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Quantifying urban light pollution — A comparison between field measurements and EROS-B imagery

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ABSTRACT

Artificial night lighting and its negative consequences are of interest in the fields of Astronomy, Human Geography, Ecology and Human Health. The majority of studies to date focused on the impacts light pollution has on our ability to view the night sky, as well as on biodiversity, ecosystems and humans. However, in recent years, with the emergence of new high spatial resolution sensors, providing detailed evaluation of night lights at the local level, more attention has been given for estimating and quantifying artificial light within cities. In this study, we evaluate urban night lights within the city of Jerusalem by combining data from two remote sensing tools: ground measurements using Sky Quality Meter (SQM) devices and space-borne measurements using EROS-B night light imagery. In addition, we examined the use of the SQM for evaluating artificial light in different view directions: upwards, downwards and horizontally. Differences in night lights were found between the three SQM view directions, with the brightest values measured in the horizontal direction (8.7–18.9 mag_{SQM} $arcsec^{-2}$, and darkest values in the downwards direction (11.2–19.5 mag_{SQM} $arcsec^{-2}$). The downwards SQM measurements were influenced by surface albedo, the horizontal direction was the most exposed to direct lights from buildings and cars, while in most locations the upwards direction represented skyglow. Using quantile regression we found strong correlations between the SQM and EROS-B brightness values. Statistically significant correlations ($R^2 = 0.53$) were found between the upwards and downwards devices to the EROS-B in the 0.95 quantile, as well as between the horizontal device to the EROS-B in the 0.90 quantile ($R^2 = 0.44$). In addition to local and external light sources, bright areas on the EROS-B image were associated with areas of low vegetation cover and high albedo. This study provides evidence for the correspondence between field and space-borne measurements of artificial lights and emphasizes the need for better understanding of light pollution at the local level and for taking into account of the three dimensional nature of light pollution.

1. Introduction

In the past century, artificial night lighting has increased tremendously in its intensity as well in its extent worldwide (Riegel, 1973; Longcore & Rich, 2004; Cinzano, Falchi, & Elvidge, 2001; Holker et al., 2010; Gaston, Bennie, Davies, & Hopkins, 2013; Small & Elvidge, 2013; Bennie, Davies, Duffy, Inger, & Gaston, 2014a). This dramatic change in night time lighting, with about two thirds of the world's population affected by light pollution (Cinzano et al., 2001), is strongly associated with urban areas which contain multiple sources of artificial light including street lights and lighting from residential, commercial and industrial areas (Elvidge, Baugh, Kihn, Kroehl, & Davis, 1997; Doll, 2008; Kuechly et al., 2012; Hale et al., 2013; Levin, Johansen, Hacker, & Phinn, 2014; Li, Ge, & Chen, 2014; Kyba et al., 2015). While artificial lighting has some clear benefits for humankind, much concern has been expressed regarding its negative effects, also known as "light pollution", and often referred to as "over lighting", "glare", or "light trespass" (Burne, 1972; Riegel, 1973; Kyba et al., 2013a; Kyba et al., 2015). Astronomical light pollution refers to the degradation of our ability to view the night sky due to atmospheric scattering of artificial lights (Cinzano et al., 2001). Ecological light pollution refers to the negative effects that alteration in natural light patterns (both temporally and spectrally) have on flora, fauna and human health (Verheijen, 1981; Rich & Longcore, 2006; Miller, 2006; Navara & Nelson, 2007; Horvath, Kriska, Malik, & Robertson, 2009; Stone, Jones, & Harris, 2009; Byrkjedal, Lislevand, & Vogler, 2012; Davies, Bennie, Inger, Ibarra, & Gaston, 2013a; Nordt & Klenke, 2013). While the impacts of astronomical as well as ecological light pollution are increasingly well documented (Hill, 1990; Longcore & Rich, 2004; Aubrecht, Elvidge, Ziskin, Rodrigues, & Gil, 2010; Rodrigues, Aubrecht, Gil, Longcore, & Elvidge, 2011; Holker et al., 2010; Davies, Bennie, Inger, & Gaston, 2013b; Davies, Duffy, Bennie, & Gaston, 2014; Inger, Bennie, Davies, & Gaston, 2014), quantifying artificial night lighting within cities using high spatial remote sensing tools is an evolving field of research with broad implications for planners and

