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Night lights from space: potential of SDGSAT-1 for ecological applications

Dominique Weber[1], Janine Bolliger[1], Klaus Ecker[1], Claude Fischer[2], Christian Ginzler[1], Martin M. Gossner[1,3], Laurent Huber[2], Martin K. Obrist[1], Florian Zellweger[1] & Noam Levin[4,5]

[1]Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Zürcherstrasse 111, 8903, Birmensdorf, Switzerland
[2]Geneva School of Engineering, Architecture and Landscape – HEPIA, University of Applied Sciences and Arts Western Switzerland, Route de Presinge 150, 1254, Jussy, Switzerland
[3]Department of Environmental Systems Science, Institute of Terrestrial Ecosystems, ETH Zürich, Universitätstrasse 16, 8902, Zürich, Switzerland
[4]Department of Geography, The Hebrew University of Jerusalem, Mount Scopus, 91905, Jerusalem, Israel
[5]Earth Observation Research Center, School of Earth and Environmental Sciences, University of Queensland, St Lucia, 4072, Saint Lucia, Queensland, Australia

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Correspondence
Dominique Weber, Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Zürcherstrasse 111, 8903 Birmensdorf, Switzerland. Tel: +41447392342; Email: dominique.weber@wsl.ch

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Abstract

Light pollution affects biodiversity at all levels, from genes to ecosystems, and improved monitoring and research is needed to better assess its various ecological impacts. Here, we review the current contribution of night-time satellites to ecological applications and elaborate on the potential value of the Glimmer sensor onboard the Chinese Sustainable Development Goals Science Satellite 1 (SDGSAT-1), a novel medium-resolution and multispectral sensor, for quantifying artificial light at night (ALAN). Due to their coarse spatial, spectral or temporal resolution, most of the currently used space-borne sensors are limited in their contribution to assessments of light pollution at multiple scales and of the ecological and conservation-relevant effects of ALAN. SDGSAT-1 now offers new opportunities to map the variability in light intensity and spectra at finer spatial resolution, providing the means to disentangle and characterize different sources of ALAN, and to relate ALAN to local environmental parameters, in situ measurements and surveys. Monitoring direct light emissions at 10–40 m spatial resolution enables scientists to better understand the origins and impacts of light pollution on sensitive species and ecosystems, and assists practitioners in implementing local conservation measures. We demonstrate some key ecological applications of SDGSAT-1, such as quantifying the exposure of protected areas to light pollution, assessing wildlife corridors and dark refuges in urban areas, and modelling the visibility of light sources to animals. We conclude that SDGSAT-1, and possibly similar future satellite missions, will significantly advance ecological light pollution research to better understand the environmental impacts of light pollution and to devise strategies to mitigate them.

Introduction

Light pollution has increased dramatically in the last decades and has become a global threat to biodiversity (Koen et al., 2018; Kyba et al., 2017; Sánchez De Miguel, Bennie, et al., 2021). Artificial light at night (ALAN) affects organisms in terrestrial and aquatic ecosystems in various, often detrimental ways. By disrupting circadian rhythms, ALAN can disturb physiological processes and alter the behaviour of nocturnal species, reducing their foraging ability and increasing predation risk (Knop et al., 2017; Luo et al., 2021). By increasing collisions with artificial light sources and reducing fertilization success, ALAN can also increase mortality and decrease reproductive success (Touzot et al., 2020; Van Doren et al., 2021). Moreover, ALAN has been shown to negatively affect migratory species that rely on natural light sources, such as the moon and stars, for navigation (Burt et al., 2023). These effects can vary widely among interacting species, causing mismatches and novel interactions that are likely to affect ecosystem functions and services. For example, there is strong evidence that ALAN negatively affects pollination (Knop et al., 2017), with negative consequences for plant reproductive success, and alters arthropod communities (Van Koppenhagen et al., 2024), which may have cascading effects on animals that feed on insects, such as bats and birds (Boyes et al., 2021; Knop et al., 2017; Rich & Longcore, 2006).

Despite the mounting evidence of the negative ecological impacts of ALAN, we still lack suitable tools and capabilities for assessing and monitoring ALAN at ecologically relevant scales (Hölker et al., 2021; Linares Arroyo et al., 2024). Reasons for this include that light pollution is difficult to quantify, due to the multifaceted character of ALAN, the complex spatial distribution of ALAN scattered in the atmosphere, and the lack of standardized measurement methods (Hölker et al., 2021). Night lights can be measured in various ways, i.e. on the ground with dedicated instruments or consumer-grade cameras (Hänel et al., 2018), or by remote sensing using unmanned aerial vehicles (UAVs), aircraft or satellites (Levin et al., 2020; Linares Arroyo et al., 2024; Mander et al., 2023). Regardless of the limitations of the current space-borne remote sensing options (Linares Arroyo et al., 2024), this approach is the most effective method to capture the spatio-temporal dynamics of ALAN over large areas (Barentine et al., 2021). Satellite radiometers have been successfully used to quantify night sky brightness (Falchi et al., 2016) and to assess the exposure of protected terrestrial (Gaston et al., 2015) and marine (Davies et al., 2016) areas to light pollution globally at coarse spatial resolution. However, such measurements of night lights at the landscape level cannot be used to disentangle different sources of ALAN or to study their relationships with local environmental parameters and features, including small habitats like rivers or ponds (Jechow & Hölker, 2019). To better evaluate how species respond to ALAN, more detailed maps are needed to consider, for example, a species' range of activity or the visibility of light sources in a complex urban environment (Bennie et al., 2014). Organisms living in or close to urban environments are exposed to highly heterogeneous lighting conditions. Dark and brightly lit areas can alternate within a few metres and are influenced by shading from topography, buildings and vegetation (Bennie et al., 2014). Further variations throughout the night and year result from the turning on and off of lights, seasonality of vegetation and snow, and of cloud cover (Levin, 2017). Mapping these fine-scale variations in lighting is crucial for preserving and restoring dark habitats and establishing networks of nocturnal corridors for biodiversity, but this approach has been largely ignored in conservation strategies due to a lack of suitable data (Sordello et al., 2022). Moreover, information on the spectral composition of ALAN is needed to consider the effects of different colours of artificial light on the visual ecology of organisms (Seymoure et al., 2019). A recent compendium of spectral response curves suggests that shorter wavelengths should be reduced to mitigate adverse ecological impacts on many species while maintaining human visual performance (Longcore, 2023). This is consistent with experimental studies showing, for example, the pronounced negative effects of blue light on insects (Deichmann et al., 2021). However, the spectral sensitivity of organisms and their biological response are highly variable, making it difficult to derive species-specific thresholds (Jägerbrand & Bouroussis, 2021). Despite the urgent and long-standing call from researchers for novel night-light satellite missions (Barentine et al., 2021; Elvidge et al., 2007; Kyba et al., 2024), night-time remote sensing lags far behind daytime remote sensing (Levin et al., 2020). Accordingly, two fundamental shortcomings of the existing freely, consistently and globally available earth observation data on night lights are the limited spatial resolution (0.75–3 km px^{-1}) and the lack of spectral information with traditional panchromatic space-borne sensors (Barentine et al., 2021).

