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RESEARCH ARTICLE

The Disappearing Green: Ecosystem Service Loss in Atlanta, Georgia

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Abstract

Urban green spaces play a critical regulatory role in sustaining ecosystem functions, however, rapid urbanization has significantly altered land-use patterns, reduced green cover, and intensified both urban heat island effects and air pollution in many cities around the world. This study assesses the spatiotemporal land-use/land-cover (LULC) changes in Atlanta, Georgia, and examines their effects on ecosystem services, urban heat island (UHI) intensity, and air-quality conditions. Landsat imagery from 1995, 2005, 2015, and 2025 was processed using Support Vector Machine (SVM) classification to quantify LULC transitions, while NDVI-based emissivity land surface temperature (LST) retrieval and interpolated PM2.5 concentrations were used to evaluate thermal and air-quality patterns. Results indicate substantial ecosystem service depletion, with forest cover declining by 19.94% and water bodies by 65.17%, while developed land increased by 83.46% between 1995 and 2025. UHI analysis for 2025 showed temperatures ranging from 21.8°C in vegetated zones to 38.4°C in highly urbanized areas, representing a relative UHI intensity of 16.6°C. Air-quality patterns revealed similarly concerning trends, with PM2.5 concentrations rising to 18–22 µg/m³ in built-up areas over 40% higher than levels in undeveloped areas. The study identifies uncontrolled population growth, urban sprawl, and infrastructure expansion as key drivers of these changes and recommends promoting infill development, expanding green infrastructure, and integrating nature-based solutions such as green roofs and bioswales in future urban planning.

Keywords: Urban Green Spaces · Land-Use Change · Biodiversity Loss · Urban Development · Green Infrastructure

Highlights

- Significant land use changes have occurred over the years, favouring the decline in green spaces in Atlanta.
- Loss of natural regulating resources burdens governing institutions and residents economically.
- Disadvantaged groups often bear a disproportionate share of environmental risks and challenges.
- Proactive planning backed by ecological principles must be prioritised in urban development.

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1. Introduction

Over the years, humanity has been dependent on nature through its provision of food, water, quality air, greenery, and life support. The concept, "Ecosystem Services," gained international recognition in the wake of concerns about the high pressure on the limited available resources, where it sought to ensure a balance in the depletion of environmental resources (Grunewald & Bastian, 2015). Ecosystem services are the provisions made available by the ecosystems to support human well-being. The concept has been used in many scholarly fields; in spatial planning, it has been used to integrate ecosystem services with environmental planning and sustainability (Von Haaren, 2011).

The global urban population is expected to increase astronomically from 4 billion in 2016 to 6 billion by 2040 (Doe et al., 2022) . The urban population of the United States currently stands at 82%, and current projections suggest that by 2040, this figure could be 87%. In the Southern United States, one of the most populous metropolitan areas that is growing at a rapid rate is the Atlanta Metropolitan Area (AMA). The current population of the AMA stands at 6.1 million as of 2020 and is expected to hit 7.9 million by 2040 (De Carvalho et al., 2023). The population growth in the area has a direct impact on land use resulting in a transition from natural areas to developed lands.

Urbanisation is typically characterised by land cover changes, which directly lead to the loss of ecosystem services, typically green spaces. The loss of these green spaces also directly leads to the loss of the benefits that ecosystem services provide to the urban population. As a result of the excessive degradation associated with urbanisation, major cities such as Atlanta are susceptible to environmental impacts such as lower air quality, increased greenhouse gas (GHG) emissions, and a higher likelihood of flooding. Furthermore, the deforestation propelled by urban expansion also affects the quality and integrity of wildlife, and it also affects watershed levels, resulting in lower water quality in urban areas.

Cities around the world are channelling resources towards creating cities that are economically, socially, and environmentally viable. A major factor that contributes to sustainable urban development is green spaces, i.e., natural and multifunctional spaces that provide social, environmental, and economic advantages to cities Appiah-Opoku et al., (2023). These green spaces are broadly defined to include parks, community woodlands, street trees, wetlands, playgrounds, and residential greenery. Due to their unique characteristics, their roles cut across the three primary facets of sustainable development, making them a key factor to consider in creating cities that are sustainable and liveable.

Irrespective of the significant contributions that green spaces provide to the urban population, urbanisation, competing land uses, and neglect have resulted in the rapid depletion of green spaces in major cities across the world. For instance, most cities in the Republic of South Africa and China have less than 10% of public park coverage in their total land area. The total coverage of green spaces in New York City is estimated at around 14% of the city's landmass (Brown and Lee, 2016; Smith et al., 2019). In Kumasi, a city historically renowned for its parks and open spaces, urban development has gradually reduced natural cover so that only about 10% of the urban area now consists of green spaces (Thompson and Green, 2015; Walker et al., 2018). In Asian megacities like Mumbai, rapid population growth and infrastructural expansion have constrained green cover to less than 8% of the city's overall landscape (Huang and Chen, 2019; Patel et al., 2021). This pattern of diminishing urban green spaces appears to be a broader trend across major cities in America, Europe, and Asia (Miller and Kumar, 2020; Doe et al., 2022).

Although numerous studies have examined land-use change, forest decline, hydrological alterations, and urban heat island dynamics in the Atlanta Metropolitan Area, meaningful gaps remain. Much of the foundational work relies on older Landsat sensors or focuses on shorter temporal windows, limiting the ability to detect long-term ecological trajectories (Sun et al., 2018; Terando et al., 2014; Van Metre et al., 2019). Existing Atlanta-focused studies typically analyse sprawl, forest loss, or hydrological impacts in isolation rather than evaluating how these changes collectively influence ecosystem services such as temperature regulation, air purification, carbon storage, and water filtration (Grunewald & Bastian, 2015; Munns et al., 2015). Consequently, the broader ecological significance of cumulative land-cover transformations, including their implications for environmental justice and resilience, remains underdeveloped within the literature (Dai, 2011; Jennings et al., 2017).

This study addresses these gaps by conducting a comprehensive, three-decade assessment using harmonised Landsat-5 TM, Landsat-7 ETM+, Landsat-8 OLI, and the newest Landsat-9 OLI-2 imagery. The employment of Support Vector Machine (SVM) classification provides greater reliability and class separability than traditional classification methods frequently used in past studies (Maulik & Chakraborty, 2017; Katukotta et al., 2025). This enables consistent comparison of land-cover categories and more precise quantification of landscape transitions, such as the 82.46% increase in developed land, the 19.94% decrease in forest cover, and the 65.17% loss of water bodies, changes that earlier studies have not fully captured with updated sensor technology (Wulder et al., 2016; Roy et al., 2014).

A major contribution of this work is the integrated assessment of land-use change, PM2.5-based air quality, and urban heat island intensification, an analytical triad rarely combined in Atlanta-focused environmental research. Prior studies have examined UHI and pollution separately (Harlan et al., 2015; Zhong et al., 2019; Ulpiani, 2021), but few have demonstrated how declining forest cover and expanding impervious surfaces simultaneously exacerbate PM2.5 concentrations and thermal hotspots (Hirabayashi & Nowak, 2016; Ryu et al., 2019; Chen et al., 2024). By interpreting these outcomes through the lens of ecosystem service decline, this study advances a functional, service-oriented understanding of Atlanta's environmental trajectory. This approach offers planners and policymakers an evidence-based foundation for nature-based interventions, green-infrastructure planning, and long-range strategies that protect ecological integrity and enhance resilience across the metropolitan region.