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ecologists (Kyba, Ruhtz, Lindemanna, Fischer, & Hölker, 2013b; Miller et al., 2013; Davies et al., 2014; Gaston, Duffy, Gaston, Bennie, & Davies, 2014; Hale, Fairbrass, Davies, & Sadler, 2015). Evaluating light pollution, especially in open areas within the urban environment, has significant importance, since these areas serve as corridors and refuges for nocturnal animals (Gaston, Davies, Bennie, & Hopkins, 2012; Bennie, Davies, Inger, & Gaston, 2014b). In this sense, as cities are becoming more influenced by night-time visible light, darker areas are disappearing from the urban environment (Gaston et al., 2014; Kocifaj, Posch, & Solano Lamphar, 2015a).

In recent years studies have been quantifying nighttime visible light (wavelengths of 400–700 nm) using space-borne night light images from sensors acquiring data at various spatial scales (Zhang, Levin, Chalkias, & Letu, 2015), from the global scale using sensors such as the Defense Meteorological Satellite Program (DMSP) (Cinzano et al., 2001; Doll, 2008; Aubrecht, Elvidge, Eakin, Ziskin, & Baugh, 2009; Aubrecht et al., 2010; Li, Xu, Chen, & Li, 2013) and Suomi-NPP Visible Infrared Imager Radiometer Suite (VIIRS) including the day/night band (DNB) (Miller et al., 2012, 2013), through to regional scale sensors such as the joint NASA and Argentina Satélite de Aplicaciones Científicas-C (SAC-C & SAC-D) and photos taken by astronauts on board International Space Station (ISS; Levin & Duke, 2012; Mazor et al., 2012; De Miguel et al., 2014; Li et al., 2014), and the local scale using EROS-B (Levin et al., 2014). In addition, dedicated aerial campaigns have been conducted to acquire night-time imagery of selected cities in the USA and in Europe (Kuechly et al., 2012; Kim, 2012; Hale et al., 2013). Another approach for understanding light pollution patterns is to model light pollution, based on precise evaluation of the surface and the land cover, extracted from LiDAR systems (as in Bennie et al., 2014b), or based on combined night-sky radiances models (Aube & Kocifaj, 2012). Validation of light pollution models and continuous monitoring of light pollution can also be done using ground field measurements employing spectral light meters and ground-based digital images (Teikari, 2007; den Outer et al., 2011; Pun & So, 2011; Nordt & Klenke, 2013; So, 2014; Pun, So, Leung, & Wong, 2014; den Outer et al., 2015; Dobler et al., 2015; Kocifaj, Lamphar, & Kundracik, 2015b).

