Changes in outdoor lighting in Germany from 2012-2016

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Abstract

Changes in the total lit area and the radiance of stably lit area in the German federal states from 2012-2016 were investigated using satellite observations from the Day-Night Band of the Visible Infrared Imaging Radiometer Suite. Most states increased in both lit area and radiance. The lit area of Bayern and Schleswig-Holstein grew most rapidly, but it is possible that their large increases are to some extent driven by a darker than usual observation in 2012. Thüringen was dramatically different from the other states, with an annual decrease in lit area, and in the radiance of stably lit areas. The rates of change measured from 2012-2015 and 2013-2016 are strongly correlated with each other (Pearson's $\rho=0.67$, $p=0.01$). In most states, least squares fits for the rate of change match the rate calculated as a ratio of 2016 to 2012. These results are therefore consistent with the hypothesis that the changes in observed radiance are due to lighting change, but this should be verified in the future when longer time series are available. Due to the (500-900 nm) spectral response of the satellite, transitions from high pressure sodium to LED street lighting that preserve total lumen output are be expected to be observed as a decrease in radiance. Since such decreases are not observed in most states, the observations of increasing light emissions in most states are not indicative of a national transition toward sustainable lighting. In addition to these results, this paper discusses the role of remotely sensed nighttime data within the context of sustainable lighting.

Keywords: Germany, sustainable lighting, light pollution, remote sensing, rebound effect, VIIRS DNB

1. Introduction

Remote sensing is a technique for determining information about a system via observations taken from some distance away. Nighttime observations of Earth at night have recently improved to allow observation of artificial lights at the scale of individual lamps via aerial photography [1,2], at the street level via astronaut photographs [3], and at neighborhood scale via satellite [4]. The near global coverage of the satellite data make it possible to assess some aspects of lighting on wide spatial scales. As the Earth undergoes a transition to solid state lighting, and on longer scales a transition to "sustainable lighting", observations of light emissions via remote sensing can provide up-to-date information about the changes taking place.

The Visible Infrared Imaging Radiometer Suite Day-Night Band (VIIRS DNB) is the first satellite sensor designed explicitly to observe artificial light emissions on the global scale [5]. It is a major improvement over the earlier uncalibrated defense satellite instrument that produced the first global views of Earth at night [6]. Recently, Kyba et al. used DNB data to examine changes in lights at the national and global level, and found that global light emissions in the DNB spectral band (500-900 nm) from continuously lit areas are increasing at a rate of 2.2%

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per year [7]. In general, they found that increases were most rapid in developing countries, with developed countries experiencing slower growth, and some of the brightest countries remaining roughly constant in the DNB spectral band. Lighting change was found to be weakly correlated to GDP change, and the average change in lights was quite close to the average change in GDP.

Satellite observations of artificial light have a number of important limitations (see [4] for an extended discussion). First, they observe only light that is either reflected or directly emitted upwards. They can therefore not measure luminous flux: a lamp directed upward would appear about 6-10 times brighter than the same lamp directed downward, as the upward directed light would not have to first reflect off a dark surface. Furthermore, since satellites generally observe at a fairly steep angle, they have reduced sensitivity to horizontal surfaces, such as illuminated signs and facades, car headlights, and light escaping from windows. Second, satellites observe in spectral bands that do not match the luminosity curve [4]. Third, the light rays satellites view have been partly attenuated by the atmosphere (particularly at shorter blue wavelengths), and atmospheric scattering results in a glow around cities, making adjacent unlit areas appear brighter than they really are.

This paper extends the work of Kyba et al. [7] by examining the changes in upward emission of light at a smaller spatial scale and at a lower radiance threshold. We aim to provide information about the changes taking place in the individual states of Germany, and more generally to discuss the role of remotely sensed data in the context of a global transition to sustainable lighting.

2. Methods

Monthly cloud-free composite DNB data files were downloaded from the National Oceanic and Atmospheric Administration (NOAA) for October and November for each year from 2012-2016 (https://www.ngdc.noaa.gov/eog/viirs/download_dnb_composites.html). These data are radiance calibrated, and consist only of observations that were taken under clear sky conditions (as determined by infrared channels of the VIIRS sensor), and without twilight illumination or stray light [8]. The fall months were chosen based on our experience using the DNB data. From April to September, the satellite is illuminated by stray light when passing over the North of Germany, and during much of that period the ground is also illuminated by scattered sunlight during the DNB overpass time, resulting in a lack of data in those areas. The winter months of December to March are problematic, because snow cover dramatically increases the radiance observed by DNB [9].

