

The cost of urbanization: Exploring the decline of ecosystem services in growing cities

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ABSTRACT

This study quantifies how rapid urbanization affects key ecosystem services in five Tanzanian cities (Arusha, Dar es Salaam, Dodoma, Mbeya, and Mwanza) using a multi-city comparative framework and spatial econometric analysis. MODIS NPP and TerraClimate hydro-climate data were integrated with spatial statistics (Global/Local Moran's I) and spatial regression models (SLM/SEM) to assess changes from 2010 to 2020. Results show substantial declines in soil water balance (25–40%) and net primary productivity-NPP (15–33%), alongside increased surface runoff (~30%), with the strongest impacts in Dar-es-Salaam and Dodoma. Significant negative relationships ($p < 0.01$) between urban expansion and ecosystem services confirm strong spatial dependence and clustered degradation, particularly along peri-urban growth fronts. By moving beyond descriptive mapping to spatially explicit inference, this study links urban form to biophysical change across diverse ecological contexts. The findings provide policy-relevant evidence to guide ecosystem-based urban planning, green infrastructure, and sustainable drainage strategies in support of SDG 11 and SDG 15.

1. Introduction

Urbanization has emerged as one of the most transformative forces shaping the Earth's surface in the twenty-first century [1,2]. While it serves as an engine of economic growth and social transformation, its rapid and unplanned expansion exerts mounting pressure on natural ecosystems and the services they provide [3]. The conversion of forests, wetlands, and agricultural lands into impervious urban surfaces alters fundamental biophysical processes such as evapotranspiration, soil infiltration, and vegetation productivity [3–5]. These changes diminish the capacity of ecosystems to regulate climate, purify air and water, and sustain biodiversity. Consequently, the degradation of ecosystem services has become a critical challenge for achieving sustainable urban development, particularly in the Global South, where the pace of urban growth often surpasses the ability of institutions to plan and manage it effectively [6–9].

Sub-Saharan Africa is experiencing some of the fastest urban growth rates in the world, driven by rapid population increase, rural-urban migration, and changing economic structures [10,11]. Tanzania exemplifies this trend, with cities such as Dar es Salaam, Dodoma, Arusha, Mbeya, and Mwanza undergoing significant spatial expansion over the

past two decades. These cities represent diverse ecological and socio-economic contexts, ranging from coastal and lacustrine environments to highland and semi-arid landscapes. Such diversity creates varying interactions between urban expansion and ecosystem processes, including vegetation dynamics, hydrological regulation, and land-atmosphere interactions [12–14]. As urban areas expand, natural landscapes are increasingly replaced by built environments, resulting in reduced ecological resilience and increasing vulnerability to environmental hazards such as flooding, water scarcity, and urban heat islands.

Although several studies have investigated the environmental impacts of urban expansion, most existing research has focused on rapidly urbanizing regions in Asia and Latin America [15–17]. For example, studies in China and India have demonstrated that urban growth significantly reduces ecosystem services such as vegetation productivity, water regulation, and carbon sequestration due to the expansion of impervious surfaces and the conversion of natural landscapes [18–20]. Similar patterns have also been reported in African cities, where uncontrolled urban sprawl has led to declining ecological resilience and increasing hydrological risks [11,21]. However, despite the rapid pace of urbanization across Sub-Saharan Africa, empirical studies that quantitatively assess the spatial relationships between urban expansion

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and multiple ecosystem services remain limited. Most studies in the African context focus primarily on land-use change detection or single environmental indicators, often without applying spatial statistical approaches to examine the strength and spatial structure of these relationships. Therefore, there remains a clear research gap in understanding how urban expansion simultaneously affects multiple ecosystem services across different African urban environments using spatially explicit analytical methods. This study addresses this gap by applying spatial econometric techniques to evaluate the relationship between urban expansion and ecosystem service decline across five rapidly growing Tanzanian cities.

This study aims to address this gap by conducting a comparative spatial assessment of urbanization and its impact on key ecosystem services across five rapidly growing Tanzanian cities between 2010 and 2020. The analysis focuses on three core ecosystem service indicators net primary productivity (NPP), soil water storage (WB), and surface runoff regulation (Q) which collectively represent the ecological capacity to sequester carbon, regulate hydrological processes, and sustain landscape productivity. The research is guided by three interrelated objectives, to: (i) quantify and map the spatial patterns of ecosystem service decline associated with urban expansion using integrated remote sensing and geospatial analysis; (ii) examine the environmental linkages between human settlement growth, land-use dynamics, and biophysical processes, highlighting the complementary roles of human geographers, who analyze urban form, population dynamics, and socio-economic transformations, and physical geographers, who investigate hydrology, vegetation change, and climatic drivers shaping the urban environment interface; (iii) apply spatial statistical models including Moran's I, Spatial Lag Model (SLM), and Spatial Error Model (SEM) in order to assess the strength and direction of the relationship between urban expansion and ecosystem service degradation, thereby generating evidence-based insights to guide urban environmental management and policy.

This study advances existing urban ecology research in three key ways. First, it adopts a multi-city comparative methodology across five

rapidly growing Tanzanian cities, enabling cross-city comparison of urbanization impacts on ecosystem services in different ecological and socio-economic contexts. Second, beyond descriptive land-cover mapping, the study applies spatial econometric models (Moran's I, Spatial Lag Model, and Spatial Error Model) to explicitly quantify the spatial dependence and strength of relationships between urban expansion and ecosystem service decline. Third, the analysis integrates perspectives from physical geography (hydrology and vegetation dynamics) and human geography (urban form and settlement expansion) to interpret urban environment interactions. By aligning the findings with SDG 11 (Sustainable Cities and Communities) and SDG 15 (Life on Land), the study provides policy-relevant evidence for ecosystem-based urban planning in rapidly urbanizing African cities.

2. Materials and methods

2.1. Study area

The United Republic of Tanzania, located in East Africa, is bordered by Kenya and Uganda to the north, Rwanda, Burundi, and the Democratic Republic of the Congo to the west, Zambia, Malawi, and Mozambique to the south, and the Indian Ocean to the east (Fig. 1). This study focuses on five major cities in Tanzania (Arusha, Dar-es-Salaam, Dodoma, Mbeya, and Mwanza) selected for their significant urban growth and varying environmental, economic, and demographic characteristics [22]. These cities represent key urban centers across the country and serve as a valuable sample for understanding the broader impacts of urbanization on ecosystem services. Arusha, located in the northeastern highlands, is an important cultural and economic hub with a rapidly growing population. Dar-es-Salaam, Tanzania's largest city and economic capital, lies along the eastern coastline, characterized by a tropical climate and coastal ecosystems. Dodoma, the political capital, is situated in the central region and has seen considerable urbanization in recent decades. Mbeya, located in the southwest, is an important gateway city connecting Tanzania with neighboring countries. Mwanza,

