

Article

Urban Land Use Efficiency in the United States: Assessing UN 2030 Sustainable Development Goals

Md Farhan Ishrak * , Adam J. Mathews * , Jay L. Newberry and Wan Yu

Department of Geography, Binghamton University, State University of New York, Binghamton, NY 13902, USA; jnewber@binghamton.edu (J.L.N.); wyu@binghamton.edu (W.Y.)

* Correspondence: mishrak@binghamton.edu (M.F.I.); adam.mathews@binghamton.edu (A.J.M.)

Abstract

Urban expansion has intensified concerns regarding land use efficiency and sustainable urban development worldwide. Despite growing global application of Sustainable Development Goal (SDG) Indicator 11.3.1, comprehensive assessments within the United States (U.S.) remain limited. This study evaluates urban land use efficiency in the contiguous U.S. between 2000 and 2020 by examining the relationship between land consumption and population growth using the ‘Land Consumption Rate to Population Growth Rate’ (LCRPGR) framework. Urban land expansion and population change were derived from integrating impervious surface data with gridded population estimates, respectively, and the indicator was calculated for 2229 urban areas to evaluate temporal and regional patterns. Results show that urban land area increased by 23% over the study period, while population grew by 31%, indicating an overall shift toward denser urban development. The median LCRPGR declined from 0.84 during 2000–2010 to 0.63 during 2010–2020, reflecting improvements in land use efficiency, although notable regional disparities remain. Cluster analysis reveals distinct spatial growth patterns, with older metropolitan areas and western cities generally exhibiting more compact development. Findings demonstrate the applicability of SDG Indicator 11.3.1 for evaluating urban land use efficiency in a U.S. context and highlight the importance of coordinated spatial planning and policy measures to support sustainable urbanization.

Keywords: urban geography; land use; sustainability; United States; spatial analysis

1. Introduction

The global urban population has grown from 746 million in 1950 to 4.5 billion in 2022, and is projected to reach 6.4 billion by 2050 [1–4]. Over 80 percent of the population in developing countries now live in urban areas, a trend closely tied to rapid expansion in urban built-up areas and corresponding increases in resource consumption and environmental strain [5–7]. When the growth of urban land outpaces population growth, it can contribute to unsustainable development patterns and exacerbate economic, social, and environmental challenges [8–10].

In the United States (U.S.), urbanization has reshaped demographic landscapes with 83 percent of people residing in urban areas in 2023, up from 64 percent in 1950, with an expected increase to 89 percent by 2050 [11,12]. Although the annual rate of land conversion for urban use has slightly declined—from 2.2 percent in 2020 to 1.7 percent in 2023—the total urban land area continues to expand [13]. Between 2000 and 2020, urban land area increased by 14 percent, and is expected to double by 2060 [14–17]. Despite



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making up only 3 percent of the country's total land area, urban areas are home to the majority of the population and exert significant influence on environmental, infrastructural, and economic systems [18,19]. Urban areas such as Atlanta, Houston, and Los Angeles illustrate the negative impacts of sprawl including traffic congestion, air pollution, and the loss of greenspace [20–23].

In 2015, the United Nations (UN) launched the 2030 Agenda for Sustainable Development, establishing 17 Sustainable Development Goals (SDGs) to guide global policy [11]. SDG 11 specifically aims to make cities inclusive, safe, resilient, and sustainable, with Target 11.3 promoting sustainable urbanization through planning [24,25]. To measure progress, SDG Indicator 11.3.1 was introduced, which calculates the ratio of Land Consumption Rate (LCR) to Population Growth Rate (PGR), offering a standardized method for assessing urban land use efficiency [26,27]. This indicator is instrumental in identifying whether urban expansion is aligned with population growth. Importantly, efficient land use is associated with benefits such as reduced infrastructure cost, better access to public services, improved housing affordability, and enhanced environmental sustainability [28,29]. In contrast, low land use efficiency, often linked to sprawl, tends to increase per capita resource consumption and diminish the advantages of urban economies [30,31]. Despite the global relevance of SDG 11.3.1, its application in a U.S. context remains limited.

Globally, implications of inefficient land use are evident in spatial patterns of urban change. In China, construction has expanded at nearly twice the rate of population growth, reflecting substantial land use inefficiency [32,33]. In the United Kingdom, land consumption has similarly outpaced demographic change in recent years [34]. Such mismatches complicate infrastructure development, increase environmental burdens, and reduce long-term sustainability [35]. Growth patterns, however, vary regionally: in Asia, Africa, and Latin America, population growth has generally outpaced land expansion, reflecting relatively denser urbanization processes, whereas in Europe and North America, built-up expansion has often exceeded population growth, indicating more land-intensive development trajectories [36]. While Europe and Australia increasingly emphasize infill development, growth containment, and land conservation strategies, rapidly urbanizing regions in Asia and Africa continue to experience large-scale spatial expansion driven by population growth and economic transformation [37–47].

Urban land use efficiency (ULUE) is conceptualized as the ratio between urban land expansion and population growth, which serves as a proxy for built-up area density [32,48,49]. Higher density levels are associated with greater economic agglomeration benefits, such as improved productivity and service efficiency [30]. While some studies evaluate ULUE by measuring land use effectiveness particularly in terms of population accommodation, others adopt an ecological-economic lens, defining it as the interaction between economic activity and environmental systems [50]. Input-output modeling provides another approach, measuring how efficiently land, capital, and labor generate economic output [33]. ULUE is therefore spatially uneven, varying across regions and urban typologies. Core urban areas typically outperform peripheral or urban fringe areas in terms of efficiency [51–53]. These variations often reflect levels of economic development, with higher income or more established urban core areas achieving higher efficiency scores [33,53]. Influencing factors include industrial clustering, population density, infrastructure investment, transportation accessibility, and institutional frameworks such as zoning regulations and land lease enforcement [52,54,55].

To support standardized monitoring, the LCRPGR metric is utilized to track urban land use efficiency. Numerous case studies have employed this approach using a variety of spatial datasets. For example, in South Africa [56], secondary cities expanded faster than primary cities in both land area and population. In Germany, Ghazaryan et al. [57]

identified disproportionately high land consumption compared to population growth, while studies in India and Poland also showed declining ULUE over time [58,59].

The availability of global spatial datasets has advanced ULUE assessments. For example, the Global Human Settlement Layer (GHSL), Global Urban Footprint (GUF), and NYU's Atlas of Urban Expansion offer consistent, high spatial resolution data on built-up areas and population [60,61]. Using GHSL, Melchiorri et al. [62] assessed nearly 10,000 global urban centers from 1990 to 2015, finding an average LCRPGR of 0.72—indicating moderate densification globally. However, North American cities showed high per capita land consumption despite slower population growth, in contrast to more efficient land use in cities in Africa and Asia. These findings highlight the relevance of LCRPGR in guiding sustainable urban development and underscore GHSL's role in elevating SDG 11.3.1 to Tier I status by addressing global data gaps [55,63].

While SDG indicator 11.3.1 is widely used to assess ULUE at the global scale, few studies apply this indicator across the U.S. Studies suggest prominent regional disparities in U.S. urbanization patterns [23,64]. Historical evidence indicates that U.S. urban expansion in the late twentieth century was characterized by rapid land consumption relative to population growth. For instance, between 1980 and 2000, the population of the U.S. grew by around 24% while the amount of urbanized land increased by over 34% [65–67]. According to the U.S. Census Bureau [68], the South and West regions experienced the largest population increases this time, a trend that has continued into the present. Between 2000 and 2020, urban land area in the U.S. expanded by approximately 14%, reflecting substantial growth associated with urban development [68]. In contrast, regions such as upstate New York have undergone prolonged population decline, accompanied by stagnant or shrinking urban footprints [8,69].

