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Urban Growth without Green Compensation: A Multi-Source Geospatial Evidence-Fusion Framework for Climate-Responsive Architectural Planning in Benghazi, Libya

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النمو الحضري دون تعويض للمساحات الخضراء: إطار لدمج الأدلة الجغرافية المكانية متعددة المصادر من أجل التخطيط المعماري المستجيب للمناخ في بنغازي، ليبيا

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Abstract: Rapid urban change in data-scarce cities is difficult to translate into defensible architectural planning because geospatial products often differ in extent, resolution, class definition, and date. This study develops a provenance-aware multi-source evidence-fusion framework for Benghazi using Copernicus EMSN080 urban-sprawl products (2017–2020) and an independent Sentinel-2 NDVI land-cover assessment (2017–2021). Copernicus shows artificial surfaces increasing from 162.253 to 168.569 km², a gain of 6.316 km² (3.89%) and a CAGR of 1.281%. The Sentinel-2 study reports urban land increasing from 57.4227 to 59.0490 km² while green space declined from 12.1338 to 8.1908 km². Re-analysis shows the green-to-urban ratio falling from 0.211 to 0.139 (−34.36%). The combined evidence supports disturbed-land infill, protection and reconnection of residual green infrastructure, lake-edge safeguards, and annual geospatial monitoring.

Keywords: Benghazi; geospatial evidence fusion; Sentinel-2; Copernicus EMS; urban green space; climate-responsive architecture; spatial planning.

الملخص: تواجه المدن شحيحة البيانات صعوبة في تحويل المنتجات الجغرافية المكانية المختلفة إلى قرارات معمارية قابلة للدفاع العلمي. تطور هذه الدراسة إطارًا واعيًا بالمصدر لدمج الأدلة متعددة المصادر في بنغازي، بالاعتماد على منتجات Copernicus EMSN080 للتمدد الحضري (2017–2020) وتقييم مستقل لغطاء الأرض باستخدام Sentinel-2 وNDVI (2017–2021). أظهرت بيانات Copernicus ارتفاع الأسطح الاصطناعية من 162.253 إلى 168.569 كم²، بزيادة 6.316 كم² تعادل 3.89% ومعدل نمو سنوي مركب 1.281%. كما أظهر تقييم Sentinel-2 ارتفاع المساحة الحضرية من 57.4227 إلى 59.0490 كم²، مقابل انخفاض المساحات الخضراء من 12.1338 إلى 8.1908 كم². وانخفضت نسبة المساحات الخضراء إلى الحضرية من 0.211 إلى 0.139، أي بنسبة 34.36%. تدعم النتائج أولوية استغلال الأراضي المتدهورة أو العارية قبل التوسع الخارجي، وحماية وربط البنية الخضراء المتبقية، وتأمين حواف البحيرات، واعتماد مراقبة جغرافية مكانية سنوية قابلة للتدقيق.

الكلمات المفتاحية: بنغازي؛ دمج الأدلة الجغرافية المكانية؛ Sentinel-2؛ Copernicus EMS؛ المساحات الخضراء الحضرية؛ العمارة المستجيبة للمناخ؛ التخطيط المكاني.

1. Introduction

Urban expansion changes the proportion, continuity, and function of built, bare, vegetated, and water surfaces. In hot and dry cities, those changes are not only land-management issues; they directly affect the options available to architects and planners for shade, evapotranspiration, ventilation, stormwater retention, public-space quality, and future heat adaptation. Recent global evidence shows that green infrastructure provides substantial urban cooling, but cities in the Global South receive markedly less cooling capacity than cities in the Global North (Y. Li et al., 2024). The planning challenge is therefore not simply to document growth, but to determine whether the evolving urban form retains enough ecological structure to support climate-responsive design.

Benghazi is an important case because rapid development, reconstruction, conflict-related displacement, and infrastructure pressure have occurred in a coastal semi-arid setting where detailed municipal datasets are fragmented. The Copernicus Emergency Management Service (CEMS) addressed this data gap through EMSN080, a 2020 Risk and Recovery Mapping activation that updated reference infrastructure, Urban Atlas-style land-use/land-cover products, urban-sprawl analyses for 2017–2020, night-light-based human-footprint products, and human-settlement mapping (CEMS, 2020). The activation was requested to support infrastructure and service planning, including sewage and drinking-water extensions (Copernicus, 2020). These products provide unusually strong provenance for a Libyan city because their lineage, acquisition period, and GIS distribution formats are documented by an official European Union service.