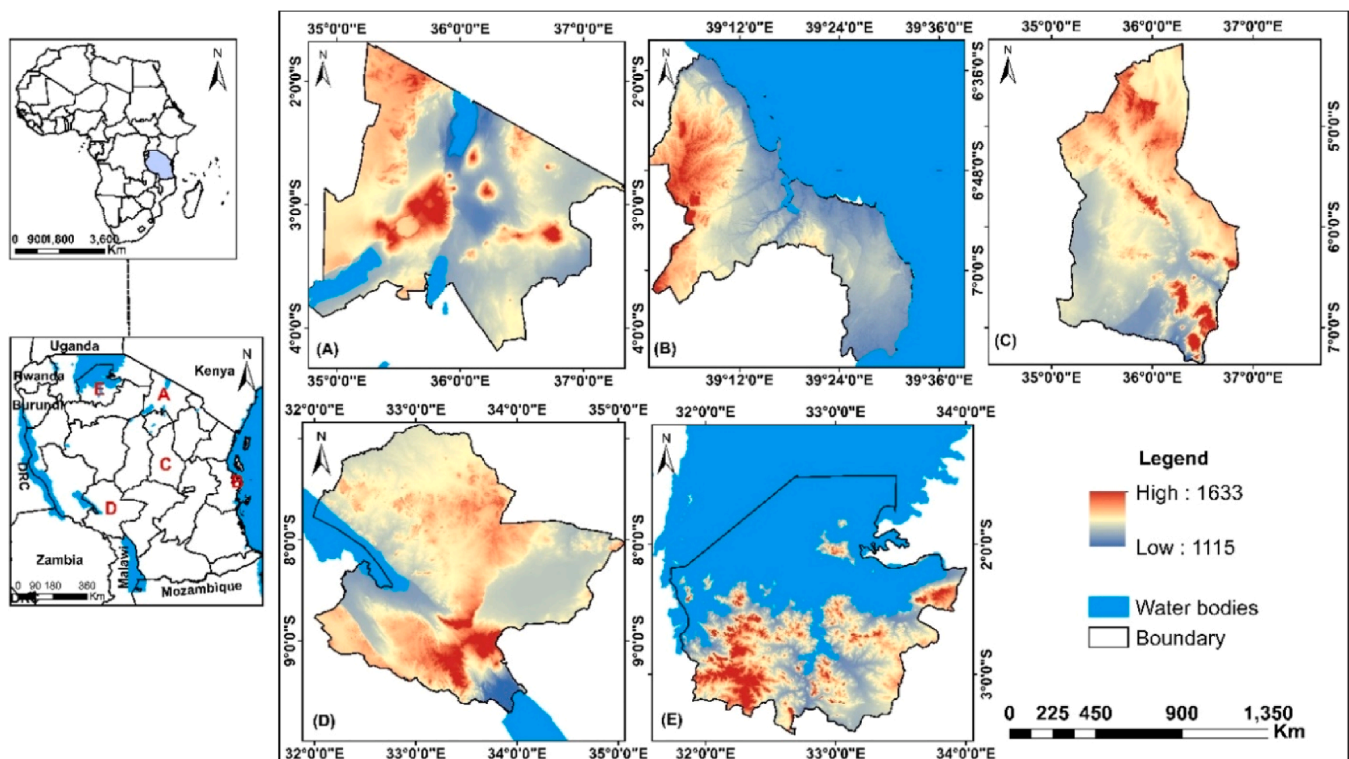


Fig. 1. Administrative division of the study area: (a) Arusha (b) Dar-es-Salaam (c) Dodoma (d) Mbeya and (e) Mwanza.

on the shores of Lake Victoria in the northwest, has a growing industrial and commercial sector.

These cities were chosen for their diverse geographical settings, population density, economic significance, and varying environmental conditions, making them ideal for studying the impacts of urbanization on ecosystem services. The study examines key parameters such as water storage, runoff, and net primary productivity (NPP) to assess how urbanization has altered the physical environment and its ability to support ecosystem services in these rapidly expanding urban centers (Table 1).

2.2. Data and analytical framework

This study employed an integrated geospatial analytical framework to assess the spatial relationships between urban expansion and the decline of key ecosystem services across five Tanzanian cities (Fig. 2). The approach combined multi-temporal satellite datasets, spatial statistical modeling, and geospatial analysis techniques to capture the dynamic interactions between land-use change and ecological functions [18,23,24]. The framework was designed to quantify three critical ecosystem-service indicators net primary productivity (NPP), soil water balance (WB), and surface runoff (Q) that collectively represent vegetation vigor, hydrological regulation, and landscape resilience. Each indicator was derived from globally recognized satellite-based products and harmonized to a common spatial resolution to ensure comparability [20,25–27]. In line with the interdisciplinary nature of this research, the framework integrates the perspectives of physical geography, which emphasizes biophysical processes and landscape dynamics, and human geography, which focuses on urban form, spatial growth patterns, and socio-economic drivers influencing ecosystem change. This integrated structure provides a comprehensive basis for analyzing how rapid urbanization alters the ecological integrity of Tanzanian cities.

Urban expansion was operationalized as a binary built-up indicator (urban = 1; non-urban = 0) to ensure consistent classification across cities and years. While this representation simplifies urban dynamics, it enables robust multi-city comparison and reduces sensitivity to classification uncertainty across heterogeneous urban forms. The indicator therefore captures contrasts between built-up and non-built-up land at the city scale examined in this study.

2.1.1. Soil water storage (Q)

Soil water storage plays a critical role in regulating ecosystem services, particularly in urban areas, where it helps mitigate flooding by providing a rapid sink for runoff and storm-water. Urbanization processes, however, significantly alter land cover, converting permeable surfaces into impervious ones, which reduces the rate of water penetration and the overall soil water storage capacity (Y [28,29]). The expansion of impervious surfaces is a key factor in increasing flood vulnerability, particularly during periods of heavy rainfall and wet climatic conditions. In many Tanzanian cities, flood-related hazards represent some of the most damaging natural disasters, exacerbating the challenges of urban resilience and sustainability [11]. For instance, a simulation of urban development in 2010 revealed that the mean runoff depth in developing urban areas was 186.34 mm, compared to 175.88 mm in rural areas, underscoring the impact of urbanization and land

Table 1
Urbanization rate and GDP of study cities.

	Arusha	Dar-es-Salaam	Dodoma	Mbeya	Mwanza
Urbanization Rate per year	5–6%	8–10%	4–5%	5–6%	5–6%
Area (urban area) Km ²	259.2	1350	2669	250	2420
GDP (USD Billions) in 2022	\$2.5	\$16.1	1.5	1.2	1.6

Source:NBS [55].

cover change on surface water storage and flood regulation (P [30,31]). The problem is further compounded by the effects of climate change [32–34] and unplanned urban expansion [16,35,36], which exacerbate the risks associated with flood hazards.

Runoff depth was used as a proxy to estimate the soil water storage capacity at the pixel level for the study area. Precipitation data were obtained from the Terraclimate dataset [25]. The USDA Natural Resources Conservation Service Curve Number (USDA-NRCS-CN) method was employed to quantify runoff depth, utilizing the hydrological soil group factor and land use/land cover classes specific to each pixel. According to the NRCS runoff equation, the runoff depth of the watershed storage is a function of the precipitation and the Curve Number (CN) (Eqs. 1 & 2).

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{1}$$

and

$$S = \frac{25400}{CN} - 254 \tag{2}$$

From the above equations, Q represents runoff depth, S is the watershed storage, P is the total precipitation, and CN is the dimensionless Curve Number, which reflects the characteristics of the land surface, including the hydraulic soil group and land use/land cover properties of the respective area. These calculations were performed using ArcMap 10.5, with soil data sourced from the harmonized FAO soil database (<http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database>). The hydraulic soil groups and CN values were estimated following methodologies outlined in previous studies [37,38] and supplementary resources from the Purdue University Long-Term Hydrologic Impact Assessment (LTHIA) documentation (<https://engineering.purdue.edu/mapserve/LTHIA7/documentation/hsg.html>).