Therein lies the motivation for this study, which seeks to uncover the rates of greenspace depletion in the Atlanta Metropolitan Area, assess the air quality of the area, assess the heat island vulnerability of the area, and identify key factors abating the depletion and discuss policy interventions to curb this menace. The Paper is structured in six sections, including this introductory section. The next section presents an extensive literature review on ecosystem services and their role in urban sustainability. The third section presents the study setting, methods, and materials on how LULC maps and other maps were generated. The fourth section presents the results and discussion of the study's findings, further exploring the impacts of the loss of ecosystem services. The fifth section discusses some policy implications and recommendations, concluding with the last chapter, which presents a summary of this study.

2. Conceptual Framework And Literature Review

2.1. Overview of Ecosystem Services

Ecosystem services are the numerous advantages that natural systems offer to human beings and consist of provisioning, regulating, supporting, and cultural services. Provisioning services are the provision of food, water, and raw materials, whereas regulating services are the mechanisms through which ecosystems influence natural phenomena, for example, climate regulation and flood control. Supporting services, the ones necessary for the generation of other ecosystem services, comprise soil formation, photosynthesis, and nutrient cycling. Cultural services are immaterial benefits associated with recreation, aesthetic pleasure, and spiritual inspiration derived from nature (Munns et al., 2015). These services' interdependence highlights ecosystems' vital function in promoting human well-being, economic development, and culture.

The degradation of these services due to human activities, land use, and climate change is of serious concern to human livelihood and biodiversity. Ecosystem degradation or loss results in the loss of services they supply, hence making communities that are dependent on such natural resources more vulnerable (Shepard et al., 2011; Tomscha et al., 2019). A comparison of historical contexts highlights the enduring impacts of ecosystem degradation, which can be applied to inform restoration and policy interventions aimed at promoting service provision (Dallimer et al., 2015). Solutions that focus on sustainable management, restoration activities, and the incorporation of ecosystem service assessments into the decision-making process are essential for mitigating the negative impacts related to ecosystem loss (Goldberg et al., 2020). In the context of the "vanishing green," understanding and valuing ecosystem services is crucial for making effective advocacy and policy-making. The integration of ecosystem service considerations into development and conservation strategies can enable the prioritisation of initiatives that ensure ecological well-being and community resilience (Thrush et al., 2017). As such, specific programs towards the restoration and conservation of ecosystems can be improved not just in terms of biodiversity but also in the essential services that underpin human communities.

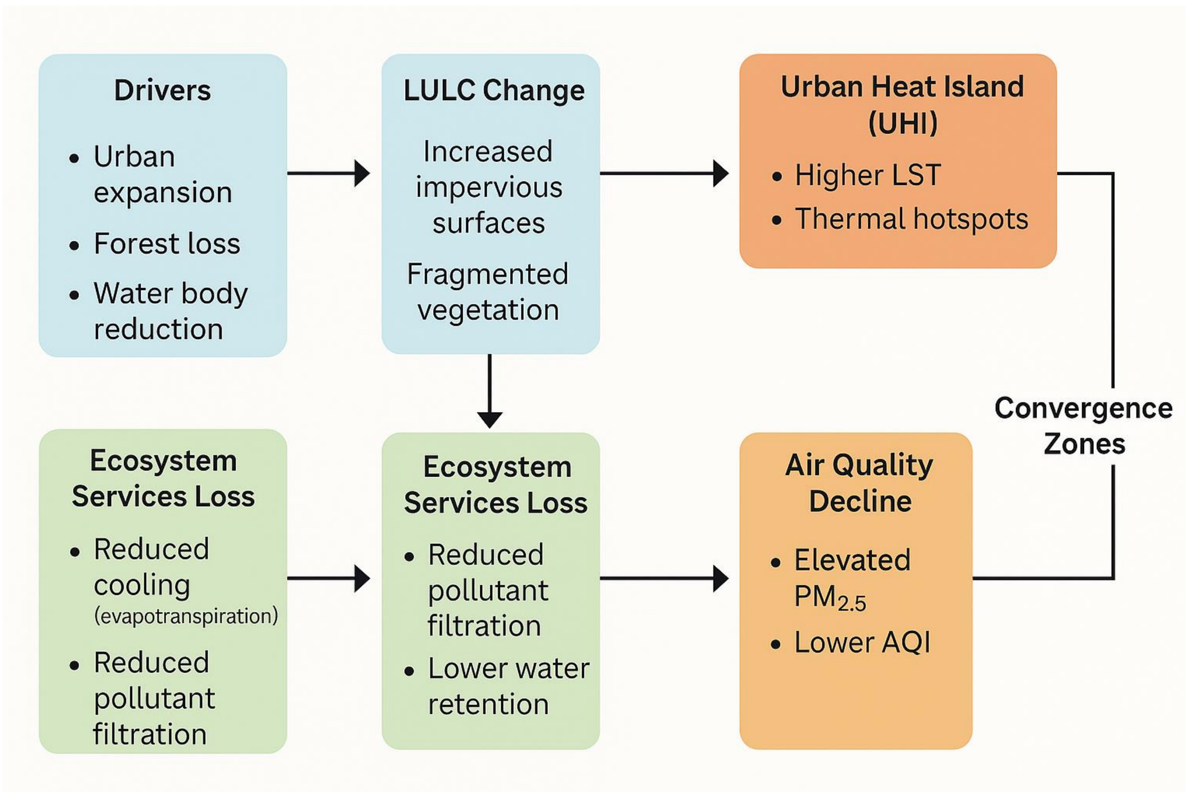

Figure 1. Conceptual Framework of LULC Change, Ecosystem Services, UHI, and Air Quality Interactions

2.2. Their Role in Urban Sustainability

Ecosystem services (ES) play a key role in fostering urban sustainability by providing essential benefits that contribute to the quality of urban life. Urban ecosystems have the potential to reduce climate-related effects, enhance air and water quality, and foster biodiversity, all of which are vital to the resilience of urban regions in the face of rapid development and climate change. With the growth of cities, incorporating ES into urban planning becomes more necessary. This requires a critical examination of the potential and flow of ecosystem services, along with analysis of the socio-economic drivers influencing these processes (Wilkerson et al., 2018; Cattani et al., 2023).

Urban green spaces (UGS) are most significant because they provide multiple functions, including carbon storage, regulation of microclimate, and enhancement of recreation and cultural uses (Breuste et al., 2013; McPhearson et al., 2014). These services not only aid ecological balance but also public health by promoting physical activity and wellness (Bertram & Rehdanz, 2015; Jennings & Gaither, 2015). With the increased demand for UGS, the challenge is to preserve and enhance these areas so that they are no t degraded and can continue to provide essential services (Semeraro et al., 2021). Furthermore, comprehensive urban planning needs to consider the complexity of ES interactions, synergies, and trade-offs (Ziter, 2015). Effective approaches can involve designing ecological networks that enhance connectivity and resilience in urban landscapes and enforcing green building codes that foster sustainable urban infrastructure (Sangha, 2024). In summary, recognising and harnessing the potential of ecosystem services (ES) is crucial in creating sustainable urban ecosystems that adapt to changing ecological conditions while promoting community health and ecological integrity (Song et al., 2020).

