dark sky" areas (*11*). If demand saturation has not been reached, then the increasing luminous efficacy made possible by the solid-state lighting revolution (*12*) will increase light emissions instead of saving energy.

Changes in outdoor lighting can only be measured on the global scale via Earth observing satellites, but no calibrated satellite sensor made global observations of night lights until recently. The well-known older images of Earth at night (*13*) were based upon an uncalibrated sensor from a defense satellite (DMSP), which had frequent and unrecorded changes in sensor gain. Despite this drawback, there have been attempts to use statistical methods to try to intercalibrate the time series. These methods sometimes rely on questionable assumptions, such as that Sicily experienced no changes in lighting over a 15 year period (*14*). In addition to the lack of an on-board radiance calibration, DMSP experienced saturation in cities, had low (8 bit) radiometric resolution, and an intrinsic spatial resolution of 5 km (*15*). Nevertheless, the inherent connection between artificial light and human activity means that DMSP data display strong correlations with many socio-economic factors (*16*).

While considerable research has been done using DMSP time series, most analyses have been focused other remotely sensed factors (e.g. human settlement, socio-economic activity, detecting fishing vessels (*17*)), and have not reported on trends in lighting itself. The few which have done so were on the national (e.g. 4% annual increase in Spain (*18*)) or continental scale (e.g. (*19*)), or else examined only a specific class of lighting (e.g. (*14*)). The official NOAA radiance calibrated DMSP time series showed little change in the sum of lights of several large cities, but the intercalibration was based on the assumption that the lights of Los Angeles did not change over the period 1996-2010 (*20*). In contrast, a recent analysis using a different methodology found a factor 2 increase in global lights from 1992-2013 ($\sim 3.5\%$ per year) (*21*). However, due to the limitations of the DMSP, and particularly the saturation in city centers, many analyses have been limited to change in lit area rather than change in radiance.

The Visible Infrared Imaging Radiometer Suite Day-Night Band (VIIRS DNB) came online just as outdoor use of LED lighting began in earnest (*22*). This sensor provides the first-ever global calibrated nighttime radiance measurements in a spectral band close to the visible (500-900 nm), with a much higher radiometric sensitivity than the DMSP, and at a spatial resolution of near 750 m (*15*). This improved spatial resolution allows neighborhood (rather than city or national) scale changes in lighting to be investigated for the first time (*23*).

Results

The cloud-free DNB data show that over the period 2012-2016, both lit area and the radiance of previously lit areas increased in most countries (Fig. 1) in the 500-900 nm range, with global increases of 2.2% per year for lit area and 2.2% per year for the brightness of continuously lit areas (see Materials and Methods). Overall, the radiance of areas lit above 5 $\mathrm{nW\,cm^{-2}\,sr^{-1}}$ increased by 1.8% per year. These factors decreased in few countries, including several experiencing warfare (e.g. Yemen (*24*) and Syria). They were also stable in only a few countries, interestingly including some of the world's brightest (e.g. Italy, Netherlands, Spain, and USA). With few exceptions, growth in lighting occurred throughout South America, Africa, and Asia. As the analysis of lit area and total radiance are not subject to a stability criterion, transient lights like wildfires can cause large fluctuations. Australia experienced a major decrease in lit area from 2012-2016 for this reason (Fig. 1A, 2). Fire-lit areas failed the stability test, however, and were therefore not included in the radiance change analysis (Fig. 1B). A small number of countries have "no data" due to either their extreme latitude (Iceland) or lack of observed stable lights above 5 $\mathrm{nW\,cm^{-2}\,sr^{-1}}$ in the cloud-free composite (e.g. Central African Republic).

Brightly lit areas are uncommon: for most countries, over half of the national light emission above the analysis threshold came from areas lit below 20 $\mathrm{nW\,cm^{-2}\,sr^{-1}}$ (Fig. 3A+B, Supplemental Fig S1-3). For context, small towns in the American West with populations of several hundreds are typically slightly above the 5 $\mathrm{nW\,cm^{-2}\,sr^{-1}}$ threshold, while the radiance observed at international airports is typically $\sim$150 $\mathrm{nW\,cm^{-2}\,sr^{-1}}$ (*23*). The area-radiance curve is often approximately power-law, but the shape and slope are not consistent across countries (Supplemental Fig., see (*25*) for a discussion of how such relationships may emerge naturally, and c.f. (*26*) for DMSP and (*27*) for higher resolution aerial photos). For example, compared to China, the USA has twice as much area illuminated with radiances in the

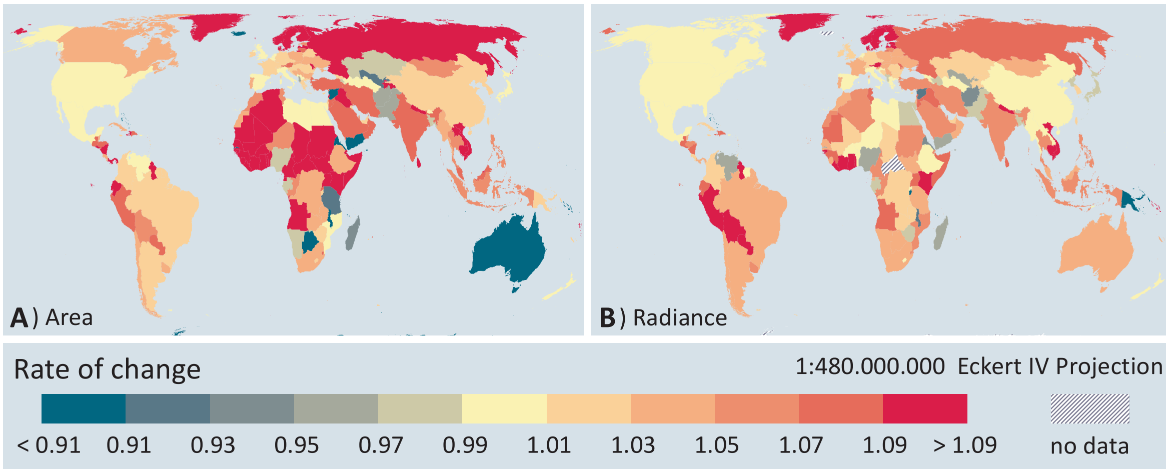


Figure 1: Annual changes in lit area (A) and the radiance of stably lit areas (B). Changes are shown as an annual rate, i.e. $\sqrt[4]{A_{2016}/A_{2012}}$, where A_{2016} is the lit area observed in 2016. See supplemental figure S28 for total radiance change instead of stable lights radiance change.

range 5–6.1 $\mathrm{nW\,cm^{-2}\,sr^{-1}}$, but nearly 20 times as much area illuminated in the range 132-162 $\mathrm{nW\,cm^{-2}\,sr^{-1}}$. The shape difference is even more striking for Bolivia and Pakistan. In many countries, there is little or no area lit above 100 $\mathrm{nW\,cm^{-2}\,sr^{-1}}$.

The global 9.1% increase in stable light radiance from 2012-2016 (2.2% per year) applies nearly independently of radiance in 2014 (Fig. 3C). In some individual countries, however, radiance change was not uniform across the 2014 radiance classes. In the United Kingdom, for example, rate of lighting change was positively correlated with 2014 radiance (Supplemental Fig. S26). Nevertheless, even large increases in bright areas have relatively little effect on the country-level radiance change, because these areas typically account for a small fraction of the national light emission (Fig 3B, Supplemental Fig.).

Summed national per capita and total light emissions above the 5 $\mathrm{nW\,cm^{-2}\,sr^{-1}}$ threshold are correlated with per capita and national GDP (Fig. 4A,B, Spearman rank-order correlation coefficient 0.76 and 0.85 respectively, $p \ll 0.001$). This confirms the results of earlier studies using DMSP data (e.g. (*28, 29*)). Nevertheless, there are large (up to order of magnitude) differences between countries with similar wealth, and the relationship between per capita light and GDP appears to be nonlinear (Fig. 4A). Note that for a small number of northern countries (e.g. Finland), the national sum of lights does not include lights located above 60° North. The size of changes in lights and changes in GDP were larger in poorer countries, and smaller in wealthier countries. For the median country, the sum of total radiance grew by 15% from 2012-2016, which is quite close to the median country's GDP increase (13%) over the same time frame. However, the Spearman rank-order correlation between GDP and light change (Fig. 4D) was only 0.17 (p=0.05). The Spearman rank-order correlation between GDP and lit area change (Fig. 4C) was slightly larger, at 0.24 (p=0.006).

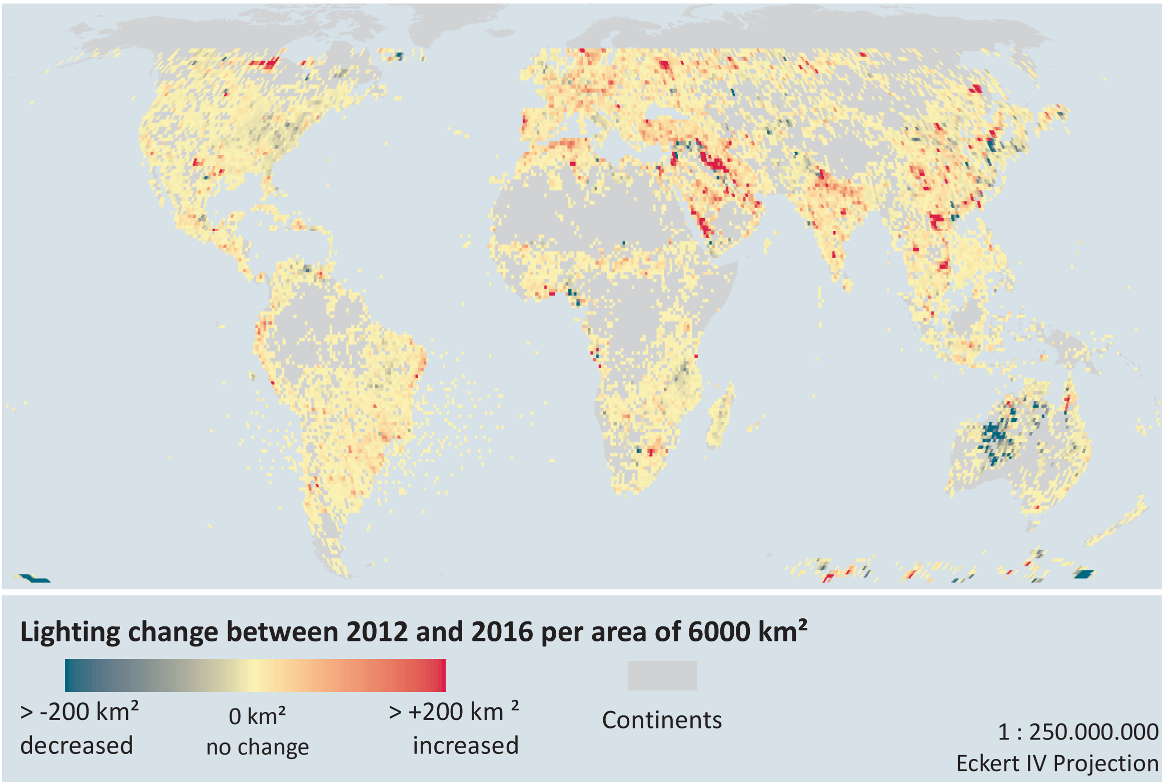


Figure 2: Absolute change in lit area from 2012 to 2016. Pixels increasing in area are shown as red, pixels decreasing in area are shown as blue, pixels with no change in area are shown as yellow. Each pixel has near equal area of 6000 ± 35 km^2. To ease interpretation, the color scale cuts off at 200 km^2, but some pixels had changes of up to ± 2000 km^2.

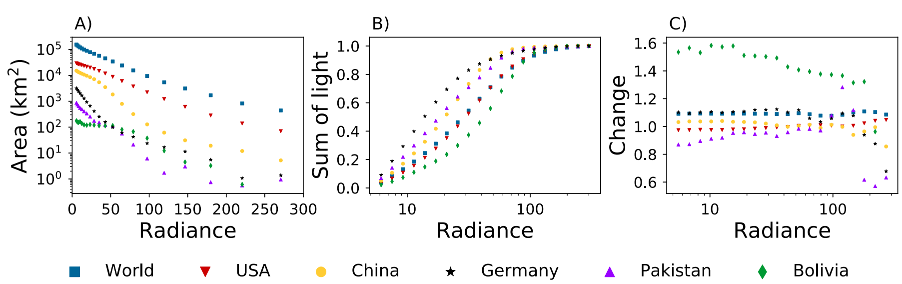


Figure 3: Patterns in lit area, radiance, and lighting change for the world and five selected countries. Panel A shows the 2014 lit area (in km^2) for each (logarithmically spaced) bin of radiance in nW cm^{-2} sr^{-1}. Panel B shows the normalized cumulative distribution of light in 2016 (i.e. what fraction of the total light is emitted below the given radiance). Panel C shows the mean change in radiance from 2012-2016 for each bin.

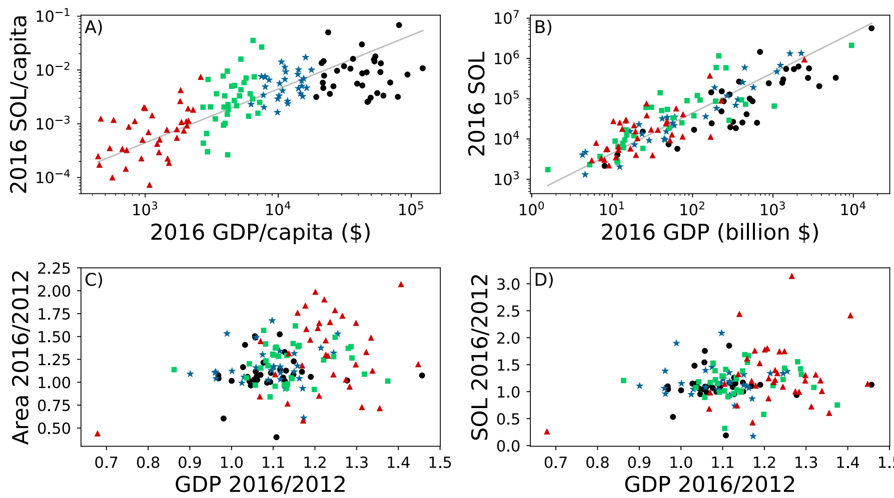


Figure 4: Relationships between light and economic parameters. (A) National sum of lights (SOL) per capita compared to per capita GDP, (B) sum of lights vs national GDP, (C) change in lit area from 2012 to 2016 vs change in GDP (one outlier not shown), and (D) change in sum of lights from 2012 to 2016 vs change in GDP. Colors and symbols indicate per capita GDP in 2016: <$2000 (red triangles), $2000-6000 (green squares), $6000-17000 (blue stars), >$17000 (black circles). Solid lines show an extrapolation based on the value of the median country.

Many large cities had decreases in DNB radiance in the city center, but increases in outlying areas. These decreases can often be directly attributed to replacement of older lamps with LEDs. This is vividly demonstrated by photographs taken by astronauts on the International Space Station of Milan, Italy, in 2012 and 2015 (Fig. 5A,B). The streetlights in the city changed from yellow/orange (sodium vapor) to white (LED), while the surrounding areas remained yellow/orange. As a result, the radiance observed by the DNB decreased (Fig. 5C), due to the sensor's lack of sensitivity to light in the range 400-500 nm (*23*). Similar transitions can be seen (and verified with newspaper accounts) in many cities worldwide.

Increases in radiance in areas around cities may result from several processes. In many cases, cities expand into new areas, causing their edges (which were previously only partly urbanized) to become brighter. In other cases, it may be due to expansion of electrification, or to increasing wealth in adjacent areas. Finally, some of the light observed by the satellite is not direct, but rather scattered by the atmosphere. For very bright cities, this causes a glow over adjacent areas that have little or no lighting. Transitions to LED lighting greatly increase this "skyglow", because the clear sky predominantly scatters short wavelength light (*31*). This effect would be considerably more noticeable if the DNB was sensitive to light below 500 nm. Similarly, while decreases in city center radiance in the DNB band likely indicate absolute energy reductions (see Methods), white LED transitions will often increase the skyglow experienced on the ground (*31–33*).

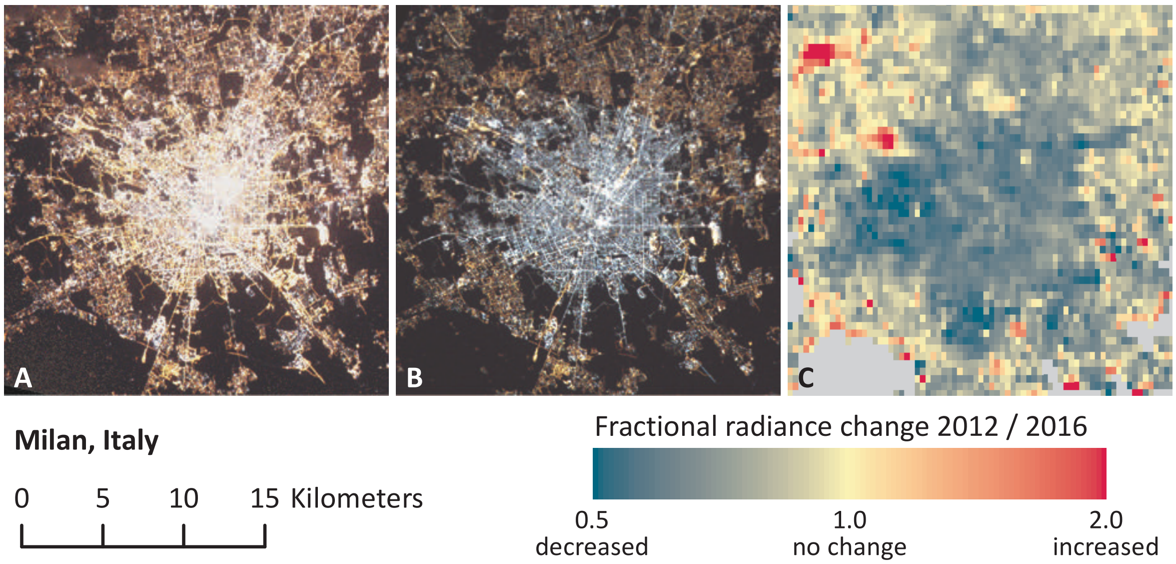


Figure 5: Change in lighting technology in Milan, Italy, observed from space. Color astronaut photographs from 2012 (A) and 2015 (B) courtesy the Earth Science and Remote Sensing Unit, NASA Johnson Space Center, with identification and georeferencing by ESA, IAU, and Cities at Night (*30*). Change from 2012 to 2016 in the DNB radiance band (C).

Discussion

Major arguments for transition to LEDs for outdoor lighting are cost savings and reductions in energy consumption (*9*). These goals have been realized in many cities that have switched to LED streetlights, and therefore decreases in observed DNB radiance likely indicate local energy savings. On the global (and often national) scale, however, these local decreases are outweighed by increases in radiance in other areas, most likely due to additional lighting being installed. This should not be surprising, as decreases in cost allow increased use of light in areas that were previously unlit, moderately lit, or lit only during the early evening hours. The "energy saving" effects of outdoor LED lighting for country-level energy budgets are therefore smaller than might be expected from the increase in luminous efficacy compared to older lamps (*34*).

The large differences in per capita light use compared to per capita GDP (Fig. 4A) suggest that in brightly lit countries, major decreases in energy consumption for outdoor lighting could potentially be achieved through reduced light use. The extremely large differences in per capita light use in Germany and USA reported in (*23*) and observed again here (Fig. 3A,B) demonstrate that prosperity, safety, and security can be achieved with conservative light use. This has also been shown on local scales: demonstration projects have shown that LEDs can allow approximately order of magnitude reductions in illuminance compared to current practice without compromising user acceptance (*35*). In addition, lighting can be reduced or turned off late at night without compromising safety in the moderately lit places responsible for the majority of artificial light emissions (*10*).

Major (factor 2 or more) reductions in the energy cost and environmental impact of lighting should be accompanied by large absolute decreases in light emissions observable from space. The fact that median country's 15% increase in lighting from 2012-2016 nearly matched the median 13% increase in GDP suggests that outdoor light use remains subject to a large rebound effect on the global scale. The results presented here are therefore inconsistent with the hypothesis of large reductions in global energy consumption for outdoor lighting due to the introduction of solid state lighting. The correlation between GDP and light increase at the national scale is likely modest due to the relatively short-term nature of the dataset, compared to the ∼20 year time window for replacement of city street lights. The size of the outdoor lighting rebound effect should therefore be re-examined when a longer time series of lights and GDP becomes available. Restricting the analysis to stable electric lighting, and lowering the analysis threshold from 5nW $\mathrm{cm^{-2}\,sr^{-1}}$ to the smallest practical value, would also likely improve such correlations.