2.2.1. Water supply (WB)

Water supply, as defined in the literature, refers to the amount of water generated through landscape runoff [39] and/or the water retained by the ecosystem [40,41]. It is a critical hydrological regulatory ecosystem service that significantly contributes to community well-being by supporting domestic needs, industrial and commercial activities, and power generation, including hydropower. Freshwater is a finite resource, and its demand is steadily increasing, making the management of water yield an essential service. Annual water yield is influenced by the water balance of a given area, which is the result of the interplay between precipitation (which adds water) and evapotranspiration (which removes water).

Water balance, in turn, is influenced by various factors, with landscape properties being a major determinant [42]. Urbanization exacerbates changes in land surface properties, increasing surface temperatures and enhancing evapotranspiration rates [21,43]. Tanzanian cities, located in tropical zones, experience a unique interaction of factors influencing water balance. Despite receiving seasonal rainfall, these cities also endure prolonged periods of high temperatures, which further intensify water loss via evapotranspiration [21]. In this study, water supply is interpreted as the balance between precipitation (P) and evapotranspiration (ET). A positive relationship exists between water supply and precipitation, while evapotranspiration negatively impacts water supply. This relationship is mathematically expressed in the following equation.

$$Q = P - ET \pm S \approx P - ET \tag{3}$$

(Wang et al., 2019)

This Eq. 3, Q represents a water supply, P denotes precipitation; ET refers to evapotranspiration, and S is the change of the water storage. On a long-time and regional scale, the change in water storage S is considered negligible [44]. Precipitation and evapotranspiration data

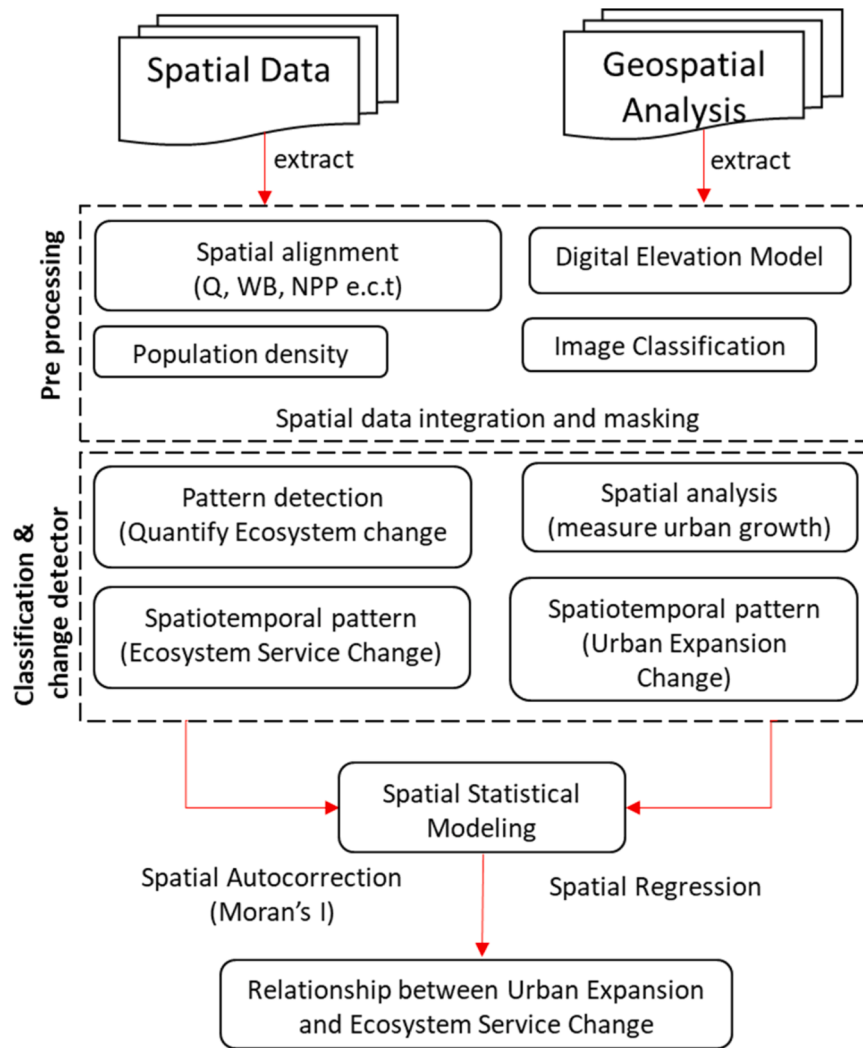


Fig. 2. Framework of the study illustrating the full methodological process linking urban expansion to ecosystem service change.

were obtained from the Terraclimate dataset raster format [25] which was accessed through the Climate Engine Database (<https://app.climateengine.com/climateEngine>).

2.2.2. Net primary productivity (NPP)

The increase in carbon emissions is a primary driver of global temperature rise and extreme weather events. In Tanzania, urbanization, along with carbon emissions and pollution, is a significant contributor to the formation of urban heat islands [45]. As plants act as critical carbon sinks, a decline in tree cover due to unplanned urban expansion poses a long-term threat to ecosystem health. Net Primary Productivity (NPP) plays a central role in terrestrial carbon cycling, regulating the balance of oxygen and carbon dioxide, and controlling atmospheric temperatures [20]. NPP is also an indicator of the ecosystem's capacity for above-ground carbon sequestration.

In this study, the MOD17A3HGF Version 6 product, which provides annual NPP data in pixel format, was utilized to map NPP for the urban ecosystems of the five cities. The annual NPP is derived from the sum of 8-day Net Photosynthesis Products (MOD17A2H) for each given year [46]. The MOD17A3HGF composite was selected due to its higher data quality, as it is derived through linear interpolation of 8-day Leaf Area Index (LAI) measurements. The dataset was accessed from the USGS NASA database using the Google Earth Engine Code Editor platform.

2.2.3. Spatial correlation test

We employed the bivariate Moran's I method to analyze the spatial correlation between urban expansion and ecosystem services, specifically examining spatial clustering and spatial dispersion, which are commonly referred to as positive and negative spatial correlations, respectively. Two types of Moran's I spatial correlation were used: Global Moran's I and Local Moran's I. Global Moran's I was applied to assess the overall extent and presence of spatial correlation between ecosystem services and urban expansion across each city. In contrast, Local Moran's I was used to examine the spatial correlation at finer, localized spatial units, identifying patterns of spatial autocorrelation within specific areas. The mathematical formulations for both methods are presented in the following equation.

$$I_{eu} = \frac{N \sum_i \sum_{j=i}^N W_{ij} z_i^e z_j^u}{(N-1) \sum_i \sum_{j=i}^N W_{ij}}$$

$$I'_{eu} = z^e \sum_i \sum_{j=i}^N W_{ij} \tag{4}$$

Where I_{eu} and I'_{eu} represent the global and local bivariate Moran's I statistics for ecosystem services and urban expansion, respectively. N denotes the total number of spatial units, and W_{ij} is an $N \times N$ spatial weight matrix used to measure the spatial correlation between the i -th

and j -th spatial units. This matrix was generated using queen contiguity with a first-order neighborhood in a 3×3 matrix [47]. Z_i^e and Z_j^u are the standardized values of ecosystem services and urban expansion, respectively, calculated using Eq. 3 for the i -th and j -th spatial units. The values of I_{eu} and I'_{eu} range from -1 to 1 . A positive I_{eu}/I'_{eu} indicates a positive spatial correlation between ecosystem services and urban expansion, meaning that a pixel with high ecosystem service values is likely to be surrounded by pixels with similarly high urban expansion values. Conversely, a negative I_{eu}/I'_{eu} value signifies a negative spatial correlation, where high ecosystem service values are surrounded by pixels with low urban expansion values. The greater the absolute value I_{eu}/I'_{eu} , the stronger the spatial correlation between ecosystem services and urban expansion. The statistical significance of the bivariate Moran's I was assessed using permutation tests, with 999 permutations conducted in this study [47,48]. The significance threshold for spatial correlation between ecosystem services and urban expansion was set at $p < 0.05$ based on the obtained pseudo-values.

