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No “true” greenery: Deciphering the bias of satellite and street view imagery in urban greenery measurement

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Highlights

- Analyzed potential biases in satellite and street view-based measurements globally.
- Identified eight factors causing disparities in these measurements.
- Trained a model to assess greenery measurement bias risk.
- Conducted quantitative analysis of urban greenery bias types in ten global cities.

Abstract

Urban greenery is a crucial element in building sustainable cities and communities. Despite the widespread use of satellite and street view imagery in monitoring urban greenery, there are significant discrepancies and biases in their measurement across different urban contexts. Currently, no literature systematically evaluates these biases on a global scale. This study utilizes the Normalized Difference Vegetation Index (NDVI) from satellite imagery and the Green View Index (GVI) from street view imagery to measure urban greenery in ten cities worldwide. By analyzing the distribution and visual differences of these indices, the study identifies eight factors causing measurement biases: distance-perspective limitation, single-profile constraint, access limitation, temporal data discrepancy, proximity amplification, vegetative wall effect, multi-layer greenery concealment, and noise. Moreover, a machine learning model is trained to estimate the bias risks of urban greenery measurement in urban areas. We find that bias in most cities primarily stem from an underestimation of GVI. Dubai and Seoul present fewer areas with overall bias risk, while Amsterdam, Johannesburg and Singapore present more such areas. Our findings provide a comprehensive understanding of the differences between the metrics and offer insights for urban green space management. They emphasize the importance of carefully selecting and integrating these measurements for specific urban tasks, as there is no "true" greenery.

Introduction

A more refined and accurate measurement of urban greenery is fundamental to building sustainable cities and communities. Urban greenery impacts residents' physical and mental well-being by promoting walkability and enhancing daily life [1], [2]. It also contributes to improving air quality, enhancing biodiversity, and regulating urban heat [3], [4]. Monitoring urban greenery at a large scale is essential for maintaining the health and functionality of urban green spaces, ensuring they provide long-term benefits to both people and the environment.

There are two main approaches to measuring urban greenery on a large scale: satellite imagery-based and street view imagery-based measurements. Over the past few decades, satellite imagery has consistently been used as a tool for greenery measurement due to its broad spatial coverage and convenient accessibility [5], [6]. Remote sensing technology can use multispectral and hyperspectral imaging to capture electromagnetic spectrum information invisible to the human eye, such as infrared and ultraviolet. These multispectral images are useful for vegetation index calculation. Indices such as the Normalized Difference Vegetation Index (NDVI) [7] and the Leaf Area Index (LAI) [8] are widely used to quantify vegetation. Such indices support large-scale greenery measurement and tracking temporal changes [6], [9]. Alternatively, street view imagery has emerged as a resource for urban greenery measurement in recent years [10]. Street view imagery is captured by ground-based imaging equipment, such as vehicle-mounted cameras [11], [12]. Such images detail surface features like buildings, roads, and trees. One widely used metric for measuring urban greenery in street view imagery is the Green View Index (GVI), which quantifies the proportion of visually perceived green elements within the images [13]. Various studies have applied GVI as a proxy of urban greenery [14], [15].

Despite the relevance of both satellite and street view imagery as valuable data sources for urban greenery mapping and analysis, they both have inherent limitations that prevent them from reflecting the "true" status of urban greenery. Satellite imagery offers a top-down view, making it impossible to capture vertical greenery such as vegetation walls (see Fig. 1(a)). In contrast, street view imagery allows observation of the vertical urban environment, but they are easily obstructed by tunnels or large trucks (see Fig. 1(b)). Moreover, in terms of data quality, satellite imagery typically has lower spatial resolution, making it difficult to distinguish small greenery elements on the ground. On the other hand, street view imagery is not uniformly distributed, with some internal roads and public pathways suffering from inadequate sampling. Such inherent limitations influence not only the accuracy of greenery measurements but also subsequent analyses and interpretations [16], [17], potentially resulting in misleading conclusions.