In the global analysis of Kyba et al. [7], effects due to the environment (e.g. atmospheric transparency, soil moisture, leaf cover) or acquisition (e.g. mix of acquisition angles, day of week, and overpass times) were assumed to have little impact on the national and global level. However, the influence of such effects becomes more important when smaller regions are analyzed. For example, mainly unlit agricultural and nature protected areas near Bremen were reported as having bright radiances in the monthly composite from October, 2016 (Figure 1). In most months, bright light sources are visible at a steelwork near 53.13°N, 8.68°E. In October 2016, however, the observed light was spread out over a large area, extending into otherwise unlit areas East of the Weser river. The observed radiance was above 6 nW/cm^2 sr up to 4.5 km from the steelwork, and above 2 nW/cm^2 sr at 6.5 km from the steelwork. One possible reason for this could be frequent fog that month, which was not identified by the satellite's infrared detector. An alternate possibility is that it could be due to light from the presence of glowing slag near the steelwork, which was then scattered by a plume of smoke from the slag.

This example suggests that on smaller spatial scales, caution should be taken in interpreting results based on observations taken in single months. The US National Oceanic and Atmospheric Administration is currently developing annual based composites, which should be less affected by such errors [8]. To reduce the impact of such events, pixels were therefore only considered lit in a given year if they were above a 3 nW/cm^{2}sr threshold in both the October and November composites. In addition, a new raster dataset was created for each year using the mean of the radiance reported in the October and November cloud-free composites.

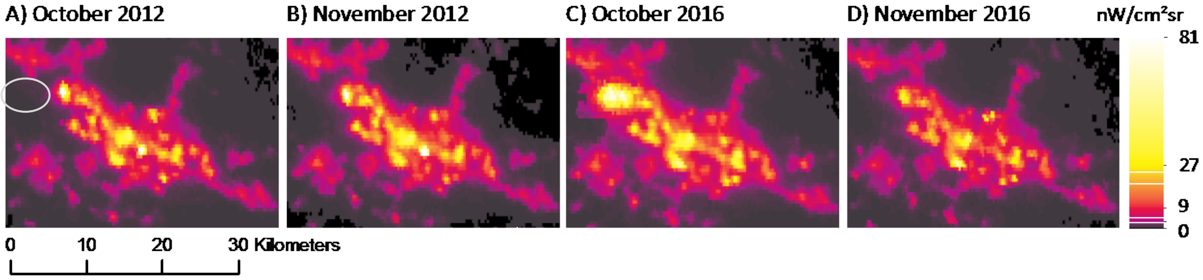

Figure 1: Radiance reported in the monthly composites for October and November of 2012 and 2016 near Bremen, Germany. The area slightly below top left indicated with an oval is unlit, but appeared to be lit in October 2016 (C), presumably due to thin clouds. The color scale is quadratic: Black <0, grey 0-3, purple=3-9, red=9-27, yellow=27-81, white >81. UTM projection 1:2,000,000.

The analysis of change in lit area and the radiance of existing lit areas pursued here is similar to that of Kyba et al. [7], with one important difference. In that analysis, the threshold for considering an area to be lit was set to 5 nW/cm^{2}sr. However, Germany is not affected by aurora light, so a lower threshold of 3 nW/cm^{2}sr could be applied here. This is useful, because most of the total light emissions in a country come from faintly rather than brightly lit areas [7, Appendix]. This means, however, that the results here cannot be directly compared to those from Kyba et al. [7]. Furthermore, instead of examining the change in lit areas in 20 bins over a range from 5-300 nW/cm^{2}sr, here only 10 bins are used, with the range reduced to 3-150 nW/cm^{2}sr. The number of bins was reduced because of the smaller areas under consideration, and the maximum light level was reduced because extremely bright areas are uncommon in Germany. For reference, in the 2012 October composite, the brightest pixel in Potsdam, the state capital of Brandenburg, was only 36 nW/cm^{2}sr, and the brightest pixel of Frankfurt airport in the same composite was 290 nW/cm^{2}sr.

For convenience, the following is a brief summary of the method used in Kyba et al. [7] and repeated here. For each pixel in the DNB composite, the surface area was calculated. Using python, a mask of areas lit above the 3 nW/cm^{2}sr threshold in each composite was created, and the total lit area summed. For calculating how stable lights are changing, the radiance of each pixel was compared to its value in 2014. If the value either differed by more than a factor of 4 from the 2014 value or was outside of the range 1-450 nW/cm^{2}sr in any year, then the pixel was discarded from the radiance change analysis. The area-weighted sum of stable light radiance was calculated for each state, and the ratio of these values from 2012 to 2016 was compared. For each state, each pixel was assigned to one of a set of 10 logarithmically distributed bins based on the observed radiance in 2014. The average radiance change in each of these bins was then calculated, in order to check for possible differences between brightly and moderately lit areas.

In addition to calculating the change in lit area as a ratio from 2012 to 2016, we also performed least squares fitting of the time series. The area lit above the 3 nW/cm^{2}sr threshold was calculated for each data set (October and November data from 2012-2016), for a total of 10 data points per federal state. In this analysis, no stability criteria were set, so the “lit area” for each month is larger than in the main analysis. The data were fit according to the equation $A(t) = (1+r)^t A(0)$, where t is the time in years relative to January 2012, $A(t)$ is the state’s lit area at time t, and r is the annual rate of lighting increase.