A separate Sentinel-2 study of Benghazi quantified changes in urban green space between 2017 and 2021 using NDVI classification with reported 92% classification accuracy (Bufarwa, 2022). Its results suggest that urban and bare-land classes expanded while green space and water declined. The coexistence of these independent observations creates an opportunity for triangulation. However, direct pixel fusion would be methodologically unsound because the products differ in area of interest, spatial resolution, classification ontology, and observation dates. This paper therefore proposes indicator-level evidence fusion: each source is first interpreted within its own measurement definition, and only dimensionally compatible trends and ratios are compared.

The computational contribution is a provenance-aware harmonization workflow that (i) reconstructs annual urban-growth indicators, (ii) derives normalized land-cover shares and annualized change rates, (iii) quantifies green-to-urban balance, and (iv) evaluates cross-source directional convergence without pretending that heterogeneous classes are identical. The architectural contribution is the translation of these indicators into design and planning actions for green infrastructure, redevelopment sequencing, open-space continuity, and data-supported development control. This combination addresses a recurring gap in geospatial urban studies: technically valid change detection is often reported without a direct path to architectural decision-making, while design recommendations are often issued without explicit quantitative provenance.

Accordingly, the study asks four questions. RQ1: What was the rate and temporal pattern of artificial-surface growth in Benghazi from 2017 to 2020? RQ2: How did the balance between urban, bare, green, and water classes change from 2017 to 2021 in an independent Sentinel-2 assessment? RQ3: Do the independent sources converge on the direction of urban expansion despite differing definitions and periods? RQ4: Which climate-responsive architectural planning priorities follow from the combined evidence without making unsupported local thermal-causality claims?

2. Related Work and Research Gap

2.1 Urban morphology, greenness, and thermal resilience

Research increasingly treats urban morphology as a nonlinear regulator of thermal conditions. Wang et al. used multiple regression, XGBoost, and SHAP to show that the relative importance and thresholds of built and green morphology vary by geographic context (Wang et al., 2025). A seven-city study published in 2026 further demonstrated that adding spatial-configuration variables can substantially improve explanation of land-surface temperature and that LightGBM with SHAP can identify planning-relevant thresholds (Wan et al., 2026). A systematic review of 101 studies found hundreds of landscape metrics but only a limited subset that were robust across landscape characters, reinforcing the need for context-sensitive interpretation rather than universal design thresholds (Eneche et al., 2024).

Green-space quantity alone is insufficient. Beele et al. showed that the configuration and aggregation of green cover can alter daytime and nighttime cooling effects (Beele et al., 2024). Li et al. found globally that the cooling efficacy of trees depends jointly on background climate, urban morphology, and tree traits; in arid climates, tree selection and placement must therefore be morphology-aware (H. Li et al., 2024). Global remote-sensing evidence likewise indicates a major cooling-capacity inequality between Global South and Global North cities (Y. Li et al., 2024). These results justify treating the loss and fragmentation of urban green space as a planning-risk signal even when a city-specific LST model is not yet available.

2.2 Mediterranean and North African planning context

Mediterranean cities combine intense solar exposure, water constraints, compact development, and rapidly changing peri-urban edges. Recent work in Tunisia linked urban expansion, vegetation loss, wetland degradation, and thermal vulnerability over four decades, translating Local Climate Zone diagnostics into heat-sensitive planning recommendations (Ben Haj Ncir et al., 2026). In Cyprus, an integrated GIS and multi-criteria framework prioritized green-space interventions by combining urbanization pressure, thermal conditions, environmental constraints, and stakeholder priorities (Eliades et al., 2025). These studies demonstrate that climate-responsive planning benefits from integrating land-change evidence with design instruments rather than treating remote sensing as a purely descriptive exercise.

2.3 Libya and Benghazi

Geospatial planning in Libya has previously been approached through multi-criteria and machine-learning-assisted city prioritization (Kalantar et al., 2019). Regional studies have also related NDVI and land-surface temperature in northeastern Libya (Hegazy et al., 2022). For Benghazi specifically, Bufarwa documented a substantial decline in urban green space between 2017 and 2021 (Bufarwa, 2022), while CEMS independently mapped land-use change, settlement structure, and urban growth (CEMS, 2020). What remains underdeveloped is a reproducible framework that reconciles these heterogeneous observations, quantifies their agreement and disagreement, and translates the resulting evidence into architecture-oriented planning diagnostics. This paper targets that gap.

