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Balancing Urban Densification and Climate Resilience with Nature-Based Solutions: Insights into 3D Spatial Patterns and Cooling Effects via Remote Sensing

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Abstract

Urban population growth is accelerating both horizontal and vertical densification, exerting increasing pressure on green infrastructure (GI)—a vital element for ensuring urban livability. GI contributes to improved air quality, biodiversity, public health, and mitigates the urban heat island effect. However, conventional two-dimensional (2D) urban analyses often overlook the vertical dimension of vegetation (e.g. Normalized Difference Vegetation Index - NDV) and built structures, limiting our understanding of GI cooling potential under densification. This study addresses this gap by employing advanced three-dimensional (3D) analysis to examine the spatial relationships between vegetation volume, urban 3D structure, and land surface temperature (LST). The specific aims were to: (1) estimate vegetation volume (VV) using voxel-based methods and building volume (BV) through mesh modelling; (2) investigate the spatial distribution of LST; and (3) analyze the correlations between the 3D indices and LST. Using Airborne Laser Scanning (LiDAR) data and Landsat 8 thermal imagery (NASA), we developed 3D indices (Vegetation 3D Density Index - V3DI; and Building 3D Density Index - B3DI) and spatial distribution of land surface temperatures. The results show that the vegetation volume is weakly negatively correlated with the building volume and the population count (coefficients equal to -0.39 and -0.29, respectively). The total VV (> 1.0 m above ground) was about 2 billion m3. The value of V3DI reached a level of 0.76 m3/m2. The volume of buildings across the country is about 330 million m3, achieving a low B3DI = 0.13 m3/m2. In the capital, the B3DI reaches 1.09 m3/m2 indicating a significant density of development. On one of the hottest days of the summer in 2019 (23 August), LST ranged from 19°C to 52°C. Higher LST values were observed in the southern regions, including Luxembourg City, primarily due to rapid urban expansion and reduced vegetation cover. The northern region exhibited lower LST values, attributable to the predominance of agricultural areas and forests. Areas with the highest VV values exhibited the lowest temperatures within the study area, a trend more pronounced in the VV data than in the NDVI data alone. The combined use of NDVI and VV improved the explanatory power of the model ($R^2 = 0.7$), compared to NDVI alone. These findings demonstrate that 3D vegetation structure provides a more robust indicator for urban heat mitigation than 2D metrics alone, offering valuable insights for climate-resilient spatial planning and the strategic implementation of nature-based solutions in urban environments.

Keywords: urban densification, green infrastructure, land surface temperature, remote sensing, GIS