Despite divergent trajectories, a comprehensive, nationwide assessment of urban land use efficiency that captures regional variation is needed. Applying the LCRPGR ratio across U.S. urban areas offers an opportunity to better understand how spatial expansion and demographic change interact in different regional contexts [70,71]. Such an analysis can provide valuable insight for federal, state, and local governments seeking to adjust urban planning strategies in support of long-term sustainability [72]. Moreover, this approach enables a comparative evaluation of U.S. cities within the broader global literature on SDG 11.3.1, highlighting distinctive development patterns and areas for improvement [73].

Specifically, this study addresses the lack of a comprehensive, nationwide evaluation of ULUE in the U.S. by examining patterns of land consumption and population growth across urban areas in the contiguous U.S. between 2000 and 2020. Focusing on the most recent two decades enables an assessment of contemporary urban expansion dynamics. Using LCRPGR, we investigate how spatial expansion and demographic change interact and how these dynamics vary across regions. By situating the most recent two decades within the broader historical trajectory of U.S. urbanization, the study contextualizes recent trends against long-term patterns of urban growth and transformation. In doing so, the study contributes U.S.-based empirical findings to the global LCRPGR literature, advancing understanding of sustainable urban development and informing future planning and land use policy decisions.

2. Materials and Methods

2.1. LCRPGR Approach

The LCRPGR indicator is calculated as the ratio of Land Consumption Rate (LCR) to Population Growth Rate (PGR) in three main steps. To obtain LCR (Equation (1)), the rate of change in urban land use over a given period is determined by taking the natural

logarithm of the ratio of urban land area between the end and the beginning of the period and dividing it by the duration of time [74].

$$LCR = \frac{\ln(Urb_{t+n}/Urb_t)}{y} \quad (1)$$

- Urb_t : Total areal extent of consumed land in the initial year (t)
- Urb_{t+n} : Total areal extent of consumed land in the final year ($t + n$)
- y : Time period between the two years (in years).

PGR is determined by analyzing the change in population over the same time frame (Equation (2)). That is, by taking the natural logarithm of the population at the end of the period divided by the population at the beginning, and, like LCR, is normalized by dividing it by the total duration. PGR serves as an indicator of how population levels shift over time, shedding light on demographic shifts [74].

$$PGR = \frac{\ln(P_{t+n}/P_t)}{y} \quad (2)$$

- P_t : Total population in the initial year (t)
- P_{t+n} : Total population in the final year ($t + n$)
- y : Time period between the two years (in years).

LCRPGR can then be obtained by dividing LCR by PGR (Equation (3)) [72].

$$LCRPGR = \frac{LCR}{PGR} \quad (3)$$

2.2. Data Collection

This study focuses on urban expansion and land use efficiency across urban areas in the contiguous U.S. as defined by the U.S. Census Bureau's 2020 Urban Area boundaries. The analysis incorporates urban areas delineated using built-up surface data, while Census administrative boundaries served as reference layers to validate and filter relevant spatial units. The U.S. Census Bureau has defined urban areas in each decennial census since 2000. In 2000 and 2010, urban areas were classified into two categories: Urbanized Areas (population $\geq 50,000$) and Urban Clusters (population between 2500 and 50,000), both requiring a minimum density of 1000 people per square mile. However, the 2020 Census introduced major changes by eliminating the Urban Cluster category and increasing the minimum urban area population threshold to 5000, while also removing the previous density criterion. These changes significantly affected the number and extent of urban areas, reducing them from 3534 in 2010 to 2586 in 2020, despite an increase in total urban population. In 2000, the urban population stood at approximately 225 million (79 percent of the U.S. population), growing to 253 million in 2010 (80.7 percent), and 268 million in 2020 (80 percent) [68,74]. The slight decline in the proportion of the population considered urban between 2010 and 2020 is primarily due to the reclassification criteria.

To analyze urban land use change, we utilized the National Land Cover Database (NLCD), the U.S. Census Urban Area boundaries, and WorldPop population estimates. The NLCD provides 30 m resolution land cover classifications for the entire U.S. For this study, the Impervious Descriptor layer from the years 2000, 2010, and 2020 was used to extract built-up areas. This layer distinguishes between impervious surfaces such as roads and other built structures, enabling accurate delineation of urban land [75]. Urban boundary shapefiles from the U.S. Census Bureau were used to validate the NLCD-derived urban extents and ensure consistency in geographic coverage across time. Each urban area is tagged with a unique identifier, allowing comparison of land cover and population changes over time.

Population data were obtained from the WorldPop Constrained, Top-down model, which generates 100 m resolution gridded estimates by redistributing census counts based on geospatial predictors such as land cover, road networks, and built-up density. The analysis calculated total urban area (in square kilometers) and associated population for each time point. These two variables were then used to compute the LCRPGR, a key indicator for assessing urban land use efficiency in line with UN SDG 11.3.1. Together, these data provide a robust foundation for evaluating spatiotemporal urbanization trends and changes in land consumption.

The study period (2000–2020) was selected to ensure temporal consistency with decennial U.S. Census population and urban extent datasets. Census population counts are baseline inputs for the WorldPop gridded population model, which distributes population into spatial grid cells using dasymetric mapping techniques incorporating land cover, infrastructure, and built-up density [76–78]. Employing two ten-year intervals (2000–2010 and 2010–2020) enabled a standardized temporal comparison of land consumption and population growth dynamics across urban areas.

2.3. Data Processing and Analysis

The NLCD includes an Impervious Descriptor product, which provides raster format data on urban built-up areas, distinguishing roads and non-road areas. This dataset offers a 30 m spatial resolution classification, where roads are coded as 1, and other built-up areas are coded as 2. To delineate urban clusters, built-up pixels were utilized following the process outlined in UN-Habitat [40]. The Impervious Descriptor layer from 2020 was reclassified to convert all pixel values into 1 (see Figure 1). The Focal Statistics tool in ArcGIS Pro 3.6 was used to generate a built-up density layer, calculating the number of built-up cells within a one-kilometer radius (approximately 564 cells) around each pixel. Output data were reclassified to determine the urbanness of each pixel, where cells with values higher than 556 were recognized as urban built-up areas, values ranging from 278 to 556 were classified as suburban, and cells with values below 278 were categorized as rural. This process also facilitated the identification of rural roads.

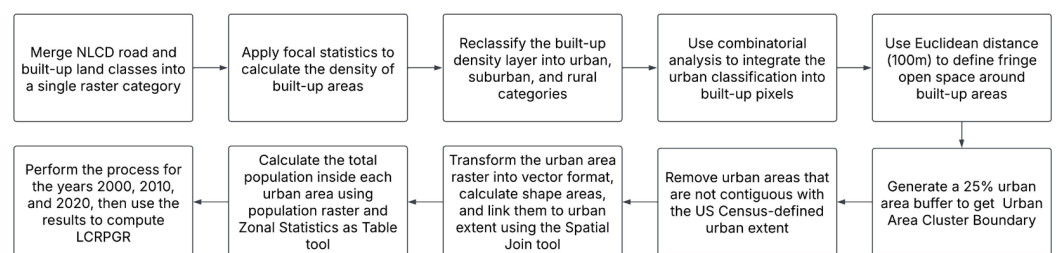


Figure 1. Data analysis workflow.