In the near-term, it appears that artificial light emission into the environment will continue to increase, further eroding Earth's remaining land area that experiences natural day-night light cycles. This is concerning, because artificial light is an environmental pollutant. In addition to threatening the 30% of vertebrates and over 60% of invertebrates that are nocturnal (*36*), outdoor artificial light also affects plants and microorganisms (*37, 38*), and is increasingly suspected of impacting human health (*8, 39*). In the longer term, perhaps demand for "dark skies" and unlit bedrooms will begin to outweigh demand for light in wealthy countries, leading to an "environmental Kuznets curve" for outdoor light. The nonlinearity between per capita light emission and GDP is reminiscent of such a relationship (Fig. 4A). If this is the case, it will be readily apparent in the continued time series of satellites observing artificial light at night.

Materials and Methods

Three analyses were conducted: an "area change" analysis, a "total radiance change" analyses, and and a "stable light radiance change" analysis. All three analyses compare relative rather than absolute changes, in order to facilitate comparisons.

The "area change" analysis measured the total area which is lit above a certain radiance threshold in 2012 and 2016. In this analysis, the radiance of individual pixels was reduced to a single bit (lit or unlit, based on a cut of 5 nW $\mathrm{cm^{-2}\,sr^{-1}}$). Areas that increased in radiance to cross the threshold in 2016 therefore increase the lit area compared to 2012, whereas increases in radiance in city centers that were already lit in 2012 have no impact on the lit area. Transient and natural light sources such as wildfires necessarily affect the area change analysis. This is because if a light is only present in the 2012 or 2016 dataset, there is no way to know if it was a formerly permanent light that turned off after 2012, a new permanent light that turned on in 2016, or a transient light in one of the two years. (NOAA is working on annual "stable lights" composites that remove firelight on the basis of infrared observations (*40*), but these are not yet published for all years, and the outlier removal method it is based upon cannot be applied to monthly data.) A selection of maps showing area changes at high resolutions using the same data but a different analysis were recently published by Nelson (*41*).

The "total radiance change" analysis measured the national sum of the radiance of all pixels that were above 5 $\mathrm{nW\,cm^{-2}\,sr^{-1}}$ in at least one of 2012 or 2016 (SOL in Figure 4). This means that the area under consideration is the same as in the area change analysis, and an identical area is considered in the two years. As in the area change analysis, transient light sources such as fire are included in the total.

The "stable light radiance change" analysis measures how radiance changed in areas continuously lit with relatively stable lights changed from 2012-2016. Transient and wildfire lights are removed by checking that the area was lit above a 5$\mathrm{nW\,cm^{-2}\,sr^{-1}}$ threshold in the entire period 2012-2016, and that the change in radiance from 2012-2016 did not exceed a set value (details below). Areas are binned according to their radiance in 2014, in order to test whether e.g. city centers have different trends compared to more modestly lit areas. Since transient and natural light sources are removed, the study area used in the radiance change analysis is smaller than the area observed in the other two analyses. Wildfires outside of artificially illuminated areas in a single year should therefore have no effect on the stable light radiance change analysis.

The DNB cloud-free monthly composites for the month of October in 2012-2016 were downloaded from the National Oceanic and Atmospheric Administration (*42*). These data include only overpasses for which clouds were not present (based on observations by infrared channels on the same instrument), and the total number of overpasses therefore differs between pixels. In a few areas, some pixels are so persistently covered by clouds that no cloud-free observations are available in a given month. In this case, the area is removed from all the analyses presented here. October is a particularly good month for comparisons of nighttime lights data for several reasons. Most importantly, stray light does not affect the observation at high latitudes in Europe, and these areas are less likely to experience snow than later in the year (however note that Austria was particularly affected by snow in October 2016). Seasonal changes in DNB observations were recently discussed by Levin and Zhang (*43*). In addition to the effect of snow, they found a negative relationship between the number of cloud-free observations and the radiance of cities. This should be further investigated, but we note that it could potentially be due to a complete lack of cloud-free observations in some of their study areas, or perhaps more likely, an interaction in their model between location, cloud cover, and season. Long-term changes in the radiometric calibration of the DNB itself are well understood and corrected (*44*).

The DNB monthly composites report the surface radiance in equal-angle pixels of 15 arcseconds in latitude and longitude. Rather than reprojecting these data onto an equal-area map, we assign a weight to each pixel based on its surface area (assuming a spherical Earth). In order to reject auroral light, composite images were cropped to cover only the region 60°S to 60°N (from the original 65°S to 75°N). Some auroral light remained over the ocean in the Southern Hemisphere (Fig. 2), so the area below 48° was removed from the analyses with the exception of 50-80°W. An array containing the surface area dA of the 15" pixels was generated in Python according to

$$dA = R_{\mathrm{Earth}}^2 \cos\theta \, d\theta d\phi \tag{1}$$

$$A = R_{\text{Earth}}^2 \int_{\theta_1}^{\theta_2} \cos\theta \, d\theta \int_{\phi_1}^{\phi_2} d\phi \quad (2)$$

$$A = R_{\text{Earth}}^2 \Big[\sin\theta\Big]_{\theta_1}^{\theta_2} \Big[\phi\Big]_{\phi_1}^{\phi_2} \quad (3)$$

where θ is the latitude in radians (i.e. $\theta = 0$ at the equator), and ϕ is the longitude.

The stable light radiance change analysis examines how radiance changed from 2012-2016 in dimly, moderately, and brightly lit areas. In order to do this, and to allow the generation of histograms, the pixel radiance (R) in the 2014 composite was used to assign each pixel a radiance class (bin), with logarithmically growing width. The low edges of these bins were assigned as

$$R_{\text{left}} = \log_{10}(R_{hi}) - \log_{10}(R_{lo})(b-1)/N + \log_{10}(R_{lo}) \quad (4)$$

Where R_{hi} is 300 $\text{nW}\,\text{cm}^{-2}\,\text{sr}^{-1}$, R_{lo} is 5 $\text{nW}\,\text{cm}^{-2}\,\text{sr}^{-1}$, N is the number of bins (20), and b is the bin number (from 1-20). The range of 5-300 $\text{nW}\,\text{cm}^{-2}\,\text{sr}^{-1}$ was chosen based on previous experience examining the night lights composites. The 5 $\text{nW}\,\text{cm}^{-2}\,\text{sr}^{-1}$ cut is far above the instrument sensitivity limit and noise level, but still low enough to include the lights from many faintly lit communities. In the October 2012 composite, not a single pixel of Paris was brighter than 300 $\text{nW}\,\text{cm}^{-2}\,\text{sr}^{-1}$ (the brightest was 230 $\text{nW}\,\text{cm}^{-2}\,\text{sr}^{-1}$ at Charles De Gaulle airport), and both Los Angeles, California and London, UK, had only a single pixel brighter than 300 $\text{nW}\,\text{cm}^{-2}\,\text{sr}^{-1}$. The rare exceptions of brighter urban areas (e.g. the Las Vegas strip) are better studied individually than as part of a global analysis.

The radiance bins for each pixel were stored in a Python array of equivalent size to the DNB data (from 60°S to 60°N). In order to reject wildfires and other temporary lights from the stable light radiance change analysis, the radiance of each pixel in the October composites for 2013-2015 was also checked. Pixels were flagged to be removed from the analysis if their radiance was outside of the range 1.67-900 $\text{nW}\,\text{cm}^{-2}\,\text{sr}^{-1}$ in any of these years. In practice this was accomplished by setting the bin number of these pixels to 0 in the Python array. At this stage, a set of binary (lit/unlit) maps were also produced for each year from 2012-2016, by testing whether each pixel was above the 5 $\text{nW}\,\text{cm}^{-2}\,\text{sr}^{-1}$ cut (Fig. 6). The area above the threshold was summed on both the global and national scales.

The radiance ratio R_{2016}/R_{2012} was then calculated for each of the individual pixels with bin numbers in the range 1-20. Pixels that changed by greater than a factor of 4 were removed from the analysis. The value 4 was chosen as large enough to accommodate most changes in rapidly brightening countries, while still rejecting extreme changes to prevent them from skewing the mean (Fig. 7). The area-corrected mean radiance difference D_b for each bin b was then

$$D_b = \frac{\sum wR_{2016}}{\sum wR_{2012}} \quad (5)$$

with a pixel area correction $w = A/\bar{A}_b$, where A is the area of each pixel, and $\bar{A}_b$ is the area of the average pixel in each bin. Only pixels that passed all cuts were included in the sums.

The analysis was repeated for each country by recalculating $\bar{A}_b$ and D_b for only the pixels within the given country's area. Country extents were converted from the shapefiles of ESRI

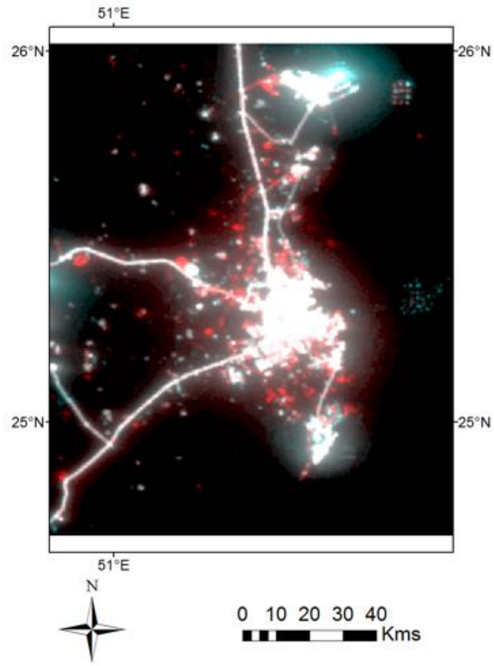
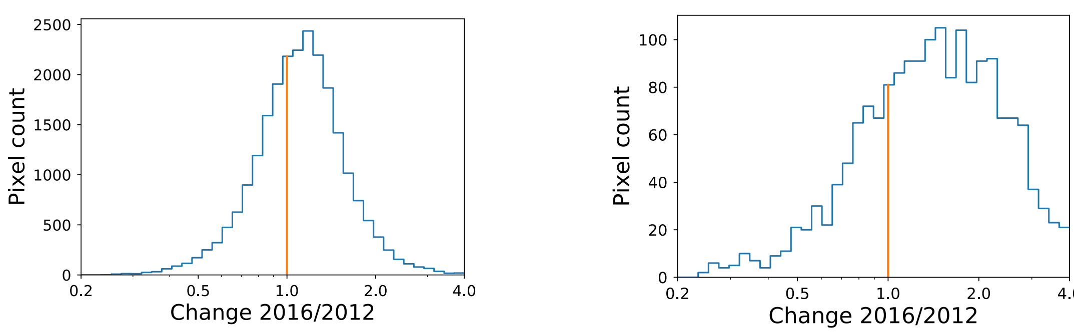


Figure 6: Expansion of DNB lighting from September 2012 (cyan) to September 2016 (red) in Doha, Qatar. Newly lit areas are expressed as bright red, as they were not lit (black) in 2012.



(A) Germany

(B) Peru

Figure 7: Histogram of changes of pixels in the 5–6.1 $\mathrm{nW\,cm^{-2}\,sr^{-1}}$ bin for Germany (A) and rapidly brightening Peru (B). Pixels were assigned to this bin based on their radiance in 2014. The vertical line shows the value 1 (no change from 2012 to 2016).

Data & Maps 2003 to a raster format, with a few corrections to reflect new boundaries (e.g. South Sudan). Overseas territories were included as part of the larger associated country (e.g. Christmas Island was included as part of Australia). Some coastal pixels are misidentified as ocean because of the limited precision of the shapefile, and therefore do not contribute to country totals. For countries with lit areas below several km^2, caution should be taken when interpreting the change in radiance in the Supplemental Figures, as these changes are driven by a small number of pixels.

Changes in national sum of lights for areas included in the total radiance change analysis were compared to GDP and population data from the World Bank (*45*). Gross Domestic Product is reported in "constant 2010 US$". A total of 134 countries had complete GDP and population data, as well as at least 100 km^2 lit above the 5 $nW\,cm^{-2}\,sr^{-1}$ threshold in both 2012 and 2016. Countries were divided in roughly equal groups based on per capita GDP in 2016 for display (Fig. 4A). The groups are $<$\$2000 (n=36, red triangles), from \$2000-6000 (n=35, green squares), from \$6000-17000 (n=30, blue stars) and $>$\$17000 (n=33, black circles). Spearman's rank-order correlation coefficients between sets of parameters were calculated in Python using "scipy.stats.spearmanr".

The 5 $nW\,cm^{-2}\,sr^{-1}$ threshold means that not all artificially produced light is included in these analyses. Away from cities, natural light sources such as airglow and reflected moonlight outshine artificial light, and systematic errors on the DNB zero point could generate large errors in the national sum of light for countries with large unlit areas. Further work would therefore be needed to estimate the total global change in artificial radiance (including areas lit below the current analysis threshold).

One of the consequences of the global transition to LED street lighting is a shift in the spectra of artificial night lights (*22, 46*). So-called "white" LEDs emit a portion of their light at wavelengths below 500 nm (blue), where the DNB is effectively blind (*23*). This means that a street light transition from (orange) high pressure sodium lamps to (white) LEDs in which surface luminance is held constant results in a decrease in the radiance observed by DNB (Fig. 5C). The measurements of change in lighting reported here are therefore actually lower bounds on the increase of lighting in the human visual range (see (*46*) for more detailed discussion).

For this reason, decreases in radiance of $\sim$30% could be due to a complete lighting transition from high pressure sodium to LED lamps rather than a true decrease in visible light. The relationship between the emission spectra of different lighting technologies (even among classes like "warm white LEDs" or "high pressure sodium") and the detection efficiencies of broadband sensors (e.g. human vision, VIIRS DNB) is complex, and will be addressed in detail in a forthcoming paper. From a remote sensing perspective, the situation could be greatly improved if nighttime satellites had color sensitivity (*47*). Nevertheless, the increased luminous efficacy of LEDs means that decreases in city lighting likely indicate decreases in energy consumption. On the other hand, despite the fact that nearly all new outdoor lighting installations make use of LEDs (*48*), new lighting necessarily implies new energy consumption. For this reason, increases in observed radiance are nearly certain to be due to increases in installed visible light, and therefore raised energy consumption.

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Supplement to: Artificially lit surface of Earth at night increasing in radiance and extent

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Supplementary information

Figures S1-3 present the normalized cumuative radiance distribution for each country in 2012 (i.e. the integral of the data in Figure 3A divided by the national sum of lights). The values represent what fraction of the total light emission of the country (above the threshold of 5 $\mathrm{nW\,cm^{-2}\,sr^{-1}}$) comes from areas with radiances below the value (in $\mathrm{nW\,cm^{-2}\,sr^{-1}}$) given in the top row. Table entries are colored in order to allow visual inspection of the data.

Figures S4-S27 are similar to Figure 3A,C from the main paper, but for each individual country with at least one pixel with radiance larger than 5 $\mathrm{nW\,cm^{-2}\,sr^{-1}}$ in 2014. The left panels show the area lit in 2014 in each of the given radiance bins. The right panels show the mean change in radiance from 2012 to 2016.

Figure S28 is similar to Figure 1 from the main paper, but showing the change in total radiance instead of the change in the radiance of stable lights (i.e. including unstable and transient lights, including fires).