The bivariate Local Indicator of Spatial Association (LISA) method was employed to visualize local spatial correlations, generating Moran scatter plots, cluster maps, and corresponding significance maps. This method illustrates the relationship between the value of ecosystem services at a given location and the average urban expansion value of neighboring locations at a specified significance level. The four quadrants generated by the bivariate LISA represent distinct types of local spatial autocorrelation: Quadrant I (high-high, HH) indicates high ecosystem service values surrounded by high urban expansion values; Quadrant II (high-low, HL) indicates high ecosystem service values surrounded by low urban expansion values; Quadrant III (low-high, LH) indicates low ecosystem service values surrounded by high urban expansion values; and Quadrant IV (low-low, LL) indicates low ecosystem service values surrounded by low urban expansion values.

Spatial correlation analysis was conducted using GeoDa 1.12 software, with input grid data first prepared and projected to the desired coordinate system. All grids were resampled to a 500 m resolution in ArcGIS 10.5 to optimize computational efficiency and reduce processing time. The urban expansion dataset was constructed to capture both spatial and temporal dimensions of urbanization. Urban pixels were reclassified with a value of 1, while all other pixels were assigned a value of 0. The reclassified images from 2010 to 2020 were then aggregated, with pixels that had the highest value (2) representing areas with the most extensive and longstanding urban development. To refine the spatial correlation analysis and enhance statistical robustness, all input variables were standardized using Eq. 5. This standardization ensured that the variables were on a comparable scale, minimizing potential bias in the spatial correlation calculations.

$$u_{ij} = \frac{U_{ij} - U_{i.min}}{U_{i.max} - U_{i.min}} \tag{5}$$

Where u_{ij} is represents the standardized value of U_{ij} , which is the original value of the i -th value of the input variable (ecosystem services or urban expansion) at the j -th spatial unit. $U_{i.max}$ and $U_{i.min}$ denote the maximum and minimum values across all grids, respectively.

2.2.4. Spatial regression analysis

In this study, spatial regression analysis techniques were employed to examine the spatial response of ecosystem services to urbanization processes in the cities of Arusha, Dar-es-Salaam, Dodoma, Mbeya, and Mwanza, Tanzania. Specifically, two spatial regression models were utilized: the Spatial Lag Model (SLM) and the Spatial Error Model (SEM). These models extend the traditional Ordinary Least Squares (OLS) regression by incorporating a spatial weight matrix that defines the geographic structure of spatial dependencies, where neighboring locations are assumed to influence the central location. This spatial structure is essential for accurately modeling spatially correlated data. Both the

SLM and SEM are considered more appropriate than OLS for spatial data with autoregressive properties, as they account for spatial dependencies among variables and spatial error correlations, respectively. The SLM captures direct spatial dependencies between variables, while the SEM models the spatial dependence in the error terms, as represented in Eq. 6 below.

$$Y = \rho WY + X\beta + \epsilon$$

$$Y = X\beta + \lambda W\mu + \epsilon \tag{6}$$

Where: Y is an $N \times 1$ vector representing the dependent variable (i.e., the standardized values of ecosystem services) for each cell in the study area. X is an $N \times M$ matrix of independent variables, which includes the values of urbanization-related variables (e.g., CUL values) and constants. The W is the spatial weight matrix that captures the spatial relationships between neighboring units, β is the corresponding vector of regression coefficients, and μ represents the spatially autoregressive error term, while ϵ is the random error term. ρ and λ denote the spatial lag parameter and spatial error parameter, respectively, which account for spatial dependence in the lagged dependent variable and the error structure.

The regression analysis was conducted using a three-step approach to examine the spatial dependence of ecosystem services on urban expansion. Initially, Ordinary Least Squares (OLS) regression was performed to explore the relationship between ecosystem services and urban expansion. The most appropriate model between the Spatial Lag Model (SLM) and the Spatial Error Model (SEM) was then determined using the Lagrange Multiplier (LM) test. To assess the model robustness, four statistical criteria were employed: R -square, Log-likelihood, Akaike Information Criterion (AIC), and the Schwarz Criterion (SC). The optimal model was identified based on the highest R -square and Log-likelihood values, along with the lowest AIC and SC values. Finally, the regression coefficients of the independent variables urban expansion, spatial lag, and spatial error were analyzed to evaluate their effectiveness as drivers of ecosystem dynamics.

3. Results

3.1. Geospatial patterns of urban expansion

Urban expansion patterns in the five rapidly growing cities of Tanzania: Dar es Salaam, Dodoma, Arusha, Mbeya, and Mwanza can be analyzed through three key aspects: scale, morphology, and natural background. In terms of scale, the largest urban growth was observed in Dar es Salaam and Dodoma, which saw substantial increases in urban areas over the decade. Dar es Salaam expanded by 279.73 km² to 418.89 km², while Dodoma's urban area grew from 38.15 km² to 132.85 km². The rapid growth in Dodoma can also be attributed to the government's decision to shift the government offices from Dar es Salaam to Dodoma, which has significantly influenced the city's expansion. This political move has led to increased investments in infrastructure, services, and administrative functions, attracting both people and businesses. In comparison, Arusha, Mbeya, and Mwanza experienced more modest urbanization, with area increases ranging from 12.23% to 28.06%. These figures reflect a trend where urban growth accelerated

Table 2
Areal increase and urban expansion of the 5 cities 2010–2020.

Region	Area increase (AI in km ²)		Urban expansion (%)	
	2010	2020	2010	2020
Arusha	31.12	59.21	12.23	22.17
Dar-es-Salaam	279.73	418.89	16.83	25.21
Dodoma	38.51	132.86	1.47	5.083
Mbeya	6.20	14.63	11.90	28.06
Mwanza	2.54	4.68	10.91	20.10

significantly in the latter part of the decade, especially in 2020 (Table 2).

The morphology of urban expansion in these cities follows a clear pattern of outward growth, primarily concentrated around the Central Business Districts (CBDs). This centrifugal expansion suggests that urbanization tends to radiate from the city center, with residential, commercial, and industrial developments spreading outward. The central areas, often characterized by higher economic and social activities, attract more people and businesses, further stimulating growth. This pattern of expansion is largely driven by factors such as resource availability, industrialization, improved transportation and communication infrastructure, and the concentration of economic and recreational opportunities (Fig. 3). Finally, the natural background in which these cities are located plays a critical role in shaping urban growth patterns. Dar es Salaam, located along the coast, faces challenges related to flooding and runoff, while Dodoma, situated in a semi-arid region, has seen more modest environmental impacts despite its rapid urbanization. In contrast, cities like Arusha and Mbeya, which lie in more diverse ecological zones, exhibit different ecological responses to urbanization, with varying effects on water balance, vegetation, and ecosystem services. The interaction between the natural environment and urban growth highlights the regional complexity of urban expansion across these cities.