Recently, data from a multispectral sensor onboard the Chinese Sustainable Development Goals Science Satellite 1 (SDGSAT-1) have become available, providing a great improvement in spatial resolution and spectral detail (Guo, Dou, et al., 2023). These developments mean it is now possible to detect ALAN at unprecedented temporal and spatial scales. Several studies have already shown the great potential of this new data source in various research fields (Chen et al., 2024; Guo, Hu, & Zheng, 2023; Jia et al., 2024; Levin, 2023; Lin et al., 2023; Liu et al., 2024), but it has hardly been applied to ecology and conservation (but see Levin et al., 2024; Wang et al., 2025). It is now time to test and integrate these new data streams to improve our understanding of the ecological effects of ALAN and to help derive management strategies to alleviate the problem.

In this perspective paper, we provide an overview of recent developments in space-borne sensors and elaborate on the potentially high value of SDGSAT-1 for ecological applications. We further discuss shortcomings that need to be resolved and identify promising avenues for sound ecological impact assessments of ALAN on ecosystems using space-borne remote sensing.

Current State of and Recent Developments in Space-Borne Night-Light Sensors

ALAN alters the spatial, spectral, temporal and directional components of night-time light regimes (Gaston et al., 2013). These four dimensions are key characteristics for monitoring light pollution and are crucial for both the design and use of appropriate measurement technology. Remote sensing offers a variety of platforms, sensors and operating modes that facilitate the collection of such information at night (Levin et al., 2020). Optical sensors are typically used to measure night light in the visible spectral range, i.e. light emitted from luminaires designed to enhance human vision after sunset. Additional bands that are also useful in this regard are a near-infrared band, which can help characterize some lighting types, such as high-pressure sodium lights, and a thermal band, which can assist in identifying clouds that mask light sources, as well as fires and gas flares based on their temperature (Barentine et al., 2021; De Meester & Storch, 2020). Efforts to quantify light pollution over large areas and to investigate its ecological impacts over time at a coarse spatial resolution have benefited greatly from dedicated satellite missions. The digital archives of the two panchromatic sensors DMSP-OLS (1992–2013) and VIIRS-DNB (initiated in 2012) provide access to global annual night-time imagery for the last three decades, as well as monthly and nightly night-time mosaics for the last decade (Levin et al., 2020). The VIIRS sensor onboard the Suomi NPP satellite is still operating and regularly measures nocturnal visible and near-infrared light in the spectral range of 0.5 to 0.9 μm with a spatial resolution of 742 m, provided as the day and night band (DNB). VIIRS-DNB is a large improvement over DMSP-OLS (3 km px^{-1}). The higher spatial resolution, improved dynamic range, and better calibration are fully exploited by an advanced processing chain used to provide high-quality and freely available standard products (Elvidge et al., 2013; Román et al., 2018). It is an indispensable source for global monitoring of ALAN and has significantly shaped our knowledge and awareness of this environmental pollutant (Kyba et al., 2017). In recent years, there has also been increased availability of multispectral imaging of the Earth at night from space (Kyba et al., 2015). The first source of colour images is photographs taken by astronauts onboard the International Space Station, starting in the early 2000s (Levin et al., 2020). While such images offer a spatial resolution that may reach 10–20 m (Sánchez De Miguel et al., 2019), their global and temporal coverage is patchy (Levin et al., 2020) and their calibration involves a complex process (Sánchez De Miguel, Zamorano, et al., 2021). An additional source of multispectral night-light imagery from space is the commercial Chinese Jilin-1 satellites, offering a spatial resolution finer than 1 m (Zheng et al., 2018). However, commercial imagery is not regularly acquired and is expensive to purchase. Additional sources of multispectral night-time imaging include high-altitude balloons (Aubé et al., 2023), aerial campaigns (Hale et al., 2013) and drones (Li et al., 2020), but these options provide limited spatial and temporal coverage and are dependent on dedicated campaigns.

In contrast to daytime remote sensing, night-time observations from space have mostly remained at a coarse spatial resolution (>250 m). This means that important small-scale aspects and spectral variations within landscapes that are relevant to environmental science, management and policies related to conservation actions (e.g. mapping of built areas, green and blue corridors), which can be successfully derived from daytime optical sensors such as those onboard Landsat and Sentinel-2 missions (Radeloff et al., 2024), can hardly be assessed at night (e.g. the layout of dark corridors). However, the first medium-resolution night-time satellite mission dedicated to science has recently become operational. SDGSAT-1 has a swath width of 300 km and is equipped with three sensors – a thermal infrared spectrometer, a glimmer imager (GLI), and a multispectral imager – to collect different day- and night-time remote sensing data on an 11-day revisit cycle (Guo, Dou, et al., 2023). The GLI is a multispectral sensor designed for measurements under low-light conditions, with three spectral bands at 40 m resolution (blue: 424–526 nm, green: 505–612 nm, red [also covering the near infrared]: 600–894 nm) and a panchromatic band at 10 m resolution (444–910 nm). Images are taken early at night, at around 21:30, when most of the lights are turned on. SDGSAT-1 has the potential to advance light pollution monitoring by fulfilling several of the recently evaluated requirements for new night-time satellite missions (Barentine et al., 2021). The SDGSAT-1 meets the proposed spatial resolution of 10 m px^{-1}, covers a large part of the suggested spectral range (370–870 nm), and allows the discrimination of three spectral bands. Compared with VIIRS (daily revisit), the temporal resolution of SDGSAT-1 is lower (11-day revisit), but the minimum requirements formulated by Barentine et al. (2021) of monthly revisits and global coverage can be met (although the SDGSAT-1 GLI does not acquire images over most of South America, and it does not acquire imagery regularly). SDGSAT-1's early-night overpass covers the peak time of ALAN better than VIIRS, which collects data after midnight. However, as acquisition times are static, the variability in light during the night cannot be assessed, and twilight illumination inhibits acquisitions during summertime in mid to high latitudes. Given that SDGSAT-1 does not acquire images on every overpass, the spatial and temporal coverage it offers vary between regions. First studies have demonstrated SDGSAT-1's ability to quantify the local variability in light intensity and spectra (Guo, Hu, & Zheng, 2023;

Levin, 2023), making it possible, for example, to distinguish among different light source types on the ground (Jia et al., 2024; Liu et al., 2024).