Country	6.1	7.5	9.2	11	14	17	21	26	32	39	48	58	72	88	108	132	162	199	244	300
Afghanistan	0.07	0.14	0.22	0.31	0.41	0.51	0.58	0.63	0.67	0.71	0.75	0.79	0.83	0.88	0.95	0.98	1.00	1.00	1.00	1.00
Albania	0.06	0.11	0.17	0.24	0.31	0.38	0.47	0.55	0.63	0.71	0.78	0.86	0.91	0.95	0.97	0.98	0.99	1.00	1.00	1.00
Algeria	0.03	0.07	0.11	0.15	0.20	0.25	0.31	0.37	0.43	0.50	0.58	0.66	0.73	0.81	0.87	0.92	0.96	0.98	0.99	1.00
Andorra	0.03	0.08	0.14	0.18	0.27	0.33	0.42	0.49	0.60	0.62	0.70	0.77	0.82	0.87	0.93	1.00	1.00	1.00	1.00	1.00
Angola	0.03	0.06	0.11	0.15	0.20	0.26	0.34	0.42	0.53	0.64	0.75	0.87	0.96	0.98	0.99	1.00	1.00	1.00	1.00	1.00
Antigua and Barbuda	0.11	0.23	0.35	0.52	0.60	0.70	0.79	0.89	0.94	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Argentina	0.02	0.04	0.07	0.09	0.13	0.16	0.21	0.26	0.32	0.38	0.47	0.57	0.70	0.83	0.92	0.97	0.99	0.99	1.00	1.00
Armenia	0.05	0.11	0.20	0.32	0.45	0.56	0.67	0.74	0.79	0.81	0.85	0.89	0.93	0.97	0.99	0.99	1.00	1.00	1.00	1.00
Australia	0.04	0.09	0.16	0.24	0.33	0.44	0.54	0.63	0.72	0.80	0.86	0.91	0.94	0.96	0.97	0.99	0.99	1.00	1.00	1.00
Austria	0.08	0.17	0.26	0.36	0.45	0.53	0.62	0.71	0.79	0.86	0.90	0.94	0.96	0.98	0.99	0.99	0.99	1.00	1.00	1.00
Azerbaijan	0.08	0.16	0.25	0.34	0.43	0.52	0.59	0.66	0.75	0.81	0.85	0.90	0.93	0.95	0.97	0.98	0.99	0.99	1.00	1.00
Bahrain	0.00	0.01	0.01	0.01	0.02	0.03	0.04	0.06	0.09	0.12	0.17	0.24	0.33	0.45	0.57	0.68	0.81	0.93	0.99	1.00
Bangladesh	0.12	0.24	0.35	0.48	0.61	0.73	0.82	0.89	0.93	0.95	0.96	0.97	0.98	0.98	0.99	0.99	1.00	1.00	1.00	1.00
Barbados	0.07	0.16	0.28	0.37	0.53	0.70	0.82	0.90	0.95	0.98	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Belarus	0.05	0.12	0.19	0.27	0.36	0.46	0.57	0.68	0.78	0.87	0.92	0.95	0.96	0.98	0.99	0.99	1.00	1.00	1.00	1.00
Belgium	0.08	0.16	0.25	0.34	0.43	0.53	0.61	0.69	0.75	0.81	0.86	0.90	0.94	0.97	0.98	0.99	1.00	1.00	1.00	1.00
Belize	0.08	0.16	0.23	0.34	0.43	0.56	0.65	0.74	0.79	0.85	0.88	0.96	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Benin	0.16	0.37	0.54	0.67	0.77	0.83	0.85	0.88	0.92	0.94	0.95	0.96	0.96	0.98	1.00	1.00	1.00	1.00	1.00	1.00
Bhutan	0.16	0.26	0.40	0.55	0.65	0.71	0.75	0.81	0.86	0.94	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Bolivia	0.02	0.05	0.07	0.11	0.15	0.19	0.24	0.30	0.37	0.46	0.56	0.68	0.79	0.89	0.95	0.98	0.99	1.00	1.00	1.00
Bosnia and Herzegovina	0.08	0.17	0.26	0.35	0.44	0.54	0.62	0.70	0.78	0.84	0.90	0.94	0.97	0.99	1.00	1.00	1.00	1.00	1.00	1.00
Botswana	0.07	0.15	0.24	0.34	0.45	0.56	0.65	0.75	0.84	0.91	0.96	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Brazil	0.03	0.07	0.11	0.16	0.21	0.28	0.35	0.44	0.53	0.63	0.73	0.81	0.89	0.95	0.98	0.99	1.00	1.00	1.00	1.00
Brunei Darussalam	0.08	0.14	0.24	0.36	0.44	0.53	0.64	0.72	0.81	0.85	0.86	0.87	0.89	0.94	1.00	1.00	1.00	1.00	1.00	1.00
Bulgaria	0.06	0.13	0.20	0.28	0.37	0.45	0.54	0.64	0.74	0.84	0.92	0.96	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00
Burkina Faso	0.08	0.15	0.23	0.31	0.39	0.51	0.62	0.76	0.86	0.94	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Burundi	0.30	0.56	0.73	0.95	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Cabo Verde	0.07	0.13	0.22	0.31	0.44	0.56	0.70	0.81	0.89	0.96	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Cambodia	0.08	0.11	0.18	0.28	0.35	0.39	0.54	0.69	0.86	0.95	0.98	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Cameroon	0.07	0.14	0.22	0.32	0.48	0.61	0.70	0.76	0.81	0.88	0.92	0.96	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Canada	0.03	0.06	0.10	0.14	0.19	0.25	0.32	0.40	0.50	0.60	0.70	0.80	0.88	0.94	0.97	0.99	0.99	1.00	1.00	1.00
Chad	0.05	0.10	0.16	0.24	0.33	0.42	0.54	0.67	0.75	0.80	0.86	0.92	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Chile	0.03	0.06	0.09	0.12	0.16	0.21	0.26	0.32	0.40	0.49	0.59	0.73	0.87	0.96	0.99	1.00	1.00	1.00	1.00	1.00
China	0.05	0.11	0.17	0.24	0.33	0.42	0.52	0.62	0.73	0.83	0.91	0.95	0.98	0.99	0.99	1.00	1.00	1.00	1.00	1.00
Colombia	0.04	0.08	0.12	0.16	0.21	0.26	0.32	0.37	0.44	0.52	0.62	0.77	0.89	0.96	0.99	0.99	1.00	1.00	1.00	1.00
Comoros	0.39	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Costa Rica	0.05	0.11	0.17	0.23	0.31	0.39	0.49	0.61	0.73	0.85	0.93	0.98	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00
Croatia	0.06	0.13	0.20	0.27	0.35	0.42	0.50	0.58	0.66	0.72	0.78	0.84	0.91	0.95	0.98	1.00	1.00	1.00	1.00	1.00
Cuba	0.07	0.15	0.23	0.32	0.41	0.52	0.64	0.77	0.88	0.94	0.97	0.98	0.99	0.99	0.99	0.99	1.00	1.00	1.00	1.00
Cyprus	0.05	0.11	0.18	0.25	0.33	0.42	0.52	0.64	0.76	0.86	0.94	0.96	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00
Czech Republic	0.06	0.13	0.21	0.28	0.36	0.45	0.55	0.64	0.74	0.82	0.90	0.94	0.97	0.98	0.99	1.00	1.00	1.00	1.00	1.00
Dem. People's Republic of Korea	0.16	0.31	0.43	0.51	0.65	0.69	0.82	0.86	0.88	0.92	0.96	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Democratic Republic of the Congo	0.05	0.11	0.17	0.24	0.32	0.40	0.51	0.66	0.78	0.90	0.97	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Democratic Republic of Timor-Leste	0.06	0.10	0.20	0.32	0.46	0.55	0.72	0.78	0.87	0.94	0.96	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Denmark	0.10	0.21	0.33	0.44	0.56	0.67	0.76	0.82	0.87	0.91	0.94	0.95	0.95	0.96	0.97	0.97	0.99	0.99	0.99	1.00
Djibouti	0.04	0.10	0.16	0.27	0.41	0.52	0.61	0.70	0.83	0.87	0.90	0.94	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Dominica	0.16	0.28	0.42	0.54	0.69	0.87	0.96	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Dominican Republic	0.04	0.08	0.13	0.19	0.24	0.31	0.39	0.48	0.59	0.71	0.85	0.95	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ecuador	0.05	0.09	0.14	0.20	0.26	0.32	0.39	0.47	0.55	0.64	0.73	0.82	0.90	0.95	0.97	0.98	0.99	0.99	1.00	1.00
Egypt	0.05	0.10	0.16	0.22	0.29	0.36	0.43	0.50	0.56	0.63	0.69	0.75	0.82	0.88	0.93	0.96	0.98	0.99	1.00	1.00
El Salvador	0.07	0.15	0.23	0.32	0.42	0.53	0.65	0.78	0.89	0.96	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Equatorial Guinea	0.03	0.09	0.17	0.31	0.42	0.53	0.69	0.77	0.91	0.97	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Eritrea	0.07	0.17	0.30	0.40	0.51	0.60	0.74	0.86	0.92	0.94	0.97	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Estonia	0.04	0.09	0.15	0.21	0.27	0.35	0.44	0.53	0.63	0.73	0.81	0.87	0.92	0.95	0.97	0.99	1.00	1.00	1.00	1.00
Ethiopia	0.07	0.15	0.25	0.36	0.51	0.64	0.74	0.82	0.86	0.90	0.94	0.96	0.97	0.98	0.98	0.99	1.00	1.00	1.00	1.00
Fiji	0.20	0.44	0.65	0.79	0.86	0.92	0.95	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Finland	0.12	0.26	0.44	0.60	0.73	0.78	0.86	0.94	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
France	0.04	0.09	0.14	0.20	0.26	0.33	0.41	0.50	0.60	0.70	0.80	0.89	0.95	0.97	0.99	0.99	1.00	1.00	1.00	1.00
FYR Macedonia	0.05	0.12	0.18	0.25	0.32	0.39	0.46	0.53	0.61	0.70	0.76	0.82	0.88	0.91	0.94	0.94	0.96	0.97	0.99	1.00
Gabon	0.07	0.15	0.23	0.33	0.42	0.53	0.63	0.70	0.76	0.81	0.86	0.90	0.93	0.97	0.98	0.98	0.98	0.98	0.99	1.00
Gaza Strip	0.10	0.23	0.36	0.49	0.62	0.73	0.84	0.90	0.95	0.97	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Georgia	0.06	0.12	0.19	0.26	0.32	0.39	0.48	0.57	0.66	0.74	0.81	0.87	0.91	0.94	0.96	0.98	0.99	1.00	1.00	1.00
Germany	0.09	0.19	0.29	0.40	0.51	0.61	0.69	0.77	0.83	0.87	0.91	0.93	0.95	0.97	0.98	0.99	0.99	1.00	1.00	1.00
Ghana	0.08	0.16	0.27	0.39	0.52	0.66	0.79	0.91	0.96	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Figure S1: Normalized cumulative radiance distribution for Afghanistan through Ghana.

Country	6.1	7.5	9.2	11	14	17	21	26	32	39	48	58	72	88	108	132	162	199	244	300
Greece	0.05	0.11	0.17	0.24	0.30	0.37	0.44	0.50	0.57	0.63	0.70	0.76	0.83	0.90	0.96	0.99	1.00	1.00	1.00	1.00
Grenada	0.20	0.46	0.73	0.85	0.93	0.96	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Guatemala	0.05	0.11	0.16	0.23	0.30	0.37	0.45	0.54	0.62	0.71	0.78	0.87	0.93	0.97	0.99	1.00	1.00	1.00	1.00	1.00
Guinea	0.22	0.47	0.69	0.83	0.85	0.89	0.93	0.96	0.97	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Guinea-Bissau	0.15	0.53	0.88	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Guyana	0.09	0.21	0.33	0.41	0.52	0.61	0.71	0.83	0.91	0.96	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Haiti	0.16	0.36	0.55	0.73	0.82	0.89	0.94	0.98	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Honduras	0.06	0.11	0.18	0.25	0.33	0.42	0.51	0.62	0.73	0.83	0.92	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Hungary	0.07	0.14	0.21	0.29	0.38	0.47	0.57	0.67	0.76	0.83	0.90	0.95	0.97	0.99	0.99	1.00	1.00	1.00	1.00	1.00
India	0.06	0.12	0.18	0.25	0.32	0.39	0.46	0.54	0.62	0.70	0.77	0.84	0.90	0.95	0.98	0.99	1.00	1.00	1.00	1.00
Indonesia	0.08	0.16	0.25	0.35	0.46	0.56	0.67	0.76	0.85	0.92	0.95	0.97	0.98	0.99	0.99	0.99	0.99	1.00	1.00	1.00
Iran	0.05	0.11	0.17	0.23	0.29	0.36	0.43	0.50	0.59	0.69	0.78	0.87	0.92	0.95	0.96	0.97	0.98	0.99	0.99	1.00
Iraq	0.04	0.08	0.13	0.18	0.23	0.28	0.33	0.39	0.46	0.53	0.62	0.70	0.78	0.85	0.90	0.94	0.96	0.98	0.99	1.00
Ireland	0.06	0.12	0.19	0.27	0.35	0.44	0.53	0.63	0.75	0.84	0.90	0.93	0.96	0.97	0.98	0.99	1.00	1.00	1.00	1.00
Israel	0.02	0.04	0.07	0.10	0.14	0.19	0.24	0.30	0.36	0.43	0.50	0.58	0.68	0.80	0.89	0.95	0.97	0.99	0.99	1.00
Italy	0.05	0.10	0.16	0.23	0.30	0.38	0.46	0.55	0.63	0.72	0.80	0.87	0.92	0.96	0.98	0.99	1.00	1.00	1.00	1.00
Ivory Coast	0.05	0.12	0.18	0.26	0.34	0.44	0.57	0.70	0.82	0.91	0.96	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Jamaica	0.08	0.16	0.23	0.31	0.39	0.51	0.65	0.77	0.86	0.93	0.97	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Japan	0.06	0.12	0.19	0.27	0.36	0.46	0.56	0.65	0.74	0.82	0.88	0.92	0.95	0.97	0.98	0.99	0.99	1.00	1.00	1.00
Jordan	0.05	0.11	0.17	0.24	0.31	0.38	0.46	0.55	0.64	0.74	0.83	0.89	0.94	0.97	0.99	1.00	1.00	1.00	1.00	1.00
Kazakhstan	0.04	0.09	0.14	0.19	0.25	0.31	0.38	0.45	0.52	0.59	0.66	0.72	0.79	0.85	0.89	0.93	0.96	0.97	0.99	1.00
Kenya	0.08	0.17	0.27	0.36	0.47	0.59	0.70	0.82	0.88	0.92	0.95	0.97	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00
Kosovo	0.07	0.16	0.24	0.32	0.42	0.51	0.61	0.73	0.81	0.89	0.96	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Kuwait	0.02	0.04	0.07	0.09	0.12	0.15	0.19	0.23	0.28	0.32	0.37	0.41	0.47	0.54	0.65	0.80	0.91	0.97	0.99	1.00
Kyrgyz Republic	0.11	0.22	0.36	0.47	0.57	0.67	0.75	0.82	0.89	0.92	0.94	0.96	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Lao PDR	0.11	0.21	0.33	0.45	0.55	0.65	0.74	0.83	0.88	0.93	0.96	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Latvia	0.05	0.10	0.17	0.24	0.31	0.38	0.48	0.60	0.71	0.81	0.89	0.94	0.95	0.97	0.98	1.00	1.00	1.00	1.00	1.00
Lebanon	0.07	0.15	0.23	0.32	0.40	0.48	0.55	0.61	0.68	0.74	0.80	0.85	0.90	0.95	0.98	0.99	0.99	1.00	1.00	1.00
Lesotho	0.12	0.23	0.37	0.55	0.68	0.74	0.83	0.87	0.95	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Liberia	0.18	0.43	0.67	0.74	0.83	0.85	0.86	0.88	0.90	0.93	0.93	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Libya	0.04	0.09	0.13	0.18	0.24	0.30	0.36	0.42	0.49	0.57	0.64	0.71	0.78	0.85	0.92	0.96	0.98	0.99	1.00	1.00
Liechtenstein	0.23	0.33	0.56	0.71	0.79	0.89	0.95	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Lithuania	0.05	0.11	0.17	0.23	0.30	0.39	0.49	0.59	0.68	0.77	0.85	0.91	0.95	0.98	0.99	1.00	1.00	1.00	1.00	1.00
Luxembourg	0.07	0.15	0.24	0.33	0.42	0.51	0.59	0.69	0.77	0.84	0.90	0.94	0.97	0.99	1.00	1.00	1.00	1.00	1.00	1.00
Madagascar	0.16	0.35	0.54	0.69	0.81	0.87	0.93	0.95	0.98	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Malawi	0.11	0.22	0.35	0.52	0.71	0.88	0.94	0.97	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Malaysia	0.03	0.07	0.12	0.17	0.22	0.29	0.38	0.47	0.61	0.76	0.88	0.95	0.98	0.99	0.99	0.99	1.00	1.00	1.00	1.00
Maldives	0.09	0.09	0.82	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Mali	0.08	0.19	0.29	0.43	0.58	0.74	0.86	0.93	0.97	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Malta	0.02	0.04	0.07	0.10	0.14	0.20	0.27	0.36	0.47	0.59	0.74	0.83	0.89	0.94	0.96	0.96	0.98	1.00	1.00	1.00
Marshall Islands	0.00	0.00	0.40	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Mauritania	0.09	0.17	0.26	0.38	0.50	0.56	0.66	0.72	0.84	0.90	0.93	0.96	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Mauritius	0.10	0.19	0.28	0.38	0.48	0.58	0.68	0.76	0.82	0.83	0.86	0.90	0.94	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Mexico	0.03	0.07	0.12	0.16	0.21	0.27	0.34	0.42	0.52	0.64	0.78	0.89	0.95	0.97	0.98	0.99	0.99	1.00	1.00	1.00
Monaco	0.04	0.12	0.25	0.38	0.53	0.60	0.67	0.71	0.71	0.82	0.82	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Mongolia	0.06	0.12	0.20	0.27	0.35	0.42	0.47	0.54	0.60	0.68	0.75	0.84	0.92	0.97	0.98	0.99	0.99	1.00	1.00	1.00
Montenegro	0.05	0.11	0.17	0.23	0.30	0.37	0.45	0.54	0.64	0.74	0.79	0.84	0.90	0.96	1.00	1.00	1.00	1.00	1.00	1.00
Morocco	0.03	0.05	0.09	0.12	0.16	0.21	0.26	0.32	0.39	0.48	0.58	0.71	0.84	0.94	0.98	0.99	1.00	1.00	1.00	1.00
Mozambique	0.06	0.13	0.22	0.31	0.42	0.54	0.64	0.74	0.81	0.87	0.92	0.97	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Myanmar	0.10	0.21	0.33	0.45	0.56	0.65	0.74	0.82	0.88	0.91	0.95	0.97	0.97	0.98	0.98	0.99	0.99	0.99	1.00	1.00
Namibia	0.05	0.11	0.19	0.28	0.38	0.48	0.61	0.76	0.86	0.93	0.96	0.98	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00
Nauru	0.11	0.41	0.53	0.73	0.87	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Nepal	0.11	0.24	0.36	0.52	0.69	0.81	0.90	0.95	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Netherlands	0.04	0.09	0.15	0.22	0.29	0.36	0.44	0.52	0.60	0.67	0.72	0.76	0.80	0.83	0.86	0.89	0.92	0.94	0.97	1.00
New Zealand	0.06	0.14	0.24	0.34	0.45	0.56	0.65	0.74	0.81	0.87	0.92	0.94	0.96	0.98	0.98	0.99	0.99	1.00	1.00	1.00
Nicaragua	0.05	0.12	0.20	0.27	0.37	0.48	0.59	0.70	0.83	0.95	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Niger	0.07	0.14	0.23	0.36	0.51	0.63	0.75	0.82	0.84	0.85	0.89	0.89	0.90	0.91	0.93	0.97	0.98	1.00	1.00	1.00
Nigeria	0.08	0.17	0.27	0.37	0.46	0.56	0.66	0.74	0.81	0.87	0.91	0.93	0.95	0.95	0.96	0.98	0.98	0.99	1.00	1.00
Norway	0.06	0.11	0.18	0.25	0.33	0.42	0.52	0.63	0.72	0.80	0.86	0.91	0.94	0.96	0.97	0.98	0.98	0.99	0.99	1.00
Oman	0.04	0.08	0.13	0.18	0.25	0.32	0.39	0.46	0.54	0.60	0.67	0.73	0.79	0.84	0.89	0.92	0.96	0.98	0.99	1.00
Pakistan	0.07	0.14	0.22	0.30	0.39	0.47	0.56	0.64	0.71	0.78	0.85	0.92	0.96	0.98	0.99	0.99	1.00	1.00	1.00	1.00
Panama	0.06	0.11	0.18	0.25	0.33	0.43	0.52	0.63	0.76	0.85	0.89	0.92	0.94	0.96	0.97	0.98	0.99	0.99	1.00	1.00
Papua New Guinea	0.07	0.15	0.21	0.28	0.38	0.47	0.54	0.63	0.73	0.84	0.90	0.93	0.95	0.96	0.98	0.99	1.00	1.00	1.00	1.00
Paraguay	0.03	0.06	0.10	0.14	0.19	0.25	0.31	0.39	0.48	0.59	0.68	0.79	0.89	0.95	0.98	0.99	1.00	1.00	1.00	1.00

Figure S2: Normalized cumulative radiance distribution for Greece through Paraguay.