2.3. Overview of Theories Related to Urbanisation and Green Space Loss

Urbanisation has significant consequences for the pattern of green spaces and the respective ecosystem services. Urban Political Ecology emphasises the socio-political factors that underlie the preference for development over nature conservation within urban areas. This theory views urban growth not merely as a change in spatial form, but also as an expression of power relationships, where the disadvantaged tend to suffer most from decreased green spaces (Dai, 2011; Yu et al., 2017). It accounts for how urban planning choices can result in disparity within the supply of green spaces, with a definite impact on socioeconomically disadvantaged populations (Dai, 2011; Wilkerson et al., 2018).

The Ecosystem Services Framework offers a comprehensive way of valuing urban green spaces. The framework classifies services into four types: provisioning, regulating, cultural, and supporting, thereby emphasising the role green spaces play in human well-being and environmental health (Fomba et al., 2024). It focuses on the necessity of including ecosystem service assessments in urban planning to ensure sustainable management of these areas that are central to urban resilience and public health (Mace et al., 2015; Dobbs et al., 2017). Urban Heat Island (UHI) Theory describes the impact of urbanisation on regional climate and temperatures. City temperatures are far higher relative to rural areas due to human activities and man-made features, according to the UHI theory. Decline in green spaces exacerbates the UHI effect because vegetation cools the air through evapotranspiration (Zhou & Wang, 2011; Yang & Li, 2023). The theory calls for an immediate increase in urban green spaces as a heat risk mitigation measure for climate change (Zhou & Wang, 2011).

2.4. Overview of Policies Framework on Green Space Conservation in the US

The preservation of urban green areas in the United States has its roots in various policy frameworks established to deal with problems arising from fast urbanisation. Among the inherent components of such programs is the Urban Forestry Act, which assists cities in enhancing tree cover and green areas, thereby expanding ecosystem services like carbon storage, air quality, and biodiversity, as Wang et al. (2023) show. This legislation authorises federal funding and sets a model for local governments to establish urban forestry programs to install and care for trees as part of urban infrastructure. Along with this, the Environmental Protection Agency (EPA) outlines programs that bring the conservation of green areas into environmental planning at the federal level. The Environmental Protection Agency's dedication to urban sustainability is reflected in its policies for mitigating urban heat islands and enhancing air quality by supporting the preservation and creation of green space (Littke, 2016; Kim et al., 2019). Its policies encourage stakeholder involvement and community participation to ensure that residents are not merely passive beneficiaries but also active contributors to green space management.

In addition, the idea of preserving biodiversity in urban planning is more commonly being included in planning techniques, and as such, local governments are assessing green spaces according to their ecological value. Green space strategies are slowly recognising the function these spaces serve to provide wildlife habitats in urban areas and the greater ecosystem (Lee et al., 2015; Gallo et al., 2017). Importantly, zoning ordinances have also helped preserve green spaces that already exist and direct new developments within urban areas to incorporate ecological features like native vegetation and habitat connectivity (Whitten, 2022). Further, the

Green Infrastructure Initiative supports multifunctional landscapes delivering ecological advantage in addition to augmenting leisure opportunities for city residents. The innovative strategy here is not only to expand biodiversity but also to supply aesthetic and social gains, emphasising the central importance of green areas in cities (Zakka et al., 2017). Overall, these policies form a strong framework aimed at protecting urban green areas, thereby guaranteeing their contribution to sustainable and resilient urban ecosystems.

3. Methods

This study employed a multi-temporal set of Landsat observations to document land-cover transitions in the Atlanta Metropolitan Area over a thirty-year period. Landsat imagery was selected because the program offers the longest, most consistent archive of medium-resolution Earth observation data globally, providing an ideal foundation for longitudinal environmental assessments. Its 30-meter spatial resolution is especially appropriate for analysing the mixture of built-up, vegetated, and transitional surfaces characteristic of large U.S. metropolitan regions.

Four cloud-free Landsat scenes representing approximately decadal intervals were used: Landsat-5 TM (1995), Landsat-7 ETM+ (2005), Landsat-8 OLI (2015), and Landsat-9 OLI-2 (2025). These data were downloaded from the USGS Earth Explorer platform. Because the imagery originated from different generations of sensors, it was necessary to harmonise them to ensure comparability. Landsat-5 TM and Landsat-7 ETM+ scenes were converted to surface reflectance using LEDAPS-based atmospheric correction procedures, while Landsat-8 and Landsat-9 datasets were corrected using the LaSRC algorithm, which processes reflectance retrievals for OLI sensors. This approach ensured that differences in sensor calibration, atmospheric conditions, and spectral response functions did not introduce spurious trends into the multi-temporal analysis.

Each image was converted from digital numbers to top-of-atmosphere radiance, then to top-of-atmosphere reflectance, and finally to atmospherically corrected surface reflectance. The official Atlanta city limits were obtained from the Atlanta Regional Commission and used to extract the study area from each Landsat scene, ensuring that all analyses were performed within a consistent spatial boundary.

The study area boundary was obtained from the Atlanta Regional Commission (ARC) Open Data website (https://opendata.atlantaregional.com/datasets/coaplangis::official-atlanta-city-limits-open-data/explore), which provides the official Atlanta city limits in shapefile format.

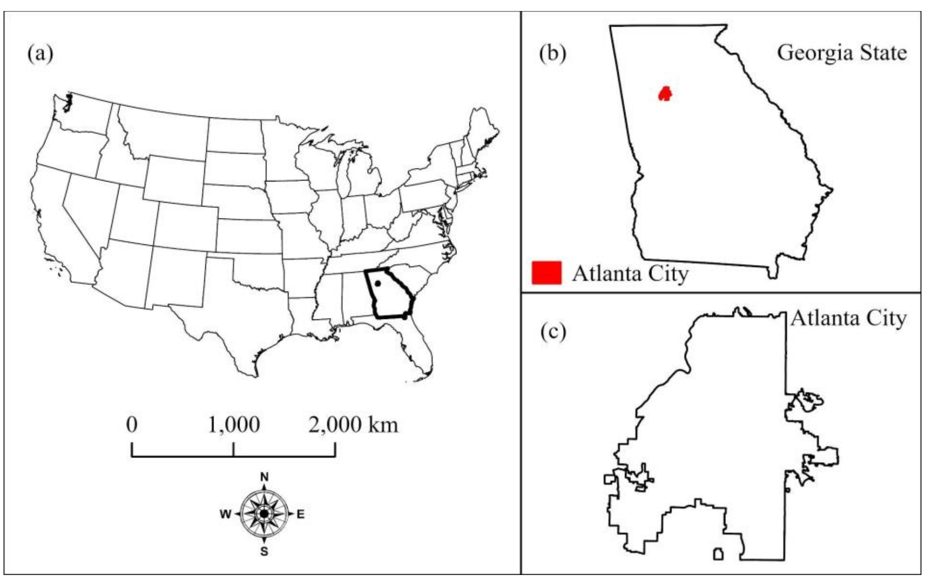

Figure 2. Map of Atlanta showing its boundaries and context within Georgia and the United States of America

Land-cover classification was carried out using the Support Vector Machine (SVM) algorithm implemented in ArcGIS Pro. SVM was selected due to its strong performance in distinguishing spectrally similar materials such as concrete, bare soil, and mixed vegetation common in heterogeneous urban landscapes. The classifier was applied independently to each time period but followed the same workflow to maintain methodological consistency. Four land-cover classes were mapped: Forest, Developed land, Water and Barren.