3. Study Area and Data

Benghazi is located on Libya's Mediterranean coast and functions as the principal urban center of eastern Libya. The CEMS EMSN080 dataset covers an area bounded approximately by 19.96431–20.21774°E and 32.00963–32.19051°N (Joint Research Centre, European Commission, 2020). The urban system includes a dense historic/administrative core, expanding residential and peri-urban areas, transport infrastructure, coastal and lagoon/water features, and a mixture of formal and limited informal settlement areas. CEMS reported that the great majority of mapped settlement structures were formal and permanent, while only eight informal or temporary areas were identified among nearly 35,000 mapped structures (Copernicus, 2020).

Table 1. Data sources, provenance, and analytical role.

Source	Period	Spatial / thematic basis	Role in this study	Quality / provenance note
CEMS EMSN080 P10 Urban Sprawl	2017–2020	Sentinel-2 change analysis over AOI01 Benghazi	Annual artificial-surface area and growth dynamics	Official EU CEMS product with documented metadata and GIS deliverables (CEMS, 2020)
CEMS EMSN080 P03 / P02 / P18	2020	VHR imagery; Urban Atlas-style LULC; reference assets; settlements	Morphological and infrastructure context	Official Risk and Recovery Mapping activation (CEMS, 2020; Copernicus, 2020)
Sentinel-2 Benghazi UGS study	2017 & 2021	NDVI-based classification of 101.3675 km² study area	Independent land-cover balance and green-space change	Reported classification accuracy: 92% (Bufarwa, 2022)
Sentinel-2 mission documentation	Mission specification	13 spectral bands; 10/20/60 m	Sensor provenance and reproducibility context	Copernicus public mission documentation (Copernicus Data Space Ecosystem, 2026)
Libya Engineering Data Portal	Current application context	Dynamic web-GIS gateway	Discovery/application context only; no unverified portal values used	Numeric analysis restricted to independently verifiable source datasets

The key methodological choice is to avoid forced geometric overlay between sources that were not produced under identical specifications. Copernicus P10 measures artificial-surface evolution across its own AOI and production workflow. The Sentinel-2 study provides a four-class accounting of urban, bare, green, and water surfaces over a fixed 101.3675 km² study area. The datasets are therefore harmonized through rates, shares, ratios, and directional agreement rather than direct pixel subtraction.

4. Methods

4.1 Provenance-aware evidence-fusion workflow

The workflow contains five stages: provenance verification, source-specific reconstruction, indicator derivation, cross-source convergence analysis, and planning translation. All reported numbers were either stated in the source products or recomputed from stated source values. No model-performance statistic is reported unless it can be reproduced from the available numerical observations.

4.2 Urban-growth indicators

For consecutive years t−1 and t, absolute growth is $\Delta A_t = A_t - A_{t-1}$ and relative annual growth is $g_t = 100(A_t/A_{t-1} - 1)$. For the full 2017–2020 interval, the compound annual growth rate is $CAGR = 100[(A_{2020}/A_{2017})^{(1/3)} - 1]$. A descriptive least-squares trend $A_t = \alpha + \beta \cdot year$ is also fitted. Because only four annual observations are available, β and R^2 are used as descriptive summaries, not as evidence for inferential significance.

4.3 Land-cover balance and green-to-urban ratio

For each Sentinel class c, the study calculates absolute change, relative change, annualized four-year CAGR, and share of the fixed study area. To express architectural ecological balance without imposing an external normative target, we define the Green-to-Urban Ratio (GUR) as GUR=Green area / Urban area. Its relative change quantifies whether green area is keeping pace with the mapped urban class. We also report the Green-Loss-to-Urban-Gain ratio (GLUG=|ΔGreen|/ΔUrban) within the same Sentinel study area. GLUG is an accounting indicator, not a causal transition probability: it does not prove that every lost green pixel became urban land.

4.4 Cross-source convergence

The independent sources use different spatial extents and class definitions, so their annualized growth magnitudes are not expected to match. We define convergence conservatively as agreement in the sign of urban change, accompanied by transparent reporting of the annualized rate gap. Copernicus artificial-surface CAGR and Sentinel urban-class CAGR are compared only as directional, scale-normalized indicators. The difference between them is interpreted as a combined effect of AOI, ontology, spatial resolution, and temporal-window differences rather than measurement error.