Country	6.1	7.5	9.2	11	14	17	21	26	32	39	48	58	72	88	108	132	162	199	244	300
Peru	0.03	0.07	0.12	0.17	0.23	0.31	0.39	0.49	0.60	0.73	0.85	0.94	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00
Philippines	0.06	0.13	0.22	0.30	0.40	0.52	0.62	0.72	0.81	0.87	0.93	0.97	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00
Poland	0.05	0.11	0.17	0.23	0.30	0.38	0.47	0.55	0.64	0.73	0.81	0.88	0.93	0.96	0.98	0.99	0.99	0.99	1.00	1.00
Portugal	0.05	0.10	0.16	0.22	0.28	0.35	0.41	0.47	0.54	0.61	0.68	0.75	0.82	0.89	0.94	0.97	1.00	1.00	1.00	1.00
Qatar	0.01	0.02	0.04	0.05	0.07	0.09	0.11	0.14	0.17	0.20	0.25	0.31	0.38	0.46	0.55	0.67	0.80	0.91	0.97	1.00
Republic of Congo	0.05	0.13	0.20	0.29	0.38	0.50	0.59	0.67	0.78	0.89	0.96	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Republic of Korea	0.04	0.08	0.12	0.17	0.21	0.26	0.32	0.38	0.46	0.54	0.64	0.77	0.88	0.95	0.98	0.99	1.00	1.00	1.00	1.00
Republic of Moldova	0.08	0.17	0.26	0.35	0.46	0.57	0.70	0.83	0.91	0.96	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Romania	0.05	0.11	0.16	0.23	0.29	0.36	0.44	0.52	0.61	0.72	0.82	0.90	0.95	0.97	0.99	0.99	1.00	1.00	1.00	1.00
Russia	0.04	0.09	0.14	0.20	0.26	0.32	0.39	0.46	0.54	0.62	0.69	0.77	0.84	0.89	0.93	0.96	0.98	0.99	0.99	1.00
Rwanda	0.07	0.16	0.29	0.38	0.48	0.57	0.71	0.81	0.86	0.90	0.95	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Samoa	0.41	0.59	0.75	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
San Marino	0.05	0.11	0.18	0.25	0.35	0.43	0.51	0.61	0.73	0.84	0.95	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
São Tomé and Príncipe	0.19	0.37	0.58	0.81	0.85	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Saudi Arabia	0.02	0.04	0.07	0.10	0.13	0.16	0.20	0.24	0.29	0.35	0.40	0.46	0.53	0.60	0.69	0.78	0.88	0.96	0.99	1.00
Senegal	0.07	0.15	0.22	0.30	0.39	0.45	0.53	0.61	0.70	0.83	0.91	0.98	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00
Serbia	0.06	0.13	0.20	0.27	0.34	0.42	0.50	0.58	0.65	0.71	0.78	0.84	0.90	0.94	0.97	0.99	0.99	1.00	1.00	1.00
Seychelles	0.08	0.21	0.31	0.40	0.49	0.62	0.76	0.82	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Sierra Leone	0.35	0.57	0.79	0.85	0.95	0.96	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Singapore	0.00	0.01	0.01	0.02	0.03	0.04	0.06	0.08	0.12	0.18	0.26	0.39	0.62	0.80	0.88	0.93	0.96	0.98	1.00	1.00
Slovak Republic	0.06	0.12	0.19	0.27	0.35	0.45	0.54	0.64	0.74	0.82	0.89	0.93	0.96	0.98	1.00	1.00	1.00	1.00	1.00	1.00
Slovenia	0.08	0.17	0.27	0.37	0.47	0.56	0.66	0.75	0.82	0.88	0.92	0.95	0.96	0.97	0.98	0.99	0.99	1.00	1.00	1.00
Solomon Islands	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Somalia	0.15	0.31	0.49	0.65	0.76	0.85	0.94	0.98	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
South Africa	0.04	0.09	0.14	0.20	0.27	0.35	0.45	0.55	0.65	0.75	0.84	0.91	0.95	0.97	0.98	0.99	0.99	1.00	1.00	1.00
South Sudan	0.13	0.19	0.27	0.36	0.50	0.60	0.67	0.77	0.82	0.89	0.90	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Spain	0.03	0.07	0.11	0.15	0.20	0.25	0.31	0.37	0.44	0.51	0.58	0.66	0.74	0.82	0.90	0.96	0.99	1.00	1.00	1.00
Sri Lanka	0.24	0.40	0.52	0.63	0.68	0.72	0.74	0.76	0.78	0.79	0.82	0.84	0.85	0.88	1.00	1.00	1.00	1.00	1.00	1.00
St Kitts and Navis	0.09	0.17	0.23	0.36	0.43	0.59	0.71	0.88	0.95	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
St Lucia	0.13	0.28	0.45	0.59	0.68	0.77	0.88	0.92	0.97	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
St Vincent and The Grenadines	0.08	0.41	0.54	0.63	0.66	0.80	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
State of Palestine	0.05	0.10	0.16	0.23	0.30	0.36	0.44	0.52	0.60	0.68	0.75	0.82	0.87	0.91	0.96	0.98	0.99	1.00	1.00	1.00
Sudan	0.06	0.13	0.20	0.27	0.35	0.43	0.52	0.60	0.67	0.76	0.83	0.89	0.93	0.95	0.96	0.98	0.99	0.99	1.00	1.00
Suriname	0.08	0.14	0.20	0.27	0.34	0.42	0.49	0.58	0.71	0.84	0.89	0.93	0.95	0.99	0.99	1.00	1.00	1.00	1.00	1.00
Swaziland	0.08	0.17	0.24	0.34	0.46	0.60	0.72	0.83	0.88	0.94	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Sweden	0.04	0.09	0.15	0.22	0.29	0.38	0.47	0.57	0.68	0.77	0.86	0.92	0.96	0.98	0.99	1.00	1.00	1.00	1.00	1.00
Switzerland	0.09	0.19	0.29	0.40	0.50	0.61	0.71	0.79	0.87	0.92	0.95	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Syria	0.08	0.16	0.24	0.31	0.40	0.47	0.54	0.60	0.67	0.74	0.80	0.85	0.89	0.93	0.94	0.97	0.99	0.99	1.00	1.00
Taiwan	0.04	0.09	0.14	0.21	0.27	0.35	0.44	0.52	0.61	0.68	0.77	0.86	0.93	0.97	0.99	1.00	1.00	1.00	1.00	1.00
Tajikistan	0.07	0.14	0.20	0.27	0.34	0.43	0.55	0.71	0.80	0.86	0.91	0.95	0.98	0.98	1.00	1.00	1.00	1.00	1.00	1.00
Thailand	0.08	0.17	0.26	0.35	0.45	0.54	0.64	0.74	0.82	0.89	0.93	0.96	0.98	0.99	0.99	1.00	1.00	1.00	1.00	1.00
The Bahamas	0.03	0.06	0.09	0.12	0.17	0.23	0.29	0.38	0.48	0.61	0.75	0.91	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00
The Gambia	0.23	0.51	0.68	0.82	0.94	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Togo	0.09	0.17	0.24	0.35	0.52	0.72	0.83	0.91	0.96	0.98	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Trinidad and Tobago	0.04	0.08	0.13	0.19	0.24	0.30	0.36	0.43	0.51	0.59	0.67	0.77	0.88	0.93	0.96	0.97	0.99	0.99	0.99	1.00
Tunisia	0.03	0.07	0.11	0.17	0.23	0.30	0.38	0.47	0.57	0.67	0.77	0.87	0.92	0.96	0.98	0.99	0.99	0.99	1.00	1.00
Turkey	0.04	0.08	0.13	0.18	0.24	0.30	0.37	0.44	0.52	0.60	0.70	0.81	0.90	0.96	0.98	0.99	1.00	1.00	1.00	1.00
Turkmenistan	0.05	0.10	0.16	0.22	0.29	0.36	0.43	0.49	0.54	0.59	0.65	0.71	0.76	0.81	0.86	0.90	0.93	0.96	0.98	1.00
Uganda	0.13	0.26	0.35	0.46	0.64	0.70	0.76	0.77	0.89	0.97	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ukraine	0.07	0.15	0.24	0.34	0.43	0.53	0.62	0.71	0.79	0.85	0.90	0.93	0.95	0.96	0.97	0.98	0.99	0.99	1.00	1.00
United Arab Emirates	0.02	0.03	0.06	0.08	0.11	0.15	0.20	0.25	0.31	0.37	0.45	0.53	0.62	0.71	0.79	0.87	0.94	0.97	0.99	1.00
United Kingdom	0.04	0.09	0.15	0.21	0.29	0.38	0.49	0.59	0.69	0.77	0.84	0.90	0.94	0.97	0.98	0.99	1.00	1.00	1.00	1.00
United Republic of Tanzania	0.15	0.30	0.43	0.53	0.62	0.71	0.79	0.86	0.92	0.96	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
United States of America	0.03	0.07	0.11	0.16	0.21	0.28	0.35	0.43	0.52	0.62	0.71	0.79	0.86	0.91	0.94	0.97	0.98	0.99	1.00	1.00
Uruguay	0.02	0.05	0.09	0.14	0.19	0.24	0.31	0.39	0.48	0.58	0.69	0.81	0.90	0.96	0.98	0.99	1.00	1.00	1.00	1.00
Uzbekistan	0.11	0.22	0.31	0.41	0.49	0.58	0.66	0.74	0.79	0.83	0.85	0.87	0.90	0.91	0.92	0.94	0.96	0.98	0.99	1.00
Vanuatu	0.08	0.12	0.23	0.24	0.25	0.34	0.36	0.37	0.41	0.41	0.51	0.58	0.59	0.64	0.81	0.81	0.81	1.00	1.00	1.00
Vatican City	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.71	1.00	1.00	1.00	1.00	1.00
Venezuela	0.02	0.05	0.09	0.12	0.17	0.21	0.27	0.33	0.40	0.48	0.57	0.66	0.75	0.82	0.86	0.89	0.92	0.95	0.98	1.00
Vietnam	0.04	0.09	0.14	0.20	0.25	0.31	0.37	0.42	0.48	0.52	0.56	0.59	0.62	0.64	0.68	0.71	0.76	0.81	0.89	1.00
Western Sahara	0.02	0.04	0.06	0.09	0.12	0.14	0.18	0.23	0.27	0.36	0.45	0.59	0.72	0.86	0.98	1.00	1.00	1.00	1.00	1.00
Yemen	0.04	0.08	0.12	0.17	0.22	0.26	0.32	0.37	0.43	0.49	0.56	0.63	0.70	0.77	0.84	0.90	0.92	0.95	0.98	1.00
Zambia	0.05	0.12	0.20	0.28	0.37	0.47	0.56	0.65	0.75	0.84	0.95	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Zimbabwe	0.18	0.35	0.53	0.67	0.78	0.87	0.92	0.95	0.98	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Figure S3: Normalized cumulative radiance distribution for Peru through Zimbabwe.

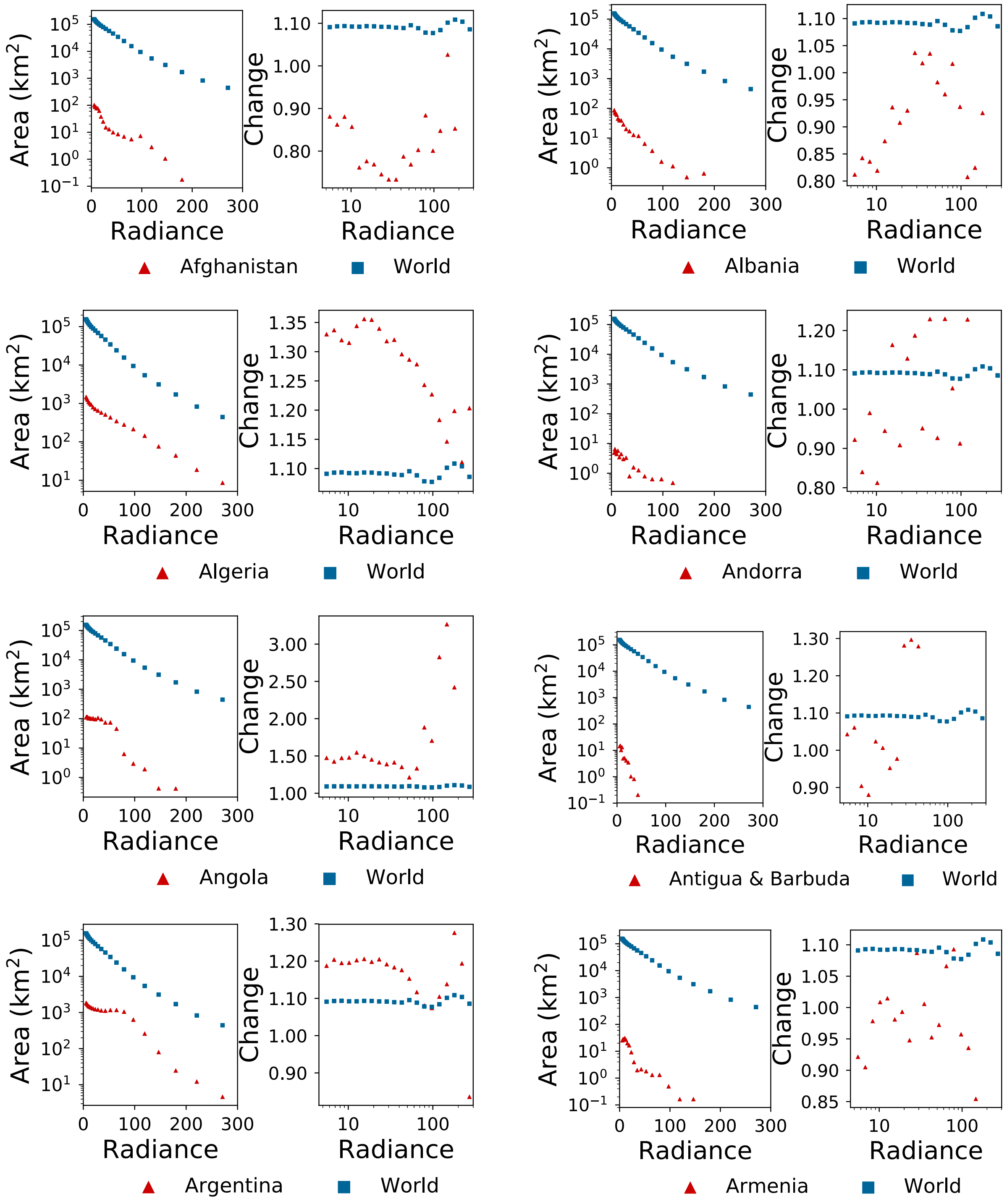

Figure S4: Lit area (2014) and radiance change (2012-2016) in Afghanistan, Albania, Algeria, Andorra, Antigua and Barbuda, Argentina and Armenia.

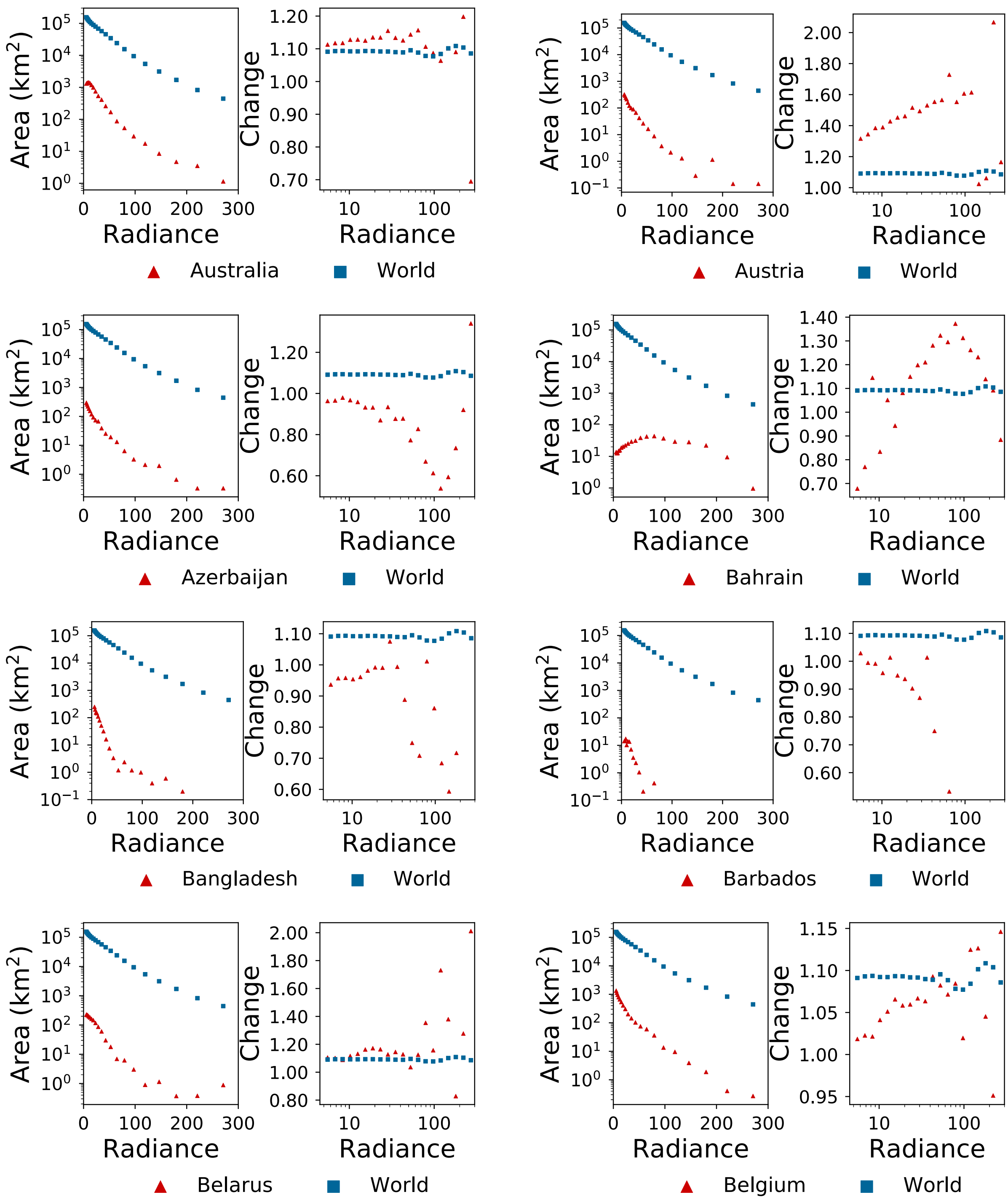

Figure S5: Lit area (2014) and radiance change (2012-2016) in Australia, Austria, Azerbaidjan, Bahrian, Bangladesh, Barbados, Belarus and Belgium.

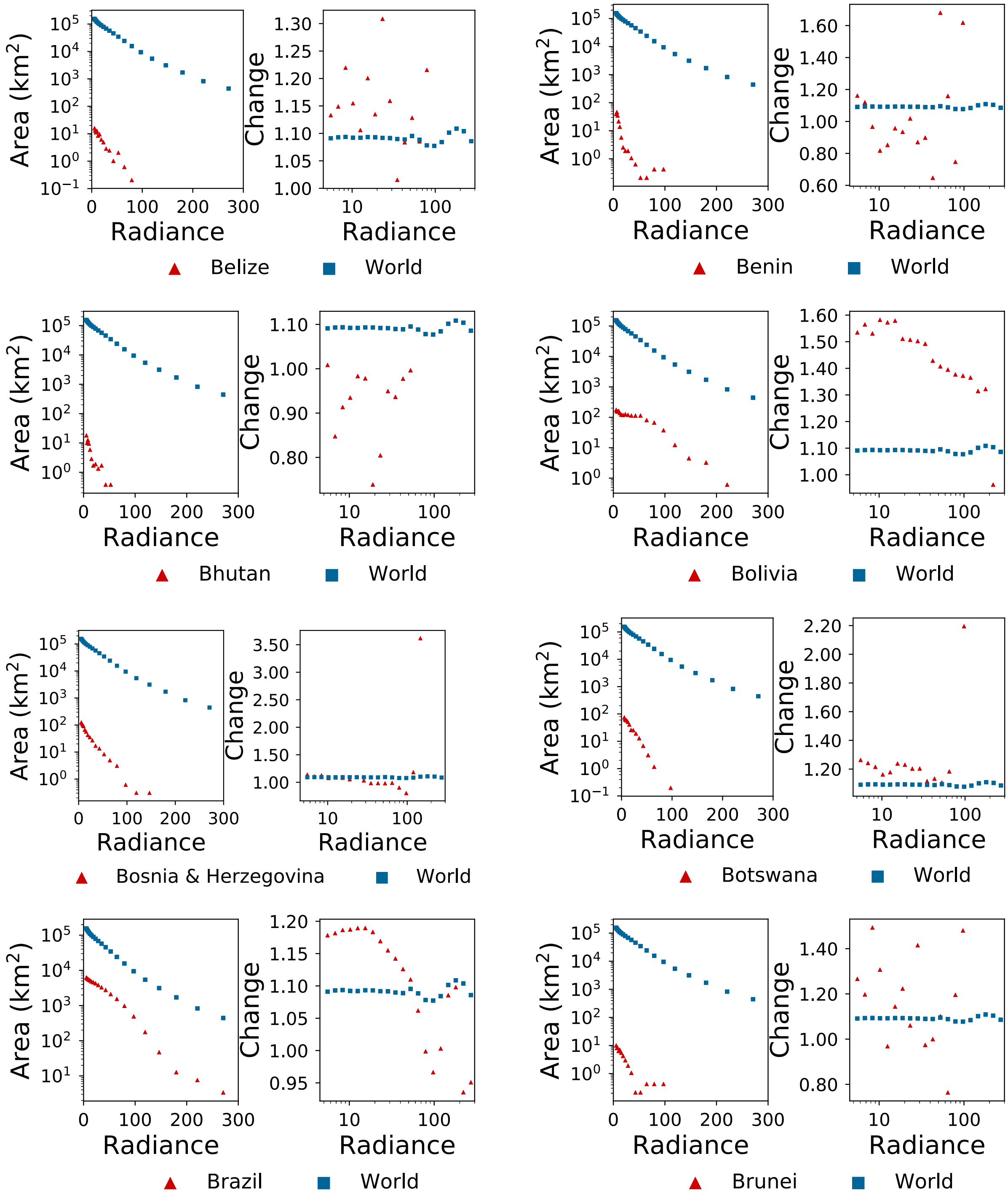

Figure S6: Lit area (2014) and radiance change (2012-2016) in Belize, Benin, Bhutan, Bolivia, Bosnia and Herzegovina, Botswana, Brazil and Brunei.

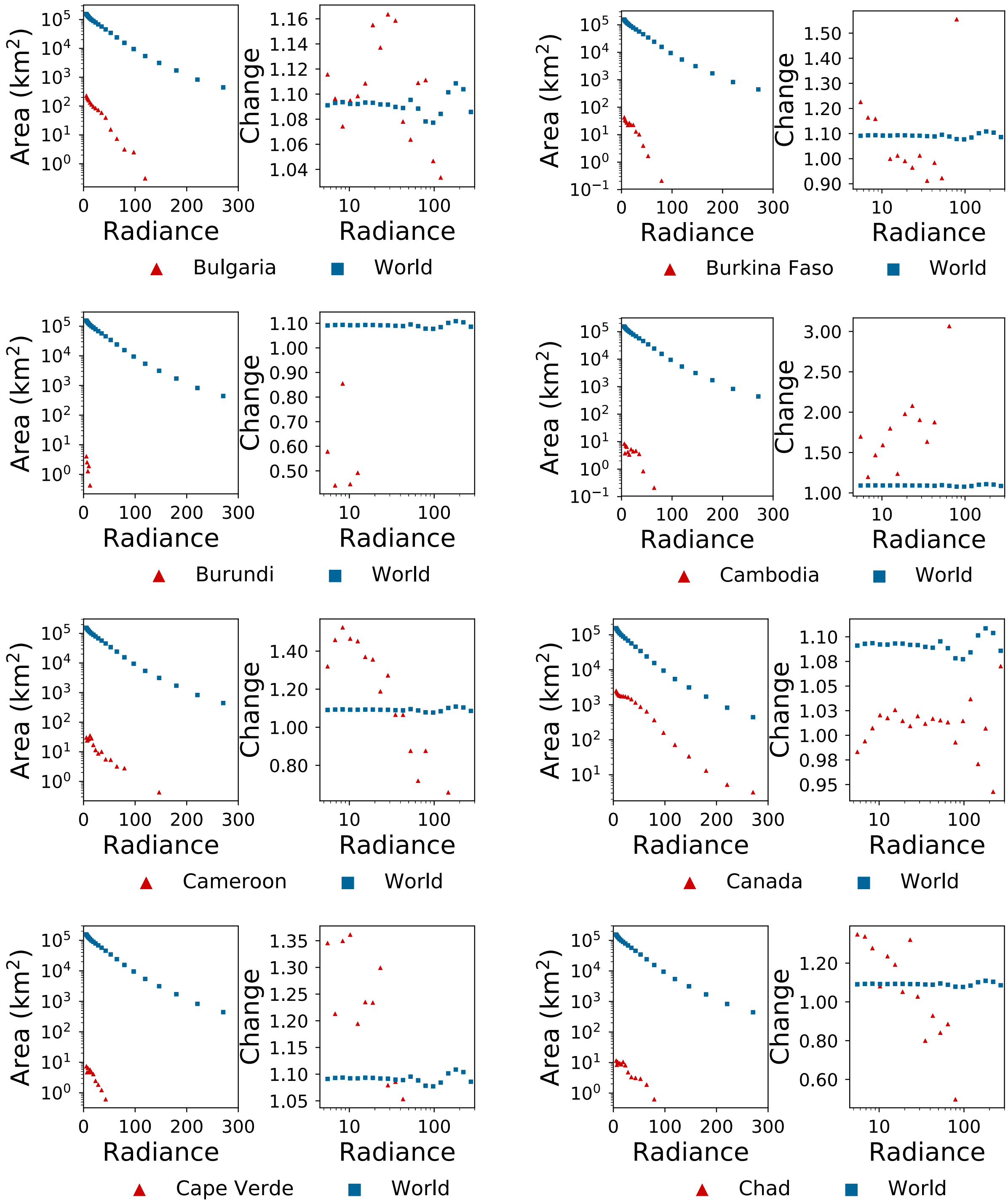

Figure S7: Lit area (2014) and radiance change (2012-2016) in Bulgaria, Burkina Faso, Burundi, Cambodia, Cameroon, Canada, Cape Verde and Chad.