Urbanness values were integrated into the NLCD built-up layer using the Combinatorial And tool, resulting in three categories: urban, suburban, and rural. Rural pixels were removed using the Reclassify tool while the remaining urban and suburban pixels were merged into a single class. The Euclidean Distance tool was employed to establish a 100 m urban fringe area, which was included in the urban extent. The Raster to Polygon tool was used to convert the raster data, representing urban/built-up areas, into vector shapes/polygons. Area in square kilometers was calculated and added as an attribute for each polygon.

For the 2020 dataset, a 25 percent area buffer was generated to establish a common urban cluster for measuring urban area and population across the years 2000, 2010, and 2020 [72]. After obtaining the area of the polygon, 25 percent of the total area was calculated by multiplying the polygon's area by 0.25 (sample processing shown in Figure 2). To create

a corresponding buffer based on this area, the buffer distance is determined using the formula for the circle radius, as shown in Equation (4).

$$\text{Buffer Distance} = \sqrt{\frac{\text{Buffer Area}}{\pi}} \quad (4)$$

This formula gives the required distance for a circular buffer whose area equals 25 percent of the original polygon's area. For instance, if the original polygon's area is 100,000 square meters, the buffer area would be 25,000 square meters, and the calculated buffer distance would be 89.4 m.

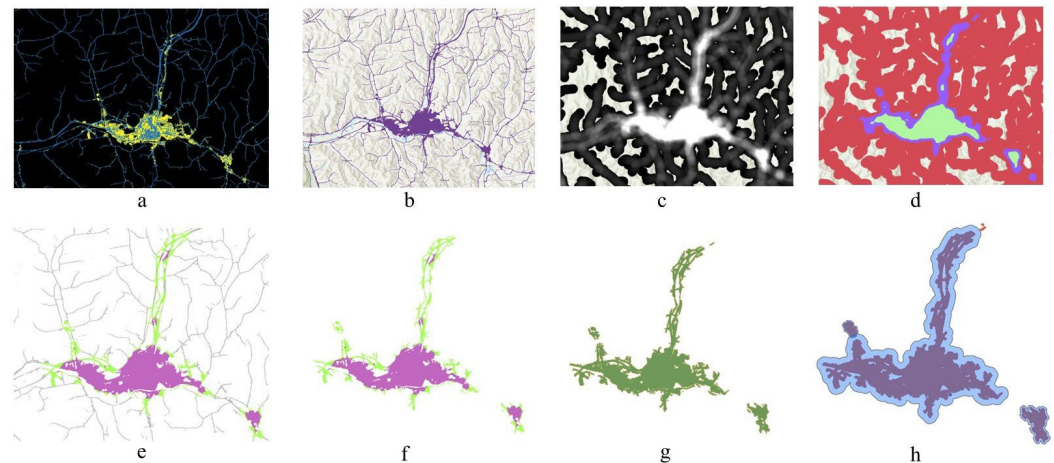


Figure 2. Example of extracting urban area from built-up raster layer; (a) Impervious Descriptor Layer with road and built-up area in separate class (blue-road, yellow-builtup); (b) The road and built-up land classes merged into one (violet); (c) Applied Focal Statistics to calculate the density of the built-up areas (Black-Less dense, White-More dense); (d) Built-up density layer reclassified into Urban, Suburban and Rural categories (Green-Urban, Violet-Suburban, Red-Rural); (e) Combinatorial Analysis used to ingest urban classification into built-up pixels (Pink-Urban, Green-Suburban, Black-Rural); (f) Rural pixels removed from the built-up layer (Pink-Urban, Green-Suburban); (g) 100 m Euclidean Distance Buffer to mark the fringe open space around the built-up area; (h) 25 percent area buffer to generated to get Urban Cluster Extent (Buffer in light blue).

Once the Urban Cluster Extent is derived from the 25 percent buffer, the urban area was calculated for the three time periods (2000, 2010, and 2020). The urban area included urban, suburban, and fringe open space categories. Administrative boundaries were used to clip and exclude any urban areas not contiguous with the U.S. Census-defined urban extent. For each year, the urban raster was converted into polygons, filtered using the U.S. Census urban area boundary, and then spatially joined with the Urban Cluster Extent shapefile, which was created from the 2020 raster.

Population data for built-up areas were obtained from the WorldPop dataset. Zonal Statistics as a Table tool was employed to sum the population and assign the values to each urban extent/shape. This population data was also transferred to the Urban Cluster Extent shapefile. As a result, a common database was created within the Urban Cluster Extent shapefile, incorporating both area and population data for the years 2000, 2010, and 2020. This procedure was consistently applied for 2000, 2010, and 2020, producing a comparable dataset. The combined dataset was utilized to compute the LCRPGR indicator, providing a detailed assessment of urban growth dynamics and population trends over the study period.

After deriving the indicators, statistical techniques were applied to analyze the temporal patterns and spatial dynamics of urban growth. Descriptive statistics, including mean, median, standard deviation, and interquartile range, were calculated to summarize changes

in the three key indicators (LCR, PGR and LCRPGR). To assess whether these changes were statistically significant between the two time periods, paired-sample *t*-tests were conducted at a 95% confidence interval. In addition, K-means clustering was employed to classify urban areas into five distinct groups based solely on the spatial proximity of urban polygons, without incorporating other explanatory variables. Subsequently, one-way ANOVA was used to test whether mean LCR, PGR, and LCRPGR values differed significantly across clusters, while Tukey's post hoc tests identified specific pairwise differences among urban growth typologies. Temporal visualizations were developed to show the evolution and spatial distribution of urban areas across the study period, providing a clearer understanding of the dynamics of urban expansion.

3. Results

3.1. Aggregated Statistical Test

As shown in Table 1, the total urban area in the U.S. was 256,046 km² in 2000, which increased by 15 percent (293,000 km²) in 2010, and by an additional 7 percent (315,000 km²) in 2020. In contrast, the growth in urban population was significantly steeper, from 143.3 million in 2000 to 166.4 million in 2010 (16% increase) and further to 188 million by 2020. These figures indicate that urban population growth outpaced the expansion of urban land. Urban density was 559.7 persons per square kilometer, which increased 6.5 percent to 596.4 Person/km² in 2020.

Table 1. Urban area and population over three time periods.

Year	Total Urban Area (km ²)	Urban Area Increase (%)	Total Urban Population (Millions)	Urban Population Increase (%)	Population Density (Person/km ²)
2000	256,046	--	143.3	--	559.7
2010	293,478	15%	166.4	16%	567
2020	315,206	7%	188	13%	596.4

Descriptive statistics (Table 2) were generated for the LCR, PGR, and LCRPGR for the periods 2000–2010 and 2010–2020, covering 2229 urban areas. The median values of both LCR and PGR declined over time, with LCR falling from 0.010 to 0.006 and PGR from 0.009 to 0.007, indicating a general slowdown in both land development and population growth. Correspondingly, the median LCRPGR—a key indicator of land use efficiency—dropped from 0.838 to 0.627, suggesting a moderate improvement in how land consumption relates to population change. The mean values support this trend: LCR declined from 0.013 to 0.009, and PGR from 0.013 to 0.010, while mean LCRPGR decreased from 1.013 to 0.680. Notably, however, the standard deviation of LCRPGR increased sharply from 10.897 to 27.499, and its range expanded dramatically from 447.03 to 1672.84, pointing to significant variability in urban land use efficiency across regions in the later decade.

Table 2. Descriptive statistics of urban expansion and population growth.

