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Modeling the health impacts of urban light pollution: Synthetic populations and behavioral interventions ☆

Héctor Antonio Solano Lamphar

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Highlights

- Introduces a modeling framework for assessing ALAN's health impacts via synthetic populations.
- Quantifies melatonin suppression under varying lighting scenarios and compliance levels.
- Identifies high-risk urban zones for targeted interventions to reduce ALAN exposure.
- Highlights the importance of policy compliance and behavioral adaptations in mitigation efforts.
- Proposes a scalable framework applicable to diverse urban environments and technologies.

Abstract

Artificial Light at Night (ALAN) poses significant public health challenges by disrupting circadian rhythms and increasing melatonin suppression. This study introduces a dynamic modeling framework employing synthetic population simulations to quantify the health impacts of ALAN under varying exposure scenarios. The model integrates spatial, temporal, behavioral, and policy dimensions, enabling the evaluation of interventions such as warm LED lighting ($\leq 3000\,\mathrm{K}$, $\leq 10\%$, emission at 450–490 nm), lighting ordinances, and community-wide curfews. Simulations demonstrate that these interventions can reduce melatonin suppression by up to 25% in high-risk zones. Clustering analysis identifies high-suppression areas, providing critical insights for urban planning and policymaking. Sensitivity analyses highlight the pivotal role of policy compliance and behavioral adaptations in mitigating ALAN's health impacts. Using synthetic populations ensures ethical compliance by avoiding real human data, while the model's scalability supports application across diverse urban contexts. Future work will integrate ground based illuminance measurements to enhance predictive accuracy and support equitable strategies for mitigating ALAN's health impacts.

Introduction

Artificial light at night (ALAN) is integral to urban life, enabling extended productivity, safety, economic activity, and social engagement. However, its widespread use introduces significant challenges, including ecological disturbances, circadian rhythm disruptions, and adverse health outcomes such as sleep disorders and melatonin suppression [1], [2], [3], [4], [5]. These effects are pronounced in densely populated urban areas, particularly in residential zones near commercial business districts (CBDs) where light spillover occurs, necessitating coordinated action by public health authorities and urban planners [6], [7]. This study focuses on residential areas, where ALAN exposure during evening hours significantly affects sleep and circadian health [4], modeling spillover from nearby CBDs.

Computational models incorporating temporal variability, behavioral dynamics, and policy considerations complement static and observational studies, providing deeper insights into ALAN's impacts [8], [9], [10]. Dynamic modeling enables evaluations of mitigation strategies in diverse scenarios [11], [12], [13]. While prior models in circadian rhythm and urban health studies focus on light spectrum or intensity [14], [15], [16], [17], [18], [19], [20], integrating urban geometry, policy compliance, and behavioral adaptations offers a more holistic perspective [21], [22], [23].

This study presents a model unifying these elements to capture environmental exposures and health outcomes in urban contexts. Using VIIRS satellite imagery from Sant Cugat del Vallès, Spain, processed via Google Earth Engine, and a synthetic population with assigned health attributes, the framework ensures analytical robustness and ethical compliance [24], [25], [26]. The model is implemented in Python, using libraries such as rasterio, numpy, pandas, and matplotlib, and integrates spatial, temporal, behavioral, and policy dimensions to evaluate interventions like LED retrofitting and regulatory measures. Synthetic populations avoid ethical concerns with real human data, enabling controlled simulations while supporting future integration of empirical data. The model's scalability accommodates diverse urban contexts. The code and synthetic data are available at https://github.com/lamphar/alan-model ↗ to ensure reproducibility.

[Commentary Note: Radiometry vs. Photometry]

VIIRS data provide radiance in $nW cm^{-2} sr^{-1}$*, a radiometric unit, whereas circadian studies require photometric units (e.g., lux). We approximate luminous flux by assigning spectral power distributions (SPDs) to each pixel based on typical light source characteristics* [27]. *Future work will integrate ground based spectroradiometric measurements or municipal lighting inventories to derive precise illuminance values, reducing uncertainty in circadian impact estimates.*

Section snippets

Methodology

Our methodology integrates three components: **Contaminant Source**, **Health Mechanisms**, and **Synthetic Population Modeling**. It combines geospatial data processing, urban geometry, exposure modeling, health outcome functions, behavioral adaptations, and policy compliance into a dynamic framework [28], [29]. Implemented in Python, the model uses rasterio, numpy, pandas, and matplotlib for data handling, spatial interpolation, statistical analyses, and visualization. The synthetic population avoids …

Results

The simulation results quantify the impact of ALAN on melatonin suppression in Sant Cugat del Vallès, revealing intricate spatial, temporal, and behavioral patterns that can inform targeted interventions. These findings show that environmental exposure, policy compliance, and individual mitigation behaviors interact strongly in shaping circadian disruption, offering actionable insights for urban health strategies.

The spatial distribution of ALAN intensity, illustrated in Fig. 1, reveals …

Discussion

This study shows that policy compliance and behavioral adaptations are critical for mitigating ALAN's health effects. Clustering (Fig. 8) identifies high-risk zones near CBDs for targeted interventions such as warm LED lighting ($\leq 3000\,\mathrm{K}$, $\leq 10\%$ emission at 450–490 nm) [1]. High compliance scenarios reduce suppression by 25%, supported by community education and retrofitting incentives. The model accounts for CBD spillover via skyglow and reflections (Eqs. (3), (5)). Planned spectroradiometric …

Conclusions

The simulations demonstrate that targeted interventions, such as warm LED lighting ($\leq 3000\,\mathrm{K}$, $\leq 10\%, \mathbf{emission\ at\ 450–490\ nm}$), and 22:00 lighting curfews, reduce melatonin suppression by up to 25% in high-risk zones, as identified through K-Means clustering (Fig. 8). These zones, housing 25% of the population (250 individuals) near CBD boundaries, experience illuminance of 35–60 lux, driving mean suppression above 0.7. Retrofitting cool LEDs to warm LEDs or enforcing curfews lowers suppression to …

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. …

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