3. Results

The annual rate of change in radiance observed in the 500-900 nm range from the Bundesländer (federal states) are shown in Table 1, Figure 2, and the figures in the appendix. Most Bundesländer increased in both lit area and radiance. In the numerical results that follow, it is important to keep in mind that these are radiances observed from above the atmosphere, not direct measures of the installed luminance. Furthermore, since the time series is relatively short, a fluctuation up or down in the initial or final year due to atmospheric or acquisition parameters can have a large influence on the observed trend.

The state with the greatest rate of change in lit area was Bayern, which increased its lit area by 45% from 2012-2016 (9.7% per year), followed by Schleswig-Holstein with 40% (8.8% per year). In both states, the fit rate of change was considerably smaller, but still far from zero: 23% for Bayern and 25% for Schleswig-Holstein. The same pattern repeated for the radiance of stably lit areas, with Schleswig-Holstein growing the fastest with a 41% increase (8.9% per year), followed by Bayern with 35% (7.9% per year). Thüringen is dramatically different from the other states, with a 18% decrease in lit area (4.9% per year) and 17% decrease in the radiance of stably lit areas (4.5% per year). The numbers reported here are based on the ratio between the starting and ending years. For most states, least squares fitting of the individual monthly datasets returned area rate increases similar to that measured by the ratio (Table 1). The exceptions to this were Mecklenburg-Vorpommern, where the fit returned no increase, as well as in Bayern and Schleswig-Holstein where both methods observed an increase, but of quite different rate as noted above. In most of the Bundesländer, both faint and more moderately lit places have grown in radiance at similar rates (see Appendix). In Bayern and Baden-Württemberg, however, the rate of increase was larger in moderately lit areas than in faintly lit areas.

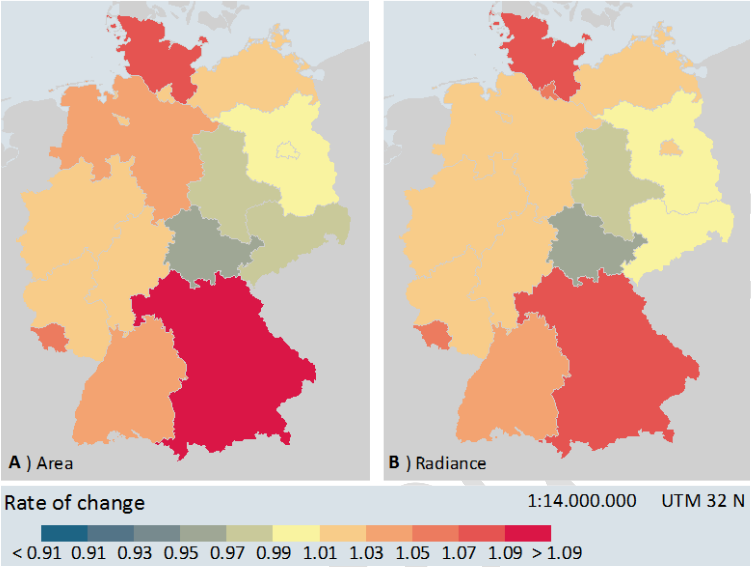

Figure 2: Annualized rate of change in lit area (A) and the radiance of already lit areas (B) from 2012-2016 for the German Bundesländer.

Table 1. Area lit above 3 nW/cm^{2}sr in each year, and the total change in lit area and radiance of lit areas over the 5 year period.

Federal State	Area 2012 (km^2)	Area 2013 (km^2)	Area 2014 (km^2)	Area 2015 (km^2)	Area 2016 (km^2)	Area Change 2012-16 (%) ratio / fit	Radiance change 2012-16 (%) ratio
Baden-Württemberg	2684	2788	2519	3036	3159	18 / 13	15
Bayern	2346	3048	3225	3147	3398	45 / 23	35
Berlin	647	661	649	659	664	2.5 / 1.5	7.4
Brandenburg	981	1003	937	941	983	0.2 / -2.7	2.4
Bremen	248	260	261	266	260	4.7 / 5.8	8.3
Hamburg	471	493	482	504	512	8.8 / 8.5	29
Hessen	1577	1483	1598	1678	1686	7.0 / 5.8	4.6
Mecklenburg-Vorpommern	454	498	464	435	496	9.2 / 0.0	11
Niedersachsen	1541	1460	1763	1690	1743	13 / 12.3	10
Nordrhein-Westfalen	5083	4855	5549	5049	5516	8.5 / 6.5	5.1
Rheinland-Pfalz	1123	1169	1087	1203	1264	13 / 7.4	11
Saarland	308	341	291	369	380	24 / 19	26
Sachsen	1219	1235	1339	1184	1137	-6.7 / -4.2	-2.0
Sachsen-Anhalt	852	845	864	838	813	-4.6 / -6.3	-5.6
Schleswig-Holstein	542	683	661	606	758	40 / 25	41
Thüringen	653	548	598	585	533	-18 / -13	-17

