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Research article

Numerical research on the effects the skyglow could have in phytochromes and RQE photoreceptors of plants

H.A. Solano-Lamphar [a, b, *], M. Kocifaj [b, c]

[a] Cátedras CONACYT, Instituto de Investigaciones Dr. José María Luis Mora, Centro Interdisciplinario de Estudios Metropolitanos (CentroMet), Plaza Valentín Gómez Farías #12 San Juan, Mixcoac, México D.F. 03730, Mexico
[b] ICA, Slovak Academy of Sciences, Dúbravská Road 9, 845 03, Bratislava, Slovak Republic
[c] Faculty of Mathematics, Physics, and Informatics, Comenius University, Mlynská Dolina, 842 48, Bratislava, Slovakia

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ABSTRACT

The increase of artificial light at night has a terrible impact on organisms with nightlife patterns such as a migration, nutrition, reproduction and collective interaction. Plants are not free from this issue as they have life cycle events occurring not only yearly but also daily. Such events relate to daytime variations with seasons in which the flowers of deciduous trees bloom and the leaves of certain trees fall off and change color. A response of plants to artificial light at night still remains poorly quantified; but recent scientific research suggest that skyglow can disturb plants processes. For instance, low levels of light affect deciduous plants, which shed their leaves as days grow short in the fall.

In this paper we model skyglow considering the features of artificial light that can affect natural processes of plants during the night. A case-study was conducted to mimic skyglow effects in real location for which experimental data exist. In our numerical simulations we found that some lighting systems can have an effect on plant photoreceptors and affect the phenology of plants. Specifically, the lamps that emit the electromagnetic energy in a wide spectral range can have greater effect on the photosensitivity of the plants. We believe the results obtained here will motivate botanists to make a targeted experiment to verify or challenge our findings. If the night light can change plant behavior under some conditions, it can have significant implications in botany, biology, or even agriculture.

1. Introduction

Skyglow includes an interaction of artificial light from cities and constituents of the atmosphere, such as air molecules and aerosol dispersed basically at troposphere level. Skyglow is well known to be a central environmental issue in the new global economy and a source of different impacts to biodiversity. Skyglow relies on inaccurately situated or designed artificial night lighting systems that degrade the nocturnal environment. It relates with climate change because fossil fuels are the primary sources of energy inputs to street lighting, thus all the light radiated to the upper hemisphere is a completely wasteful use of energy. In addition, a considerable reduction of luminance contrast between the affected sky and stellar bodies' luminance is due to skyglow. Among such issues artificial light at night disturbs biological processes of most photosensitive living organisms.

Contemporary developments in Solid State Lighting (SSL) have directed to an increased interest in using light emitting diodes (LED) having an affordable price and allowing important energy savings (Humphreys, 2008; Pimputkar et al., 2009; Haitz and Tsao, 2011). As documented by several authors, these technologies often stand for a mismanaged source of artificial radiation that could cause an alteration of nightlife environment (Longcore and Rich, 2004; Navara and Nelson, 2007; Falchi et al., 2011; Gaston et al., 2013; Pawson and Bader, 2014).

The effects of skyglow on biodiversity are day by day more known and the studies more frequent from ecological and biological perspectives. Nevertheless, those studies primarily consider the effects of artificial light on insects and vertebrates (Moore et al., 2001; Anisimov, 2003; Vera et al., 2010; Fox, 2012; Cho et al., 2015; Solano Lamphar and Kocifaj, 2015; Solano Lamphar and Kocifaj, 2013), including ecosystem services (Lyytimäki, 2013).

* Corresponding author. Hacienda El Conejo 116, El Jacal, 76180, Santiago de Querétaro, Mexico.
E-mail addresses: hsolano@institutomora.edu.mx (H.A. Solano-Lamphar), kocifaj@savba.sk (M. Kocifaj).

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Animals are not the only organisms influenced by the light of the night sky (Neil and Wu, 2006; Solano Lamphar, 2010), thus a valuable research has arisen around the skyglow effects on plants. Plant photoreceptors play various roles in leaf and stem growth, timing of flowering, fruit production, and other life developments (Briggs, 2013). These organisms generate their own food over the process of photosynthesis. They capture radiant energy from different light sources through chlorophyll and convert the carbon dioxide and water into sugars which are used as energy font (Krause and Weis, 1991). Such mechanism is crucial in the plant development (including aquatic ecosystems) (Kirk, 1994). For instance, a popular laboratory plant the mustard *Arabidopsis thaliana* has nine photoreceptors that interact with visible radiation. This is why the skyglow should not be ignored e.g. in analysis of how different levels of light can affect the endogenous clock of plants (Fankhauser and Staiger, 2002).