3.2. Spatial patterns of ecosystem services

The spatial distribution of ecosystem services demonstrates considerable variation, reflecting the diverse landscapes and ecological conditions across different regions. Provisioning services, such as agricultural productivity, are shaped by factors including climate, soil quality, and land management practices, leading to distinct spatial patterns of service availability. Similarly, regulating services such as water purification and climate regulation are influenced by the composition and health of specific ecosystems, resulting in geographic variations in their distribution [49]. Cultural services, such as

recreational opportunities and aesthetic value, are likewise impacted by the spatial arrangement of ecosystems and their accessibility to human populations. Fig. 4 illustrates the spatial distribution of three key ecosystem services: Water Balance (WB), Net Primary Productivity (NPP), and Runoff Depth (Q) across five cities in Tanzania. The analysis reveals notable differences in the provision of these services across the cities. For example, Arusha exhibited the lowest NPP, while Dodoma recorded the highest NPP. In contrast, Arusha had the highest (Q), with Dodoma showing the lowest values for this metric. Regarding WB, Dodoma demonstrated the highest levels, whereas Mbeya had the lowest. These variations highlight the complex and context-dependent nature of ecosystem services across urban areas in Tanzania.

3.3. Spatial correlations between ecosystem services and growth

The global bivariate Moran's I results show an interesting variation in the correlation between the three ecosystem services and the urban expansion at a confidence interval of 5% (Table 3 and Fig. 5).

NPP showed a constant negative spatial relation with urbanization in all five major cities of Tanzania. However, the degree of the negativity varies, with Mbeya and Dar-es-Salaam cities showing the highest negative spatial correlation (Moran's I value of -0.527 and -0.479 , respectively). This suggests that carbon sequestration and oxygen cycling by the ecosystem in these two cities are drastically declining with the urbanization rate. For the case of Arusha and Dodoma, the lowest degree of negative correlation suggests that NPP is less drastically declining than in Mbeya and Dar-es-Salaam.

WB was an ecosystem service with many variations between the five selected cities. WB was prepared to show the balance between water gain and loss via precipitation and evapotranspiration. Arusha, Mwanza, and Dodoma had positive Moran's I value (0.404 , 0.217 , and 0.177 , respectively) suggesting that more water was retained. The reason for this can be adduced to the loss of vegetation and the replacement by less evaporative surfaces such as impervious surfaces of roads and buildings

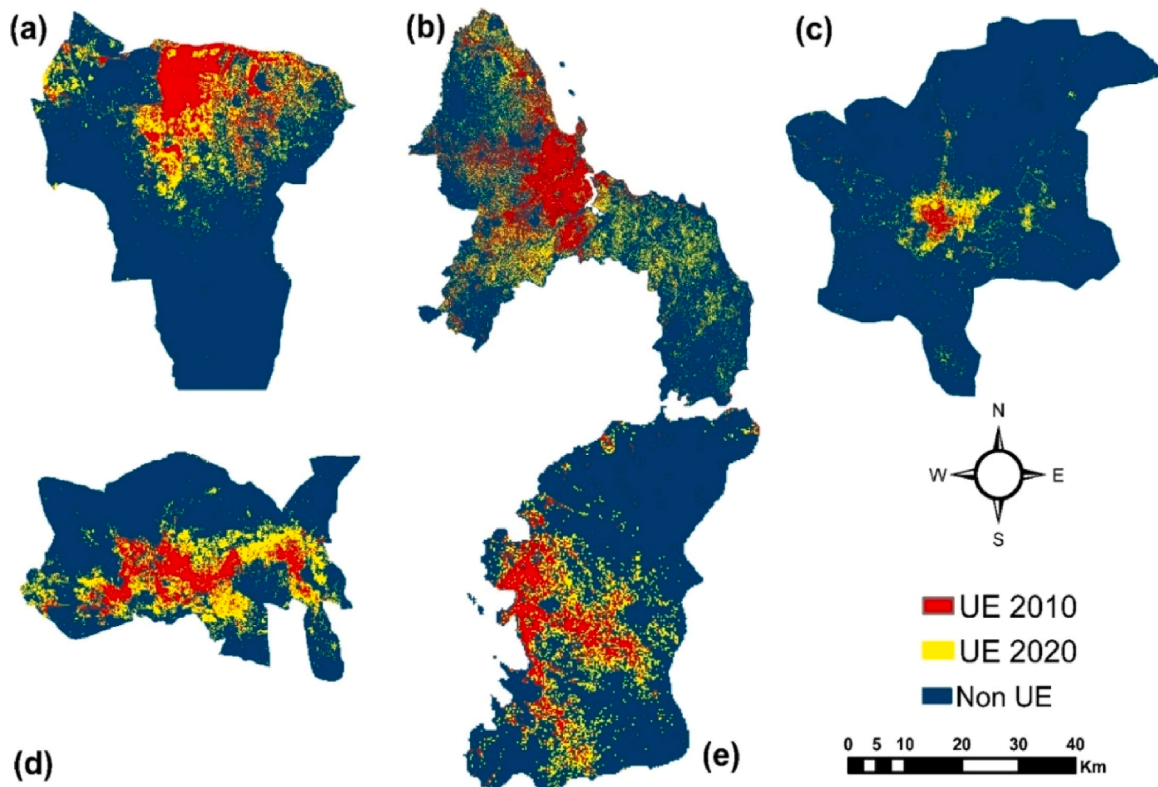


Fig. 3. Urban expansion pattern.