A more detailed view of the change in areas that are lit or unlit is shown in Figure 3. Here, Germany has been divided into near-equal regions of approximately 100 km^2, and the change in area lit above 3 nW/cm^{2}sr within each region is shown. Dramatic increases in upward radiance were observed over a very large area in Bayern (e.g. Fig. 4). While the overall pattern may be related to environmental factors, is also possible that in some cases the changes are due to the replacement of older lamps with LEDs. For example, in the village of Sünching, the entire street lamp system was replaced with LED during 2015-2016 (personal communication with Verwaltungsgemeinschaft Sünching), and the highest radiances in the town were observed at the end of the time series. It should be kept in mind that since the DNB instrument has sensitivity to near infrared light emitted by some high pressure sodium lamps, but no sensitivity to the blue light emitted from LEDs [5], the luminance emitted in such areas has likely increased by a larger factor than was observed in the DNB radiance time series [4]. More detailed plots showing how radiance changed in lit areas are available in the Appendix.

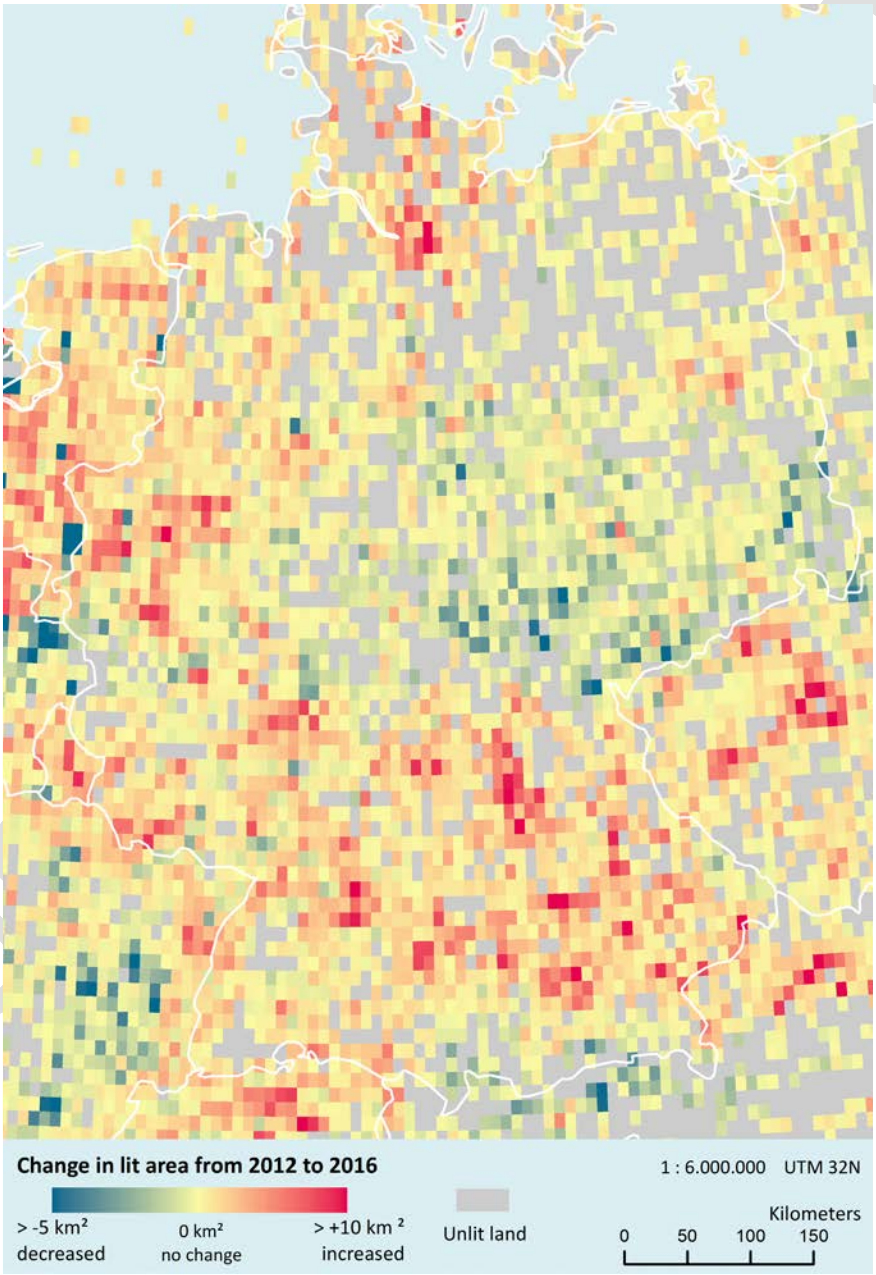

Fig. 3. Locations where lit area changed in Germany. Each pixel has an area near 100 km^2. Lit area increased (up to 19.5 km^2) in the red

areas, and decreased (up to -5.7 km^2) in the blue areas. Note that to for improved visibility, the color scale is twice as steep for increases compared to decreases.

