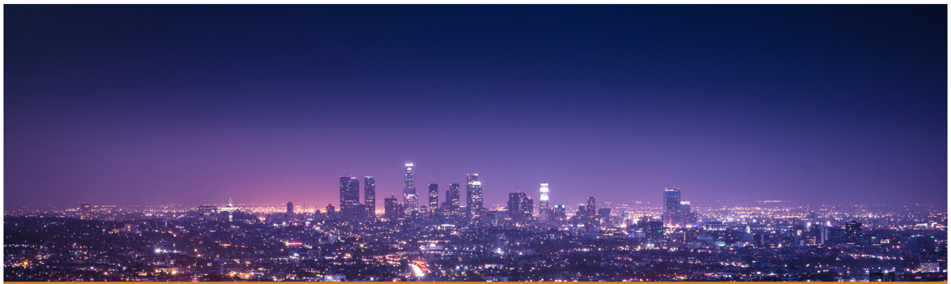

The global increase in light at night points to the urgency of continued improvements in lighting technology, in terms of both efficiency and degree of control.

Light at Night—A Delicate Balance

Response to Kyba et al. 2017, "Artificially lit surface of Earth at night increasing in radiance and extent"

LED street lighting has been in the news a lot recently, but the coverage has sometimes underscored how easy it can be to draw unwarranted conclusions. That's because the issues involved are based on complex science that encompasses everything from spectral power distribution to Lambertian reflectance to melanopic lux, and it's not always a simple matter to get the intertwining strands straight. An important study by Kyba et al. on light at night, published in the November 2017 issue of *Science Advances*, has generated a number of news stories that draw tenuous conclusions about street lighting, which in many cities around the world is being converted from conventional high-pressure sodium (HPS) to energy-efficient LED technology. In brief, the study analyzed global upward radiance data collected via satellite between 2012 and 2016 and found that, on the whole, the Earth is getting brighter at night, especially in less-affluent countries.

Perhaps the most important takeaway from the study is the stark evidence that local populations in many places around the world consider their outdoor lighting inadequate. So it should be neither alarming nor surprising that, thanks in part to the increasing availability and affordability of LED lighting products, such areas are increasingly emerging from the darkness—a trend that is expected to continue. However, rather than signifying waste, this is actually a mark of human progress, with a wide range of benefits.

In addition to the world's developing regions, many developed areas have also increased their output of upward light. And for similar reasons, any conclusions about whether these increases represent excessive use of light or are addressing real needs must take into account a great deal of other data, much of which was not accessed for this study.

Lighting permeates virtually every aspect of our society and is a hallmark of modern civilization. Growth in the global use of lighting—at least to the point where the perceived needs of the local populations are satisfied—is inevitable as long as humans exist on the planet. **This underscores the importance of continued improvement in lighting technology, in terms of both efficiency and degree of control**. Such continued improvements are the best and most equitable means of mitigating any negative aspects of growth in the use of lighting.

Key results of the study

Titled "Artificially lit surface of Earth at night increasing in radiance and extent," the study that appeared in the November 2017 issue of *Science Advances* was conducted by Kyba et al. based on digital data from the Visible Infrared Imaging Radiometer Suite (VIIRS) Day-Night Band (DNB) sensor on Suomi NPP, an Earth-observing satellite of the U.S. National Oceanic and Atmospheric Administration. By documenting nightly light levels over multiple years, the satellite provides a useful time series of observed changes in light radiating from the Earth, which can be parsed into various time periods of interest.

> *"**The study's results were never intended to imply that the continued pursuit of increased efficiency and lowered cost of lighting technology is inappropriate, any more than they meant to imply that increasing the GDP of countries around the world is inappropriate**. These results do suggest, however, that measures to mitigate the negative consequences of wasteful lighting practices are becoming of critical importance as the general growth of lighting of all types continues around the world. **High-performance lighting technology, and the knowledge and will to deploy it appropriately, are the keys to success** in this endeavor."*

The study analyzes data acquired during the five-year period between 2012 and 2016 (inclusive) and discusses the observed data trends. Media coverage of the study[1] reveals some apparent confusion about the findings and what can be appropriately inferred from them. This document is intended as a public response to both the published study and the subsequent media stories and interpretations. In brief, the study found that:

- Overall, the Earth is getting brighter at night, as viewed by satellite radiometry in the spectral band 500-900 nm (referred to as the Day-Night Band, or DNB). Detected radiance increased in many, but not all, geographic areas, and lighted areas generally increased in size.
- The relative magnitude of changes in lighting registered by the satellite was larger in less-affluent countries and smaller, or even flat, in wealthier countries.
- Wide variations were sometimes detected among developed countries of similar economic stature. For example, in the data, Belgian cities appeared dramatically brighter than German cities.