Training samples were created through manual digitisation using multiple false-colour composites to maximise spectral separability. At least 50 polygons were collected for each category for each year, with sampling distributed across the full spatial extent of the city. To reduce bias, training and validation datasets were separated: 70% of polygons were used for training, and 30% were reserved exclusively for accuracy assessment.

All samples were cross-checked using temporally matched high-resolution imagery available in Google Earth Pro. Ambiguous or mixed pixels were removed, and additional samples were added in areas where spectral overlaps were likely. This iterative refinement helped reduce potential classification confusion between forest and shrubland, between barren and built-up areas, and between water bodies and darkly shadowed surfaces.

Each classification result was evaluated using a confusion matrix. Producer's accuracy, user's accuracy, overall accuracy, and the kappa statistic were calculated for all four years. These metrics allowed the study to quantify the reliability of the classifications and ensured that the multi-temporal comparison was grounded in robust accuracy assessment.

3.1. Urban Heat Island Analysis

Urban heat patterns were assessed using an emissivity-corrected Land Surface Temperature (LST) retrieval for 2025. Thermal infrared data (Band 10) from Landsat-8/9 TIRS were processed through a sequence of steps. First, digital numbers were converted to at-sensor radiance using radiometric calibration constants. Radiance values were then transformed into brightness temperature (Kelvin) using the standard Landsat thermal conversion formula.

Because emissivity varies across land-cover types, an NDVI-based emissivity correction was applied. NDVI thresholds were used to distinguish bare ground, mixed pixels, vegetated areas, and water bodies. Land surface emissivity was estimated for each pixel and incorporated into the final LST equation:

$$LST = \frac{BT}{1 + (\frac{\lambda \cdot BT}{\rho}) ln\, (\varepsilon)}$$

where BT represents brightness temperature, λ is the wavelength of emitted radiance, ρ is a constant derived from Planck's law, and ε is emissivity. The final LST product was expressed in degrees Celsius.

To highlight the relative intensity of heat across the city, a UHI raster was created by subtracting the coolest LST value in the study area from each pixel. This approach identifies localised thermal hotspots without requiring comparison to a rural reference zone.

3.2. Air Quality Analysis

Air quality analysis was based on annual PM2.5 concentration and Air Quality Index (AQI) data obtained from EPA monitoring stations in and around Atlanta. A total of twenty-four (n = 24) stations were included, though their spatial distribution is not uniform; most are located in the central and northern portions of the metropolitan area.

Because the number of monitoring stations is limited and their distribution does not meet the statistical assumptions required for kriging (e.g., stationarity and sufficient spatial density), Inverse Distance Weighting (IDW) was used to interpolate PM2.5 and AQI values into continuous surfaces. IDW is well-suited for sparse datasets because it assigns greater influence to nearby points and does not rely on variogram modelling. The resulting raster surfaces were generated at 30-meter resolution to match the LULC and LST datasets, enabling spatial comparison.

The interpolated surfaces were compared visually and descriptively with land-cover and temperature outputs to identify general patterns. Converging zones of high PM2.5 and elevated temperatures were highlighted as areas where environmental stressors co-occur.

4. Results And Discussions

This section summarises the findings in terms of land use and land cover change (LULCC) analysis, air quality, and urban heat island (UHI) effect to evaluate how anthropogenic pressure has changed the provision of ecosystem services.

4.1. Land Use Land Cover Change

Urban expansion has been the primary driver of significant land cover changes in the Atlanta Metropolitan Area throughout the three-decade period from 1995 to 2025. Four main groups are identified through the analysis of classified Landsat imagery and land cover statistics: developed, forest, water, and barren regions (see Figure 3). A comparison of LULC in the chosen years reveals significant changes in land distribution as well as a clear urbanisation tendency.

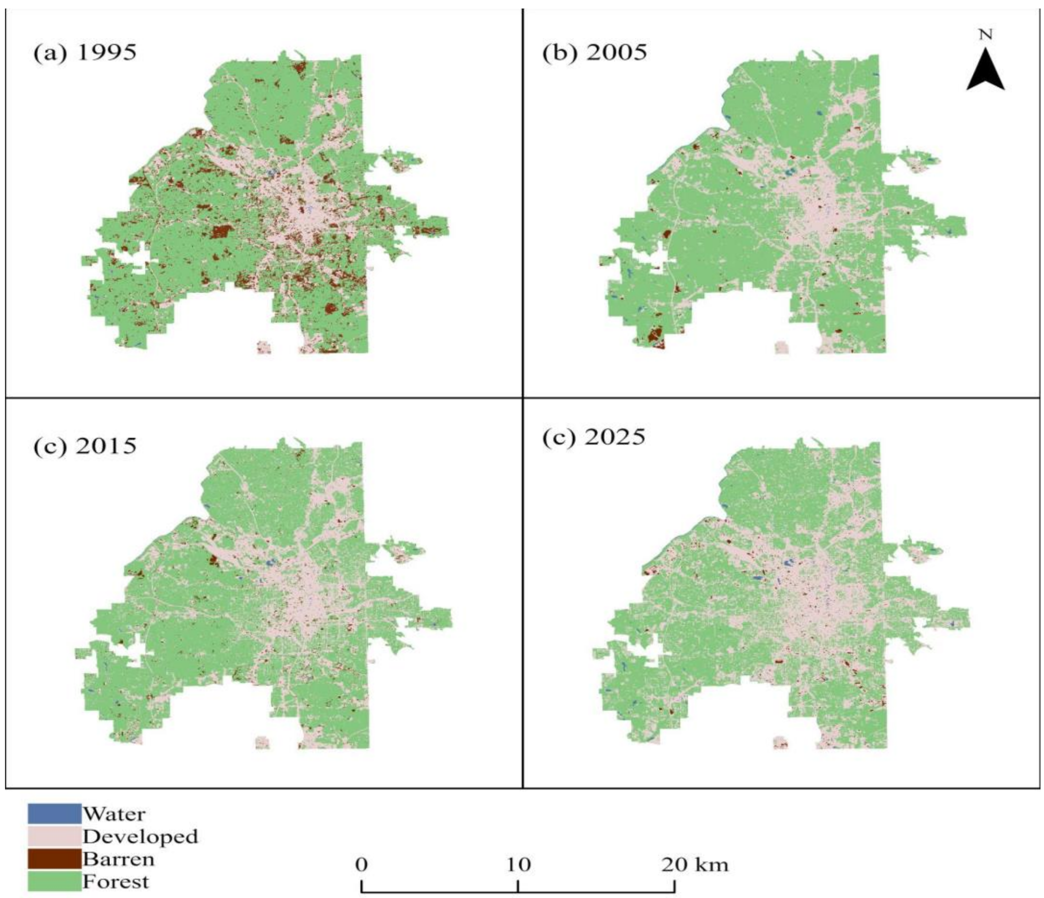

Figure 3. Atlanta Metropolitan Area Land Cover Classification Map (1995–2025) (Source: Authors' construct, 2025.)

From Table 1, forest areas decreased from 287,308 ha in 1995 to 230,000 ha by 2025, representing a 19.94% decline. While forest loss occurred gradually, averaging 4.29%, 7.27%, and 9.80% over each decade, the cumulative impact is ecologically significant. The continuous deforestation has ramifications for carbon sequestration, biodiversity, and climate regulation. Forest fragmentation significantly diminishes landscape connectivity, threatening ecosystem resilience. The most noticeable change is the 82.46% rise in developed land from 1995 to 2025, from 86,107 ha to 157,125 ha. Particularly between 2005 and 2025, when growth continuously exceeded 21% every decade, urban development has expanded steadily. By replacing permeable surfaces with impervious infrastructure, this growth has mostly come at the expense of forests, water bodies, and arid landscapes. This has increased runoff, changed hydrology, and intensified heat island effects.