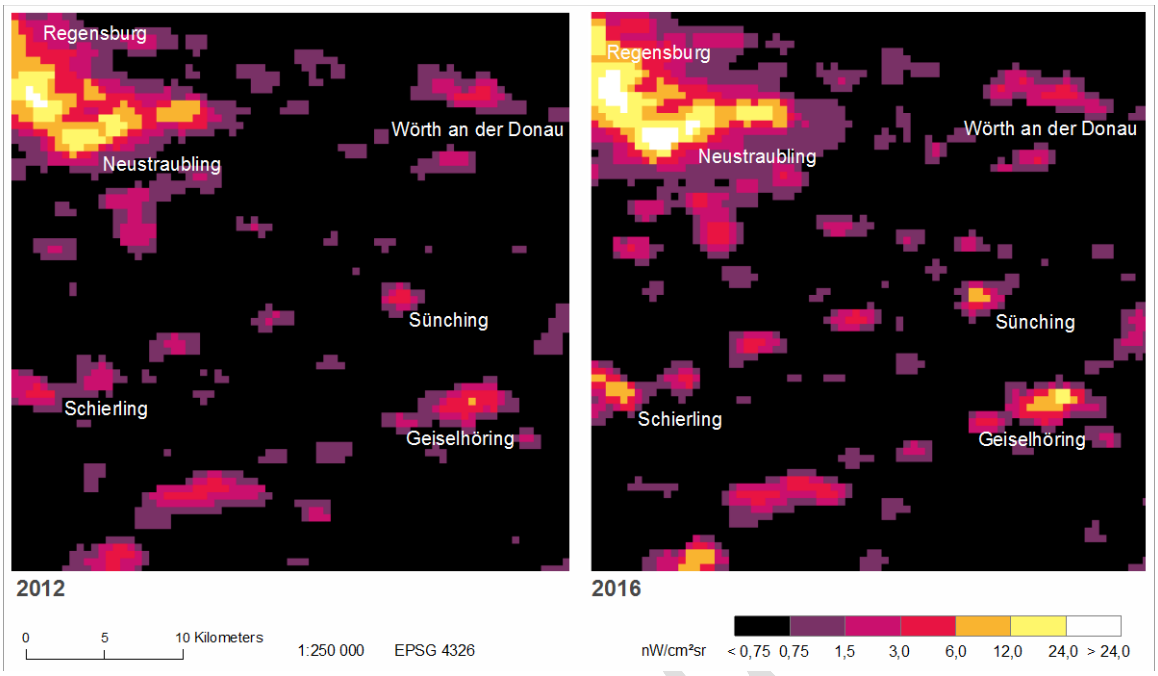

Fig. 4. Light emissions during October 2012 and 2016 from the area of Bayern near the town of Sünching.

Given the geographic patterns in the light changes (Figures 3 and 4), and the variability from year to year (Tab. 1), it is worth questioning whether the observed changes, particularly the rapid increases and decreases in specific states, could potentially be due to an unknown systematic effect in the DNB observations. For example, could the decreases perhaps be due to persistent thin cloud cover in the center of Germany in 2016 but not 2012, or some sort of additional temporary lighting in 2012? One way to evaluate this is to examine the changes observed over the overlapping 3-year periods 2012-2015, and 2013-2016. Real changes to permanently installed lighting that took place during the 2-year period 2013-2015 should be included in both cases, whereas systematic data effects that are specific to a single year should affect only one of the observations. The total 3-year change observed during the overlapping periods (Fig. 5) is well correlated (Pearson's ρ=0.67, p=0.01), consistent with the expectation for real changes in lighting. While the growth rate of each state is not perfectly consistent, the overall trend of increases or decreases in light is consistent in nearly all states.

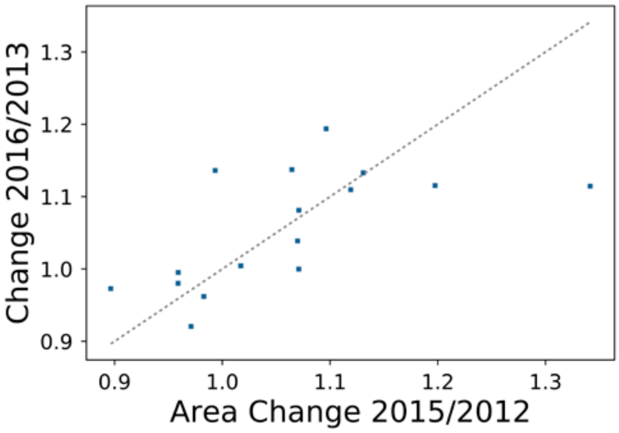

Fig. 5. Changes in the area lit above 3 nW/cm^{2}sr from 2012-2015 compared to the change detected for 2013-2016 for each of the 16 German federal states. The dotted line shows y=x.