	LCR		PGR		LCRPGR	
	2000–2010	2010–2020	2000–2010	2010–2020	2000–2010	2010–2020
Median	0.01	0.006	0.009	0.007	0.838	0.627
Mean	0.013	0.009	0.013	0.01	1.013	0.68
Std. Deviation	0.014	0.014	0.017	0.015	10.897	27.499
IQR	0.013	0.008	0.018	0.014	1.114	1.067
Range	0.308	0.431	0.325	0.401	447.028	1672.842

To evaluate temporal changes in urban development indicators, paired samples *t*-tests were conducted comparing the periods 2000–2010 and 2010–2020 (Table 3). The analysis revealed that both the LCR and the PGR experienced statistically significant decline over time. Specifically, the mean LCR was significantly higher during 2000–2010 than in 2010–2020, suggesting a reduction in the pace of land development in the more recent decade. Similarly, the PGR also showed a significant decrease, indicating slower population growth in urban areas. In contrast LCRPGR, which reflects land use efficiency relative to population change, did not differ significantly between the two decades. This suggests that despite absolute declines in land and population growth, the proportional relationship between them remained relatively stable over time.

Table 3. Paired samples *t*-test comparing indicators across two decades.

Indicator Comparison	<i>t</i>	df	<i>p</i> -Value
LCRPGR (2000–2010 vs. 2010–2020)	0.534	2228	0.297
LCR (2000–2010 vs. 2010–2020)	8.463	2228	<0.001
PGR (2000–2010 vs. 2010–2020)	7.616	2228	<0.001

Notes. The alternative hypothesis for each test was that the value in the earlier decade is greater than the later one. Significant *p*-values ($p < 0.05$) indicate a statistically significant change over time.

3.2. Comparison of Urban Areas by Population Size Classification

According to the Organization for Economic Cooperation and Development (OECD) [76], urban areas can be categorized into four types based on population size: small (less than 200,000), medium (200,000–500,000), metropolitan (500,000–1.5 million), and large metropolitan (greater than 1.5 million). Based on this classification and 2020 population data for U.S. urban areas, this study identified 18 large metropolitan, 19 metropolitan, 49 medium, and 2143 small urban areas. Analysis of the median LCRPGR across these urban categories revealed a noticeable decline from 2000–2010 to 2010–2020 (Figure 3). Large metropolitan areas experienced a sharp drop in median LCRPGR, falling from 0.638 in the first decade to 0.366 in the second. Small and medium-sized urban areas also exhibited a decrease, the change was comparatively smaller. These findings align with existing research suggesting that, regardless of city size, population growth has increasingly outpaced land consumption, indicating a trend toward more compact urban development.

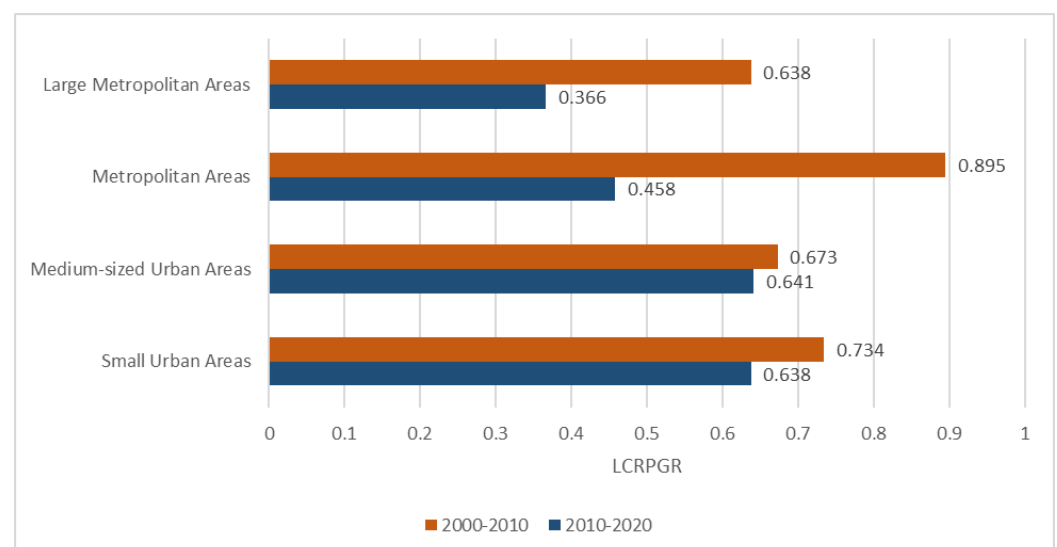


Figure 3. Median LCRPGR for different city size for two time periods.

To assess whether there were statistically significant differences in LCRPGR values among the different urban size categories, a one-way ANOVA test was conducted for both time periods. The test results indicated no significant variation in LCRPGR among the four urban types in either decade. This suggests that the trend of declining land consumption relative to population growth has occurred uniformly across cities of all sizes, reflecting a broadly consistent pattern of urban expansion across the U.S.

Figure 4 presents scatterplots illustrating the relationship between LCR and PGR across two time periods: 2000–2010 and 2010–2020 for different sized cities. The plots reveal a noticeably wider dispersion of values in the latter period, indicating increased variability. This observation is consistent with the descriptive statistics, where the standard deviation was higher for 2010–2020, further confirming greater fluctuation in both indicators during that decade. Outliers are predominantly associated with small urban areas, suggesting that these cities experienced more erratic growth patterns compared to medium and large urban areas. Although city size categories are color-coded in the scatter plots, there is no clear visual clustering or separation based on city size. This observation supports the results of the ANOVA test, which found no statistically significant differences in LCRPGR values among city size classes.

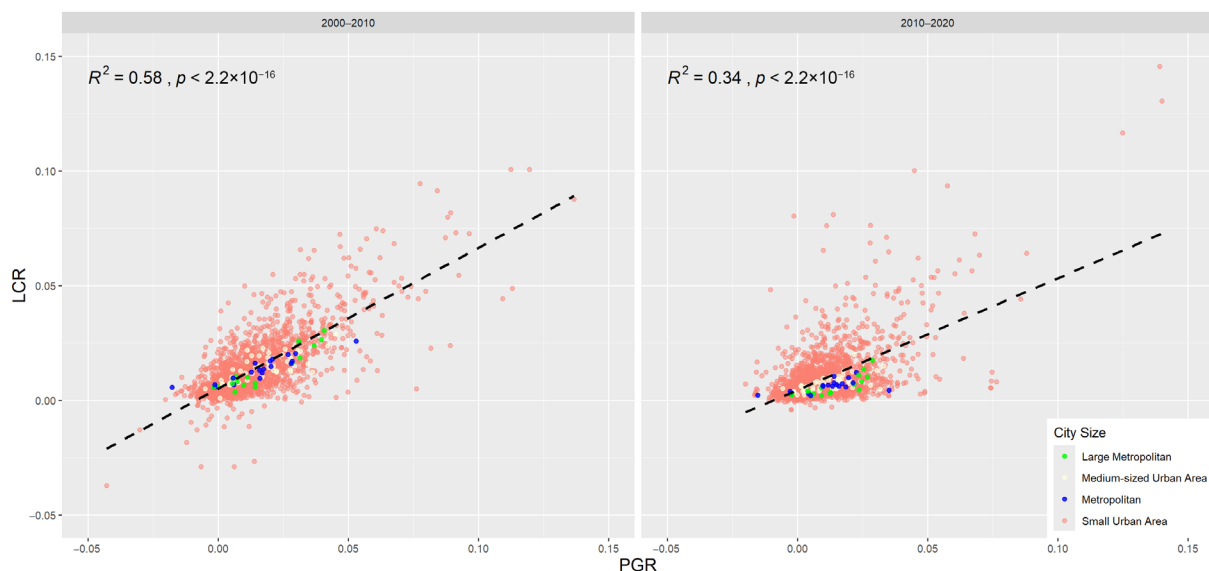


Figure 4. Scatterplot of LCR and PGR for two time periods.