Issues that cannot be resolved from measurements in the Kyba et al. study

- *Origin of the light*. The satellite measurements cannot identify distinct individual contributions from, for example, street lighting, buildings, façade lighting, vehicles, signage and billboards, parking facilities, and gas flares, unless the source is limited to only one or a few possible choices across an isolated area, such as a forest fire or gas flare.
- *Efficiency*. How efficiently the uplight is being generated and used—and conversely, how much is being wasted—cannot be determined.
- *Suitability of current illumination levels*. There is no means of accurately interpreting whether source locations are currently underlighted or overlighted according to their perceived need.
- *Environmental impacts*. Corresponding light pollution or related environmental impact of the measured radiance is a complex function of multiple factors and was not estimated in this study.
- *Drivers of the increased lighting*. Definitive explanations for observed lighting changes in any given area—such as economics, changes in individual wealth, expanding population, land-use changes, and sociopolitical response to conditions (e.g., crime or terrorism)—require independent research that was not conducted for this study.
- *Details of spectral content*. The precise spectrum of the light is unknown, most notably its "blue" content, given the satellite sensor's limited spectral response and inability to measure below 500 nm. This limitation also means there is insufficient information to predict potential health or environmental effects from incremental changes in blue-wavelength content.
- *Ancillary benefits or costs*. Any gains or losses in productivity, safety, or aesthetic considerations associated with the light emission were not investigated.

Before further discussion of these points, it is important to delineate facts related to light that reaches the satellite, and inferences that can be reasonably made from those facts.

Facts

- The satellite primarily sees light traveling upward at relatively steep (i.e., near-vertical) angles, and only in the 500-900 nm spectral range.
  - Near-horizontal light is not directly observed by the satellite.
  - Because of its diffuse nature, increased brightness of the sky within the atmosphere—or sky glow—contributes to the light observed by the satellite, but to such a small degree (corresponding to only the near-vertical component) that it makes an irrelevant contribution in most lighted areas. The measured uplight in this study is therefore not a measure of sky glow.
  - As observed by the satellite, direct uplight has much more impact than light reflected from a surface, having avoided absorption and diffusion by that surface. A typically assumed ground reflectance (albedo) in atmospheric modeling is 15%, meaning 85% of the incident or direct beam is absorbed and 15% is reflected in an assumed Lambertian distribution. The amount of light reflecting in

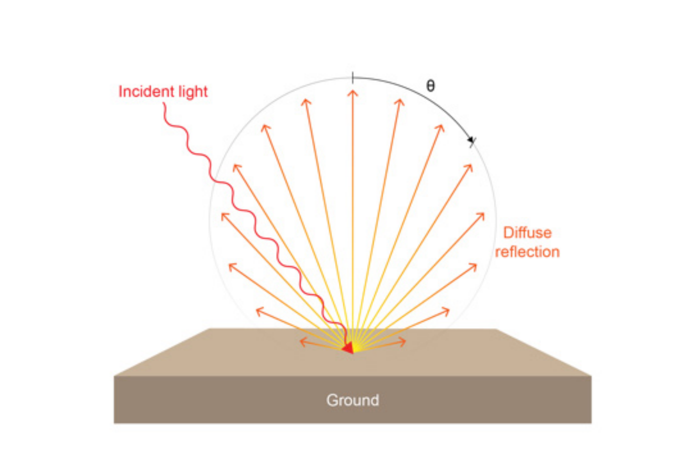

Figure 1. Reflection from a horizontal Lambertian surface.

[1] See, for example, The Washington Post, USA Today, National Public Radio, LA Times, Sky and Telescope.

