学 位 論 文 内 容 の 要 旨/Dissertation Abstract

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Geospatial analysis of urbanization dynamics and ecosystem services for sustainable urban development in Dhaka city, Bangladesh

(バングラデシュのダッカ市における持続可能な都市開発のための都市化動態と生態系サービスの地理空間分析)

Urbanization is one of the most significant social transformations of the contemporary era. In the 21st century, urban areas, including Dhaka, are increasingly facing challenges from natural and human-induced crises, such as flooding, air pollution, and the urban heat island effect. Urbanization dynamics and ecosystem service assessment are essential to enhance urban resilience against these threats. The relationship between ecosystem services (ES) and urbanization is crucial for sustainable development. Rapid urbanization threatens Dhaka city's natural capital, affecting ES's delivery through changes in land use and land cover (LULC). This study categorized LULC classes and functions from 2000-2021 using the Common International Classification of Ecosystem Services (CICES) framework, utilizing multitemporal satellite images and spectral signature-based indices. Five major LULC types were identified: waterbodies, forest and vegetation, built-up areas, agricultural land, and bare land. The findings revealed a 94% increase in built-up areas and a 70% decrease in water bodies. Bare land initially increased until 2018 but later decreased due to conversion to built-up areas. Agricultural land decreased by 60%, particularly in rural-urban fringe areas, with bare land experiencing the highest conversion rate at 48.94% of its total area. From 2000 to 2021, 16.80% of agricultural land, 21.64% of forest and vegetation, and 12.63% of waterbodies were converted to built-up areas.

Ecosystem services refer to the benefits humans obtain from these LULC classes, categorized into provisioning, regulating, supporting, and cultural services. When these services are quantified in monetary terms, they are called ecosystem service values. ESV was globally aligned and adjusted with regional correction factors, developing region-specific coefficients for the study area. Using GIS zonal statistics, the study calculated region-wise mean ESV, finding the highest mean value in the rural-urban fringe area in 2000 (36.12%) and the lowest in the NI area (11.29%). Over the study period, ESV significantly decreased, particularly in the rural-urban fringe area (-87.95%) and other urban zones. Conversion of waterbodies resulted in an ESV loss of $273 million. ESV losses were observed across all ES types: provisioning (-71.59%), regulating (-69.44%), and cultural services (-62.45%), increasing the city's vulnerability to flooding, waste assimilation, and pollution. The research also examined the trade-offs between the ecosystem service bundles (provisioning, regulating, and cultural). The most synergistic relationship between provisioning and regulating ES trade-offs was observed in agricultural areas ($R^2 = 0.97$),

followed by waterbodies ($R^2 = 0.74$) and forest and vegetation ($R^2 = 0.68$). For regulating vs. cultural ES trade-offs, built-up regions exhibited the highest R^2 value (0.99) due to their aesthetic value, followed by forest and vegetation ($R^2 = 0.98$) and waterbodies ($R^2 = 0.93$). No significant relationship was identified in bare land and agricultural land between these ES types. In provisioning vs. cultural ES trade-offs, the strongest relationship was found in waterbody areas ($R^2 = 0.90$), followed by forest and vegetation ($R^2 = 0.78$), with no significant relationship identified in bare land areas.

This study utilized the Digital Building Height Model to calculate the vertical profile of the city, revealing that the most significant urban development occurred in the northwest and middle east parts of the study area. These vertical profile datasets were then used to measure the degree of urbanization through technomass. Technomass is a three-dimensional indicator encompassing human-made material stocks such as buildings and infrastructure. The volumes and rates of technomass showed positive trends both spatially and temporally, varying significantly across the study area—from 6,213.52 m^3/ha (the lowest in 2000 in the fringe area) to 105,432.15 m^3/ha (the highest in 2021 in the OCBD region). A Geographically Weighted Regression (GWR) model was employed to analyze geographic spatial relationships between urbanization indicators (nighttime light data (NTL), population density (PD), and technomass) and changes in ecosystem service value (ESV). The local R^2 values, ranging from 0 to 1, indicated that technomass was the most suitable indicator for analyzing urbanization's impact on ESV ($r > 0.61$), followed by NTL ($r > 0.56$) and PD ($r > 0.54$). Pearson's correlation analysis revealed a significant negative correlation ($p < 0.01$) between ESV and the urbanization indicators. Technomass exhibited a strong negative association with ESV ($r > -0.96$), followed by PD ($r > -0.94$). Additionally, there was a significant positive correlation between technomass and NTL/PD, while the correlation between technomass/NTL/PD and ESV was negative. The study found that areas with higher urbanization levels experienced a significant decline in ESV. The highest rate of ESV decline (87.55%) was observed where urbanization intensified, with a net ESV decrease of 68.34% and a technomass increase of 243.11% throughout the study period. Bivariate Local Indicators of Spatial Association (LISA) cluster maps indicated that areas with high urbanization levels corresponded with very low ESV values. This study highlights the effectiveness of using technomass analysis techniques to understand the spatiotemporal dynamic evolution of the relationship between urbanization and ESV. It suggests that the government should focus on various aspects of urbanization and selectively promote ecological protection, restoration, and construction within the identified spatial clustering areas.