4.5 Planning interpretation rule

Planning recommendations are admitted only when they satisfy two conditions: (i) they follow directly from the observed land-cover direction or from established urban-climate literature, and (ii) they do not require an unmeasured Benghazi-specific thermal coefficient. Thus, the paper supports protecting and reconnecting green infrastructure because green area declined sharply and the wider literature consistently associates green infrastructure with cooling benefits (Y. Li et al., 2024; Beele et al., 2024; H. Li et al., 2024). It does not claim a specific °C cooling benefit for Benghazi because a local LST attribution model has not been executed in the present analysis.

5. Results

5.1 Artificial-surface growth, 2017–2020

Copernicus EMSN080 records a steady increase in artificial surfaces from 162.253 km² in 2017 to 168.569 km² in 2020. The net increase was 6.316 km², equivalent to 3.89%. The CAGR was 1.281% per year. Annual increments were 1.751, 2.884, and 1.681 km², showing that the strongest expansion occurred in 2018–2019. The descriptive linear fit produced a slope of 2.183 km² $year^{-1}$ and $R^2=0.989$; with n=4, this high R^2 should be interpreted as a compact description of monotonic short-term growth rather than a long-term forecast model.

Table 2. Copernicus EMSN080 artificial-surface growth in Benghazi.

Year	Artificial surfaces (km²)	Annual change (km²)	Annual change (%)	Interpretation
2017	162.253	—	—	Baseline
2018	164.004	1.751	1.079	Continued expansion
2019	166.888	2.884	1.758	Peak annual increment
2020	168.569	1.681	1.007	Expansion continued at lower rate

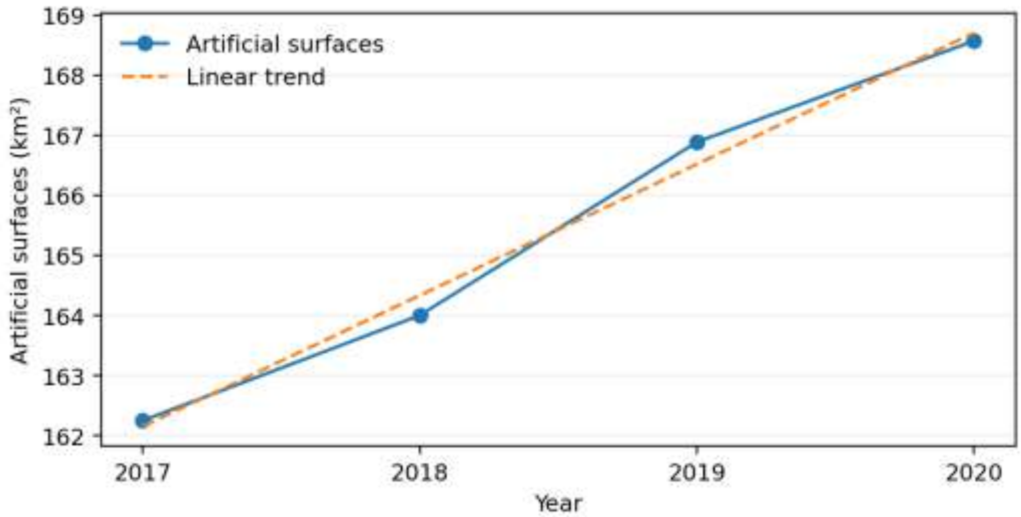

Figure 1. Artificial-surface growth and descriptive linear trend (β=2.183 km² year⁻¹; R²=0.989).

5.2 Land-cover redistribution, 2017–2021

The independent Sentinel-2 assessment covers a constant 101.3675 km² study area. Urban land increased by 1.6263 km² (2.83%), and bare land increased by 2.6851 km² (9.10%). In contrast, green space decreased by 3.9430 km² (-32.50%), while water decreased by 0.3684 km² (-15.99%). The fixed-area accounting therefore shows a redistribution of 4.3114 km² toward the urban and bare classes, exactly balanced by the combined decrease in green and water classes. Green-space loss accounts for 91.46% of that decrease-side accounting balance and water for 8.54%. This is a compositional accounting result, not a pixel-level transition matrix.

Table 3. Sentinel-2 land-cover change and derived annualized indicators.