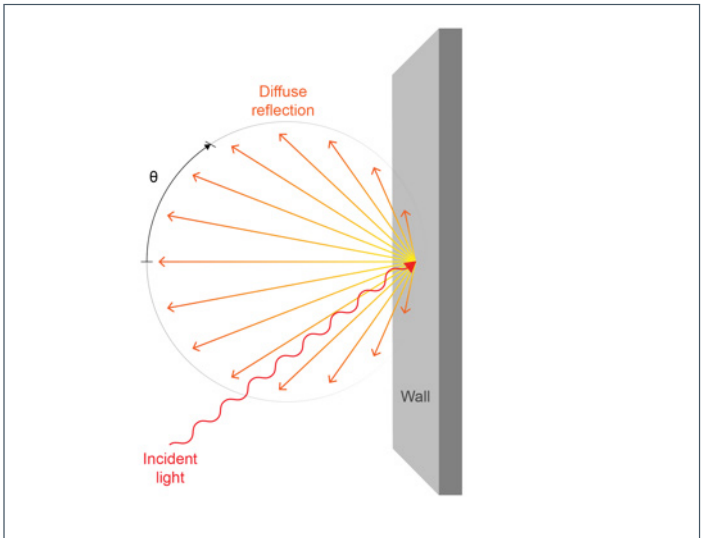

Figure 2. Reflection from a vertical Lambertian surface.

any given direction from that surface is proportional to the cosine of its angle from a line drawn perpendicular to the surface (depicted as the angle Θ in Figure 1), meaning that more light is reflected at angles near-perpendicular to the surface than parallel to it.

- Reflected light from building façades influences the satellite measurements differently than reflected light from the ground, due to the different geometry. Given the assumption of a Lambertian reflecting surface, this means significantly less total reflection at near-vertical angles than at angles perpendicular to the surface (Figure 2). The majority of the light reflected by a vertical façade is directed to generally more-horizontal angles that are significant contributors to sky glow (and that, again, were not observed by the satellite).

- Lighted area is increasing globally and in most countries, but an increase was not observed in some locations—such as the U.S., where overall upward radiance levels remained constant over the period studied.
- Globally, areas already lighted in 2012 tended to get brighter. In the U.S., on average, dim places became a bit dimmer and bright places became a bit brighter (with much variation in each category).
- Globally, many cities are converting their streetlights to LED.
  - Even if roadway-reflected luminances were held constant in transition from HPS to white LED, logically such places would appear to have darkened in the DNB data, due to the noted measurement limitations below 500 nm. However, other factors also apply (see the Roadway Illumination sidebar).
  - Such a darkening was observed in many cities that have switched to white LED streetlights.

Possible inferences from the facts

- Most countries appear to be increasing their amounts of installed lighting.
- In the U.S., if total upward radiance appears constant, but cities switching to LEDs would logically appear darker to the satellite, then there must be new light sources/additional lighting making up the difference.
- The overall lighted area in the U.S. did not appear to change, so changes in upward radiance around the nation must be originating from within existing lighted areas. There is either a higher density of LED street lighting compared to the former HPS streetlights (less likely) or an increase in lighted areas of non-street-lighting sources such as parking lots, billboards, security lighting, sports arenas, infill development, and park and landscape lighting (more likely).
- Globally, energy use of new lighting installations may be growing faster than the energy savings achieved by LED conversion of older installations. (This cannot be measured directly by the satellite, but can be inferred from the measured results.) Such a trend could be facilitated by such factors as lower costs of lighting, increasing wealth within a community, and population growth.

Discussion

Much of the following discussion pertains to the U.S., but situations can differ widely among countries.

The average annual global increase in upward radiance from 2012 to 2016 reported in the Kyba et al. study was 2.2%, with wide variation among individual countries or regions—for example, the U.S. was reported as having no observable change overall, whereas Bolivia increased by 32%. A variety of possible explanations can be posited for the changes observed or lack thereof, but the measurements themselves cannot pinpoint which of these specifically apply, or to what extent.

In the U.S., converting municipal street and outdoor lighting from HPS and other sources to LED has unequivocally reduced energy use on both a per-luminaire basis and a national basis.[2] However, the Kyba et al. study notes that, globally, energy savings from one application, such as street lighting, may have been partially or fully offset by growth of lighting in that and other applications; and from the satellite's 2.7-million-foot

2 LEDs reached a cumulatively installed penetration of 28.3% of the estimated 44.1 million street and roadway lights in the U.S. in 2016, saving about 15 trillion Btu of source energy in that year, according to the DOE report *Adoption of Light-Emitting Diodes in Common Lighting Applications*, July 2017.