The urban thermal environment in Dhaka city has been significantly impacted by rising urbanization and population growth. The research examined the spatiotemporal Surface Urban Heat Island (SUHI) phenomenon and evaluated the urban heat mitigation potential of ecosystem services using the InVEST Urban Cooling Model. Findings indicated that SUHI values in Dhaka are closely related to Land Use and Land Cover (LULC) classifications. Areas with the lowest SUHI values, primarily located around the urban fringe with abundant water, forests, and vegetation, and larger urban green spaces, showed greater cooling. Intermediate SUHI values were found in the NI and NCBD areas, characterized by grasslands and water bodies. Conversely, the urban core, with minimal vegetation, exhibited the highest SUHI values. Over the study period, the mean SUHI increased in all LULC classes, with notable rises in built-up and bare land areas, from 2.75°C to 3.24°C and 1.12°C to 1.47°C, respectively, between 2000 and 2018. However, a significant reduction in SUHI values occurred in 2020 due to

decreased commercial activities during the COVID-19 pandemic, with built-up areas dropping from 2.75°C to 1.01°C and bare soil from 1.12°C to 0.52°C. The InVEST UCM model was used to calculate the temporal changes in heat mitigation scenarios for Dhaka city, with the Cooling effects index ranging from zero to one (higher values indicating greater Cooling effects). Results showed a decrease in the average Cooling effects index from 0.57 to 0.30 between 2000 and 2020, reflecting a 47.55% reduction. Using GIS zonal statistics, the study found the highest heat mitigation index (HMI) in the rural-urban fringe area (69.85%) in 2000, and the lowest in the new industrial area (20.36%). Over the study period, the new industrial area experienced the most significant HMI decrease (-64.58%), followed by OCBD (-62.42%), fringe areas (-44.37%), NCBD (-33.22%), and the inner city (-28.44%). The study highlighted that the conversion of green spaces to other land uses significantly reduced heat mitigation capacity, especially in fringe areas and newly developed central business districts (CBD). Regions with higher HMI were mostly found in areas with better hydrological conditions and vegetation. Pearson's correlation analysis showed a significant negative correlation ($p < 0.01$) between Land Surface Temperature (LST) and HMI ($r = -0.77$). The rural-urban fringe area exhibited the strongest negative correlation in HMI changes ($r > -0.70$), followed by the inner city ($r > -0.61$), NCBD ($r > -0.46$), OCBD ($r > -0.40$), and the NI region ($r > -0.06$). The study identified a robust negative association between LST and HMI changes across the entire study area, indicating that the conversion of natural land to artificial uses has reduced HMI values.

Overall, this research provides a comprehensive view of ecosystem services and urbanization patterns, highlighting their impact on ecosystem service values (ESV). Several solutions were proposed to address this degradation, with the prevention of converting natural land to artificial land being the most crucial. The findings suggest that integrating regional parameters into ESV calculations can yield more accurate estimations. These key insights offer valuable guidance for city planners and environmentalists in Dhaka and across Bangladesh to review and enhance environmental policies. The study also recommends introducing payment for ecosystem services (PES) schemes to incentivize the preservation and restoration of natural habitats, which will improve the city's environmental quality. Finally, the key findings of this research can be considered and widely applied not only in other cities of Bangladesh but also to other international ones that are facing difficulties and challenges in their ecosystem service management, especially in urban areas.