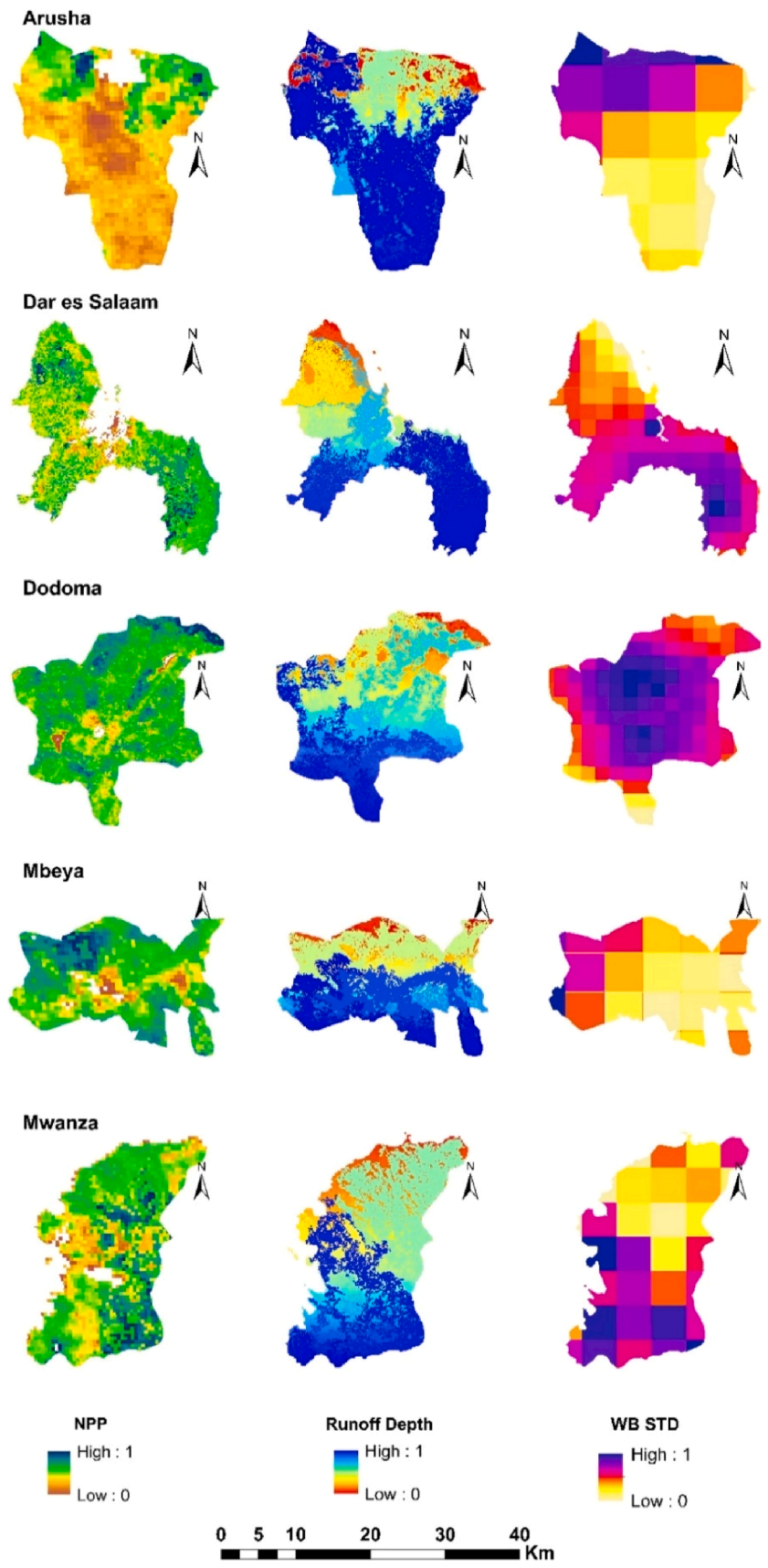


Fig. 4. Spatial patterns of ecosystem services.

Table 3
Bivariate Moran's I analysis between individual ecosystem services and urban expansion.

Ecosystem services	Arusha	Mbeya	Mwanza	Dodoma	Dar-es-Salaam
NPP	-0.102	-0.527	-0.269	-0.119	-0.479
Q	0.406	0.381	0.06	0.257	0.216
WB	0.404	-0.124	0.217	0.177	-0.093

whilst rainfall may remain less affected. Mbeya and Dar-es-Salaam had a

negative correlation between WB and urban expansion and thus peculiar correlation can be caused by climate change and the decline of rainfall in parts of Tanzania [21,50] including parts of Mbeya and Dar-es-Salaam.

Runoff depth (Q) reflects the amount of water available on the surface runoff. It reflects the ability of the ecosystem to control surface runoff by storing a part of surface runoff to mitigate overflows and other water-related disasters. In all of the five analyzed Tanzanian cities, runoff depth has a positive spatial correlation with urban extension. This signifies a constant decline in the water storage capacity of the ecosystem in these cities as a result of urban expansion. In Dar-es-

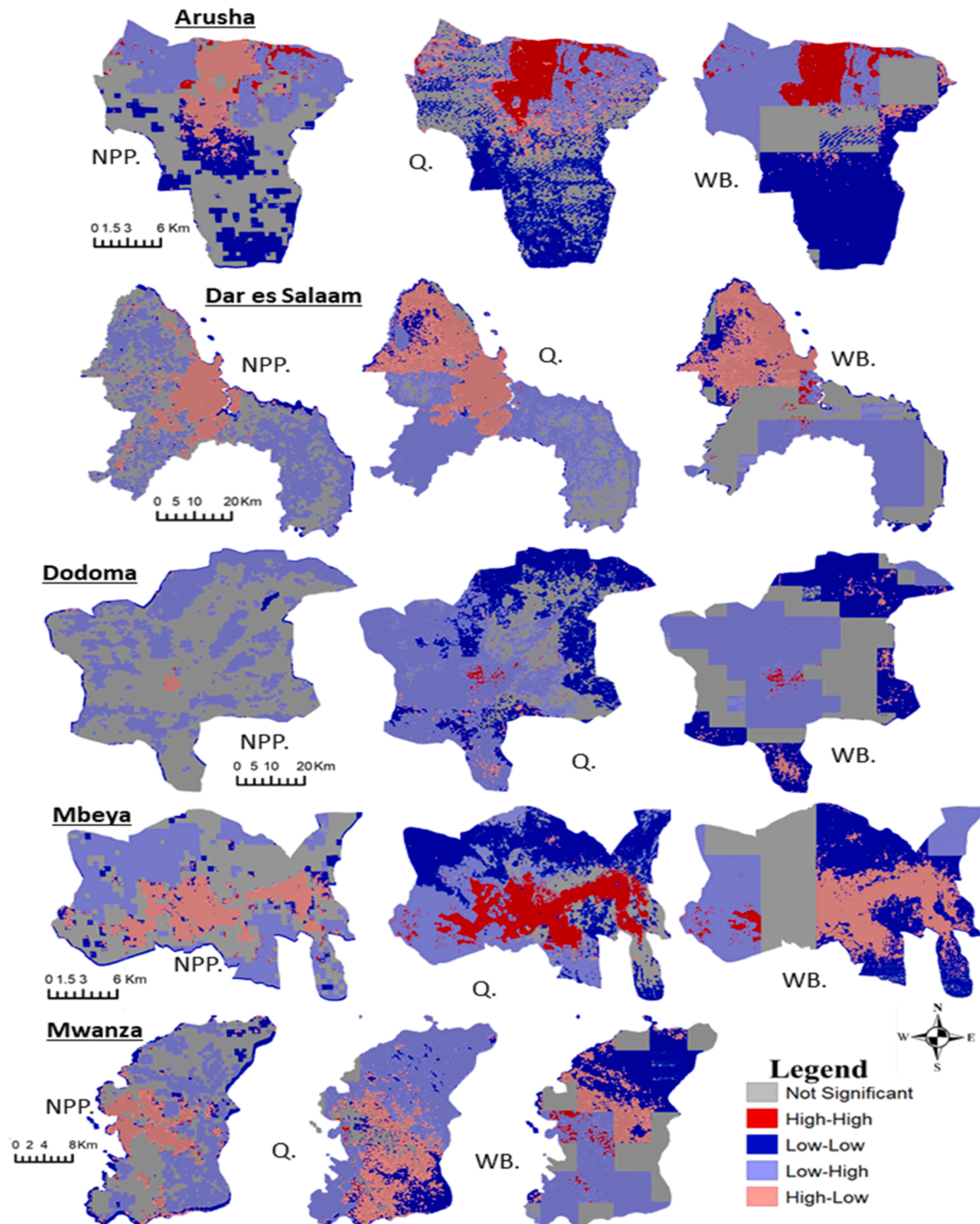


Fig. 5. LISA cluster maps between individual ecosystem services (NPP - Net primary productivity, Q - Runoff Depth, and WB - Water Balance) with comprehensive urbanization level.