As illustrated in Figure 1, the higher spatial resolution of SDGSAT-1 enables assessments of small-scale variability in light intensity that is not captured by VIIRS. This provides information directly related to artificial light sources whose light is emitted or reflected upwards and facilitates linkages to local environmental parameters such as land cover, land use and habitat type. For example, light-sensitive habitats at the transitions between adjacent natural and urban landscapes can be identified, along with 'dark refuges' within cities.

In addition to evaluations of light intensity (Bolliger, Hennet, Wermelinger, Bösch, et al., 2020), assessments of the impacts of the spectral composition of ALAN have become increasingly important with the transition from former lighting technologies (such as high-pressure sodium, HPS) to light-emitting diode (LED) technology, both indoors and outdoors (Bolliger et al., 2022; Van Koppenhagen et al., 2024). VIIRS-DNB measurements, which are currently the main source for monitoring light pollution, are subject to large uncertainties due to the 'blue blindness' of the sensor (Sánchez De Miguel, Bennie, et al., 2021). With three spectral bands at 40 m spatial resolution, SDGSAT-1 could improve this situation by capturing the spectral variability in ALAN caused, for example, by the light emitted from different types of street lighting (Fig. 2). Our comparison with ground measurements collected with the LANcube V2

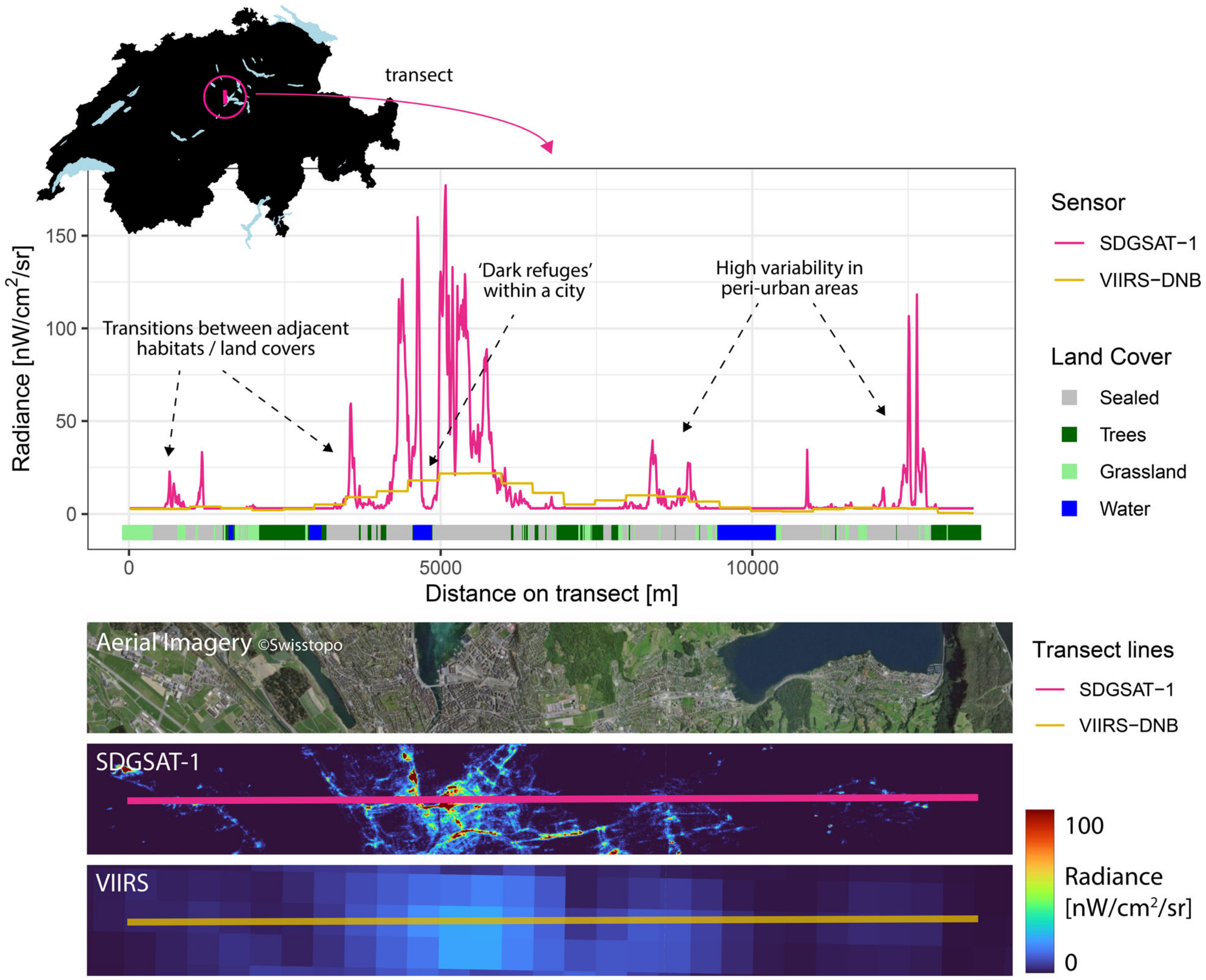

Figure 1. Light intensities along a transect through the city of Lucerne (Switzerland), demonstrating the high spatial variability recorded by the SDGSAT-1 GLI (median panchromatic radiance for2023/2024) compared with that from VIIRS-DNB (2020), and its linkage to local and ecologically relevant parameters such as land cover (CLC + Backbone 2021; European Environment Agency, 2024).