Roadway Illumination

Roadway lighting design is partly driven by meeting specified metrics of illumination everywhere within the target area. Because bulb-based technologies require substantial reshaping of their 360° initial light output to fit that area, precise control over their distribution is difficult and can result in "hot spots," significant light trespass, and other visible issues in a typical installation (see Figure 3). Together, these issues translate into much excess lighting and waste.

In contrast, the light distributions from LED products are more easily tailored to deliver the target illumination level more evenly across the lighted area. Correct design using LEDs typically means less overlighting and a significantly lower average illuminance across the target space (Figure 4).

Benefits of LEDs are not just about lumens per watt; improved optical performance brings benefits, too.

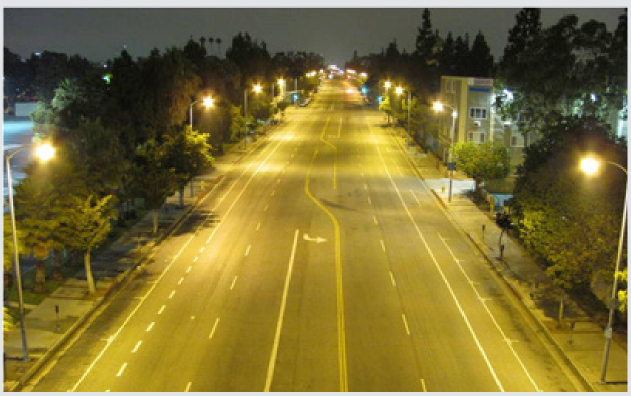

Figure 3. Visible non-uniformities characterize illumination from HPS and other bulb-based products.

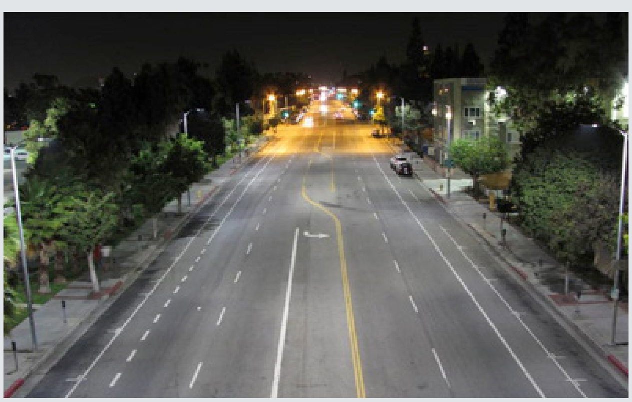

Figure 4. The capability for improved optical control and more-uniform distribution is clearly visible after conversion to LED. *Photos: LABSL*

view (i.e., across country borders, with all light sources combined), that may well be true. However, this potential realization in no way detracts from the savings achieved by converting U.S. street lighting to LED, nor from the merit that continues to exist in the pursuit of additional LED conversions and improvements in the U.S. or anywhere else.

In fact, the goals of **increased efficiency and judicious use of light have become doubly important**, as the observed trend of growth is likely to continue, given that many areas of the world remain significantly beneath demand saturation even for basic lighting services—in particular, developing countries and those with rapidly shifting populations.[3] New lighting in areas on the outskirts of cities and towns may arise when these areas are newly populated and exterior lighting is desired for easier nighttime travel, commerce, and perceived safety. Continued development within existing city boundaries is likely to have a similar result. This trend does not automatically mean that the new lighting is wasteful or inefficient. Rather, increasing use of electric light is an inevitable byproduct of increased population and its aggregation in urban environments, combined with GDP growth that makes lighting more affordable to a greater number of that population. A valid alternative perspective is that **increased efficacy of the light sources has allowed many previously deprived areas to obtain the benefits of lighting, while holding energy use constant** (or at a tempered rate of increase).

The VIIRS sensor picks up an amalgamation of all light sources (including non-electric sources such as gas flares or forest fires), and does not "see" almost a third of the visible spectrum, corresponding to wavelengths shorter than 500 nm, which include all "blue" wavelengths that have been the source of much recent discussion. Levels of increase or decrease of these wavelengths in the night sky were not measured in this study and thus technically remain unknown.