To examine the strength of the relationship between LCR and PGR, a Pearson correlation analysis was conducted. For the 2000–2010 period, the correlation was strong, with an R^2 value of 0.58 and a p -value less than 0.05, indicating a statistically significant and moderately strong linear relationship. However, for 2010–2020, the correlation weakened, with an R^2 value of 0.34 ($p < 0.05$). This decline suggests that the relationship between land consumption and population growth became more irregular in the latter decade, reflecting less predictable urban growth dynamics in recent years.

3.3. K-Means Clustering

To analyze regional variation in urban expansion, K-means clustering was employed to group urban areas across the U.S. The analysis resulted in five distinct cluster groups, labeled 0 through 4 in Figure 5. Group 0 encompasses the Northeast including major metropolitan areas such as New York City, Boston, and Philadelphia. Group 1 comprises key West Coast urban centers such as Los Angeles, San Francisco, and Seattle. Group 2 covers urban regions in Texas and its neighboring states. Group 3 represents portions of

the Midwest, incorporating significant urban agglomerations such as Chicago, Milwaukee, and Minneapolis. Finally, Group 4 spans the southeastern U.S., encompassing major cities along the East Coast such as Atlanta, Tampa, and Miami. These clusters serve as the basis for comparing the urban expansion analysis results, facilitating an assessment of regional variation in urban expansion patterns across the identified clusters.

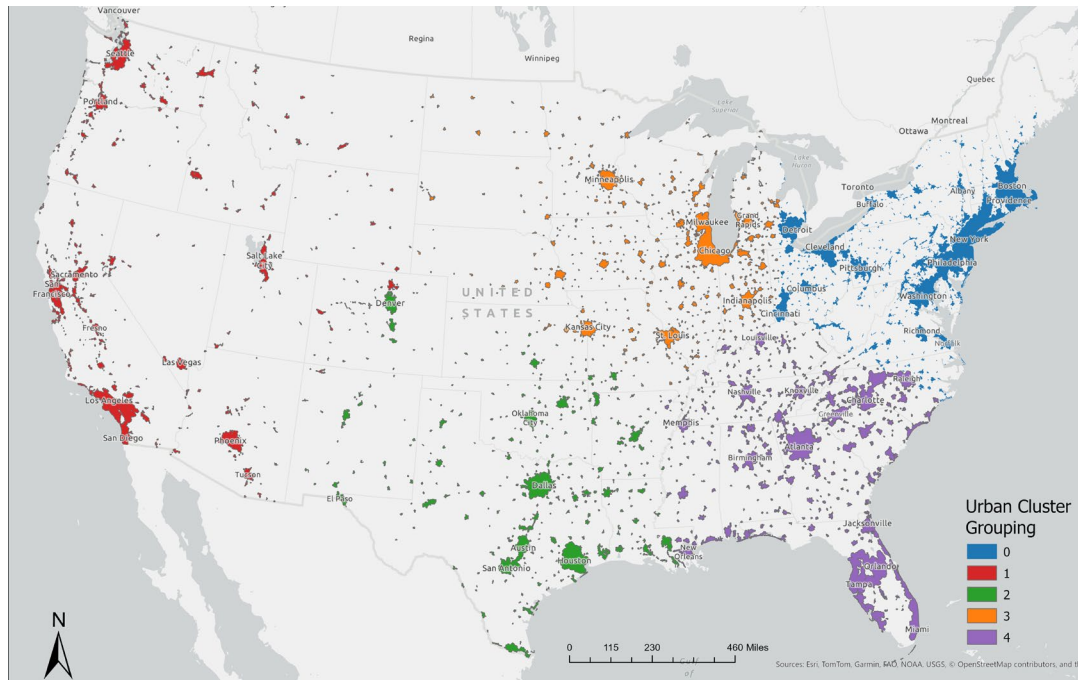


Figure 5. Grouping urban areas with K-Means clustering.

The spatial and statistical analysis of U.S. urban areas from 2010 to 2020 reveals significant variations in LCR across the five identified clusters. The clustering results highlight distinct regional patterns in urban growth and land use efficiency. The ANOVA in Table 4 demonstrates a statistically significant difference in land consumption rates among the five clusters ($F = 7.012$, $p < 0.001$). This indicates that urban areas in different groups exhibit significantly different rates of land consumption between 2010 and 2020. The Tukey HSD post hoc test provides pairwise comparisons between the clusters, showing which clusters significantly differ from each other in terms of LCR (Table 5).

Table 4. Urban cluster groups and their LCR comparison through ANOVA.

Cases	Sum of Squares	df	Mean Square	F	p
Cluster Groups	8.091×10^{-4}	4	2.023×10^{-4}	7.012	<0.001
Residuals	0.060	2096	2.885×10^{-5}		

Note 1. Type III Sum of Squares. Note 2. Outliers removed.

Group 0 (Northeast) has significantly different land consumption rates compared to Group 1, 2, and 4, with p -values ranging from <0.001 through 0.002. Group 2 (Texas) shows significant difference from group 3 with p -value of 0.034. The analysis highlights regional disparities in land consumption across U.S. urban areas. Northeast cities exhibit significant differences in land use compared to the west and southern urban clusters.

The one-way ANOVA presented in Table 6 evaluates the differences in PGR across the five identified urban clusters. The analysis reveals a statistically significant variation in PGR among the clusters, with an F -value of 69.235 and a p -value of less than 0.001. This indicates that at least one cluster exhibits a significantly different population growth rate

compared to the others. The substantial F-value suggests that the variability in population growth rates between clusters is much greater than the variability within each cluster, providing strong evidence for regional differences in population growth dynamics. These results underscore the existence of significant regional disparities in population growth rates across the United States, highlighting that urban clusters in different regions.

Table 5. Tukey's Post Hoc comparison among urban cluster groups.

		Mean Difference	SE	df	<i>t</i>	P _{Tukey}
0	1 *	−0.001	3.710×10^{-4}	2096	−3.717	0.002
	2 *	−0.002	3.924×10^{-4}	2096	−4.101	<0.001
	3	-5.299×10^{-4}	3.498×10^{-4}	2096	−1.515	0.553
	4 *	−0.001	3.712×10^{-4}	2096	−3.956	<0.001
1	2	-2.303×10^{-4}	3.968×10^{-4}	2096	−0.581	0.978
	3	8.489×10^{-4}	3.547×10^{-4}	2096	2.393	0.117
	4	-8.977×10^{-5}	3.758×10^{-4}	2096	−0.239	0.999
2	3 *	0.001	3.770×10^{-4}	2096	2.862	0.034
	4	1.406×10^{-4}	3.970×10^{-4}	2096	0.354	0.997
3	4	-9.386×10^{-4}	3.549×10^{-4}	2096	−2.645	0.063

Note 1. *p*-value adjusted for comparing a family of 5 estimates. Note 2. Outliers removed. * Indicates significant results at 95% confidence interval.

Table 6. Urban groups and their population growth rate comparison through ANOVA.

Cases	Sum of Squares	df	Mean Square	F	<i>p</i>
Cluster ID	0.023	4	0.006	69.235	<0.001
Residuals	0.174	2139	8.144×10^{-5}		

Note. Type III Sum of Squares.

The raincloud plot in Figure 6 illustrates the regional variation in population growth rates among the identified urban cluster groups from 2010 to 2020, with the bottom panel depicting the national distribution. Group 1 exhibits the highest median population growth, indicating significant expansion in the Pacific and Mountain divisions encompassing urban centers like Los Angeles, Salt Lake City, Tucson, and Seattle. Compared to the overall U.S., PGR in this region is much higher.