Class	2017 (km²)	2021 (km²)	Δ km²	Relative Δ (%)	CAGR (%/yr)	Share change (pp)
Urban	57.4227	59.0490	1.6263	2.83	0.701	1.604
Bare land	29.5072	32.1923	2.6851	9.10	2.201	2.649
Green space	12.1338	8.1908	-3.9430	-32.50	-9.357	-3.890
Water	2.3038	1.9354	-0.3684	-15.99	-4.263	-0.363

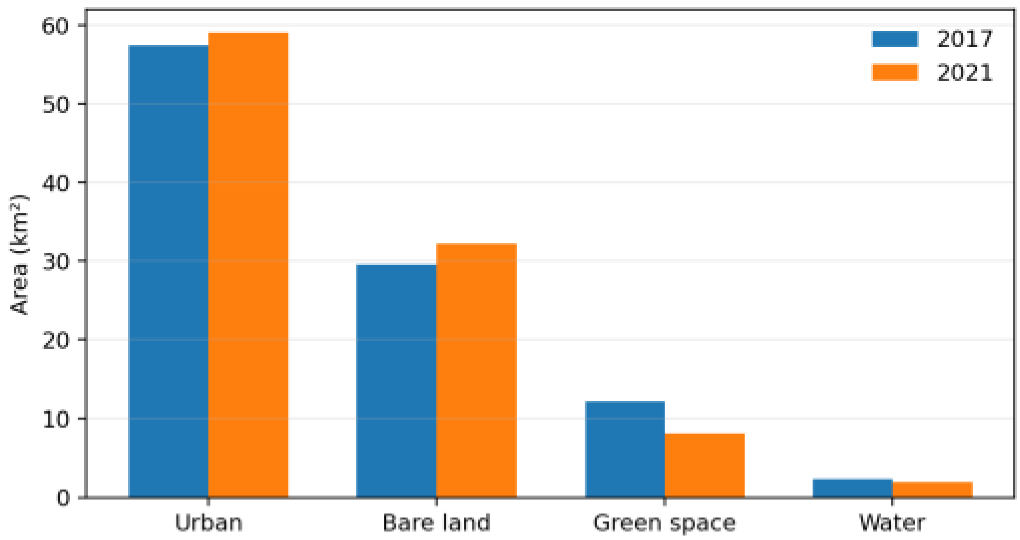

Figure 2. Land-cover areas reported for the 2017 and 2021 Sentinel-2 assessment (Bufarwa, 2022).

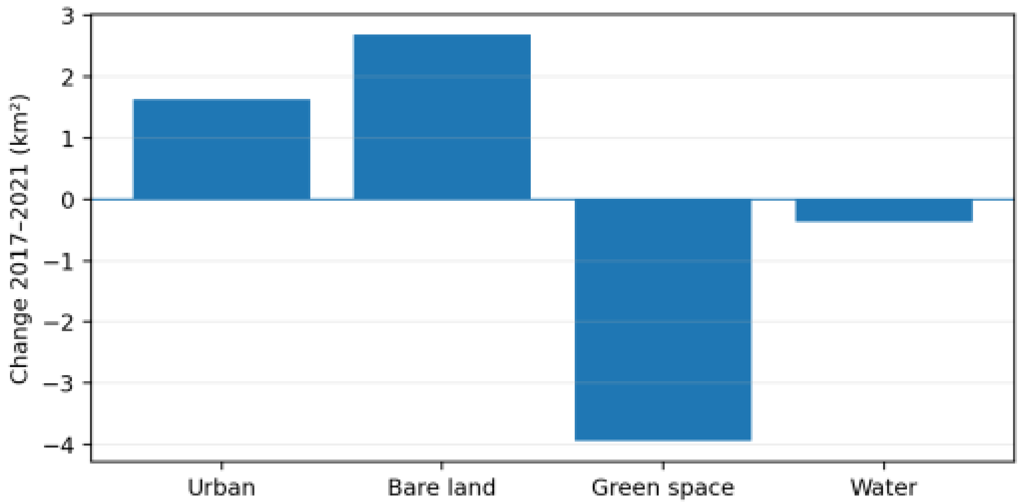

Figure 3. Change in land-cover composition within the fixed Sentinel-2 study area.

5.3 Green-to-urban balance

The green-space share of the Sentinel study area fell from 11.97% in 2017 to 8.08% in 2021, a decline of 3.89 percentage points. Over the same period, the urban share rose from 56.65% to 58.25%. The GUR consequently fell from 0.211 to 0.139, a 34.36% reduction. Put differently, the mapped green area per unit of mapped urban area declined by roughly one third in four years. Green-space loss (3.943 km²) was 2.42 times the urban-class gain (1.626 km²) within the same study area. This ratio is particularly relevant for architectural planning because it indicates that urban growth was accompanied by a much larger contraction of the green-space stock rather than a proportional green-space expansion.