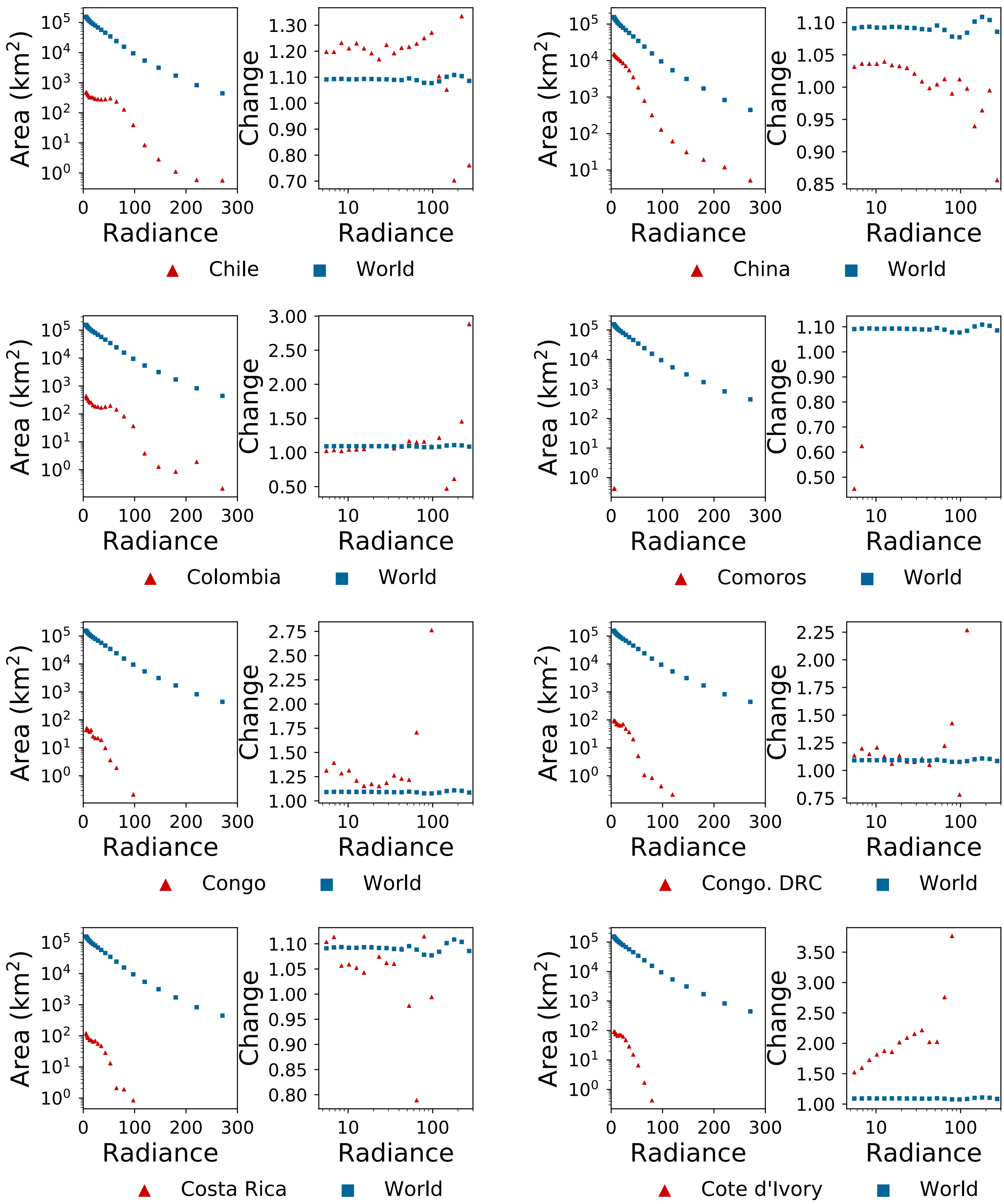

Figure S8: Lit area (2014) and radiance change (2012-2016) in Chile, China, Colombia, Comoros, Republic of the Congo, Democratic Republic of the Congo, Costa Rica, and Cote d'Ivory.

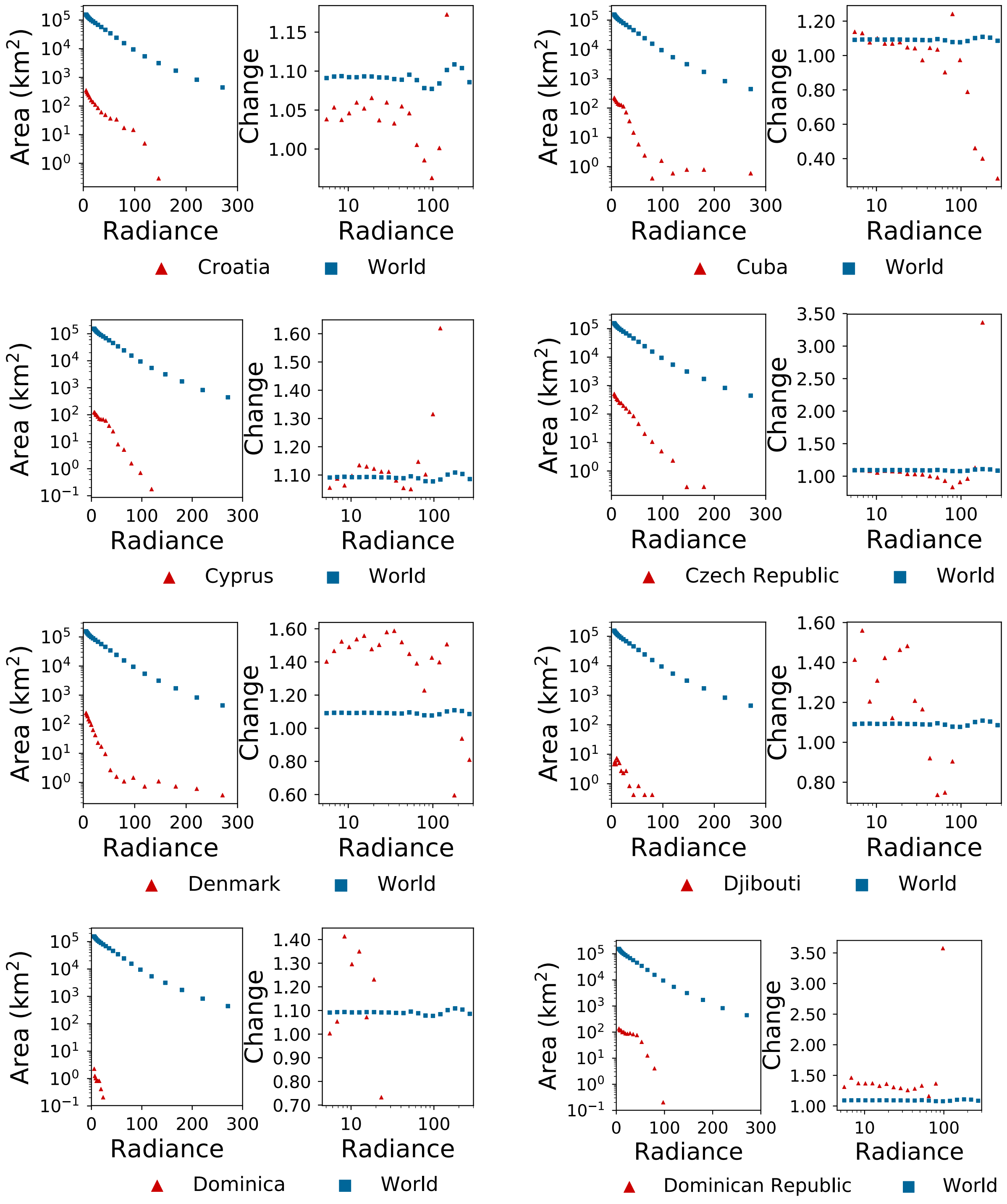

Figure S9: Lit area (2014) and radiance change (2012-2016) in Croatia, Cuba, Cyprus, Czech Republic, Denmark, Djibouti, Dominica, and Dominican Republic.

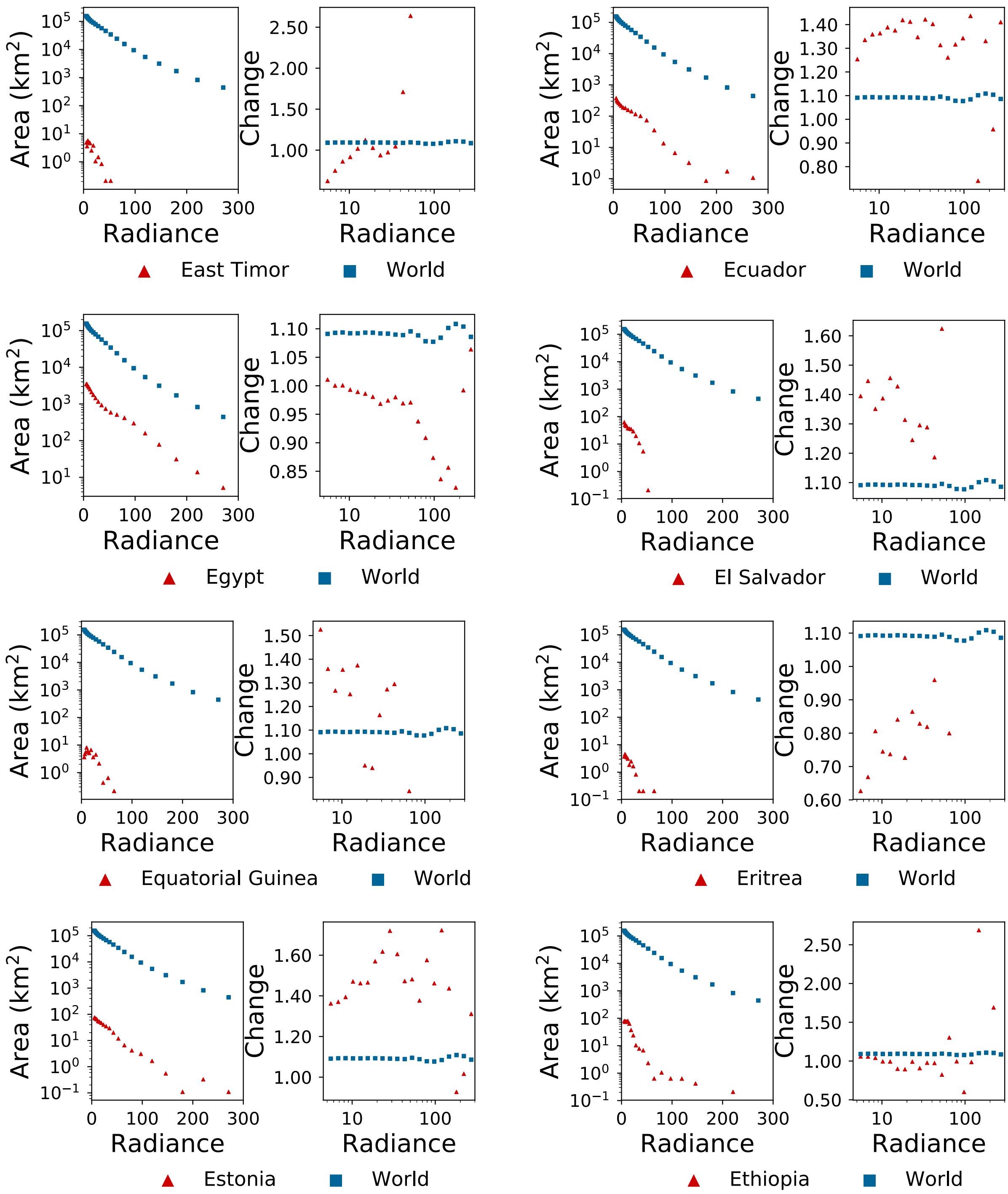

Figure S10: Lit area (2014) and radiance change (2012-2016) in East Timor, Ecuador, Egypt, El Salvador, Equatorial Guinea, Eritrea, Estonia, and Ethiopia.

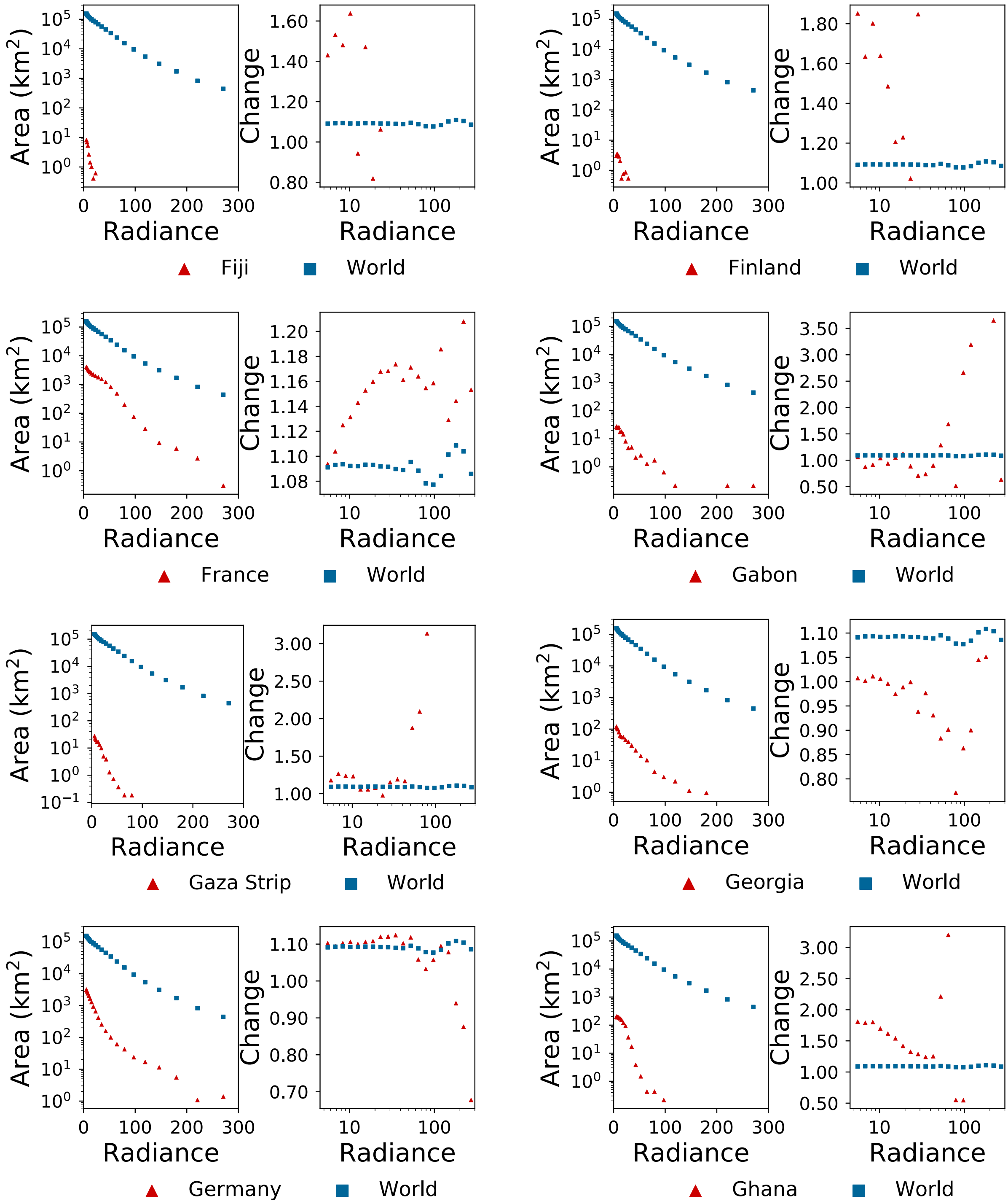

Figure S11: Lit area (2014) and radiance change (2012-2016) in Fiji, Finland, France, Gabon, Gaza Strip, Georgia, Germany, and Ghana.

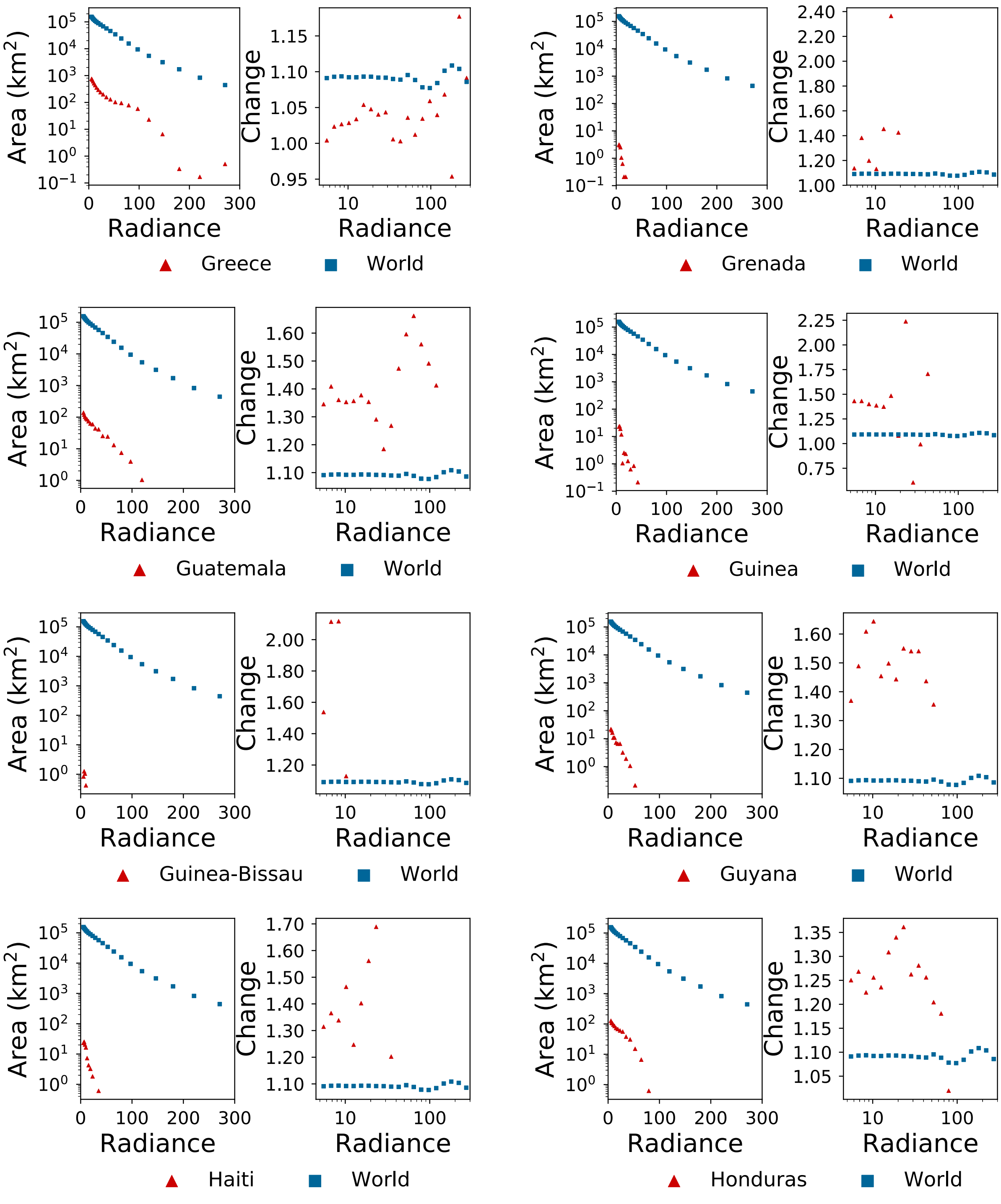

Figure S12: Lit area (2014) and radiance change (2012-2016) in Greece, Grenada, Guatemala, Guinea, Guinea-Bissau, Guyana, Haiti, and Honduras.