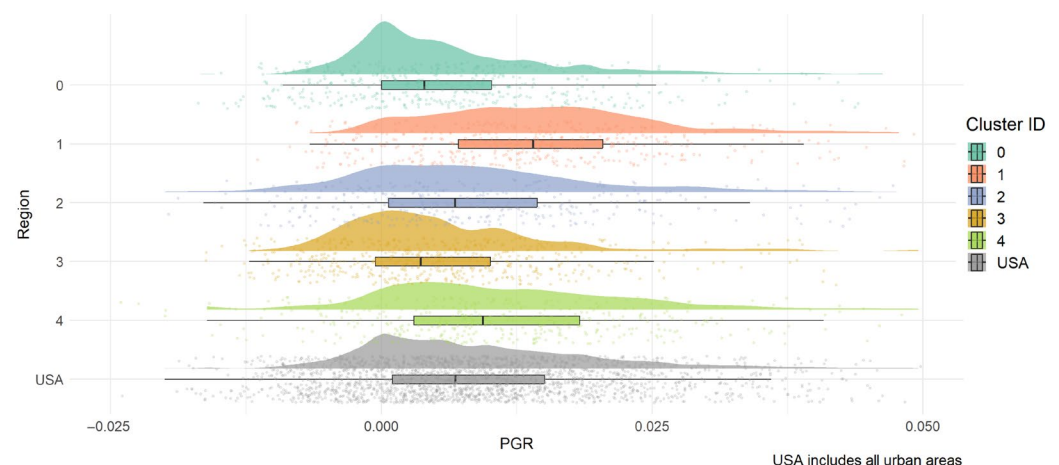


Figure 6. Raincloud plots showing PGR variation among urban cluster groups.

In Figure 7, all five regions exhibit a decrease in LCRPGR values during the 2010–2020 period, showing more compact growth pattern in recent decades. Among these regions, Cluster 1 (which includes West Coast cities) maintained a relatively low LCRPGR, with the latest value recorded at 0.50. This lower value suggests more denser urban development, indicating that population growth in these cities has outpaced land consumption. Cluster 3 (Midwest) showed the largest decrease in LCRPGR indicating a sharp decline in urban expansion.

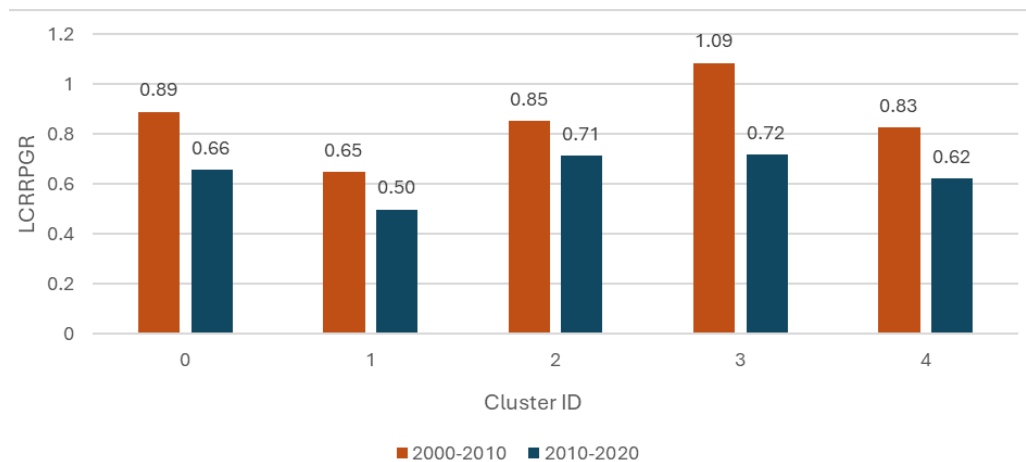


Figure 7. Comparison of median LCRPGR.

Conversely, Group 0 and 3 display the lowest population growth rates during this period. Group 0, which includes early developed cities such as New York and Boston, reflects population saturation most likely due to its long-standing urban development, prior road pattern and limited expansion opportunities. Similarly, Group 3, encompassing historically established cities such as Chicago and Indianapolis, exhibits minimal population growth, likely due to similar saturation effects. Notably, Group 4 demonstrates a substantial population growth trend, reflecting the rapid expansion of southeastern regions such as Atlanta, Tampa, and Miami in recent years [77].

3.4. Temporal Comparison Through Visualization

The spatial distribution of LCRPGR values across two decades reveals notable shifts in urban growth patterns. As shown in Figure 8, a color gradient from cool to warm tones represents the variation in values, with an LCRPGR of 1 indicating a balanced and sustainable relationship between land consumption and population growth. During the 2000–2010 period, approximately 26 percent of urban clusters fell within the near-sustainable range of 0.8 to 1.2. This share decreased to around 20 percent in the following decade (2010–2020), suggesting a modest decline in overall land use efficiency.

While 95 percent of urban areas experienced an increase in built-up area, only 80 percent recorded population growth. A comparative analysis of LCRPGR values between the two periods reveals an overall decline, reflected in the predominantly blue classes in Figure 8 (2010–2020 map). The median LCRPGR value dropped from 0.84 in 2000–2010 to 0.63 in 2010–2020, moving further away from the sustainable benchmark of 1. Even though the LCRPGR values moved away from the sustainable benchmark, the reduction in LCRPGR values might signal a shift toward more efficient land use and a move away from sprawling, land-intensive development patterns. However, a more detailed analysis of urban planning strategies during these periods is needed to fully understand the underlying causes. Additionally, consistently high negative LCRPGR value is observed in the Rust Belt region, indicating significant population decline over the past 20 years.

This trend highlights the region's ongoing economic stagnation and industrial decline, contributing to reduced population growth and land use changes [78].