Water bodies decreased by 65.17%, from 2,585 ha in 1995 to only 900 ha in 2025. This loss is likely due to both the physical conversion of wetlands and small lakes, as well as degradation caused by neighbouring development. Meanwhile, barren lands, often transitional or underdeveloped buffer zones, have decreased by 77.45%, indicating that these areas were among the first to be developed for infrastructure and habitation. The high coefficients of variation for water (38.42%) and barren lands (51.74%) indicate significant year-to-year variability and vulnerability to anthropogenic activities.

Table 1. Statistics on Land Use and Land Cover Change (1995–2025)

Category	1995	2005	2015	2025	% Change (95–05)	% Change (05–15)	% Change (15–25)	% Change (95–25)	CV (%)
Water	2,585	2,300	1,700	900	-11.03%	-26.09%	-47.06%	-65.17%	38.42%
Developed	86,107	104,225	128,825	157,125	+21.03%	+23.64%	+21.94%	+82.46%	24.15%
Barren	15,525	10,000	6,000	3,500	-35.59%	-40.00%	-41.67%	-77.45%	51.74%
Forest	287,308	275,000	255,000	230,000	-4.29%	-7.27%	-9.80%	-19.94%	8.38%
Total	391,525	391,525	391,525	391,525					

4.2. Air Quality

To further understand the interaction between land cover patterns, thermal conditions, and air quality, a simple correlation assessment was performed. PM2.5 concentrations were compared with land surface temperature values derived from the emissivity-corrected LST map, as well as with the percentage of developed land within buffer zones surrounding the monitoring stations. The results showed that areas with higher development intensity and elevated LST values tended to exhibit higher PM2.5 concentrations, consistent with the co-occurrence of UHI hotspots and degraded air quality illustrated in Figure 4. These findings reinforce the link between the expansion of impervious surfaces, heat retention, and localised declines in air quality.

Air quality and thermal comfort in the Atlanta area have been directly impacted by ecosystem degradation in addition to changes in land use. Where urban density is highest, there is a localised decline in air quality, according to a spatial study of EPA monitoring station air quality data interpolated using IDW. Higher particulate matter (PM2.5) concentrations and lower AQI ratings are found in areas with the most loss of green cover.

From Figure 4, high PM2.5 zones (b) are associated with low AQI zones (a), particularly in central and northwestern part of the city. This This highlights PM2.5's role as a primary contributor to the overall decline in air quality (Cheng et al., 2021). These degraded zones are likely associated with extensive urban development, high traffic volumes, and poor vegetative cover. The loss of forest areas, as documented in the LULC data, directly reduces the ecosystem's regulating services. Trees and plants serve as natural filters for airborne pollutants such as PM2.5 (Hirabayashi & Nowak, 2016; Ryu et al., 2019; Nowak, 2023). The 19.94% loss of forest over three decades certainly impaired natural filtration, resulting in higher PM concentrations.

According to Jennings and Gaither (2015), urban green spaces are critical for reducing particle exposure and improving public health, especially in densely populated areas.

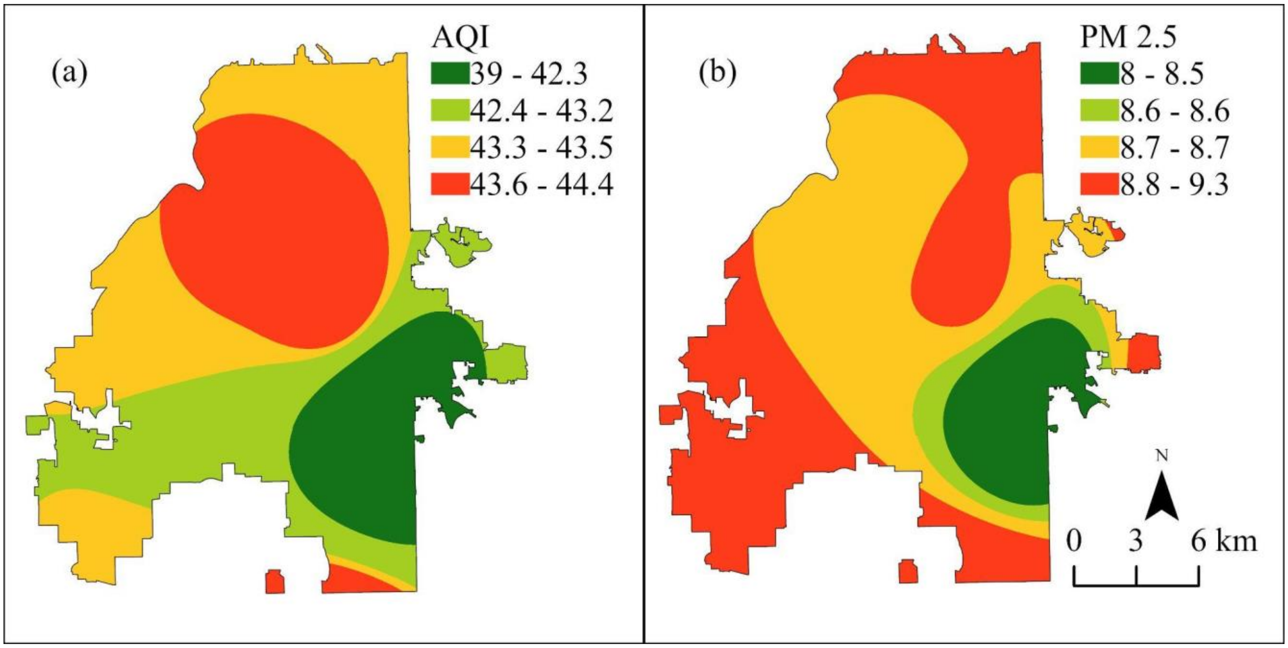

Figure 4. Spatial distribution of Air Quality Index (AQI) and PM2.5 concentration (Source: Author's construct, 2025.)

Moreover, PM2.5 levels exceeding 8 µg/m³ can pose long-term respiratory and cardiovascular hazards (WHO, 2021; Chen et al., 2024; Sangkham et al., 2024). Residents of central and northern Atlanta are disproportionately exposed to these dangers, which is consistent with urban political ecology theory (Dai, 2011; Jennings et al., 2017), which holds that lower-income or marginalised communities are frequently subjected to poor environmental conditions. The increased AQI and PM2.5 readings are most likely associated with urban heat island (UHI) zones already found in the 2025 thermal imaging. Areas with higher PM2.5 tend to retain more heat, resulting in a feedback loop of poor air quality and high temperatures (Zhou et al., 2023). The UHI effect prevents air mixing and traps pollutants at the surface.

4.3. Heat Island Effect

The UHI map created from Landsat thermal data reinforces this finding: high-temperature zones are significantly associated with areas of intensive development and scant vegetation. The replacement of vegetated areas with impermeable surfaces increases heat absorption and decreases evapotranspiration, resulting in higher urban temperatures and thermal discomfort. Temperatures vary from 0°C (green zones) to around 22.3°C (red zones). Urban Heat Island creation is inextricably connected to land cover change and urban expansion. According to LULC data from Table 1, Atlanta's forest cover decreased by approximately 20% between 1995 and 2025, while built land increased by approximately 82%. This is consistent with Zhou & Wang (2011) and Yang & Li (2023), who found that impermeable surfaces and vegetation loss increase solar heat retention and reduce nighttime cooling, exacerbating UHI impacts. These data lend support to the Urban Heat Island Theory, which describes built-up regions as thermal hotspots caused by anthropogenic heat, diminished vegetation, and albedo.