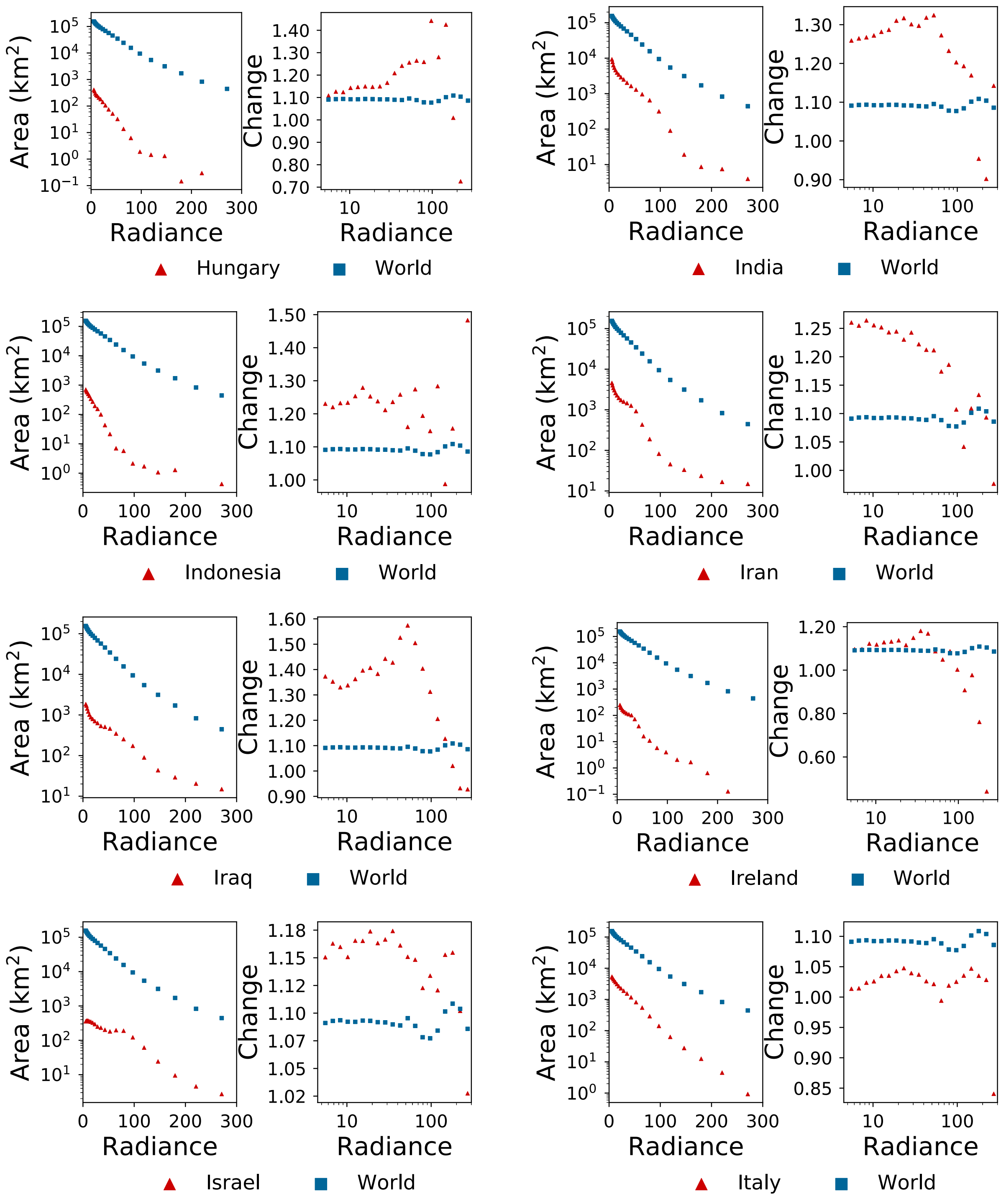

Figure S13: Lit area (2014) and radiance change (2012-2016) in Hungary, India, Indonesia, Iran, Iraq, Ireland, Israel and Italy.

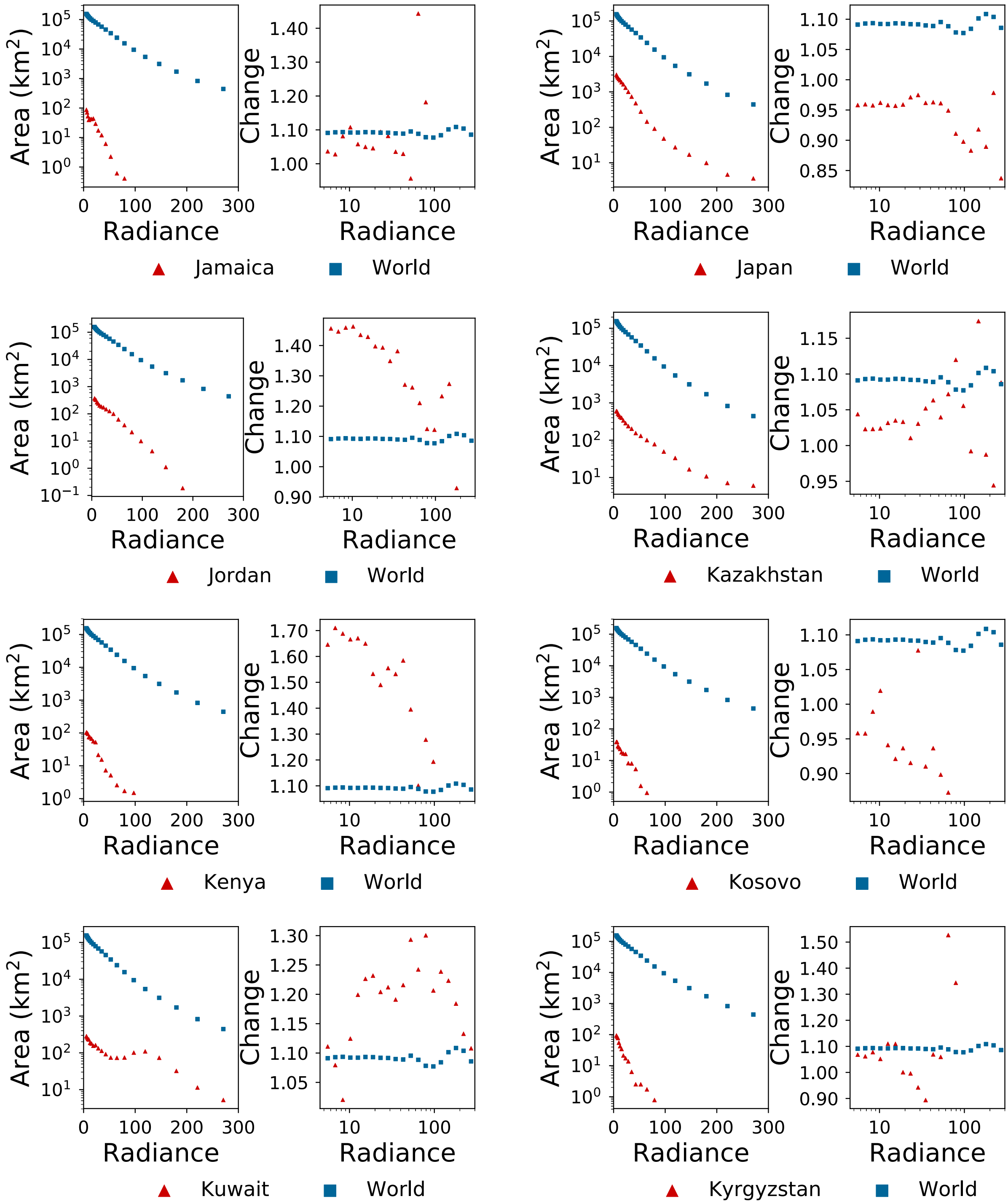

Figure S14: Lit area (2014) and radiance change (2012-2016) in Jamaica, Japan, Jordan, Kazakhstan, Kenya, Kosovo, Kuwait and Kyrgyzstan.

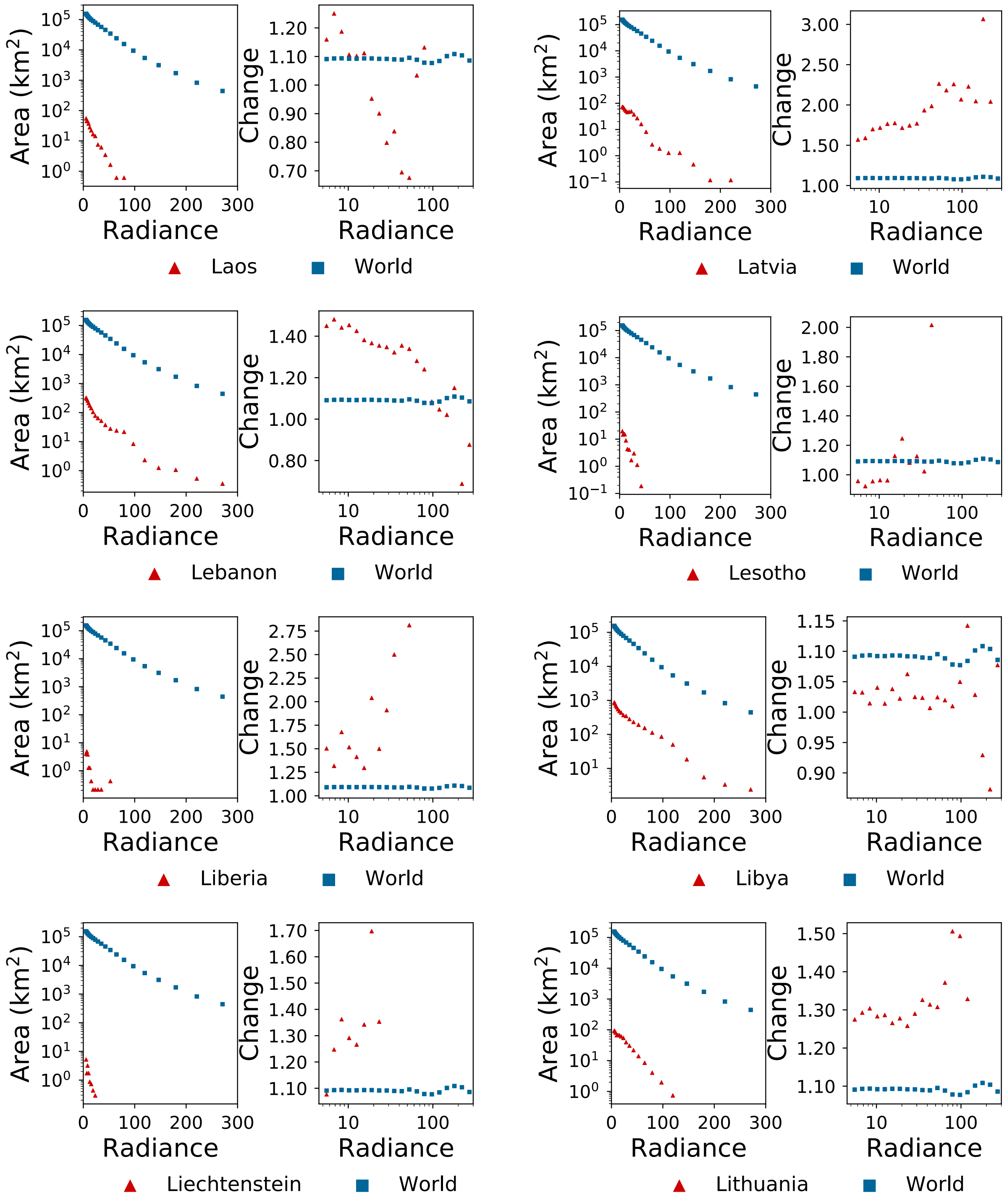

Figure S15: Lit area (2014) and radiance change (2012-2016) in Laos, Latvia, Lebanon, Lesotho, Liberia, Libya, Liechtenstein and Lithuania.

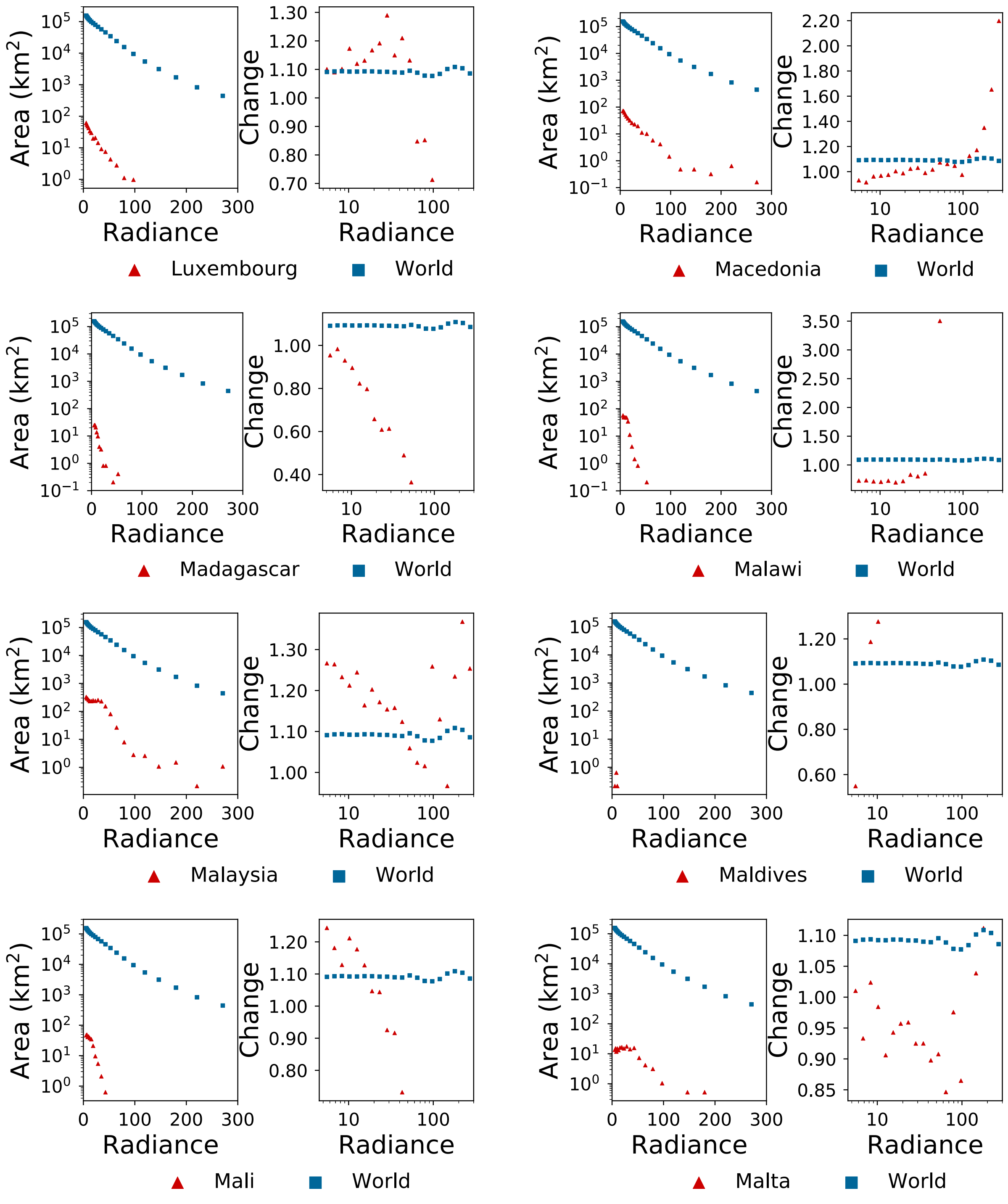

Figure S16: Lit area (2014) and radiance change (2012-2016) in Luxembourg, Macedonia, Madagascar, Malawi, Malaysia, Maldives, Mali and Malta.

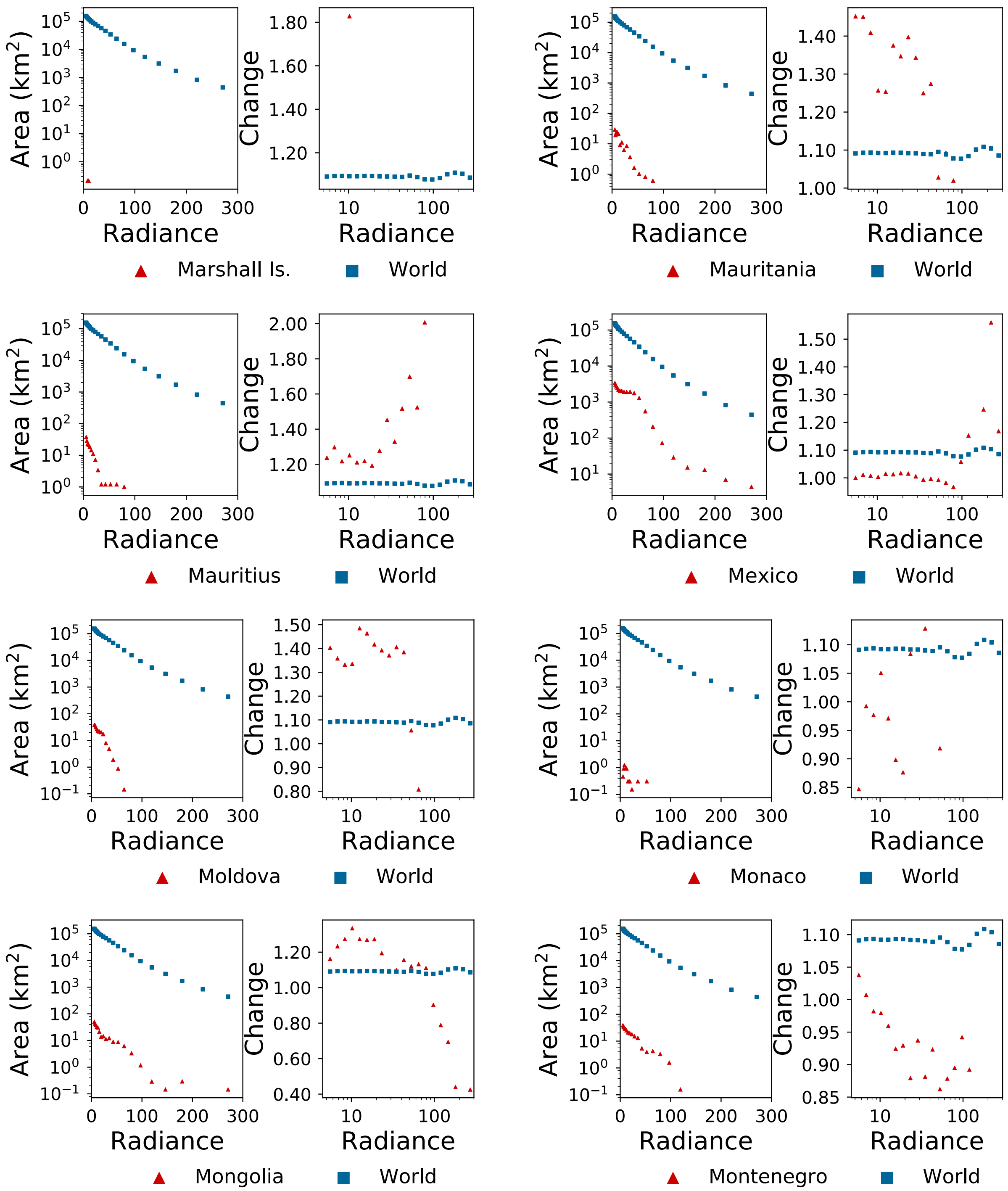

Figure S17: Lit area (2014) and radiance change (2012-2016) in Marshall Islands, Mauritania, Mauritius, Mexicao, Moldova, Monaco, Mongolia and Montenegro.