Although space-borne measurements provide us with a synoptic view of artificial lights and light pollution, they mostly represent artificial light which is emitted upwards (although due to its wide swath width, VIIRS night-time imagery measures radiance in scan angles of up to 52°, and thus it also acquires some radiation emitted diagonally; Liao, Weiss, Mills, & Hauss, 2013), and may thus be limited in evaluating light pollution as experienced by people, animals and plants at the ground level in different directions (Bennie et al., 2014b). In addition, space-borne imagery is limited in its ability to provide continuous measurements of night-lights, in contrast with ground based cameras (Dobler et al., 2015). Evaluating light conditions in the field is important for answering various questions, such as designing lights to create the perception of safety at night without generating excessive light pollution (Boyce, Eklund, Hamilton, & Bruno, 2000; Narendran, Freyssinier, & Zhu, 2015), understanding how street lighting affects invertebrate communities (Davies, Bennie, & Gaston, 2012), understanding the effects of night illumination on melatonin release (Dominoni, Goymann, Helm, & Partecke, 2013) and quantifying the exposure of people to night time lights from outdoor lights while sleeping (Pauley, 2004). While several papers discuss the modeling of artificial night light in various directions (Kocifaj, 2007; Luginbuhl et al., 2009b; Kyba et al., 2013b; Kocifaj et al., 2015a), few studies attempted to quantify the distribution of light pollution in different directions in urban areas. In a recent study conducted in Berlin, two cameras, assembled on an aerial platform, were used for evaluating urban upward light distribution in two directions (Kyba et al., 2013b). Another research conducted in two regions, Bratislava (Slovakia) and Los Mochis (Mexico), used two DSLR cameras, with different apertures, to evaluate the ratio of the zenith radiance relative to horizontal irradiance (Kocifaj et al., 2015b). Another approach to measure light pollution in different directions has been used at Virginia Tech Campus in Arizona, where two light meters were used simultaneously, one measuring upwards and the other measuring in the downwards direction for evaluating direct light, from light fixtures, and reflected light, from the ground level (Kim, 2012).

Therefore, our aim in this paper was to estimate urban light pollution (mainly in open areas within the city) by combining data from high spatial resolution night time imagery acquired by EROS-B (Levin et al., 2014), and from ground measurements using the photosensitive "Sky Quality Meter" (SQM) produced by Unihedron (Cinzano, 2005). In addition, we examined for the first time, the use of the SQM in three different view directions: pointing upwards to the sky, downwards towards the ground and towards the horizon. This enabled us to evaluate directional differences in light pollution resulting from direct light, reflected light and scattered light, and to better understand how light pollution is perceived by organisms at the ground level. We assumed that the correspondence between space-borne remote sensing of light pollution and ground based measurements, will depend on the direction in which light pollution was measured on the ground, on surface parameters of albedo and vegetation cover, and on the spatial resolution in which the comparison is being made.

2. Materials and methods

2.1. Study area

The research was conducted in Jerusalem, which is located in the Judea Mountains, between 650 and 850 m above sea level. Jerusalem is the capital city of Israel and is also Israel's largest city in terms of its municipal area, (covering 126 km^2) and population size (829,900 in 2013) (The Central Bureau of Statistics, 2014). The built-up areas (57% of the municipal area) vary in their function (residential, commercial and light industry), age and density in the city. While the residential areas are widely spread across the city, light industrialized areas are clustered, mostly, at the city edges (Choshen, Doron, Shapira., & Israeli, 2014). Most of the larger open areas are located at the city edges (Jerusalem Forest), while smaller open areas are located inside the city (e.g., the Wohl Rose Garden, the Botanical gardens) (Fig. 1a–b). Due to its highly diverse open spaces and the city's unique location at the transition area between the desert and the Mediterranean climate regions, the city has an impressive range of habitats and rich biodiversity (Bino et al., 2008; Roumani, Kaplan, Balaban, Geldman, & Wachtel, 2013).

For this research, we selected six open areas which were used as field sites; the Jerusalem Forest, located in the west edge of the city, the Wohl Rose Garden, Sacher Park, the Valley of the Cross and the Botanical gardens all located in the city center, and the Gazelle Valley located in the south-west of the city (Fig. 1b). These selected open spaces differ in their topographic setting, vegetation cover and in their location along the gradient between the city centre and the city's edge (Bino et al., 2008).

2.2. SQM ground field measurements

In the current study, most of the ground filed measurements were carried out within the city open areas. For these measurements we used four SQM-LU devices. Originally, this device had been designed for measuring the brightness of the night-sky and so was mainly used by astronomers (Teikari, 2007). The device uses a logarithmic scale and measures the amount of incoming light as brightness values in units of magnitude per square second of arc (mag_{SQM} arcsec^{-2}). The SQM values in night-time conditions normally range between 16 and 23 mag_{SQM} arcsec^{-2}, with higher values representing lower light levels (e.g., a reading value of 16 mag_{SQM} arcsec^{-2} represents an area where