Salaam, urban expansion had a seemingly high positive correlation value with runoff depth (0.216) suggesting the city to be the most affected (compared to the other cities) as reflected by the recent urban flooding and water-related disasters such as waterborne diseases (like malaria and cholera) caused by the stagnant waters [51].

Another key observation arises from the Local Indicators of Spatial Association (LISA) cluster map generated through the bivariate Moran's I analysis, which examines the relationship between individual ecosystem services and the urbanization process. The analysis reveals a marked decline in ecosystem services within the city centers of the five major cities studied. High-High (HH) clusters are concentrated around the city centers, indicating urban areas with elevated water supply levels. This pattern is likely the result of increased impervious surface development, which enhances surface runoff and reduces evapotranspiration. Conversely, Low-Low (LL) clusters are predominantly found in the peripheral areas, farther from the urban centers. A consistent spatial pattern across all five cities is observed, where the regions just beyond the urban boundaries exhibit High-Low (LH) values, suggesting that these areas are less impacted by urbanization and retain relatively intact ecosystem functions. This uniformity in the distribution of ecosystem services highlights the gradient of urbanization and its effects on ecosystem integrity.

The results (Fig. 4) indicate that non-significant areas are predominantly located in the periphery, away from the city center, exhibiting a spatial pattern similar to that of urban expansion. This suggests that in these areas, urbanization alone may not be the primary driver of ecosystem variations, and other factors may also contribute to the observed spatial distribution of ecosystem services. The strong spatial clustering observed in Moran's I, LISA maps, and spatial regression results indicates that the binary built-up indicator captures meaningful contrasts between urban and non-urban land at the city scale examined in this study.

3.4. Spatial dependence

Table 4 summarizes the Ordinary Least Squares (OLS) regression results for the relationship between urban expansion (UE) and three key ecosystem service indicators WB, Q, and NPP across five Tanzanian cities. The low R² values (mostly below 0.2) suggest that OLS alone inadequately captures spatial dependence between urbanization and ecosystem functions. Moran's I values were significant at the 1% level for nearly all models, confirming the presence of spatial autocorrelation. The high values of the LM-lag and LM-error tests further indicate that the SLM and SEM outperform OLS in explaining the observed relationships. The robust LM diagnostics identified the most appropriate spatial model for each ecosystem service and city, demonstrating that spatial regression provides a more reliable and realistic framework for analyzing how urban expansion influences ecological dynamics.

Spatial regression results revealed that NPP exhibited significant positive spatial lag coefficients in all cities, suggesting that vegetation productivity is spatially clustered and influenced by neighboring conditions. However, urban expansion consistently showed negative relationships with NPP, indicating that increasing built-up areas diminish vegetation productivity, with the strongest effects observed in Arusha, Dodoma, and Dar es Salaam. Runoff (Q) displayed positive spatial dependence across all cities, implying that urbanization increases surface runoff and reduces infiltration, particularly in Arusha and Dodoma. Water balance (WB) demonstrated mixed responses: negative in Dar es Salaam and Mbeya signifying reduced groundwater recharge and slightly positive in Dodoma, Arusha, and Mwanza, possibly due to localized hydrological resilience. These findings collectively confirm that spatial models capture the spatially structured nature of ecosystem service degradation, emphasizing the interconnectedness of urban ecological processes across Tanzanian cities (Table 5).

Table 4 Results of OLS regressions between individual ecosystem services and urban expansion for the five cities.

Variables	Mwanza			Mbeya			Dar			Dodoma			Arusha		
	WB	Q	NPP	WB	Q	NPP	WB	Q	NPP	WB	Q	NPP	WB	Q	NPP
Constant	0.430945	0.525071	0.546448	0.221231	0.493537	0.512853	0.593303	0.773715	-992.457	0.628079	285.447	-93.2133	47.2559	0.432493	-286.717
UE	0.109235	0.064395	-0.14575	-0.07652	0.088199	-0.18172	7.41E-07	1.24E-05	0.453245	0.110945	57.6361	-525.538	11.1779	0.313955	-1484.96
R-square	0.041866	0.015953	0.080735	0.031006	0.124215	0.261405	0.000002	0.00264	0.003151	0.034687	0.082514	0.011452	0.121771	0.329499	0.065746
Log Likelihood	232.588	289.928	338.952	243.698	851.625	583.556	1270.85	6465.22	-61393.1	6454.88	-54140.5	-87971.7	-104.237	-60.2015	-9838.54
AIC	-461.175	-575.856	-673.903	-483.396	-1699.25	-1163.11	-2537.7	-12926.4	122790	-12905.8	108285	175947	212.473	124.403	19681.1
SC	-450.236	-564.916	-662.964	-473.563	-1689.42	-1153.28	-2524.14	-12912.9	122804	-12891.3	108300	175962	222.43	134.359	19691
Moran's I	1.7638	46.6765	41.6635	57.7065	28.7891	26.6505	155.2965	112.0087	112.572	193.6738	114.1352	81.1458	56.2973	18.6486	35.1712
Lagrange Multiplier (lag)	5015.586	2055.087	1872.371	3277.252	874.7154	878.3931	24078.42	12494.49	12671.56	37307.2	12784.36	6667.761	3153.312	670.509	1314.907
Robust LM (lag)	85.717	28.4053	153.5374	26.0582	68.0896	186.3598	0.1534	0.8508	21.0861	294.3689	205.057	96.2247	126.5496	346.596	98.1475
Lagrange Multiplier (Error)	4967.942	2158.48	1719.162	3280.783	813.9374	697.1419	24078.58	12524.38	12650.71	37453.1	13004.45	6571.94	3123.666	340.5132	1216.799
Robust LM (Error)	38.0722	131.7986	0.3285	29.5891	7.3116	5.1086	0.3181	30.7373	0.239	440.2767	425.1538	0.4042	96.9036	16.6009	0.0395

4. Discussion

This section discusses the implications of the findings for understanding urban-driven ecosystem service decline and for informing ecosystem-based urban planning in rapidly growing cities. Building on this overall framing, the first objective, to quantify and map the spatial patterns of ecosystem service decline, revealed that degradation is spatially heterogeneous and concentrated along peri-urban growth fronts. This pattern reflects the spatial diffusion of urbanization described by Alonso's land-use theory and the urban environmental transition model, whereby urban expansion radiates outward from city cores and consumes ecologically productive land along development corridors. The marked declines in NPP and water balance in Dar-es-Salaam and Dodoma further highlight how ecological responses to urban pressure vary across coastal, highland, and semi-arid contexts. Taken together, these results show that the multi-city comparative perspective strengthens inference by demonstrating that the magnitude and configuration of ecosystem service decline depend on local biophysical and socio-economic conditions. The spatially explicit results also demonstrate the utility of geospatial indicators as early-warning signals for identifying ecological hotspots under urban pressure.

Beyond identifying where degradation occurs, the second objective examined the linkages between settlement growth, land-use change, and biophysical processes, confirming a strong coupling between socio-economic development and environmental response. The observed relationships between land conversion, reduced soil water balance, and increased surface runoff align with human-environment systems theory, which emphasizes how social processes drive physical environmental change. By integrating perspectives from human geography (urban form and settlement dynamics) and physical geography (hydrology and vegetation processes), the analysis provides a more comprehensive explanation of ecosystem service decline. The consistency of these patterns across cities further indicates that land-use change associated with urbanization is a dominant driver of ecosystem vulnerability in rapidly growing African cities.