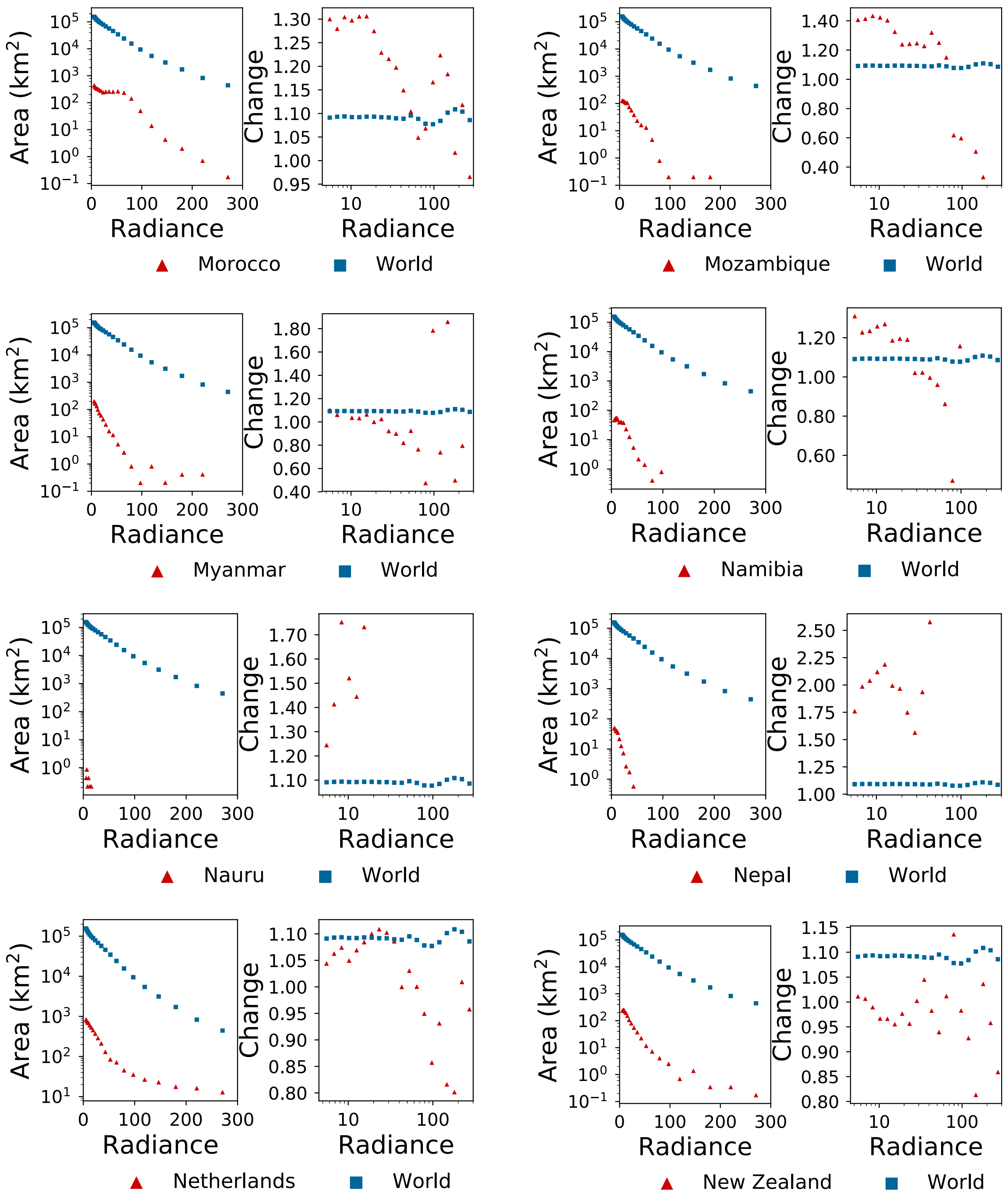

Figure S18: Lit area (2014) and radiance change (2012-2016) in Morocco, Mozambique, Myanmar, Namibia, Nauru, Nepal, Netherlands, and New Zealand.

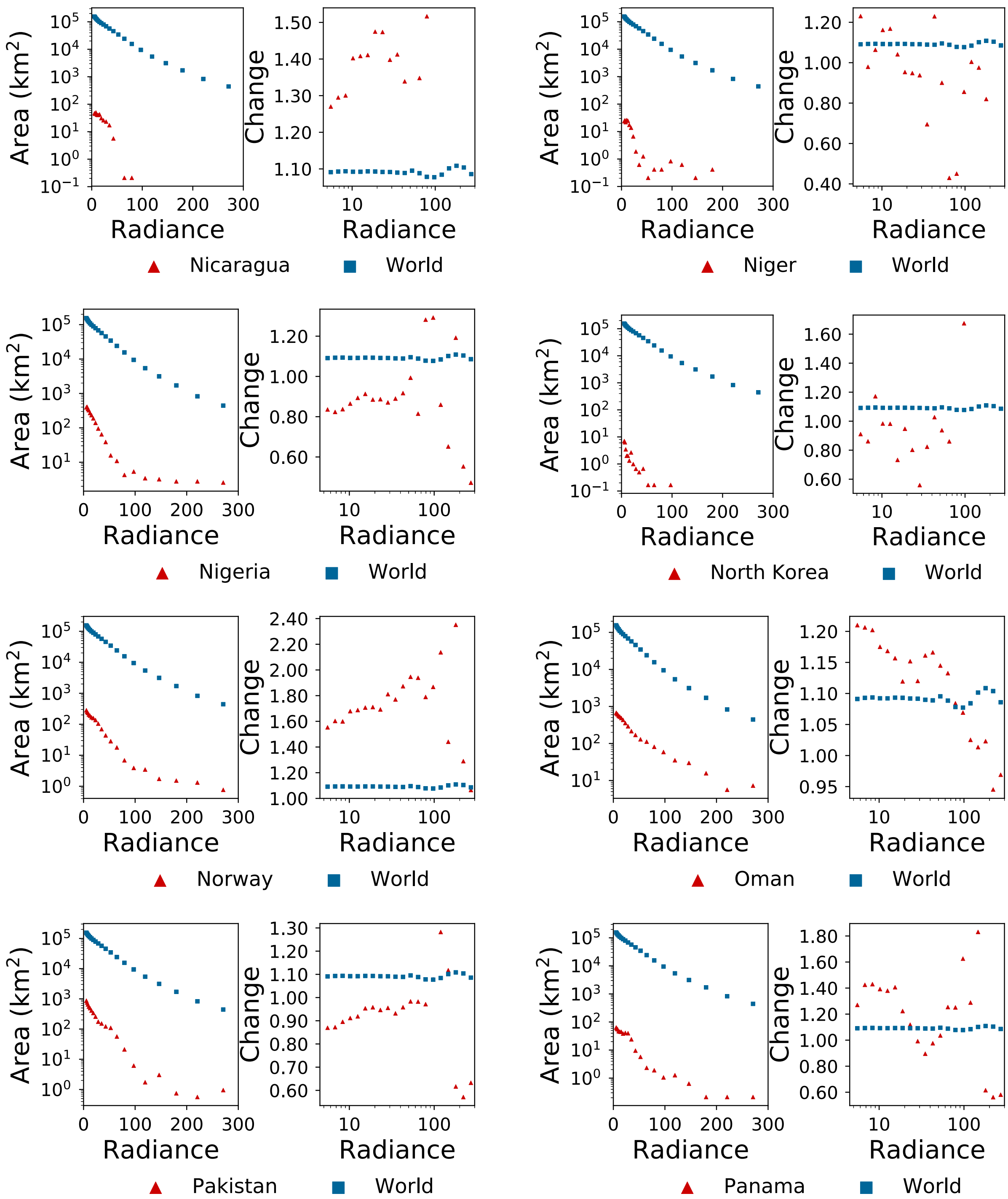

Figure S19: Lit area (2014) and radiance change (2012-2016) in Nicaragua, Niger, Nigeria, North Korea, Norway, Oman, Pakistan, and Panama.

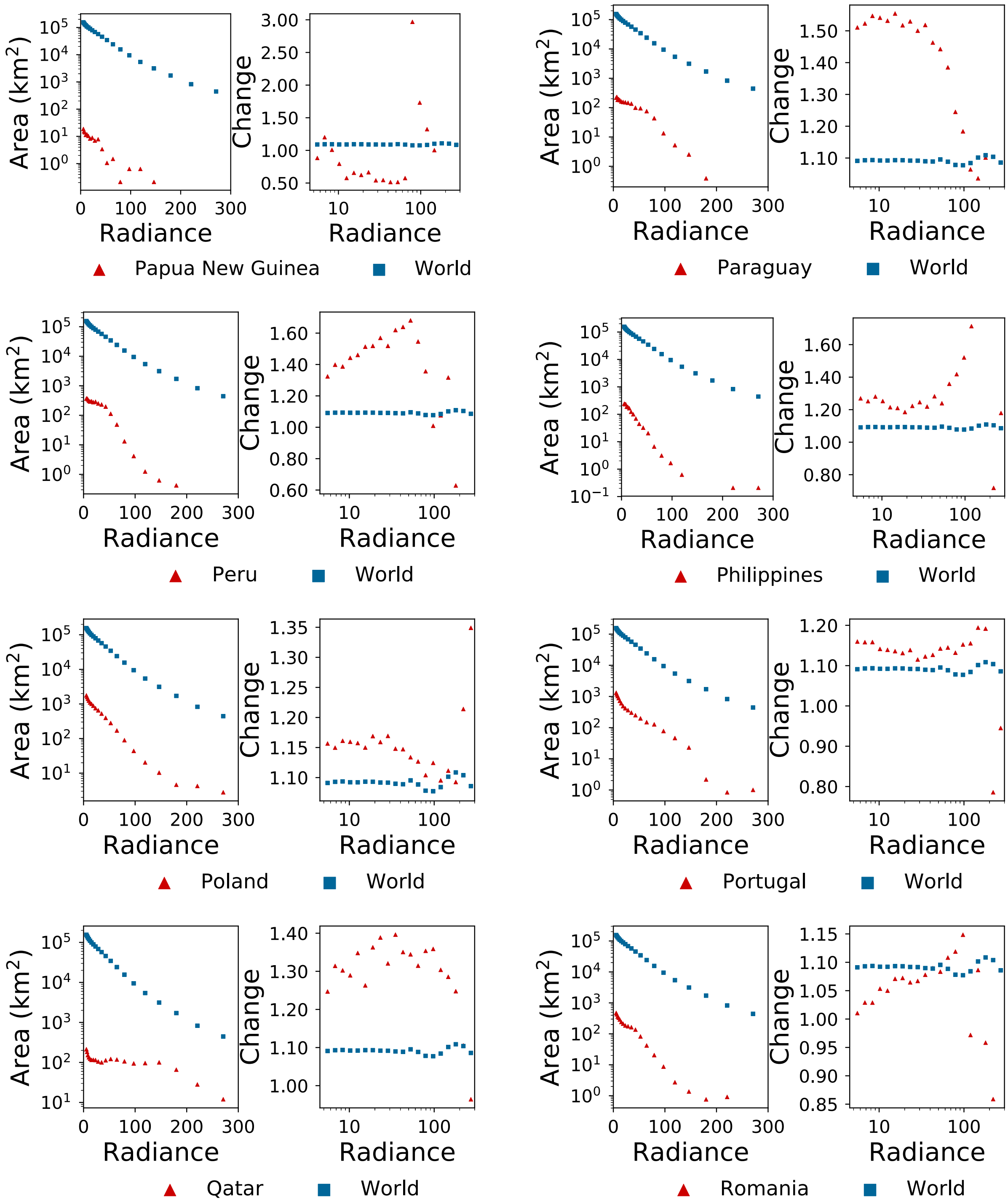

Figure S20: Lit area (2014) and radiance change (2012-2016) in Papua New Guinea, Paraguay, Peru, Philippines, Poland, Portugal, Qatar, and Romania.

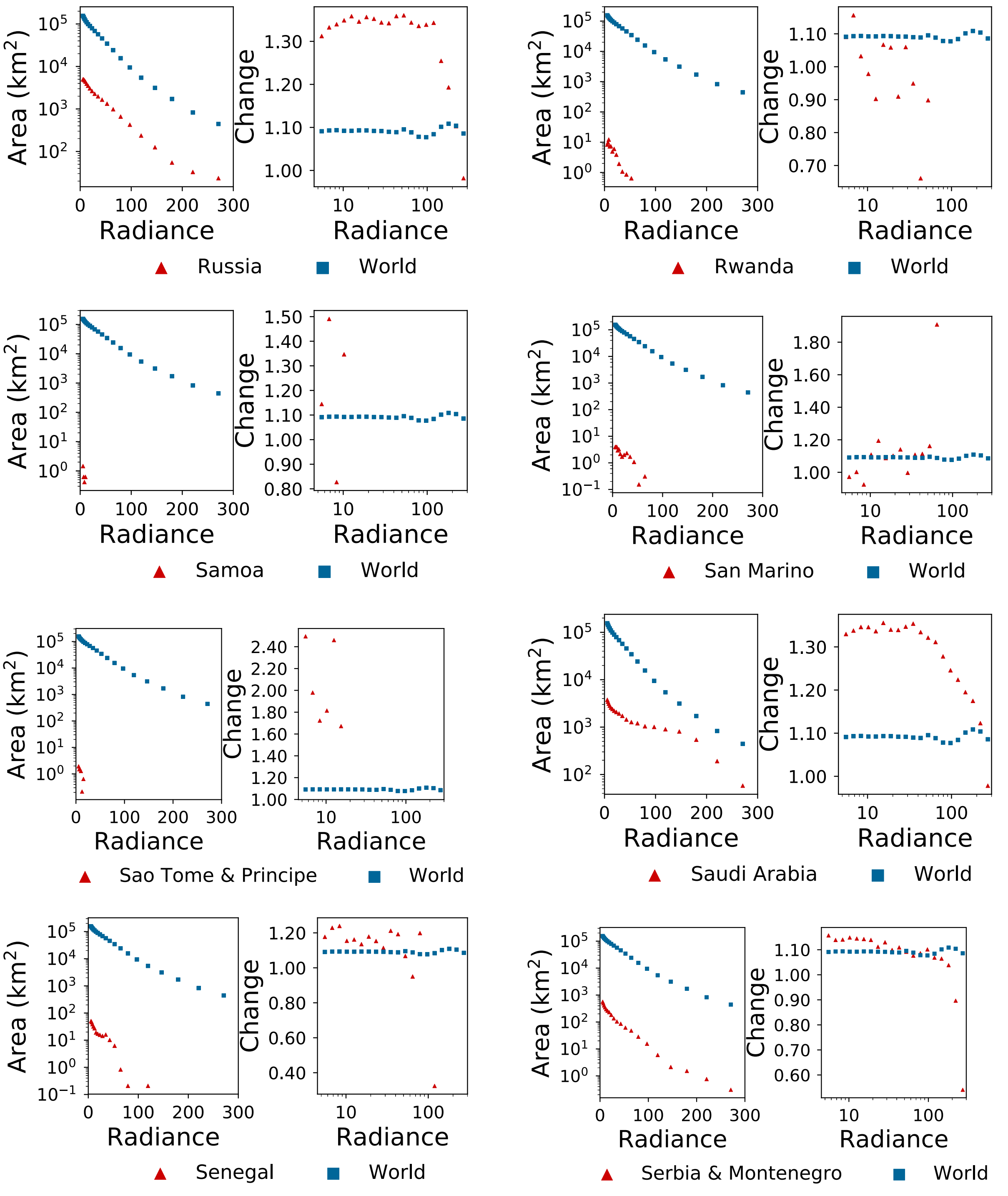

Figure S21: Lit area (2014) and radiance change (2012-2016) in Russia, Rwanda, Samoa, San Marino, Sao Tome and Principe, Saudi Arabia, Senegal, and Serbia and Montenegro.

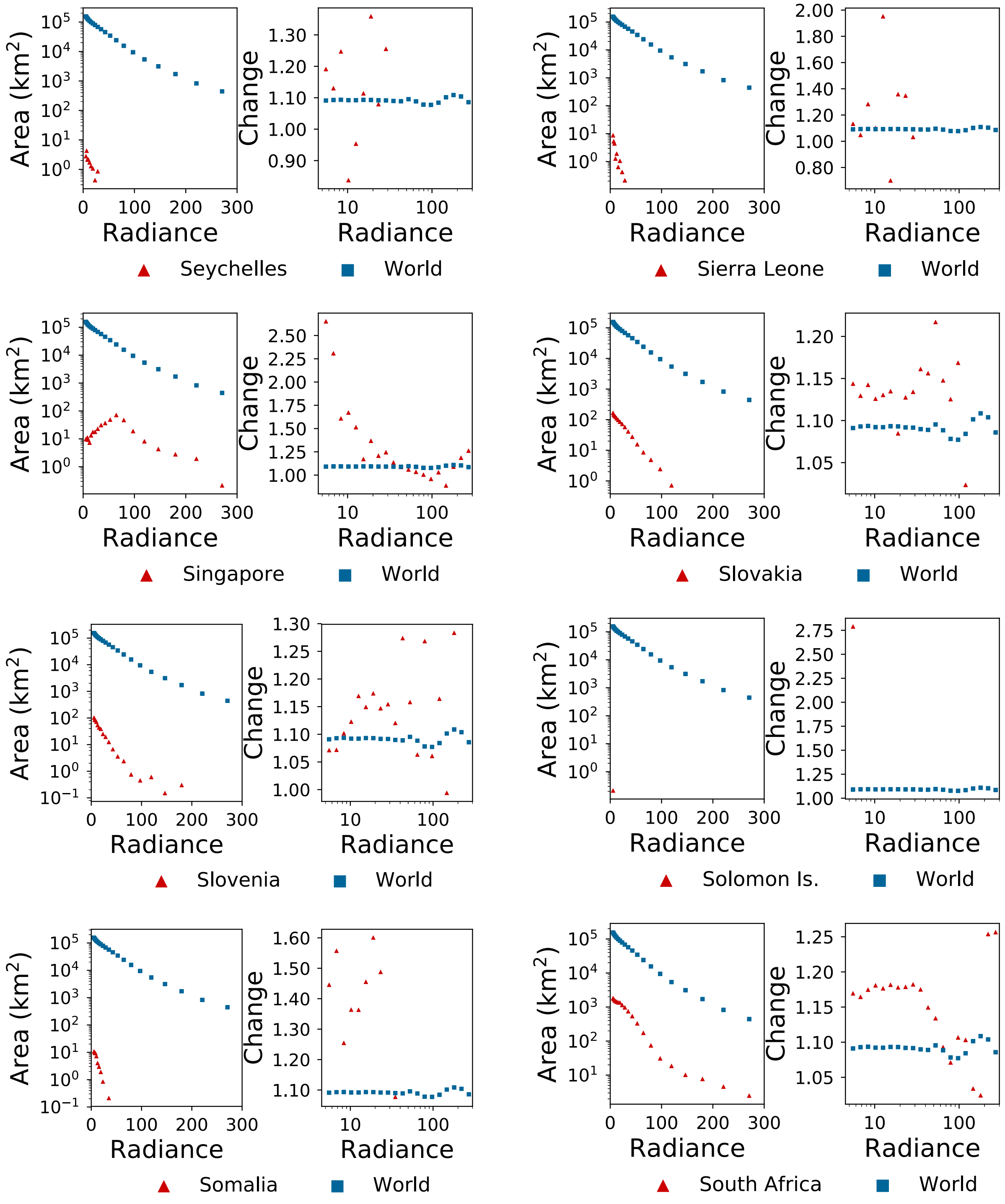

Figure S22: Lit area (2014) and radiance change (2012-2016) in Seychelles, Sierra Leone, Singapore, Slovakia, Slovenia, Solomon Islands, Somalia, and South Africa.