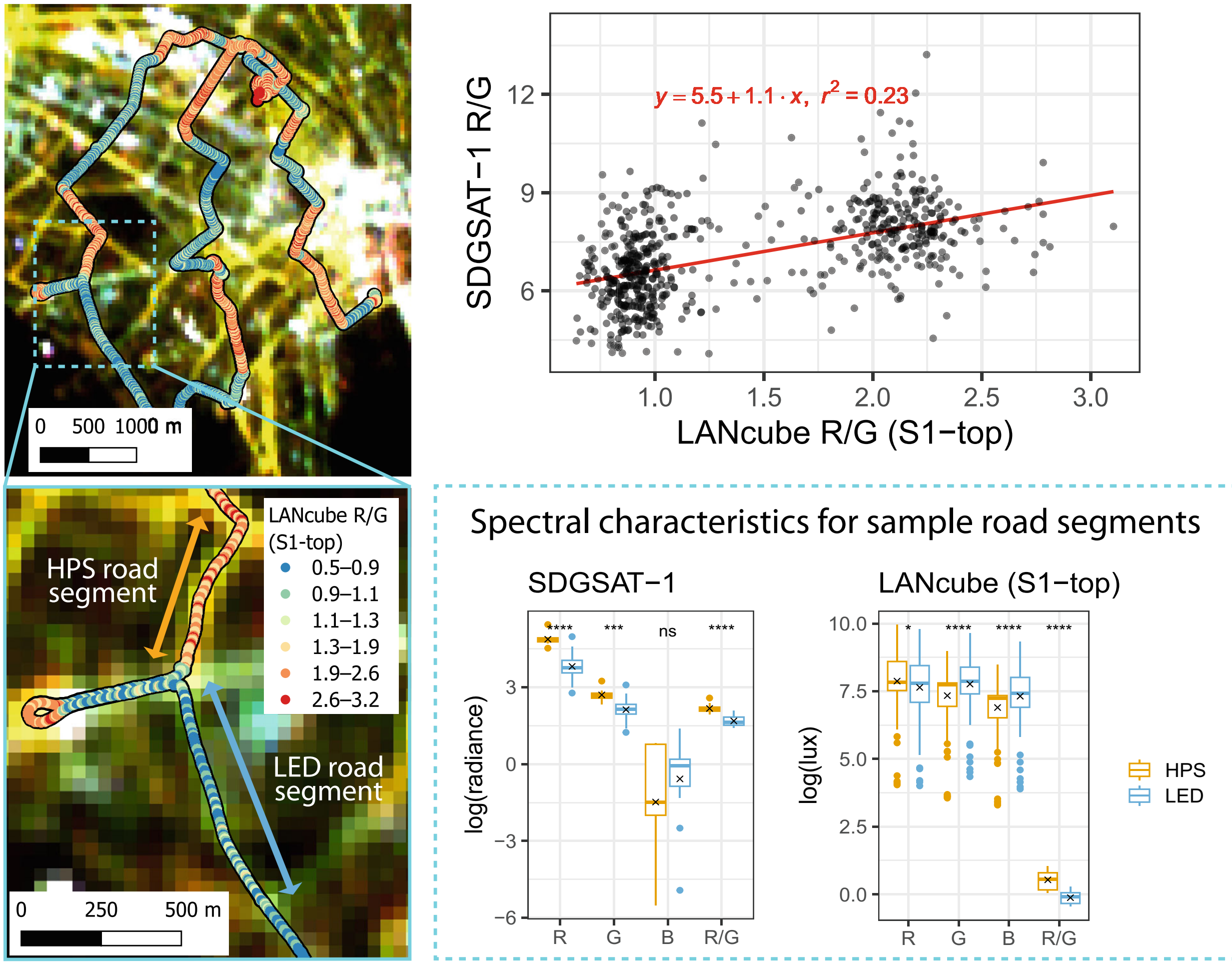

Figure 2. The spectral characteristics (RGB and red/green [R/G] band ratios) of SDGSAT-1 (median radiance composite for 2023/2024) are compared with ground measurements taken in 2024 with the LANcube V2 photometer (Aubé et al., 2020) in Zurich (Switzerland), demonstrating the potential and limitations of SDGSAT-1 for assessing the spectral composition of artificial light at night (ALAN) caused, for example, by different street lighting technologies (HPS vs. LED). Streets with different types of lighting can be distinguished by SDGSAT-1, but the differences are less clear than those derived from ground measurements. Statistical differences based on Wilcoxon Rank Sum test are denoted as follows: ns: $P > 0.05$, $^{*}P \leq 0.05$, $^{***}P \leq 0.001$, $^{****}P \leq 0.0001$.

photometer (Aubé et al., 2020) confirms that LANcube and SDGSAT-1 have similar spectral patterns, enabling us to distinguish between streets in the city of Zurich (Switzerland) that are lit with different lighting types, e.g. using the red/green (R/G) band ratio. The R/G ratio is a simple indicator that can be used to distinguish between LED and HPS lamps (Labrousse et al., 2025; Sánchez De Miguel et al., 2022). Such band ratios and other spectral indices (Jia et al., 2024) could assist, for example, to identify 'whiter' or blue-rich lighting technologies (e.g. white/blue LEDs) that are likely to have pronounced negative environmental impacts (Deichmann et al., 2021; Gaston et al., 2012; Longcore et al., 2018). However, this distinction is clearer in our ground measurements (taken in the upwards direction) than in SDGSAT-1 pixels (observing downwards) for several reasons, such as atmospheric scattering, the medium pixel size of SDGSAT-1, and the multiple sources of artificial light that are mixed within a single pixel (Levin, 2023). Furthermore, the proportion of blue light recorded by SDGSAT-1 is much lower than that from LANcube ground measurements (Fig. 2), probably due to the downward scattering of much of the blue light (Kocifaj, 2018). Above, we have emphasized the high relevance of fine-scale maps of light intensity and spectra to capture the landscape-level heterogeneity of ALAN. In the following sections, we explore three example applications for ecology and conservation using SDGSAT-1 data.

New Perspectives for Ecological Applications

The fine-scale spatio-temporal monitoring of ALAN derived from novel space-borne sensor technologies opens new avenues for basic and applied ecology. In the following sections, we elaborate on some of these opportunities but also discuss the limitations of SDGSAT-1, with the aim to stimulate further research in this field.

Habitat quality of protected areas

Protected areas are biodiversity hotspots, host endangered species, or unique ecosystems and landscapes. The aim of their legal protection is long-term conservation. Monitoring the effectiveness of habitat protection is needed to ensure that conservation goals are being met and to detect potential changes (Bergamini et al., 2019). While many aspects of habitat quality are implemented in current monitoring schemes, night-time darkness, as an important quality of natural habitats, is mostly ignored in such programmes (Koen et al., 2018). Monitoring the two forms of ALAN, direct light emissions and artificial skyglow, using spatially continuous data from night-time satellites makes it possible to roughly estimate the exposure of protected areas to light pollution on a global scale (Garrett et al., 2020; Gaston et al., 2015; Sung, 2022). However, the currently available methods are limited in their ability to assess the ecological threats of light pollution on these habitats and their specific communities (Barentine, 2019; Jägerbrand & Bouroussis, 2021). For some endangered species, low light levels, such as those caused by artificial skyglow, may already be detrimental, whereas for others, only direct exposure to individual light sources at much higher light levels may be problematic. In addition, many other factors, such as light colour or landscape features that influence the distribution and visibility of ALAN (e.g. shading by vegetation) should be considered. Furthermore, there is limited knowledge about the light sensitivity of individual species, which makes it very difficult to define species-specific thresholds (Jägerbrand & Bouroussis, 2021). Advanced remote sensing products that provide data on ALAN at all ecologically relevant scales are needed to tackle these challenges and better support conservation management.