Additionally, the loss of vegetative land impairs regulatory services like temperature regulation, air purification, and stormwater management. According to Anbazu & Antwi (2023) and Chen (2023), urban green spaces (UGS) are critical for moderating UHI through shading and evapotranspiration. As demonstrated by this heat map (see Figure 5), Atlanta's vegetal loss has resulted in increased localised warmth, decreased thermal comfort, and increased public health hazards, particularly for vulnerable groups. UHI hotspots are heavily overlapping with the high PM2.5 concentration and poor AQI zones (see Figure 4). This is consistent with research (e.g., Ulpiani, 2021; Zhong et al., 2019) that demonstrates UHIs impair atmospheric mixing, trapping pollutants like PM2.5 near the surface. Meenar et al. (2023) and Harlan et al. (2015) found that UHI consequences are not fairly distributed. Low-income and marginalised areas are frequently disproportionately affected due to limited access to green space, inadequate house insulation, and increased exposure to pollutants and heat stress.

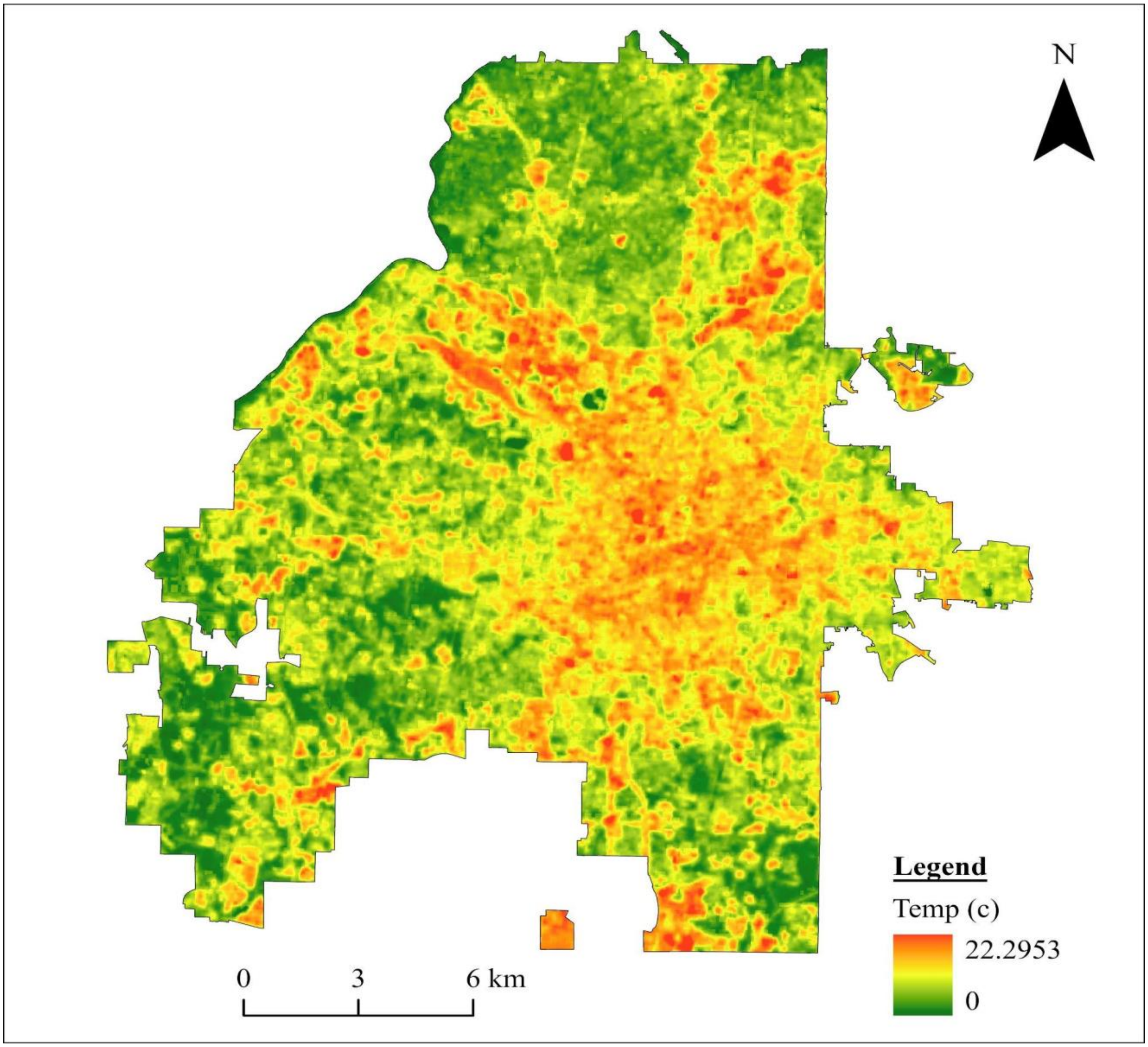

Figure 5. Urban Heat Island Intensity Map of the Atlanta Metropolitan Area (Source: Author's construct, 2025.)

Although the classification results provide clear multi-decadal trends, some uncertainty remains due to differences in Landsat sensor resolutions and the potential for classification confusion among spectrally similar classes. Water and barren land categories, in particular, may be sensitive to turbidity, seasonal moisture, and shadow effects. In addition, the air quality component relied on a limited number of EPA monitoring stations, which introduces uncertainty into interpolated PM2.5 and AQI surfaces, especially in areas far from monitoring points. These limitations do not undermine the main findings but should be considered when interpreting spatial patterns across the study area.

4.4. Key Drivers of Change

4.4.1. Urban Sprawl and Population Growth Population growth and urbanisation are central to understanding the rapid transformation of ecosystems in the Atlanta metropolitan region. As the global population has surged from 5 billion in the 1980s to over 7.8 billion in the mid-2020s (Gu et al., 2021), urban centres across the world have expanded rapidly to accommodate new demands for housing, food, and infrastructure. In the United States alone, population growth of 79 million is projected between 2017 and 2060 (Vespa & Medina, 2018). This demographic expansion fuels urbanisation, which is projected to encompass 68% of the global population by 2050 (United Nations, 2018). The Southeastern U.S., particularly Atlanta, exemplifies the impacts of this trend. Characterised by a medium-to-low-density development pattern, the region's sprawl contributes to the conversion of vast tracts of forest and water bodies into built environments (Abbasnezhad et al., 2023; Sampson et al., 2024). Our LULCC data reflect these changes starkly: developed land has increased by 82.46% from 1995 to 2025, while forest cover declined by 19.94% and water bodies by a significant 65.17%.