4. Discussion

The satellite observations are indicative of large differences in the trends of outdoor light emissions among the German federal states. In some areas, changes in radiance and lit area may perhaps be due to villages and towns transitioning from older lamps to LEDs. The DNB has no sensitivity from 400-500 nm, where white LEDs generally have a blue peak, so the increases observed suggest increases in total visible light emissions. It is not yet known whether the light increases are due to changes in street areas, or perhaps new or brighter lamps for other purposes (e.g. advertising). These data call into question whether the transition to LEDs for outdoor lighting is actually saving much (or any) energy at the state level, due to a rebound effect [7, 10, 11].

We were not able to ascertain the reason for the decreases in light in Thüringen, Sachsen, and Sachsen-Anhalt. One possibility that was suggested to us was deterioration of existing mercury or (to a lesser degree) sodium lighting. Another possibility is transitions to LEDs which preserved the total luminous light output, but reduced the light visible to the satellite sensor. Kyba et al. observed just such an effect for an LED transition in the city, but not surroundings, of Milan, Italy [7]. Understanding of the causes behind lighting changes will require future interdisciplinary collaboration between experts in remote sensing, lighting, and planning.

In many rural areas of Germany, the existing lighting in villages is characterized by low uniformity. Many communities also apply part-night lighting. In some cases the entire village lighting system is turned off after a curfew, while in others some fraction (usually half) of the luminaires are turned off. Since the Suomi NPP satellite that carries the VIIRS sensor has an overpass time after midnight, many or most DNB observations will “undercount” the typical nighttime radiance of such areas. With a conversion to LED, reductions in energy cost could potentially tempt some villages to run the lamps all night. These areas would then appear to have “new” lights in the DNB composite images. Relatedly, a street lighting change that increases uniformity could potentially increase total light emissions, regardless of whether LED or older technologies were used.

Given the low volume of vehicular and pedestrian traffic in many German villages after midnight, it is worth asking whether overhead street lighting with high uniformity is really a sustainable lighting solution. Steinbach et al. examined the lighting practices of 62 local authorities in England and Wales, and found that part night lighting had little to no impact on rates of traffic accident or crime (in fact, there was weak evidence for *decreases* in crime in areas that switched lights off) [12]. Perhaps the lighting needs of smaller German communities could be met through a combination of reflective elements for traffic direction, and way-finding lighting for pedestrians. Both could be accomplished with bollards, and given the small size of many villages, perhaps an on-demand lighting solution could be found.

Green et al. found that most village residents in the UK were either not aware or not concerned when part-time lighting was implemented [13]. However, a major concern of “turning off lights” for a minority of residents was due to the sense of “going backwards”. A lighting approached tailored to the needs of residents and small towns could potentially alleviate such concerns, as the transition could be truthfully marketed as a “modern” lighting solution. Public consultation during such a transition would surely be important to ensure support for the outcome. Rather than representing a failure of disinterested public authorities to provide a public service, perhaps well designed context-specific lighting could indicate a central government’s recognition of the needs specific to such communities. In addition to reducing energy consumption, it is important to note that reduced and more carefully applied lighting would be beneficial for animals (e.g. [14-16]), plants (e.g. [17, 18]), and whole ecosystems (e.g. [19]). The impact of light on insects (e.g. [20, 21]) may be of particular interest in the rural German context, as a recent study observed an approximately 80% decrease in the abundance of flying insects in areas far from German cities [22]. More carefully applied lighting would also reduce skyglow, leading to increased visibility of stars [23, 24]. This may be of particular interest to those living in rural areas, for purposes of increasing astrotourism [25-27].

By the sustainability criterion of using only the minimum amount of light necessary (see discussion in [28]), many or even most areas in cities in wealthy countries are not currently sustainably lit. For example, American cities are 3-5 times brighter per capita than German cities [4]. Since Germany is not dramatically less safe than the USA, this must surely imply that American cities are using considerably more light than is necessary for public safety. In fact, current recommendations by standardization bodies likely fail this simple test for sustainability, as they proscribe light levels well beyond what is necessary for recognizing obstacles and faces. Anyone who has ever experienced a walk through an unlit open area at night under full moonlight will recognize that safely walking can be easily accomplished at levels around 0.1 lux [29]. The same visual task is more challenging if glaring light sources are present (e.g. overly illuminated advertisements). However the problem in that case is not a lack of light, but rather an overly large scene contrast. A sustainable response to the problem would be to limit the glare, not to add additional ambient light. Fotios et al. recently showed that a factor of 20 increase in lighting (from 0.1 to 2 cd/m^2) has almost no impact on reaction times [30], a further indication that it is high time to re-evaluate the evidence base for current norms.