We analysed and compared SDGSAT-1 and VIIRS night-light data within and adjacent to protected biotopes of national importance in Switzerland (BAFU, 2023) to demonstrate the importance of capturing local variability in light intensity (Fig. 3). To differentiate between ALAN inside and outside protected areas, or to assess whether a certain buffer zone of limited light pollution exists around these areas, high-resolution night-time light data are required, especially for smaller protected areas. The analysis with SDGSAT-1 supports our expectation that little or no ALAN is detected within the protected areas (Fig. 3D), but that many sites, depending on the habitat type, have a limited buffer zone to ALAN (Fig. 3E). With VIIRS, much higher radiance values were measured in the protected areas (Fig. 3D), likely due to the coarse spatial resolution, which results in pixel values also being influenced by adjacent external light sources. Access to detailed maps on light intensity and colour can contribute to the development of adaptation strategies for light management, such as dimming or turning off lights at certain times during the night or in critical seasons. Additionally, these maps can help to prioritize the establishment of new protected areas, buffer zones, and dark corridors. Furthermore, our example shows that the assessment of habitat quality should combine both SDGSAT-1 and VIIRS data, e.g. to also consider diffuse skyglow (Falchi et al., 2016), which affects much larger areas than the direct light emissions measured by SDGSAT-1.

Bat commuting-flight corridors

ALAN leads to habitat fragmentation for light-avoiding animals, for example by disrupting important wildlife corridors and landscape connectivity (Laforge et al., 2019). Several bat species living near or within urban settlements rely on such dark spaces to commute from their roosts to foraging sites after sunset (e.g. *Myotis myotis* and *Rhinolophus hipposideros*). Identifying, protecting, and restoring these dark corridors is essential to prevent further declines of endangered bat species (Rowse et al., 2016). Depending on the species-specific foraging strategy, different landscape characteristics – such as the vertical complexity of vegetation and terrain – define suitable routes, and low light levels are crucial for many species (Voigt et al., 2021). The selection of a specific commuting path depends on very small-scale structures, and the modelling of such corridors therefore relies on high-resolution environmental data. Detailed information on 3D terrain and vegetation characteristics has become widely available from LiDAR acquisitions and global high-resolution products (Lang et al., 2023), but this level of detail is lacking for global night-time light data (Linares Arroyo et al., 2024). Night-time images from SDGSAT-1 could fill this gap, facilitating for the first time a detailed and large-scale assessment of light pollution at a spatial scale relevant to bats.

As part of the ecological infrastructure planning for Switzerland (BAFU, 2021), flight corridors for bats have been modelled for more than 200 roosting sites using bat activity and fine-scale environmental data, but without any information on artificial light (Ravessoud, 2017). In practical applications, the modelled flight corridors are used by

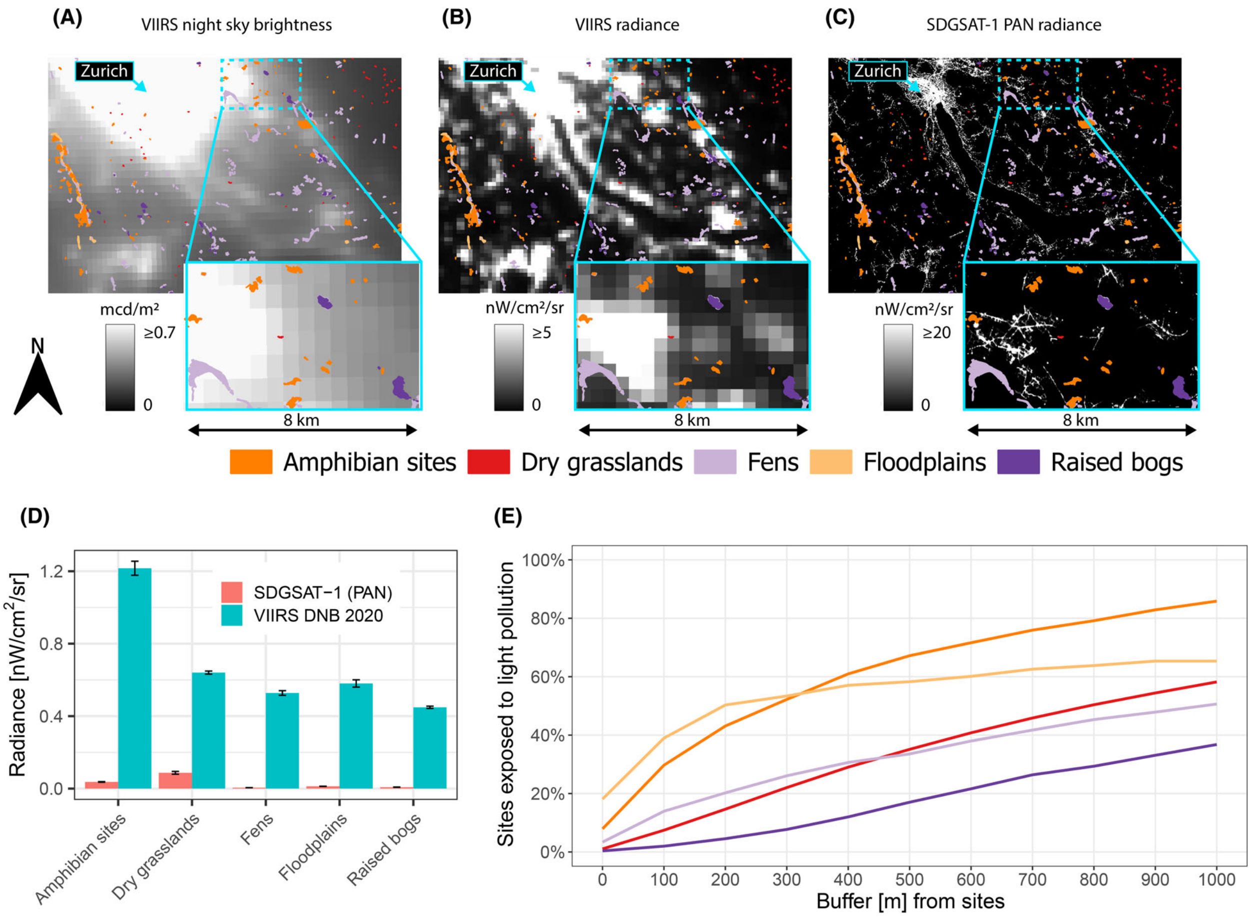

Figure 3. Example maps of light pollution around Zurich (Switzerland) based on VIIRS-DNB and SDGSAT-1 GLI, and their relationships with biotopes of national importance in Switzerland (A–C). Comparison of mean radiance values for the whole of Switzerland between VIIRS and SDGSAT-1(D), and exposure of protected areas to nearby light sources based on SDGSAT-1 (E). Night sky brightness (A) is derived from the World Atlas 2015 (Falchi et al., 2016), and radiance values for VIIRS (B, D) and SDGSAT-1 (C– E) are from 2020 (mean composite) and 2023/2024 (median composite of the panchromatic band), respectively.