Urban expansion directly affects ecosystem service provision. Studies in the Upper Chattahoochee Watershed, a critical water source for Atlanta, have shown that development near water bodies degrades water quality, disrupts wildlife habitats, and diminishes carbon storage capacities (De Carvalho et al., 2023). Similarly, Van Metre et al. (2019) projected that urban land use across the Southeast, including Atlanta, could increase by 165% by 2060, with aquatic systems facing threefold increases in degraded stream kilometres. Beyond hydrological impacts, urban sprawl diminishes terrestrial ecosystem services. Li et al. (2022) and Appiah-Opoku et al. (2023) noted that the loss of green spaces directly undermines biodiversity support, local climate regulation, and the availability of recreational landscapes. Sun et al. (2018), in modelling Atlanta's land use changes from 1985 to 2012, found major declines in carbon storage and habitat quality. Abbasnezhad et al. (2023) further projected that 14,000 hectares of natural deciduous and mixed forests in the Upper Flint River Watershed would be converted to urban areas. This change will drastically reduce regional biodiversity and landscape integrity. Our data also show increased variability in water and barren land categories (CVs of 38.42% and 51.74% respectively), reflecting both ecological volatility and heightened land-use pressures.

4.4.2. Real Estate Development and Gentrification Real estate and housing development represent one of the most transformative drivers of land use change in the Atlanta metropolitan area. Fuelled by population growth, economic expansion, and a preference for low-density residential models, urban development has surged across the region. The Piedmont area, which includes Atlanta, is projected to nearly triple its urban land cover between 2009 and 2060, rising from 17,800 km² to between 40,100 and 54,800 km² (Terando et al., 2014; Van Metre et al., 2019). The LULCC data support these projections. From 1995 to 2025, developed land increased by 82.46%, growing from 86,107 to 157,125 hectares. This growth trajectory underscores how real estate expansion directly converts ecologically significant land types, particularly forests and water bodies, into impervious surfaces. This transformation is not only extensive but consistent, as indicated by the relatively low coefficient of variation for developed land (24.15%).

These changes have profound ecological consequences. Shiferaw et al. (2025 show that in Georgia, the hydrological impacts of land conversion include increased surface runoff, diminished water filtration, and erosion of stream bank stability. These findings reflect conditions observed in our dataset, where forest cover declines by nearly 20% and water area drops by 65.17%, further amplifying vulnerabilities to flood risks and water quality degradation. Moreover, as residential areas replace forests and wetlands, key ecosystem services such as carbon sequestration, biodiversity support, and microclimate regulation are severely compromised.

Sullivan et al. (2018) highlighted similar trends in Florida, where real estate expansion altered hydrology and led to habitat losses. This parallels the Atlanta region's inland transformations. Beyond ecosystem degradation, real estate-led land use change fragments habitats, creates ecological edges, and disrupts species migration patterns. Haddad et al. (2015) emphasised how landscape fragmentation can undermine ecosystem service provision on a systemic scale. Our data reveal that alongside built-up land expansion, barren areas often ecological buffers declined by 77.45%, pointing to the loss of transitional and shock-absorbing landforms.

4.4.3. Transportation Infrastructure Expansion (Highways, Transit Projects) Urban infrastructure, particularly transport networks, plays a dual role. While critical for economic activity, it imposes significant environmental costs when poorly planned. Roads, railways, and utilities often destroy habitats, encourage species migration, and facilitate the spread of pollutants (Wang et al., 2018; Chen & Chi, 2022). Our LULCC dataset reveals a striking 77.45% decline in barren land from 1995 to 2025. This reduction suggests that areas previously undeveloped or marginal, often used as buffers or corridors, have been increasingly converted into built environments, including transportation infrastructure. Such transformations compromise habitat continuity and reduce ecosystem resilience, reinforcing the argument that infrastructure expansion is a critical driver of fragmentation.

In Georgia, transportation expansion has mirrored population growth and housing demand. This includes road extensions and highway widening, contributing to the fragmentation of Atlanta's forest ecosystems (Abbasnezhad et al., 2024; Appiah-Opoku et al., 2025). Road infrastructure disrupts ecological corridors, increasing the isolation of wildlife populations and impeding gene flow. These impacts are well-documented globally, such as in the Amazon, where transportation infrastructure accelerates deforestation (Roy, 2023). Gent (2018) further emphasises that poorly aligned transport networks can isolate species, disrupt genetic diversity, and reduce ecosystem support, compounding ecological degradation.

Vehicle-wildlife collisions, reduced vegetation buffers, and increased surface runoff are common side effects of expanding transport networks, as evidenced by studies such as Gent (2018) and Chen & Chi (2022). These highlight how transportation infrastructure contributes to ecological fragmentation and compromised regulating services. These reduce the capacity of ecosystems to deliver regulating services and exacerbate urban heat island effects, a concern for metropolitan areas like Atlanta, where green cover is already diminishing.

4.5. Impacts of the Loss of Ecosystem Services

4.5.1. Environmental Impact The environmental consequences of ecosystem service degradation are far-reaching. One of the most critical issues is the disruption of biogeochemical cycles, especially nutrient cycling. Land use change introduces new anthropogenic nutrient sources such as agricultural runoff, treated wastewater, and urban stormwater (Sutton et al., 2016). These pollutants cause eutrophication in water bodies and reduce the functional diversity of aquatic systems. In the Upper Flint Watershed, forest conversion and monoculture plantations exacerbate erosion risks and diminish water retention (Abbasnezhad et al., 2024). As forests disappear, their ability to buffer extreme weather events and filter runoff diminishes. Stream flow declines and increased groundwater extraction further compromise water availability, a growing issue for the Atlanta region (Emanuel & Rogers, 2016).

Biodiversity loss is another major concern. The fragmentation of working lands in Georgia and surrounding states reduces habitat size, quality, and connectivity (Coffin et al., 2021). Ecosystems lose their capacity for self-regulation, leading to cascading failures in services like pollination, pest control, and seed dispersal. Southeastern grasslands, for example, are essential for carbon sequestration, pollination, and nutrient cycling, but are increasingly threatened by land mismanagement and urban encroachment. Dubeux and García (2022) underscore that poor land management, compounded by urban pressures, diminishes these regulating services, resulting in increased greenhouse gas emissions and reduced resilience to climate change. Moreover, changes in the structure and composition of ecosystems reduce their resilience to climate change. Fragmented and simplified landscapes have less capacity to absorb climatic shocks, increasing vulnerability to temperature extremes, flooding, and invasive species in rapidly urbanising areas such as Atlanta (Haddad et al., 2015).

Urbanisation in Atlanta, as shown by our LULCC data, has led to a dramatic increase in developed land (82.46%) between 1995 and 2025. This expansion comes at the cost of vegetative cover and forested areas, which have declined by nearly 20%. As vegetative surfaces are replaced with impervious ones, the natural ability of ecosystems to regulate temperature, retain water, and filter pollutants is diminished. This change increases surface runoff, reduces groundwater recharge, and amplifies pollutant loads in nearby water bodies. The loss of water area, which exceeds 65%, further exacerbates these effects by limiting the hydrological buffering capacity of the landscape. As these environmental stressors accumulate, the risk of feedback loops, in which diminished vegetation accelerates further ecological degradation, becomes more severe, especially in a rapidly growing urban centre like Atlanta.

4.5.2. Social and Health Implications The degradation of ecosystem services in the Atlanta region carries significant implications for both public health and social equity. Land-use changes, particularly the conversion of forests and wetlands to urban and developed areas, are directly linked to deteriorating air quality and increased disease risks. Gourevitch et al. (2021) demonstrated that such transformations elevate atmospheric concentrations of pollutants like nitrogen oxides (NO_x), ammonia (NH_3), volatile organic compounds (VOCs), and sulphur dioxide (SO_2). These pollutants serve as precursors to fine particulate matter (PM2.5) and ground-level ozone, both of which are strongly associated with respiratory and cardiovascular diseases. Notably, the adverse health impacts of degraded air quality disproportionately affect low-income, urban, and non-white populations, thereby exacerbating existing health disparities.