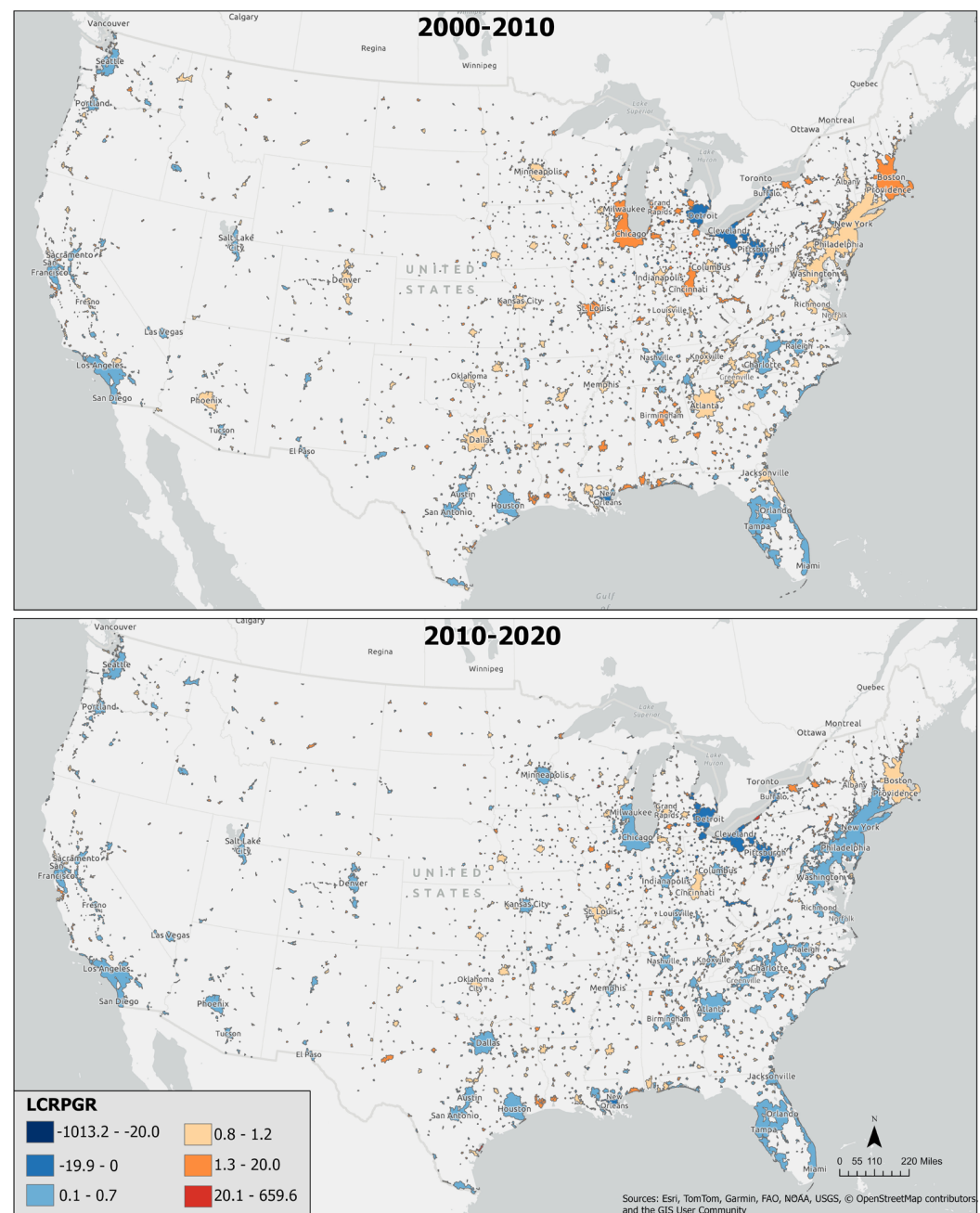


Figure 8. Comparison of LCRPGR in U.S. urban clusters over time.

After analyzing the deviation of LCRPGR values from the ideal sustainable value of 1 across the two time periods, it is observed that only 42 percent of the areas have moved closer to 1, while 58 percent have deviated further. Additionally, during the 2010–2020 period, 46% of urban clusters exhibited a PGR value greater than the LCR value, compared to 40% in the 2000–2010 period. This shift suggests a transition toward more land-intensive urban development, potentially indicating a departure from previous sprawling growth patterns.

As shown in Table 7, during the 2010–2020 period, 47.6 percent of urban clusters exhibited LCRPGR values between 0 and 1, which was slightly more than 2010–2000 period. However, LCRPGR values greater than 1 declined from 43.4 percent in 2000–2010

to 34.7 percent in 2010–2020. This shift implies that fewer areas experienced disproportionate land expansion relative to population growth, potentially indicating a move away from sprawling development patterns. Conversely, the proportion of urban clusters with LCRPGR values less than 1 increased from 14.4 percent in 2000–2010 to 17.6 percent in 2010–2020. This suggests that a growing number of urban areas have undergone population growth with relatively less land expansion, which may reflect densification or more efficient land use practices. Nevertheless, when considering the full 20-year period (2000–2020), approximately 40.8 of urban areas still exhibited high land consumption rates relative to population growth, highlighting substantial opportunities for further improvement toward more sustainable urban development patterns.

Table 7. LCRPGR range over the years.

LCRPGR	2020–2010	Percent	2010–2000	Percent	2000–2020	Percent
<0	377	17.6%	298	14.4%	333	15.9%
0 to 1	1019	47.6%	878	42.3%	903	43.2%
>1	743	34.7%	900	43.4%	852	40.8%

4. Discussion

U.S. urban land area increased by approximately 23 percent between 2000 and 2020, while the U.S. Census [15,79] reported a more modest 14 percent increase during the same period [18]. Several factors may explain this discrepancy. This study includes smaller urban areas and employs NLCD data, which captures low-density development that may not meet Census urban classification criteria. The Census defines urban areas based on a minimum threshold of 2500 persons per square mile, potentially excluding peri-urban or sparsely developed zones that are functionally urban. This difference is also reflected in the population density figures: while the U.S. Census reported an average urban density of approximately 965 persons per square kilometer in 2010, this study's estimates yielded a significantly lower density of 567 persons per square kilometer, largely due to the inclusion of low-density expansion. These contrasts suggest that morphological delineations, rather than administrative definitions, can yield different interpretations of LCRPGR and urban land-use efficiency.

Comparable low-density growth dynamics are observed internationally. Melchiorri et al. [62] reported only a 4% increase in North America's population density between 1990 and 2015, reinforcing the region's low-density growth pattern. In Great Britain, from 2013 to 2016, land consumption increased by 4.3%, while population grew only 1.5%, suggesting a decline in land use efficiency [34]. Similarly, Australian cities display low densities, e.g., Melbourne (521 persons/km²), Sydney (441 persons/km²), and Canberra (573 persons/km²), reflecting a broader trend of suburban, low-density expansion [80].

The median LCRPGR value for U.S. urban areas decreased from 0.838 (2000–2010) to 0.627 (2010–2020), suggesting a shift toward infill and densification in recent decades. This trend aligns with Smart Growth principles and supports theories that mature urban systems gradually transition from outward expansion to inward consolidation. Previous research corroborates these findings. ref. [81] documented that U.S. sprawl, which accelerated after World War II, peaked around 1994 and has since declined. Similarly, ref. [82] observed a policy shift toward form-based zoning codes promoting mixed-use, walkable neighborhoods, while Lopez [83] and Chakraborty et al. [84] noted slowing sprawl and the rise in densification in the Global North. These empirical patterns also reflect earlier planning critiques of low-density suburbanization, particularly Duany [85] that posited that postwar

automobile-oriented sprawl undermined urban efficiency and necessitated a return to compact, mixed-use development models. Boeing [86] further highlighted a resurgence of grid-like street patterns enhancing walkability and reducing car dependency—both indicators of declining sprawl intensity.

Spatial variation further underscores the uneven geography of U.S. urban expansion. Older U.S. cities such as New York, Chicago, and San Francisco exhibited lower urban expansion rates, consistent with their pre-automobile, gridded street networks that limit outward growth. In contrast, cities in the western and southern U.S. have experienced varying degrees of expansion depending on local policies and economic conditions. Lopez [50] identified stabilization or reversal of sprawl in western cities such as Portland and San Jose, where growth management policies and urban containment strategies have been effective. These patterns emphasize that sprawl is not inevitable but influenced by income levels, demographic shifts, and policy interventions. Notably, more than half of total U.S. sprawl expansion occurred during the 1970s, after which the rate of outward growth steadily declined.

In many major metropolitan areas—including New York, Boston, San Francisco, and Los Angeles—outward expansion has slowed due to high housing costs, restrictive zoning, and geographic constraints [87–89]. These barriers have led to limited land supply and higher infill densities, resulting in slower population growth in core urban areas. Consequently, much of the recent urban growth has shifted toward smaller or peripheral cities [90,91]. For example, within the San Francisco Bay Area, cities such as Stockton and Tracy have absorbed spillover growth from the core [92–94]. Similar dynamics are observed near Chicago, where cities like Grand Rapids and Madison have experienced increased population growth due to affordability advantages [95]. Broader interstate migration patterns reflect these shifts: outflows from high-cost states such as California toward states like Texas and Florida have accelerated, reflecting both economic opportunity and housing affordability [95].