Aerial or space-based remotely sensed data cannot on their own determine whether lighting is sustainable. However, they can inform us of the trends in total emissions, and are useful in comparing cities to one another. If cities are currently overlit, then increases in light emissions observed by remote sensing indicate movement away from sustainability. Future cubesat missions [31] or new camera installations on the International Space Station may potentially provide much higher resolution views, as well as more detailed spectral information. Both of these would be valuable in identifying areas where the lighting appears particularly unsustainable given the context. Finally, we note that it is possible that for the results from remote sensing such as those presented here to be affected to some extent by local systematic effects related to the data acquisition (e.g. for the DNB, large scale weather, combined with the imaging angles used to make the composites). The recent launch of a second VIIRS instrument will help to disentangle environmental from instrumental effects, and NOAA expects the total VIIRS time series to span several decades., The greater the length of time that goes on, the more reliable trends observed from remote sensing will be.

5. Conclusion

The data demonstrate that space-based remote sensing of night lights are able to identify trends in total lighting output at the state level. Most German federal states experienced increases in light emissions from 2012-2016, with two states appearing to decrease in both total radiance and lit area. The observed trends for most states appear to be robust based on comparisons to data from 2013 and 2015, but the satellite data is still new, and further work is necessary to understand the extent to which large-scale environmental conditions could affect the observations. While remotely sensed data cannot replace local examination to determine if installed lighting is sustainable, they are an excellent complimentary tool.

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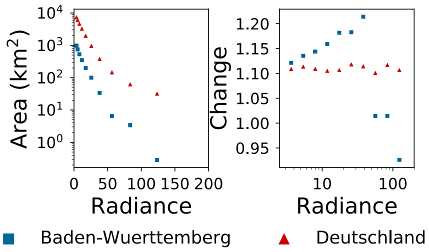
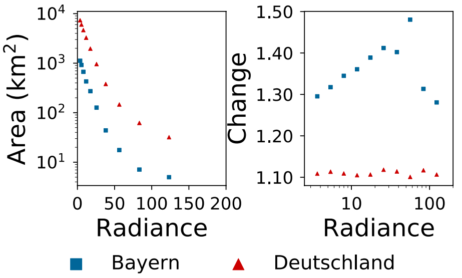
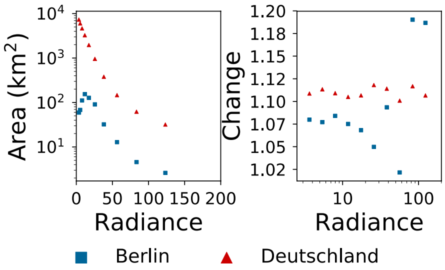
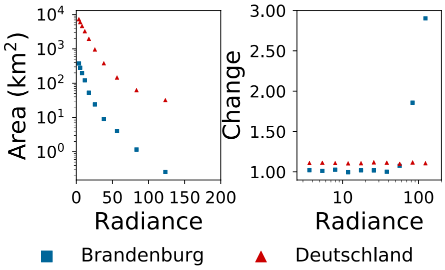
Appendix

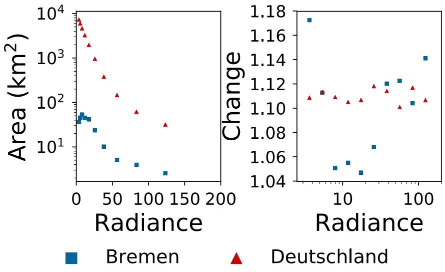
The series of figures below show the lit area for logarithmic bins in radiance (left) and the radiance change from the period 2012-2016 for each German federal state (right). In the case of bins with only a few km^2 area, rates of change are dominated by only a handful of extremely bright pixels, and should be expected to be less stable than averages of tens or hundreds of km^2.