The conversion of natural landscapes to urban areas further compounds health risks by altering ecological disease dynamics. Gourevitch et al. (2021) also identified a link between land cover changes and increased risk of vector-borne diseases such as West Nile Virus (WNV). As forests and wetlands are replaced by croplands or impervious urban surfaces, ecological conditions favour mosquito populations that transmit WNV. This dynamic highlights how land degradation not only undermines regulating services like water filtration, mainly due to the water area in Atlanta decreasing by 65.17% over the years, and air purification, but also directly increases exposure to zoonotic diseases. Similarly, Dong et al. (2022) and Manu et al. (2022) affirmed that land cover changes, particularly the conversion of forest and water lands for settlements and other human activities, reduce the cooling buffer in the cities and, hence, the continued reduction of ecosystem services such as cooling greatly increases heat-related morbidity.

Moreover, the interplay between land cover change and public health risks extends to fire management. Afrin and Garcia-Menendez (2021) found that smoke from prescribed fires in Georgia contributes to elevated morbidity and mortality, particularly in socially vulnerable communities. As forest cover in Atlanta continues to decline (−19.94% between 1995 and 2025), fire management interventions become both more necessary and more hazardous. This duality underscores how ecosystem degradation creates compounding health threats, especially for populations already burdened by social and economic vulnerabilities.

Socioeconomic disparities further influence patterns of ecosystem degradation. Adhikari et al. (2021) emphasise that wealthier landowners, those with conservation-focused values, or larger property holdings are more likely to engage in stewardship practices that mitigate ecosystem losses. In contrast, economically disadvantaged communities often lack the resources or incentives to prioritise conservation, increasing their exposure to the cascading effects of environmental decline. In the context of Atlanta, where urban expansion has surged by over 80% in three decades, these disparities risk entrenching cycles of ecological degradation and social vulnerability.

4.5.3. Economic Impacts The economic toll of ecosystem service loss is profound and growing. Globally, the value of ecosystem services lost each year is estimated at $6.3 trillion, representing about 10% of global GDP (Sutton et al., 2016). These costs are not merely abstract; they manifest in public expenditures, increased infrastructure maintenance, and health impacts. In Georgia, regulating services like water filtration and flood protection are highly valued. Using the value transfer method, these services are estimated at $7,755/ha/year (Benez-Secanho & Dwivedi, 2021; Tu, 2013). With urban growth, potential losses from diminished water regulation alone may exceed $40 million annually (Benez-Secanho & Dwivedi, 2021; Tu, 2013). Such economic losses could rise even further as development continues to outpace conservation.

The LULCC dataset provides quantitative evidence of these transformations. Water area has decreased by 65.17%, barren land by 77.45%, and forests by nearly 20%. These changes not only erode the ecological foundation of the region but also reduce property values, increase insurance costs, and challenge municipal planning. Ecosystem service loss also undermined Atlanta's long-term sustainability. Natural systems that once provided services for free must now be replaced or compensated for with engineered solutions, often at a higher cost and with lower efficiency. For example, stormwater systems must be upgraded to account for the loss of natural infiltration, and air quality may require technological interventions as vegetative buffers decline.

Patton et al. (2015) conducted an economic valuation of carbon sequestration across several U.S. National Wildlife Refuges, revealing significant monetary benefits from preserved ecosystems. Georgia's Okefenokee Refuge alone was valued at US$146 million in stored carbon, highlighting the economic worth of intact wetlands and forests. While urban areas like Atlanta do not offer the same scale of carbon storage, ongoing deforestation and wetland conversion still lead to considerable economic losses through reduced carbon sequestration potential. This example illustrates the broader economic risks posed by rapid urban expansion without ecosystem consideration.

4.5.4. Policy Implications In rapidly urbanising areas like Atlanta, the findings of the study have important ramifications for sustainable development policy, environmental governance, and urban planning. An urgent need for coordinated, science-based policy interventions is highlighted by the extent and pace of land cover change, which over the past 30 years has seen 82.46% increase in developed land, a 65.17% loss of water bodies, and a roughly 20% decrease in forest cover.

Urban sprawl in Atlanta is a result of inadequate frameworks for growth management that compromise ecological integrity. To lessen outward sprawl, local governments can encourage infill construction and higher-density zoning as ways to implement smart growth principles. Urban development boundaries should be legally protected to protect agricultural and natural areas. Local governments should strengthen zoning reforms by revising zoning laws to mandate the inclusion of green infrastructure in development planning and to incorporate ecosystem service valuation.

Moreover, the degradation of vital ecosystem services is indicated by measurable losses in water area, forest cover, and barren buffer zones. Policymakers may include ecosystem service valuation in cost-benefit analyses of infrastructure and land development projects. Ecological impact assessments should be mandatory and specifically take into account long-term losses in climate resilience, air quality, and water control. To monitor changes in ecosystem value in tandem with gross domestic product and local budgets, invest in natural capital accounting systems.

Adaptive green infrastructure and nature-based solutions are essential in light of the worsening air quality, increased surface runoff, and increased urban heat islands. This calls for bioswales, urban tree canopies, and green roofs in new construction, especially in areas with high PM2.5 and UHI. Restoring damaged wetlands and waterways should be a top priority to restore biological corridors and hydrological services. To improve environmental justice and public health outcomes, policymakers should preserve and grow urban green spaces in underserved communities.

Additionally, planning for both land use and mobility must be linked due to the role that transportation infrastructure plays in ecosystem fragmentation. To maintain habitat connectivity, policymakers need to map biological corridors prior to road expansions. Promote transit-oriented development concepts to lessen reliance on cars and the increase of impermeable surfaces. Install stormwater management systems, vegetated buffers, and wildlife crossings on existing along existing transit routes.

5. Conclusion

The study revealed significant changes in land use and land cover from 1995 to 2025 in the Atlanta Metropolitan Area. These changes were influenced by infrastructural development, urbanisation, and real estate development. Water bodies decreased by more than 65% and forests by about 20% during this time, while built land increased by more than 82%. The region's ecosystem services have been severely affected by these changes, resulting from economic growth, population expansion, and governmental oversight.

Deteriorated air quality, heightened urban heat island effects, decreased biodiversity, and weakened climate resilience are only a few of the many interrelated and complex implications. Poor air quality, high PM2.5 concentrations, and UHI zones all overlap spatially, suggesting that underprivileged communities bear a disproportionate share of the environmental dangers. Additionally, the region's capacity to control water flows, store carbon, and sustain wildlife habitats has been undermined by the loss of biological buffers like barren and forest lands.

Economically, the loss of natural regulating services imposes growing costs on municipalities and residents. Replacement with designed infrastructure, such as stormwater systems or air quality initiatives, is not only more expensive but also frequently ineffective. This underscores the need to preserve and restore ecosystems as a cost-effective, multi-benefit infrastructure. Atlanta's trajectory highlights the broader global challenge of balancing urban development with environmental sustainability. This calls for a paradigm shift from reactive mitigation to proactive planning based on ecological principles. To take into consideration the social, economic, and ecological aspects of land use, policies must abandon sectoral silos and adopt integrated methods. As urban areas continue to expand, it is not only environmentally necessary but also socioeconomically necessary to coordinate growth with the protection of natural capital.

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