Photoperiodism is an evolving response of plants to the light-dark cycles, yet another essential process to their development (Smith, 1982). Three types of photoperiods control the flowering reaction of many plants. In this sense, short day plants flower in response to long periods of night darkness, meanwhile long day plants flower in response to short periods. Moreover, neutral day plants flower without considering the length of the night, but they flower earlier and abundantly under long daylight regimes. Roman et al. (2000) have reported that artificial light can be an important effect to the impairment of both photosynthetic efficiency and photoperiod. Unfortunately, there are only a few studies that have investigated the consequences that low illumination levels can cause in plants (Whitman et al., 1998).

According to Bennie et al., "understanding the impacts of artificial night-time light on wild plants and natural vegetation requires linking the knowledge gained from over a century of experimental research on the impacts of light on plants in the laboratory and glasshouse with knowledge of the intensity, spatial distribution, spectral composition and timing of light in the night-time environment" (Bennie et al., 2016). Therefore, the modeling of the brightness of the night sky, in conjunction with theoretical knowledge, is crucial in the characterization of nocturnal radiation. Hence, it is suitable to determine how the skyglow affects the photoreceptors of plants through innovative simulations.

Plants have an enormous importance in the life of our planet. Such significance relies on the trophic chain: animal herbivores eat plants to sustain themselves and are eaten by carnivores. In this process, plants obtain energy that rises along the food chain. The electromagnetic radiation that plants receive from sunlight reaching the earth and penetrating the atmosphere is the key ingredient in the photosynthesis process, which is fundamental for plants to get energy.

However, the response of plants to day and night light are quite different. Unnatural night lighting can affect different activities that can only happen during nightlife settings. Light and darkness have an essential influence on the vital functions of plants periods of the day throughout the year. Different reactions occur on plants due to illumination. Those reactions are expressed in the processes of growth and development, which are commonly called photoperiodism. In this paper, we model skyglow taking into account different atmospheric conditions and artificial light emissions that can disturb the natural processes of plants during the night. Specifically, we simulate the downward radiative fluxes as perceived by plants near the city of Bradford for which the experimental data on light pollution exist (Somers-Yeates et al., 2016). This work is intended to model plant responses to the artificial light produced by a lighting system in the region. As indicated earlier in this document, there is a plenty of works studying the negative impacts that light pollution could have on animals. However, the way in which the plants react when exposed to the light at night is largely unknown. In spite of a number of indirect indicia, no serious quantification of the phenomena exists. To the best of our knowledge, no controlled experiments have been performed, and the theoretical development in the field is in its beginnings. This pioneering paper addresses a fundamental phenomenon in light interaction with plant sensors and it is the first time the effects are quantified for phytochromes and RQE photoreceptors of plants. Such numerical experiment must be performed prior to field experiments that are expensive and time-consuming. The results achieved here could be useful for Botanist, Plant Molecular Biologists but also illumination engineers who deal with artificial lights. The modeling performed in this study can be made in any geographical area and for various sources of artificial light.

2. Methods

Modeling the diffuse light field in an inhomogeneous nocturnal atmosphere is a non-trivial task that is difficult to solve theoretically and numerically due to the complexity of the radiative transfer methods. On the one hand, the atmosphere is a random disperse medium with highly heterogeneous physical and optical properties. On the other hand, ground-based light sources have dissimilar distributions making the problem more challenging. The sky brightness depends on many different factors, in particular the emission function of ground-based sources. The amount of light emitted from an urbanization correlates with the behavior of individuals socialized within the community and all the features that affect the society system (economic, cultural, consumption habits, the urban structure, among others).

Another important factor is the atmosphere. Part of the light emitted from a city or town escapes into the sky and undergo significant absorption and scattering in the lower troposphere most typically due to air molecules, aerosols and other airborne particles that redirect artificial light back to the ground and illuminate otherwise dark land areas. Such illumination can disturb the night elementary cycle and produce an imbalance in natural night conditions (Kocifaj and Solano Lamphar, 2013). However, the atmospheric constituents only act as modulators of the radiation that relies as well on the characteristics of the urban lighting system.

2.1. Light sources

Although natural and artificial sources are both causing skyglow, a great deal of effort has been expended to identify and better control the street lighting parameters dominating the light pollution propagation in the nocturnal environment (Narisada and Schreuder, 2004; Stone et al., 2009; Davies et al., 2012; Kocifaj and Solano Lamphar, 2013). The spectral radiance of the lamps and diverse distributions of the ground based light sources make the issue more challenging as these factors require a special attention in solving the radiative transfer equation in a local atmosphere.

Six types of light sources traditionally used for artificial night illumination were chosen to simulate skyglow numerically taking into account information provided by the City of Bradford Metropolitan District Council, the office responsible for public lighting development and maintenance. The environmental information including e.g. the lighting inventory for the territory of interest was accessed through Environmental Information Regulations (EIR) (Bradford Council, 2016), while three most frequently used lighting technologies (LPS, HPS, and MH) were selected for further analysis (see Fig. 1).

The analysis carried out for this study was supplemented by 3 LED sources (Fig. 2), as LED technology normally requires less