While the first two objectives clarify spatial patterns and underlying processes, the third objective demonstrates the methodological contribution of this study. Significant Moran's I statistics and spatial regression coefficients show that ecosystem service degradation exhibits strong spatial dependence, with clustered impacts along infrastructure corridors and peri-urban growth fronts. This confirms that urban ecological change is spatially structured rather than randomly distributed and that spatial econometric models provide more reliable inference than non-spatial approaches. Importantly, the direction and magnitude of the estimated effects are consistent with findings from China, India, and Latin America, suggesting that the trade-offs between urban expansion and ecosystem functionality observed in Tanzania reflect broader processes operating in rapidly urbanizing regions. By providing new empirical evidence from sub-Saharan Africa and applying a transferable spatial econometric framework, this study contributes insights that extend beyond the case cities and can inform ecosystem-based urban planning in other data-scarce contexts.

The first objective to quantify and map spatial patterns of ecosystem service decline was achieved through spatial analysis of NPP, soil-water balance, and runoff. The spatial patterns reveal that ecosystem degradation is not uniform but concentrated in peri-urban areas where development pressure is most intense. This reflects the diffusion pattern of urban growth theorized by Alonso, [52] and later by the urban environmental transition model, suggesting that spatial expansion radiates outward, consuming ecological space along growth corridors. The reduction in NPP and WB across Dar es Salaam and Dodoma highlights how different ecological zones respond uniquely to urban stress, emphasizing the value of a multi-city comparative approach. These findings reinforce the argument that quantitative spatial analysis can provide an early-warning mechanism for identifying ecological hotspots vulnerable to urban pressure.

Table 5
Results of the spatial regression models.

Variables	Mwanza			Mbeya			Dar-es-Salaam			Dodoma			Arusha		
	WB	Q	NPP	WB	Q	NPP	WB	Q	NPP	WB	Q	NPP	WB	Q	Variables
WES	0.961847		0.839866	0.982058	0.748017	0.802196	0.989394	0.850911	0.883763	0.990121	0.797344	0.760073	0.977683	0.71951	W_ES
LAMBDA		0.794819		0.227976	0.121563	0.105921	0.584459	0.7774644		0.63208	0.536842				LAMBDA
Constant	0.01503	0.513417	0.0884	-0.00515	0.031816	-0.05351	-7.76E-07	1.34E-05	-118.952	-0.27747	0.111315	-21.552	0.007111	0.08369	Constant
UE	0.008921	0.117105	-0.03169	0.958295	0.527898	0.658197	0.978371	0.670748	0.704097	0.978031	0.570141	-126.33	0.011636	0.143212	UE
R square	0.90342	0.540096	0.593364	1698.208	1110.19	907.766	12916.51	9599.644	57972.7	24889.78	7580.999	85907.7	0.958275	0.61854	R square
Log Likelihood	2044.31	850.4786	929.262	-3392.42	-2214.37	-1809.53	-25829	-19195.3	-57972.7	-49775.6	-15158	-171821	1394.85	191.878	Log Likelihood
AIC	-4082.63	-1696.96	-1852.52	-3382.58	-2199.62	-1794.78	-25815.5	-19181.7	115972	-49775.6	-15143.5	171843	-2783.7	-377756	AIC
SC	-4066.22	-1686.02	-1836.12	-3382.58	-2199.62	-1794.78	-25815.5	-19181.7	115972	-49761.1	-15143.5	171843	-2768.77	-362.821	SC

The second objective to examine the environmental linkages between human settlement growth, land-use dynamics, and biophysical processes was addressed by analyzing how socio-economic development interacts with physical environmental systems. The results demonstrate a close coupling between demographic change, land conversion, and hydrological disruption. This aligns with the human environment systems theory, where social processes (settlement expansion, infrastructure development) directly drive physical responses such as reduced infiltration and altered runoff. In this study, both human geographers concerned with spatial form and population density and physical geographers focused on hydrological and ecological systems contribute complementary insights that explain the mechanisms behind ecosystem decline. The observed reduction in soil-water balance and rise in surface runoff across multiple cities exemplify this interdisciplinary relationship, confirming that human-induced land-use change is the dominant factor influencing ecosystem vulnerability.

The third objective to apply spatial statistical models to determine the relationship between urban expansion and ecosystem-service degradation was achieved using Moran's I and spatial regression techniques. The results showed strong spatial dependence, meaning that urban-induced ecological changes tend to cluster spatially, particularly along infrastructure corridors and peri-urban growth fronts. This spatial clustering supports the idea of spatial diffusion of urbanization, a concept central to urban growth models, where development spreads through adjacent influence rather than random dispersion. The significant coefficients in the spatial lag and error models indicate that as urban area increases, ecosystem services decline in a predictable, statistically measurable pattern. Comparatively, these results mirror global studies from China [19], India [18,53] and Latin America [15,54], which report similar trade-offs between urban expansion and ecosystem functionality. By providing new empirical evidence from sub-Saharan Africa, this research expands the global understanding of urban ecological interactions and underscores the urgent need for planning frameworks that integrate ecosystem-based management into city development policies.

A limitation of this study is the use of a binary urban indicator, which does not capture gradients of urban intensity such as building density, impervious surface fraction, or functional land-use diversity. As a result, the estimated effects reflect contrasts between urban and non-urban land rather than incremental changes in urban intensity. Future research should incorporate continuous urban metrics (e.g., impervious surface fraction, GHSL built-up density, or nighttime lights) to better capture within-urban variation and refine estimates of urban ecological impacts.

5. Conclusion

This study advances understanding of how rapid urbanization affects the flow of key ecosystem services across five Tanzanian cities. By integrating geospatial data and spatial statistical modelling, it demonstrates that urban expansion significantly reduces net primary productivity, soil water balance, and runoff regulation, confirming that the physical environment's capacity to provide essential services declines as built-up areas intensify. These findings directly respond to the study's objectives quantifying ecosystem-service decline, examining human environment linkages, and modelling spatial interactions while extending urban growth theory through evidence of structured ecological trade-offs. Compared to prior studies focused on vegetation or carbon sequestration [11,20,39], this research provides a broader spatial perspective, highlighting how land conversion and infrastructure development alter soil and water-related functions crucial for sustaining urban ecosystems.

The observed decline in ecosystem services underscores the urgent need to embed ecosystem-based planning and monitoring within urban governance frameworks. Policies promoting green infrastructure, sustainable drainage systems, and wetland restoration can mitigate the

impacts of impervious surface expansion while enhancing resilience to water shortages and flooding. Future research should build on this work using higher-resolution data, machine learning techniques, and socio-economic indicators to capture finer-scale variations in ecosystem response. Integrating ecological valuation with spatial planning can help balance development goals and environmental sustainability, advancing progress toward SDG 11 (Sustainable Cities and Communities) and SDG 15 (Life on Land) while shaping a more resilient urban future for Tanzania and other rapidly urbanizing regions.

Disclosure statement

The authors declare no conflicts of interest.

Data availability statement

The data supporting this study's findings are available from the corresponding author, upon reasonable request.

Supplementary Materials: The authors declare that no supplementary materials are associated with this manuscript.

CRedit authorship contribution statement

Neema Simon Sumari: Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Fanan Ujoh:** Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Camillius Sanga:** Writing – review & editing.

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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