local roost managers to identify deviations of the actual flight paths and to mitigate potential conflicts with construction planning and existing light exposure. The integration of a brightness variable derived from night-time drone imagery in some test areas (n = 20) already showed a significant improvement in bat corridor modelling (Fuchs, 2021). SDGSAT-1 could provide an operational way to include ALAN in bat corridor modelling, making it possible to assess the exposure of such potentially optimal corridors to ALAN and to identify priority areas for the implementation of specific light pollution mitigation measures (as illustrated in Fig. 4). Given the importance of the fine-scale variability of ALAN for bat corridors, the higher-resolution panchromatic band (10 m) of SDGSAT-1 provides substantial advantages over the individual RGB bands (40 m), even though emissions in the blue spectrum are considered to have the greatest ecological impacts (but see Bolliger, Hennet, Wermelinger, Blum, et al. (2020) and McNaughton et al. (2021)). In the bat corridor modelling test, which employed night-time drone imagery, the greater mouse-eared bat (*Myotis myotis*) and the lesser horseshoe bat (*Rhinolophus hipposideros*) were the two species tested. Of these, only the less light-sensitive species, *Myotis myotis*, exhibited a strong response to blue light (Fuchs, 2021). Although SDGSAT-1 does not capture all light sources in the Burgdorf test area due to the sensitivity and resolution of the sensor, the main night-time lighting pattern appears to be well captured (Fig. 4A,B), providing valuable insights into potential conflict areas, such as illuminated road crossings (Fig. 4D). It may therefore be possible to improve the modelling of these corridors using SDGSAT-1 imagery in addition to information on small-scale surface structures, which could prove very useful for the effective management of local roosts.

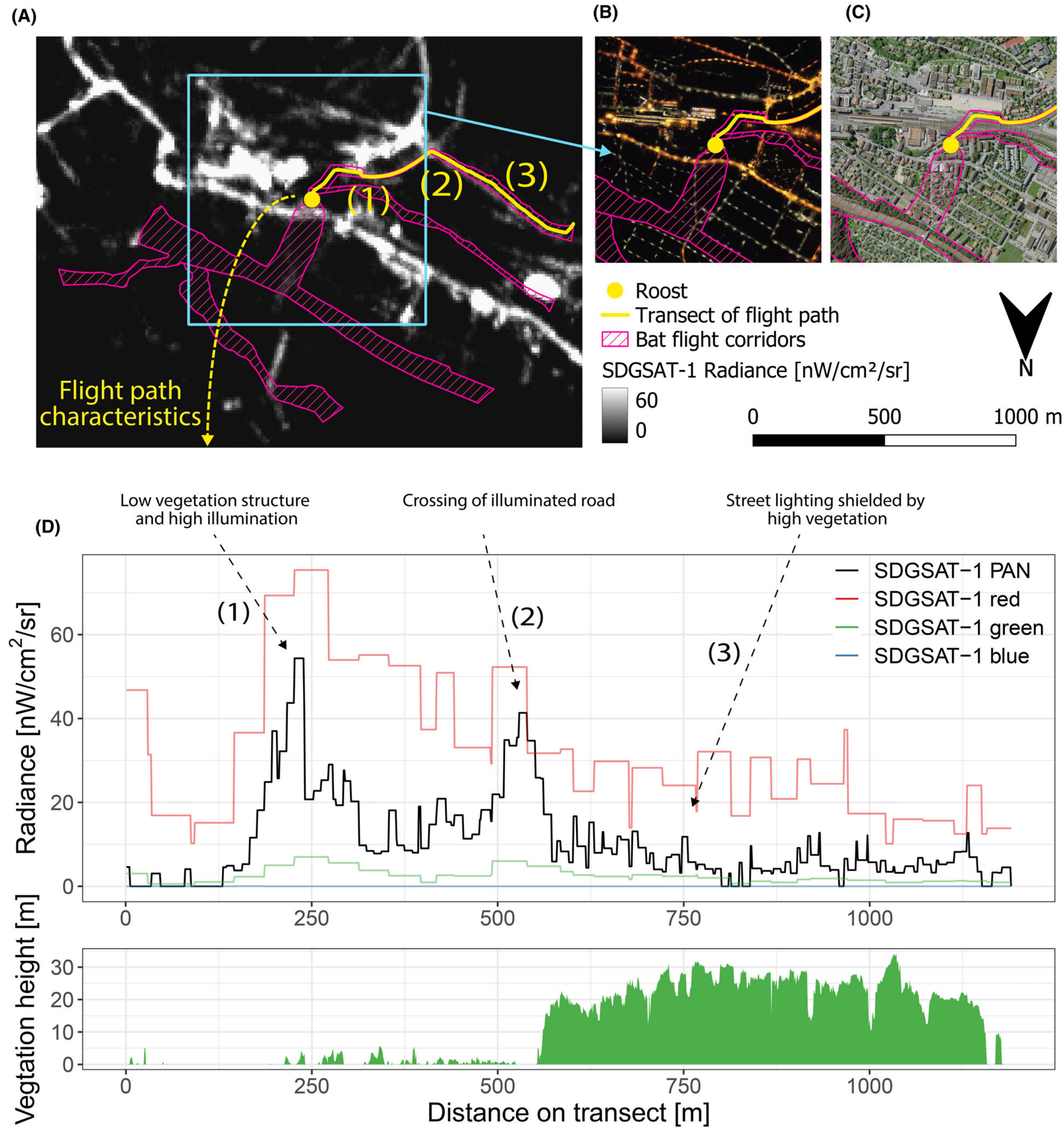

Figure 4. Modelled bat commuting corridors (located in Burgdorf, Switzerland) and night lights detected by SDGSAT-1 GLI (A; median panchromatic radiance for 2023/2024), corresponding night-time drone imagery (B; acquired in 2020), and aerial imagery (C; acquired in 2021 ©Swisstopo) as a high-resolution reference. The transect (D) of the modelled flight path from the roost location to the foraging site shows light (D-top) and vegetation (D-bottom) characteristics along the path and indicates potential conflict areas.