Moreover, the satellite primarily sees light directed upward at a relatively steep (i.e., near-vertical) angle. This means that light traveling at a low angle of elevation above the horizon—such as that emitted from a dropped-lens cobrahead fixture or emitted or reflected from a building, for example—goes largely unnoticed except for the relatively small portion ultimately scattered in a near-vertical direction that successfully exits through the top of the atmosphere. Light emitted at an angle just above the horizontal plane is generally the most effective for increasing the brightness of the sky within the Earth's atmosphere (i.e., sky glow), due to its having the longest travel path through the atmosphere and hence the largest opportunity to be scattered. One consequence of not being able to measure such light is

3 See, for example, this Energy Access Outlook 2017 page from the International Energy Agency.

that a primary component of the contribution to sky glow from the installed base of HPS fixtures in 2012 was not documented. Thus, any decreases in sky glow gained by replacing those cobrahead fixtures with 0%-uplight LED luminaires was missed, and these can be substantial.[4] Conversely, the inability to detect sky glow from this data could also mean that, from a ground-based perspective, any given area might actually be brighter than the satellite measurements indicate. This caveat especially applies to areas continuing to install dropped-lens fixtures using traditional lighting sources, or anything else with a high horizontal component, since horizontal emissions and associated sky glow are not being measured.

For this reason, the 2017 *Science Advances* paper did not address or claim to address changes in sky glow. The DNB observations are downward-facing and primarily detect upward-traveling light that has penetrated the atmosphere on its way into outer space. Mathematical post-estimations of related levels of sky glow were not performed in the study, and in fact would be significantly complicated by the missing range of wavelengths below 500 nm, which is the part of the visible spectrum most scattered in the Earth's atmosphere.

Similarly, the study did not directly measure light pollution, which includes sky glow but also other issues such as glare and light trespass. These are ground-based effects and thus occur independently of the light reaching the satellite position. As a result, conclusions regarding increased light pollution can only be speculative, making the assumption that such increases generally accompany increased uses of light.

Conclusions

All anthropogenic-based sources of light are by definition "unnatural" and thus, while offering numerous benefits to society, also bring potentially undesirable effects. Some of these effects are unavoidable. We need light to reflect off of objects in order for us to see them; that some of this light winds up in the night sky and ultimately in outer space is an inevitable consequence of our unnatural lighting of objects of all types. The more the global population as a whole raises its standards of living to approach those of developed countries, the more such light is likely to appear in the night sky from all regions of the world.

What can and should be addressed, however, is whether the amount of light that is genuinely needed is being appropriately delivered. Excess lighting should be avoided, as should poorly designed lighting systems that send light in unproductive or even harmful directions. Such systems are wasteful at best and may potentially be much more problematic with respect to their effects not only on human health, but also on the health and well-being of non-human species (both flora and fauna). Adherence to the principles of good lighting design helps mitigate much of this negative potential.

The increased levels of light leaving Earth undoubtedly contain much of both types: a portion that is an inevitable result of lighting our environment (including interior and exterior applications and vehicular and non-electric light sources), and another portion that represents waste. The relative contributions of each type cannot be independently determined from the measurements in the Kyba et al. study.

It must also be acknowledged that no single source or lighting end-use is solely responsible for light at night, and this fact fundamentally underlies the study's findings of continued growth. All sources of light exposed to the exterior environment contribute to what the satellite detects. Such sources are present throughout all sectors of the economy, including residential, commercial, industrial, and transportation applications. In addition, as individual end-uses transition to lighting sources offering better quality and improved control, the relative contributions of each end-use (and hence their significance in future discussions of this type) will shift over time.

Finally, and perhaps most importantly, **the study's results were never intended to imply that the continued pursuit of increased efficiency and lowered cost of lighting technology is inappropriate, any more than they meant to imply that increasing the GDP of countries around the world is inappropriate**. These results do suggest, however, that measures to mitigate the negative consequences of wasteful lighting practices are becoming of critical importance as the general growth of lighting of all types continues around the world. **High-performance lighting technology, and the knowledge and will to deploy it appropriately, are the keys to success** in this endeavor. ■

The authors would like to gratefully acknowledge the thoughtful assistance of Dr. Christopher Kyba in the review and preparation of this response document.

4 For example, see the DOE Investigation of LED Street Lighting's Impact on Sky Glow.

Authors:

Kinzey, Bruce R. and Naomi J. Miller,
Pacific Northwest National Laboratory

U.S. DEPARTMENT OF ENERGY BATTELLE

For more information, visit:
ssl.energy.gov

PNNL-SA-131714 • March 2018