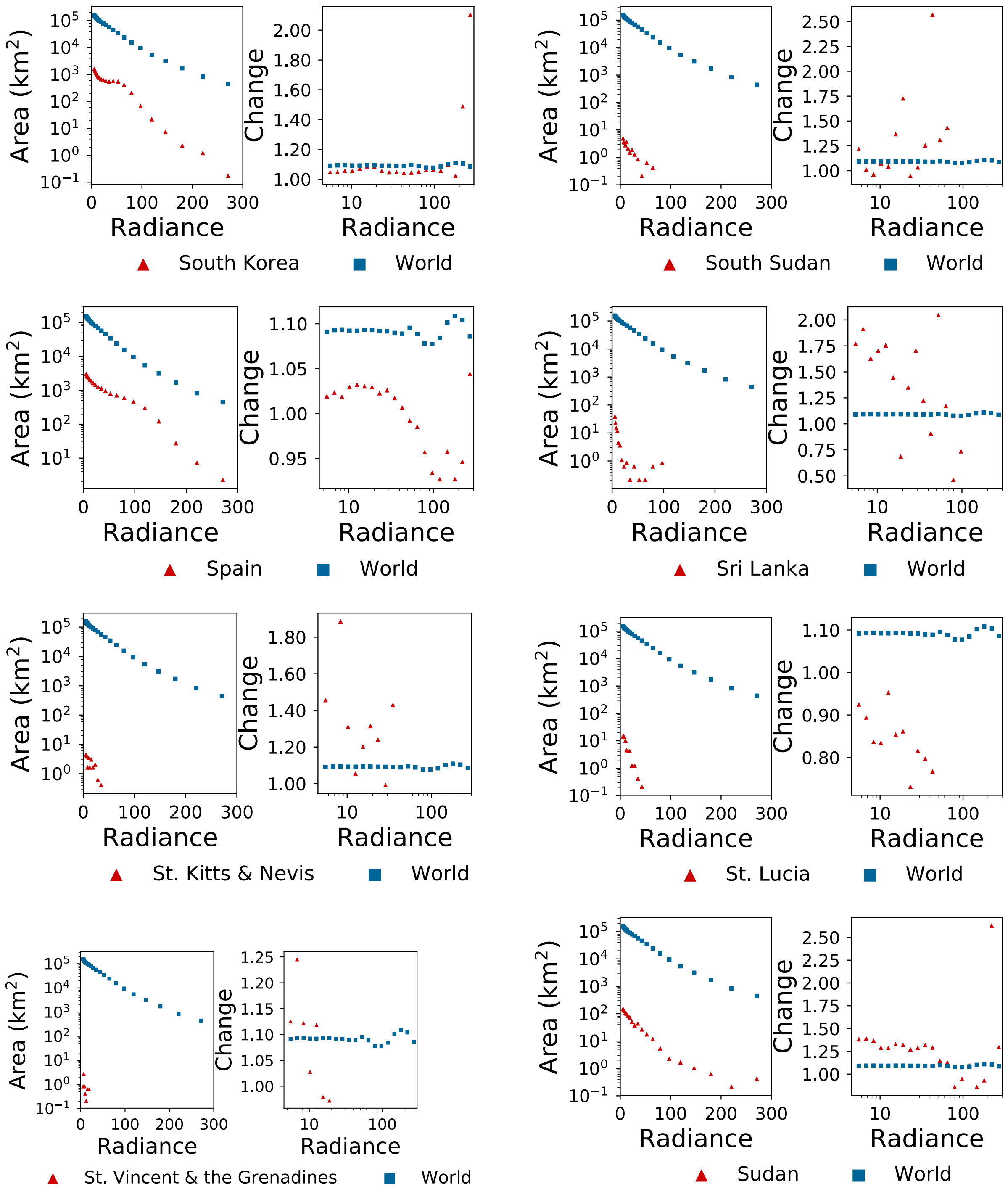

Figure S23: Lit area (2014) and radiance change (2012-2016) in South Korea, South Sudan, Spain, Sri Lanka, St. Kitts and Nevis, St. Lucia, St. Vincent and the Grenadines, and Sudan.

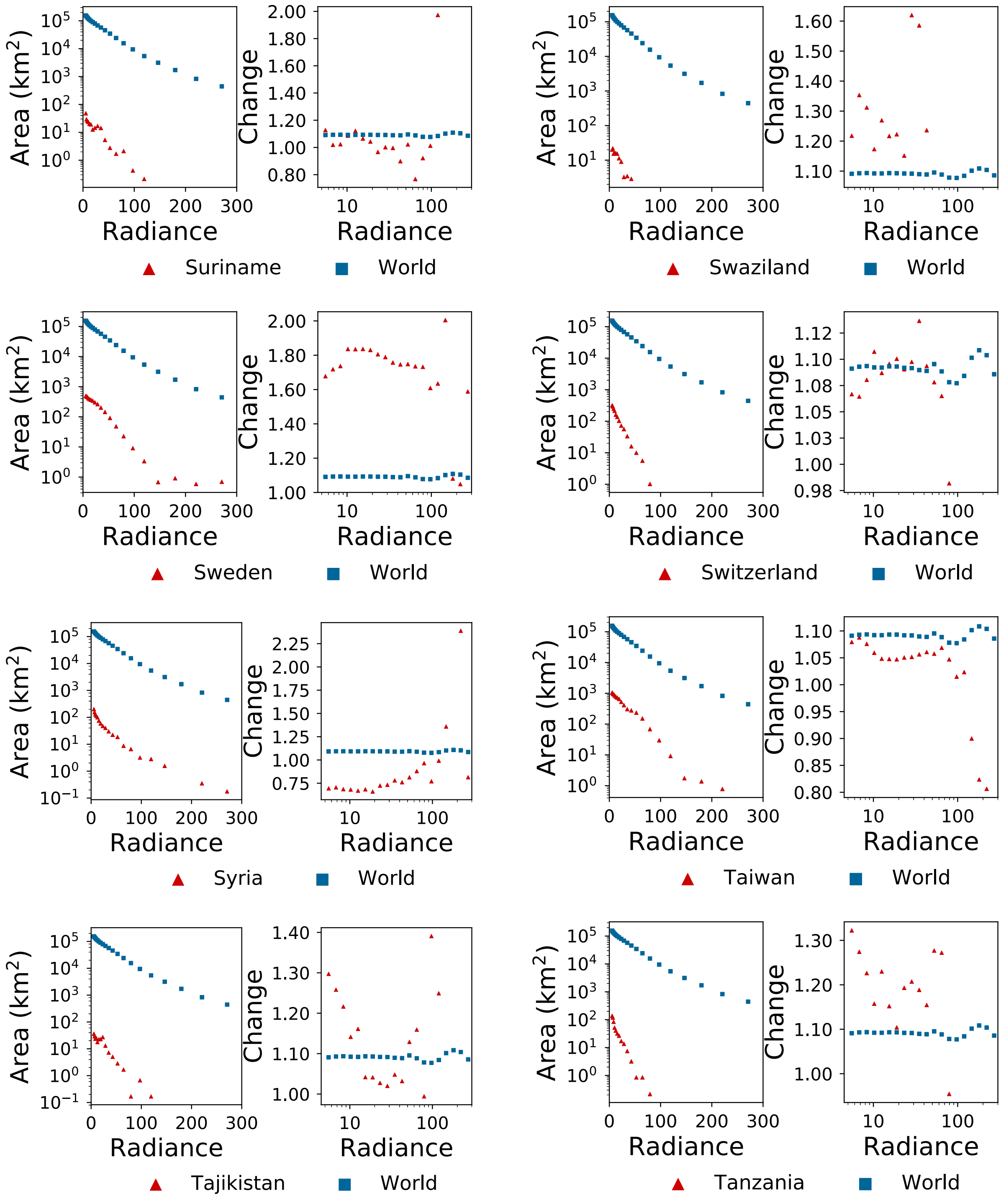

Figure S24: Lit area (2014) and radiance change (2012-2016) in Suriname, Swaziland, Sweden, Switzerland, Syria, Taiwan, Tajikistan, and Tanzania.

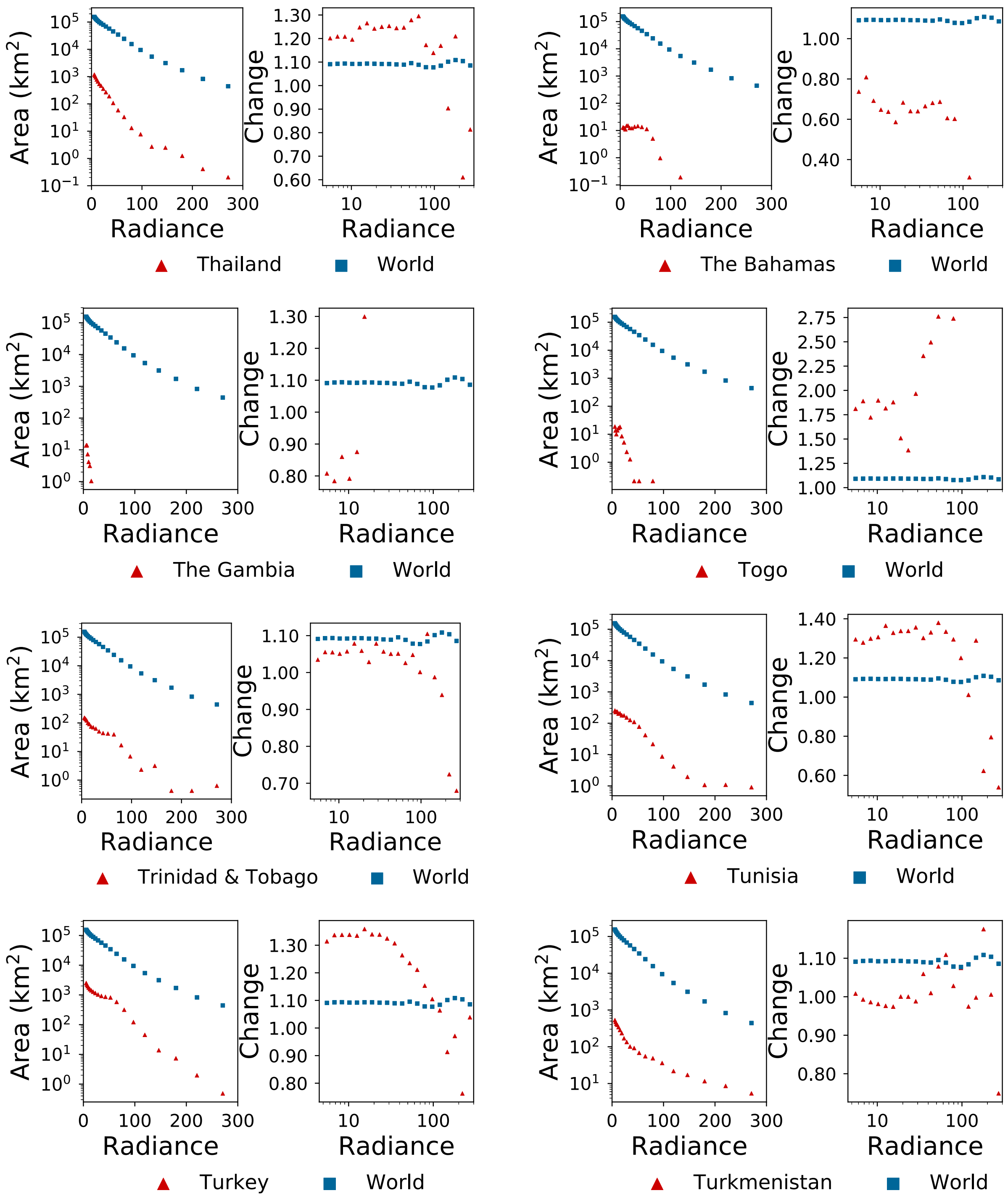

Figure S25: Lit area (2014) and radiance change (2012-2016) in Thailand, The Bahamas, The Gambia, Togo, Trinidad and Tobago, Tunisia, Turkey, Turkmenistan.

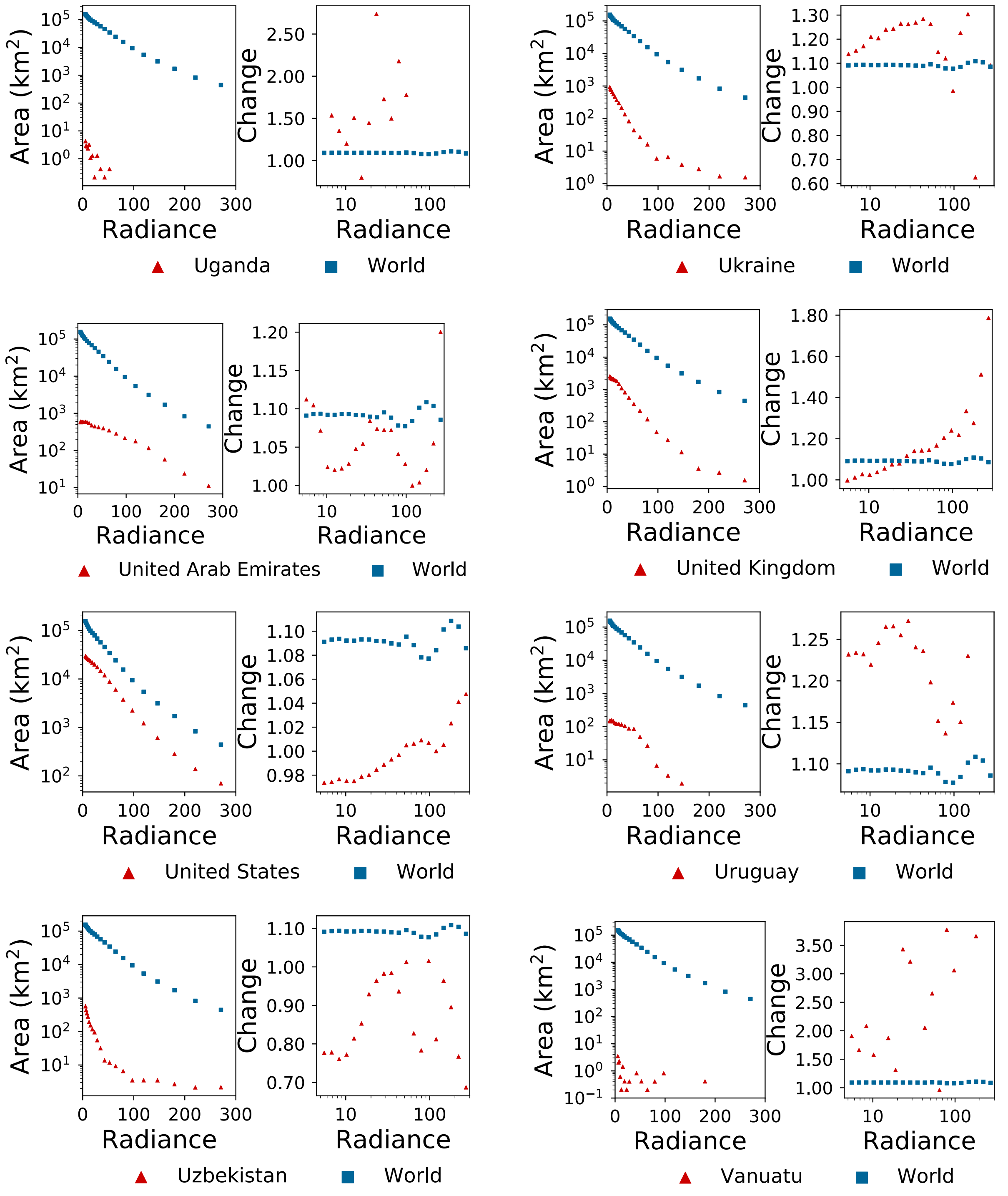

Figure S26: Lit area (2014) and radiance change (2012-2016) in Uganda, Ukraine, United Arab Emirates, United Kingdom, United States, Uruguay, Uzbekistan, and Vanuatu.

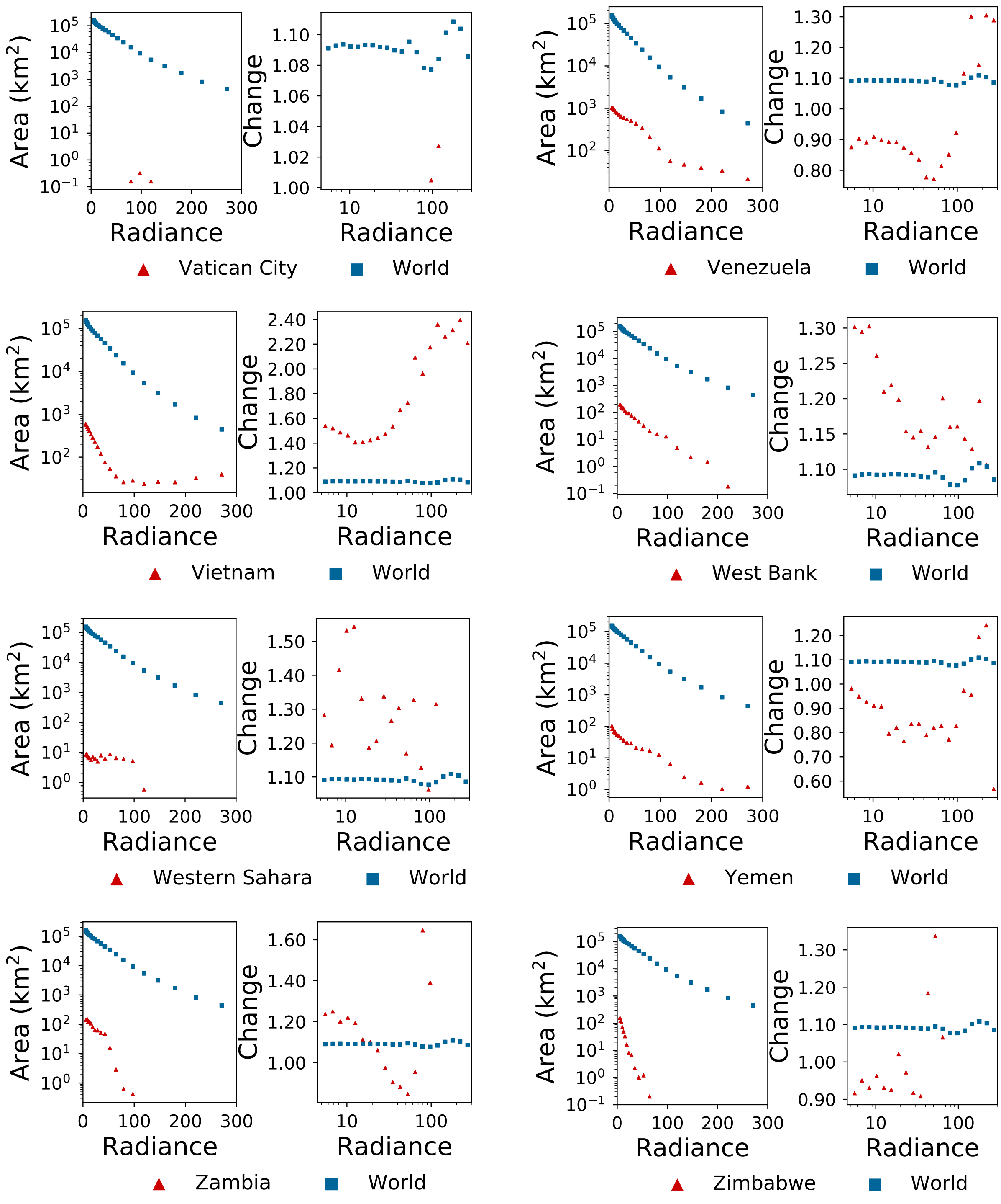

Figure S27: Lit area (2014) and radiance change (2012-2016) in Vatican City, Venezuela, Vietnam, West Bank, Western Sahara, Yemen, Zambia and Zimbabwe.

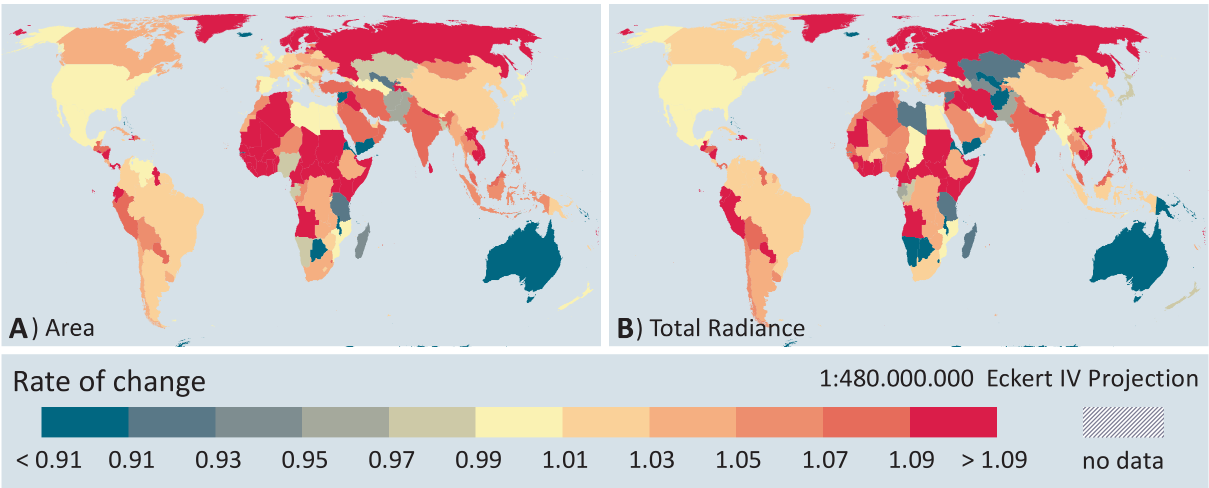

Figure S28: Annual changes in lit area (A) and total radiance (B). Changes are shown as an annual rate, i.e. $\sqrt[4]{A_{2016}/A_{2012}}$, where A_{2016} is the lit area observed in 2016. The difference to Figure 1 in the main paper is that here the change in total radiance is shown, rather than the change in stable lights.