Modelling the visibility of light sources for animals

In contrast to the above examples, focusing on direct light emissions, the impact of ALAN can also be assessed by the perception of light sources in animals' surrounding environment (Ranzoni et al., 2019), influencing their movements. This approach requires knowledge of the precise position of all light sources within a large territory to model the visibility of the light sources from an animal's perspective. As this kind of dataset does not exist at a national or regional level, remote sensing represents the best alternative data source for large areas. With its panchromatic band resolution of 10 m px^{-1}, SDGSAT-1 offers a great opportunity to detect individual or groups of light sources (Fig. 5A,B). After the light sources from SDGSAT-1 imagery have been extracted to spatial points, the impact of ALAN can be quantified using viewshed modelling. Viewshed analysis makes it possible to define the areas of the territory where the light sources are visible from within a certain radius, while considering landscape elements, such as topography, vegetation, and buildings, as shading elements for ALAN (Ranzoni et al., 2019). The resulting map provides information on the number of lights (or groups of lights) visible from each pixel within the selected radius and therefore quantifies the potential impact of ALAN on wildlife connectivity (Fig. 5C). A simplified binary analysis could be conducted to distinguish areas impacted by light pollution from areas constituting the nocturnal continuum.

Given the spatial resolution of 10 m px^{-1}, with SDGSAT-1 it is not possible to distinguish every light source, for example in dense clusters of street lights. Compared with Jilin-1 order-based night-time satellite imagery (Zheng et al., 2018), which has a resolution of 1 m px^{-1}, 80–90% fewer individual light sources were detected using SDGSAT-1. In the case of a viewshed approach, however, this limitation did not alter the result strongly, as only 7–15% classification differences were observed between Jilin-1 and SDGSAT-1 when binarily

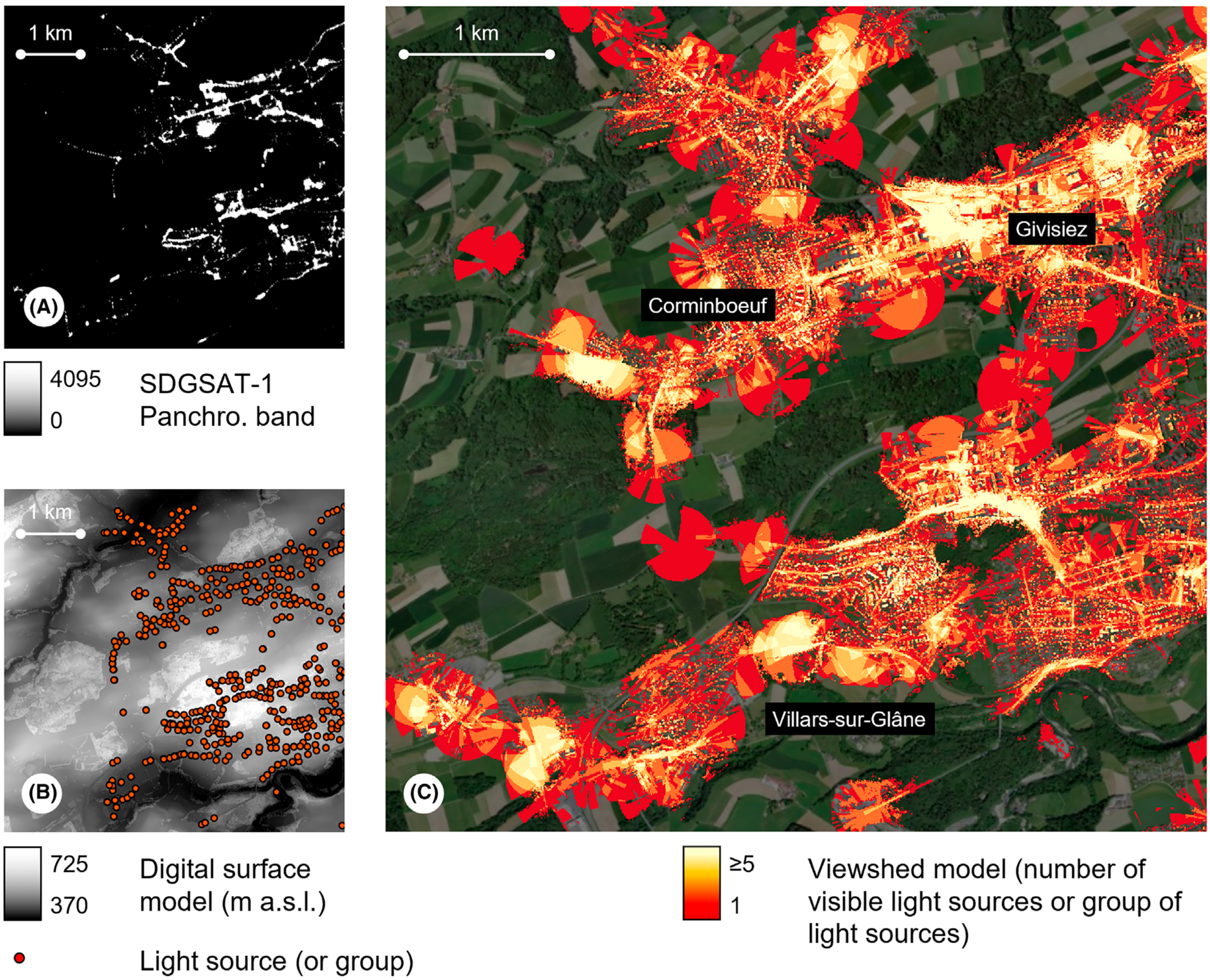

Figure 5. The main steps involved in modelling light pollution with the viewshed approach: (A) SDGSAT-1 panchromatic band for part of the city of Fribourg (Switzerland); (B) extracted individual light sources and groups of light sources as vector points, overlaid on the SwissSURFACE3D digital surface elevation model (©Swisstopo); (C) viewshed result quantifying the potential impact of artificial light at night (ALAN) on wildlife (©HEPIA/BAFU), overlaid on an aerial orthophotograph (©ESRI).

classified viewshed results were considered. Interpreting results on a relative scale (greater vs. lower impacts) rather than on the absolute number of light sources is therefore advised. In addition, it has been shown that novel luminaires with tailored shielding strongly reduce light spill (Dietenberger et al., 2024). This could have a large impact on the viewshed model, affecting both the detectability of such light sources from space and its visibility on the ground from nearby locations.

The approach presented here shows that SDGSAT-1 facilitates the mapping of light sources perceived by animals as they move across the landscape. Such maps could be used for the implementation of an ecological infrastructure (BAFU, 2021; Benedict & McMahon, 2002). The method presented here is adaptable to different focal species and can be a valuable decision-making tool for planning, e.g. to prioritize zones where darkness should be restored or preserved. Including night-time darkness in the ecological infrastructure enables consideration of both physical landscape elements and non-structural barriers generated by ALAN, which affect the functional connectivity for many species. Compared with the knowledge and awareness of blue-green infrastructure, dark infrastructure has been largely ignored so far (Sordello et al., 2022), but research in this area can now be strengthened with new data streams from SDGSAT-1.