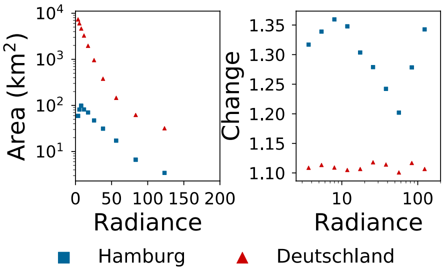


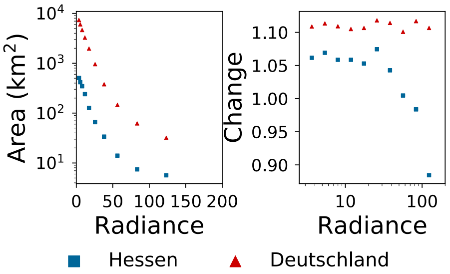


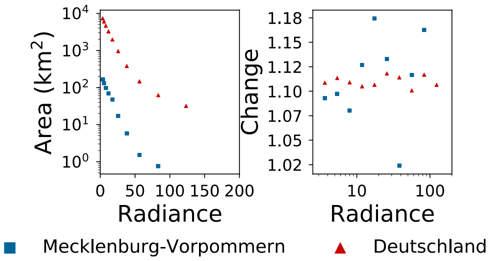


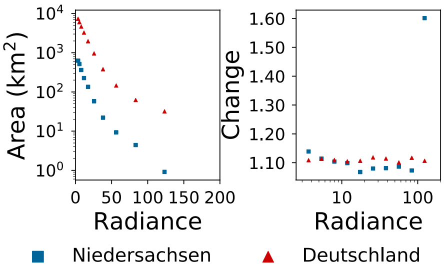


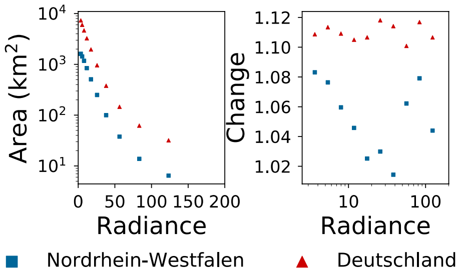


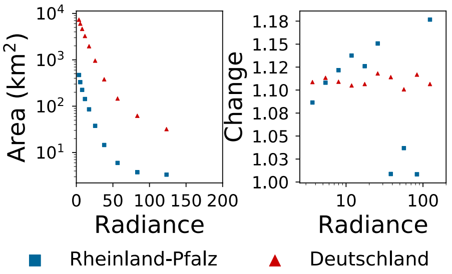


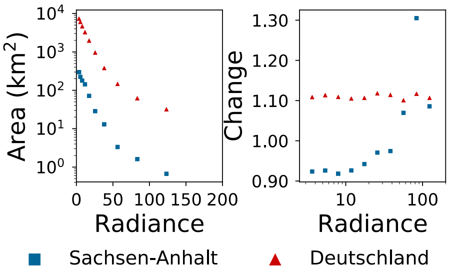


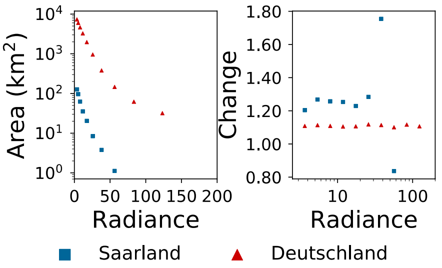


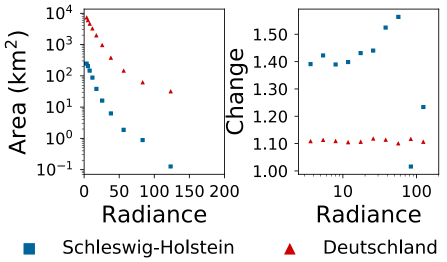


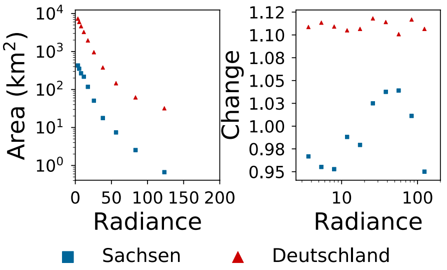


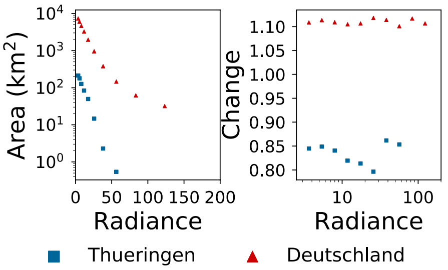

10^4
10^3
10^2
10^1
Area (km^2)
0 50 100 150 200
Radiance
1.18
1.15
1.12
1.10
1.08
1.05
1.03
1.00
Change
10 100
Radiance
■ Rheinland-Pfalz
▲ Deutschland


10^4
10^3
10^2
10^1
10^0
Area (km^2)
0 50 100 150 200
Radiance
1.30
1.20
1.10
1.00
0.90
Change
10 100
Radiance
■ Sachsen-Anhalt
▲ Deutschland


10^4
10^3
10^2
10^1
10^0
Area (km^2)
0 50 100 150 200
Radiance
1.80
1.60
1.40
1.20
1.00
0.80
Change
10 100
Radiance
■ Saarland
▲ Deutschland


10^4
10^3
10^2
10^1
10^0
10^{-1}
Area (km^2)
0 50 100 150 200
Radiance
1.50
1.40
1.30
1.20
1.10
1.00
Change
10 100
Radiance
■ Schleswig-Holstein
▲ Deutschland


10^4
10^3
10^2
10^1
10^0
Area (km^2)
0 50 100 150 200
Radiance
1.12
1.10
1.08
1.05
1.03
1.00
0.98
0.95
Change
10 100
Radiance
■ Sachsen
▲ Deutschland


10^4
10^3
10^2
10^1
10^0
Area (km^2)
0 50 100 150 200
Radiance
1.10
1.05
1.00
0.95
0.90
0.85
0.80
Change
10 100
Radiance
■ Thueringen
▲ Deutschland