Although existing literature recognizes potential biases in satellite and street view-based measurements of urban greenery across different urban environments, these biases and their causes have not been systematically discussed. For example, [18], [19] both noted that satellite-based measurements often miss vertical greenery, such as individual trees or other green elements, particularly in densely urbanized areas [20], [21]. [18] suggested using an NDVI:GVI ratio as an indicator of vertical greenery in such scenarios to address this type of bias. Regarding street view measurements, [20] found that the density of street view sampling points also affects the measurement of urban greenery, leading to the proposal of a Standardized Green View Index (sGVI) that calculates the GVI of an area weighted by the locations of the sampling points. Additionally, there is extensive literature discussing the correlation between NDVI and GVI, with most studies finding a moderate correlation, with correlation coefficients ranging approximately from 0.40 to 0.76 [18], [21], [22]. These studies provide valuable insights into the quantitative differences between the two greenery measurement methods, but the qualitative factors behind them are typically discussed through local findings combined with specific research questions. The subtle nuances of these differences and their underlying factors remain to be fully understood. Furthermore, most past studies have been conducted on local datasets, and their results may not be generalizable to other regions [23], [24]. Therefore, there is a need to systematically examine and categorize the causal factors behind the differences between satellite and street view-based measurements on a global scale, providing directions for more sensitively interpreting these indices.

To address this research gap, this study computed the values of NDVI and GVI across ten cities worldwide, characterized by diverse geographical locations and climates, and conducted a quantitative analysis of the differences and trends between them. Based on the characteristics of these differences, we identified eight main factors that could potentially cause biases. Furthermore, we trained a machine learning model to assess the risk of bias in greenery measurements based on satellite and street view data, allowing for an assessment of greenery measurement bias risks across broader urban areas. Through this qualitative and quantitative analysis of greenery measurements, we provide deep insights for future precise measurements of urban greenery and related research fields. This study not only enhances our understanding of urban greenery measurement techniques but also reveals the effectiveness and limitations of different measurement tools applied in various global cities.

Section snippets

Methods

Fig. 2 illustrates the workflow of this study, which comprises five parts: data collection, greenery extraction, difference analysis, bias identification, and bias quantification. Initially, we collected Sentinel-2 satellite imagery and Google Street View imagery across ten global cities. Subsequently, greenery was extracted from these two distinct data sources: NDVI was calculated using raster calculation from satellite images, and GVI was derived using semantic segmentation models from street …

Differences between satellite-based and street view-based urban greenery

NDVI and GVI serve as representative indices for satellite-based and street view-based urban greenery, respectively. The choice of a 100-meter grid was made to ensure both data representativeness and measurement accuracy. As a finer spatial resolution, a 100-m grid effectively illustrates the characteristics and differences of urban greenery as measured from satellite and street view perspectives.

Fig. 3(a) illustrates the statistical distribution of NDVI and GVI across various cities, …

No true Greenery

This paper systematically identifies eight principal factors contributing to bias from a global perspective: distance-perspective limitations, single-profile constraints, access restrictions, temporal data discrepancies, proximity amplification effects, vegetative wall effects, multi-layered greenery concealment, and noise. We have quantitatively estimated the bias risks prevalent across all urban areas. It is important to note that while we have identified the primary factors causing biases in …

Conclusion

In summary, this study underscores the complexities and inherent biases associated with measuring urban greenery through satellite and street view imagery. By systematically identifying eight main factors contributing to these biases, we have highlighted the discrepancies between NDVI and GVI measurements across various global cities. The quantification of bias types and their spatial distributions provides a nuanced understanding of how these factors manifest in different urban environments. …

CRediT authorship contribution statement

Yingjing Huang: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation. **Rohit Priyadarshi Sanatani:** Writing – original draft, Methodology, Data curation. **Chang Liu:** Methodology, Formal analysis, Data curation. **Yuhao Kang:** Validation, Methodology, Data curation. **Fan Zhang:** Writing – review & editing, Validation, Supervision, Resources. **Yu Liu:** Writing – review & editing, Supervision. **Fabio Duarte:** Validation, Supervision, …

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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