Conversely, fast-growing metropolitan areas—including Dallas, Houston, Austin, Nashville, and Charlotte—are attracting in-migration due to affordable housing, flexible zoning, favorable tax regimes, and strong regional economies [96–98]. Economic specialization has further reinforced this trend—technology in Austin, energy in Houston, and finance in Dallas [99,100]. These dynamics have produced concurrent increases in both land consumption and population growth, although with greater efficiency than earlier waves of suburban expansion.

Urban containment policies illustrate the influence of governance on land use efficiency. Portland's early adoption of an Urban Growth Boundary (UGB) effectively curbed sprawl but later required flexibility through "urban reserves" to accommodate long-term growth. Seattle's growth management approach, by contrast, emphasized densification within designated urban centers rather than enforcing a fixed boundary [101]. Such adaptive strategies demonstrate how planning frameworks can balance land conservation with urban expansion. Future policy reforms that encourage infill and mixed-use development, particularly around transit corridors, may further enhance land-use efficiency.

Comparable governance interventions are also evident internationally, where urban containment, infill promotion, and growth management policies have been institutionalized to guide land consumption and improve urban land-use efficiency. In Europe, Urban Infill Development (UID) has evolved from a discretionary planning approach into a regulatory necessity, strongly shaped by the European Union's No Net Land Take (NNLT) agenda targeting zero net land conversion by 2050 [37,38]. As a result, infill and soft densification have become important for managing urban growth while advancing land conservation and housing priorities [37–45]. Similar approaches are evident in Australia, where metropolitan

growth boundaries, transit-oriented development, and urban consolidation strategies have been widely implemented to contain fringe expansion and promote higher-density development [46,47].

Global projections indicate that Asia—led by China and India—will account for nearly half of high-probability urban land expansion worldwide by 2030, underscoring the region's dominant role in shaping future urbanization patterns [102,103]. In Asia, policy frameworks have largely emphasized growth containment and spatial optimization through compact city strategies, transit-oriented development, greenbelt regulations, and integrated land-use planning. In China, the use of urban growth boundaries, vertical density, and land quota systems, alongside TOD investments in China and India, reflects efforts to channel expansion into infrastructure-efficient urban forms [104,105]. Similarly, greenbelt controls in South Korea and Singapore illustrate how centralized land assembly and long-term master planning (i.e., state-led approaches) can help to manage land consumption and promote compact development [106,107].

Africa is currently experiencing the fastest rate of urban expansion globally, with growth projected to accommodate a substantial share of the world's future urban population [108,109]. National Urban Policies aligned with SDG frameworks provide strategic planning guidance, while slum upgrading initiatives address service deficits and tenure insecurity in informal settlements [110,111]. New town and satellite city developments such as housing programs in Addis Ababa and planned settlements in Nigeria aim to accommodate population growth and relieve pressure on urban cores [112]. Concurrent investments in mass transit systems, including BRT networks in cities like Lagos and Dar es Salaam, seek to structure expansion along transport corridors and foster more efficient urban form [54].

Comparative LCRPGR analyses further contextualize U.S. performance within global urbanization trajectories. Estoque et al. [113], in a global assessment of LCRPGR across 200 countries, found a 24% improvement in global land-use efficiency between 1975–2000 and 2000–2015, as the global average LCRPGR declined from 1.34 to 1.02. This suggests that land consumption is becoming increasingly proportionate to population growth, though regional disparities remain pronounced. An assessment by Liu et al. [50] of more than 300 Eurasian cities further highlights these disparities, with Europe and Japan exhibiting comparatively low land and population growth rates indicative of mature urbanization, whereas most regions—particularly South and Central Asia—recorded LCRPGR values above the global average, reflecting land expansion outpacing demographic change, especially in small to medium-sized cities. In China, LCRPGR values remain high (1.96), exceeding recommended thresholds [32]. Similarly, studies from Africa and Europe report persistent inefficiencies, including inefficiencies in Ethiopia [54], Poland [59], and Portugal [114], all of which document LCRPGR values above 1, indicating that land expansion continues to outpace population growth in many cities. Collectively, these results illustrate how national development trajectories, policy regimes, and urban governance contexts shape the balance between land use and demographic change.

Temporal analysis reveals a gradual decoupling between urban land expansion and population growth across U.S. urban areas. During 2000–2010, urban land expanded by 15% while population grew by 16%, indicating a balanced trajectory. Between 2010 and 2020, however, land area increased by only 7% compared to a 13% population increase indicating densification and more efficient land utilization. Correlation analyses revealed a stronger coupling between land and population growth in the earlier decade, suggesting that as cities mature, land expansion becomes less responsive to population increases.

Regional clustering analyses further illuminate the spatial heterogeneity of U.S. urban growth dynamics. Clustering analyses identified distinct groupings across the New

England, Middle Atlantic, and East North Central regions, revealing varying relationships between LCR and PGR. Western and northeastern urban areas generally displayed lower expansion rates and higher efficiency, while smaller or mid-sized cities in other regions showed more erratic growth trajectories. These patterns underscore the complexity of urbanization processes and the limitations of one-size-fits-all interpretations of LCRPGR. Importantly, cluster analysis adds value by identifying spatial typologies of urban growth that are obscured in national averages, enabling more context-sensitive interpretation of land-use efficiency patterns (i.e., not ignoring regulatory differences by state).

Findings indicate a structural shift in U.S. urbanization toward more compact, infill-oriented development, particularly within older and policy-constrained metropolitan regions. Declining LCRPGR values signal improving land-use efficiency driven by both market forces and planning interventions. However, persistently elevated LCRPGR levels in certain regions underscore uneven progress and the continued importance of coordinated zoning reform and growth management. In this context, advocacy for revising conventional zoning codes, promoting mixed-use development, and investing in mass transit [85] reinforces the broader transition toward walkable, compact, and socially inclusive urban environments.

This study's findings are limited by use of secondary datasets such as impervious surface maps and gridded population estimates, which may introduce classification errors or uncertainty, particularly in low-density or sparsely populated areas. The use of fixed Census urban boundaries may also exclude peri-urban built-up zones and affect efficiency estimates. Additionally, the LCRPGR indicator has limitations in shrinking or slow-growing cities and should be interpreted cautiously; future research could improve accuracy by using parcel-level land data, functional urban boundaries, and higher-resolution population datasets [48].

5. Conclusions

This study evaluated ULUE across the contiguous U.S. from 2000 to 2020 using SDG Indicator 11.3.1. By integrating impervious surface data with gridded population estimates, the analysis quantified land consumption and demographic change across more than 2200 urban areas, revealing pronounced spatial and temporal variation. Urban land expanded by approximately 23 percent during the study period, while population grew by 31 percent, indicating an overall trend toward densification. Declining median LCRPGR values further suggest a structural shift toward more compact development, although nearly two-fifths of urban areas continue to exhibit inefficient land consumption patterns.

Methodologically, this study demonstrates the applicability of SDG Indicator 11.3.1 for high-resolution, intra-national analysis using harmonized remote sensing and gridded population datasets. From a policy perspective, the results emphasize the importance of coordinated spatial planning, growth management, and zoning reform in shaping urban land outcomes. The observed efficiency gains in regions with containment policies and infill incentives suggest that governance capacity and regulatory frameworks play decisive roles in moderating land consumption.

Overall, while evidence points to incremental progress toward more compact urbanization in the U.S., uneven regional outcomes underscore the continued need for targeted policy action. Integrating spatial indicators such as LCRPGR into planning evaluation frameworks will be essential for monitoring sustainable urban growth and guiding equitable land development strategies going forward.

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