LIMITATIONS AND CHALLENGES

SDGSAT-1 is the first satellite to provide free, medium-resolution, and multispectral night-time light imagery to the scientific community, with great potential for ecological applications, as described above. However, there are also several shortcomings and challenges. Some of these limitations are directly related to the SDGSAT-1 GLI, whereas others are more general constraints of space-borne measurements of nocturnal light.

First, there is a lack of experience and studies for a sound evaluation of the effective use of SDGSAT-1 for ecological applications, and the long-term perspective of the mission is unclear. In addition to uncertainties regarding the continuation of the programme, constraints towards area-wide monitoring are that SDGSAT-1 does not acquire images on every overpass, neither throughout the year nor for many areas of South America (south of the Amazon Basin), and that users are given a limited download quota by default. Moreover, the static acquisition times do not allow, for example, the quantification of adaptive light management during the night (e.g. dimming). A possible solution to this would be the launching of a constellation of three or more SDGSAT-type satellites, each with its own overpass time, e.g. 22:00, 00:00 and 02:00. The current overpass time of the SDGSAT-1 of around 21:30 is too early in the summer season at higher latitudes, and thus a later overpass time would enable the acquisition of more night-time-light images after civil twilight. The SDGSAT-1 GLI has three sensors, but the red band also covers the near-infrared region. For a better representation of the human perception of lights, we recommend that a future SDGSAT mission split the current red band into two bands: red and near infrared; this would also make it easier to compare its measurements with those from ground-based photometers that do not cover the near infrared. Another limitation of the glimmer sensor is that it is not sensitive enough to low light levels (see Fig. 4 for a comparison with drone imagery). Consequently, residential streets with low light levels may appear dark on the SDGSAT-1 night-time images (Levin et al., 2024).

Furthermore, the currently available SDGSAT-1 GLI products require extra effort to create consistent data over space and time, including noise removal (Liu et al., 2023; Liu et al., 2024; Zhang et al., 2022) and cloud masking either based on visual inspection of the image or, if a thermal image was acquired at the same time by SDGSAT-1, using image classification methods. We have also found inconsistent geometric accuracy and spatial shifts between scenes, which were also reported in other studies (Chen et al., 2024; Yu et al., 2023) and make time series analyses challenging. Scientists and practitioners would greatly benefit from improved SDGSAT-1 products and documentation, standardized and higher-level processing routines, and easier access to the data, e.g. by making the data available on the Google Earth Engine cloud-platform (Gorelick et al., 2017). Although SDGSAT-1 demonstrates and offers new opportunities for ecological light pollution research, it has not yet reached the stage of a reliable and easily accessible monitoring system. This is also reflected in the fact that some of the requirements formulated by Kyba et al. (2024) in a comprehensive report on future night-light missions, which also target ecological applications, have not yet been met by SDGSAT-1.

Lastly, general constraints for the assessment of night lights from space need to be considered. Among many other factors (e.g. sensor resolution and sensitivity), a major limitation of space-borne sensors is that mostly upward emitted or reflected light is recorded, meaning that horizontal light emission and reflectance, to which many species are exposed, are missed with measurements from space and can only be measured using ground-based observations (Levin et al., 2020; Vandersteen et al., 2020). Although the acquisition of images from varying viewing angles, as in the case of VIIRS-DNB and SDGSAT-1, introduces substantial uncertainties (Wang et al., 2021) and complicates the comparison of individual observations, it can provide complementary information on night lights and should be considered for future satellite missions (Kyba et al., 2022). For example, street lights near tall buildings may only be visible from certain viewing angles. In addition, the detectability of ALAN also depends on the capabilities of the sensor and its alignment with novel luminaires, such as sensitivity to emissions from street lights with aggressive shielding (Dietenberger et al., 2024) or unconventional spectral ranges (e.g. UV; Kyba et al., 2024). In this study, we have focused on terrestrial ecosystems, but light pollution also plays an important role for aquatic ecosystems (Hölker et al., 2023). It is important to consider that the interaction of ALAN with water differs greatly from that with land. For example, water reflects much less of the light and may appear dark to a space-borne sensor (Jechow & Hölker, 2019). Furthermore, to fully assess the ecological impacts of ALAN on aquatic systems, three-dimensional and multispectral maps are necessary, as the bathymetric distribution of light depends on the penetration depth across different spectra (Tamir et al., 2017).

This brings us to the point that the multifaceted character of ALAN can only be addressed to a limited extent by satellites. Their combination with other remote sensors and in situ measurements is essential to (1) understand and quantify ALAN data delivered by satellites, (2) examine hourly changes in light pollution during the night, and (3) form conclusive ecological impact assessments and advance monitoring of ALAN, for example by upscaling from photometers to UAVs and satellites.

Conclusions

Our study emphasizes the importance of advancing ALAN monitoring from space for basic and applied ecology, and it highlights the novel opportunities of SDGSAT-1 for ecological applications. Using three example applications, we have demonstrated the importance of mapping light intensity and spectra at a fine spatial resolution to complement existing global products for monitoring light pollution at the landscape level. Detailed maps of ALAN for large areas are (1) key resources for scientists studying the ecological stressors affecting species and organisms across spatial and temporal scales, and (2) serve as a fundamental database for conservation management, for example for assessing habitat quality, identifying conflict zones, and planning dark corridors for biodiversity. However, to boost the use of SDGSAT-1 GLI for science and practice, further research is needed, data quality and accessibility issues must be solved, and the continuation of the mission must be ensured. Since ALAN has many dimensions, combining different monitoring techniques, including in situ and space-based measurements, is a promising avenue to capture this complexity.

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Author Contributions

Dominique Weber: Conceptualization; methodology; data curation; investigation; validation; formal analysis; visualization; writing – original draft; project administration; writing – review and editing; software. **Janine Bolliger:** Writing – review and editing. **Klaus Ecker:** Writing – review and editing. **Claude Fischer:** Writing – review and editing. **Christian Ginzler:** Conceptualization; supervision; writing – review and editing. **Martin M. Gossner:** Writing – review and editing. **Laurent Huber:** Visualization; data curation; formal analysis; writing – review and editing; software. **Martin K. Obrist:** Writing – review and editing. **Florian Zellweger:** Writing – review and editing. **Noam Levin:** Writing – review and editing; conceptualization; supervision; data curation; formal analysis; investigation; software.

Data Availability Statement

Research data are not shared. This is because the example applications discussed in this perspective paper are only broadly outlined and some are based on ongoing research. Consequently, sharing the data is not appropriate at this stage. However, the SDGSAT-1 GLI satellite imagery are freely available from the official website.

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