Table 4. Derived planning indicators.

Indicator	Value	Planning meaning
Copernicus urban CAGR (2017–2020)	1.281%/yr	Artificial surfaces expanded in every observed annual interval.
Sentinel urban-class CAGR (2017–2021)	0.701%/yr	Independent source confirms positive urban growth.
Green-space CAGR (2017–2021)	-9.357%/yr	Rapid contraction of the mapped green-space stock.
Green-space share change	-3.890 pp	Green infrastructure occupied a smaller fraction of the study area.
Green-to-urban ratio	0.211 → 0.139	Green area did not keep pace with mapped urban area.
Green loss / urban gain	2.42:1	Each 1 km² of net urban-class gain co-occurred with 2.42 km² of net green-space loss within the same land-cover budget; not a causal pixel transition.
Cross-source CAGR gap	0.580 pp/yr	Magnitude differs by source definition/AOI, but direction is consistently positive.

5.4 Cross-source convergence

Copernicus artificial surfaces grew at an annualized rate of 1.281% during 2017–2020, while the independent Sentinel urban class grew at 0.701% during 2017–2021. The absolute gap is 0.580 percentage points per year. The magnitudes should not be averaged because the class definitions and AOIs are different. Nevertheless, both sources independently indicate positive urban expansion from a 2017 baseline. This directional convergence strengthens the inference that Benghazi was expanding during the study period, while the Sentinel evidence separately establishes that the green-space share was declining.

6. Discussion

6.1 What the fused evidence establishes

The strongest defensible conclusion is not that one particular urban form caused a measured temperature increase; the present data do not support that causal statement. The stronger conclusion is that two independent geospatial sources converge on continuing urban expansion and that a high-resolution Sentinel-2 assessment documents a simultaneous deterioration of the city's green-to-urban balance. This matters because the literature consistently identifies green-space quantity, configuration, and tree placement as important components of urban thermal resilience (Eneche et al., 2024; Y. Li et al., 2024; Beele et al., 2024; H. Li et al., 2024). The evidence therefore establishes a planning-risk trajectory even without assigning a Benghazi-specific temperature coefficient.

The short Copernicus time series also shows that urban growth was not a single-year anomaly. Artificial surfaces increased in each annual interval, with the highest increment in 2018–2019. The lower 2019–2020 increment does not indicate reversal; it still represents positive expansion. The Sentinel observations extend the temporal window to 2021 and independently retain the same sign for urban growth while documenting substantial vegetation decline. This is exactly the type of situation in which evidence fusion is useful: different data products need not match numerically to reinforce a common directional diagnosis.

6.2 Why the difference between sources is informative

A common but problematic practice is to merge land-cover statistics from different products as if labels such as 'urban' and 'artificial surfaces' were interchangeable. Here, the Copernicus CAGR is almost twice the Sentinel urban-class CAGR. Rather than treating this as an error, the framework preserves it as a reproducibility warning. CEMS P10 was designed for city-growth analysis over the EMSN080 AOI, whereas the Sentinel study used an NDVI-oriented four-class scheme over a 101.3675 km² study area. The rate gap therefore quantifies the sensitivity of urban-change magnitude to data definition. For planning, the robust information is the direction of expansion; for regulation, a municipality should adopt one stable ontology and AOI before using annual targets or compliance thresholds.

6.3 Architectural interpretation

The most important architectural signal is the 34.36% decline in the green-to-urban ratio. This indicates that the city's ecological surface stock did not expand alongside the urban footprint. From a climate-responsive design perspective, the remaining green areas should therefore be treated as infrastructure rather than residual land. Contemporary evidence shows that urban greenery can reduce heat exposure, but cooling performance depends on spatial configuration, morphology, climate, and species selection (Y. Li et al., 2024; Beele et al., 2024; H. Li et al., 2024). The appropriate response is consequently not a generic instruction to 'plant more trees'; it is a spatial design strategy that protects existing green patches, reconnects fragmented open-space systems, prioritizes shade at pedestrian routes and public facilities, and uses drought-appropriate vegetation arrangements compatible with Benghazi's water constraints.

The increase in bare land is also architecturally important. Bare land rose by 2.6851 km² in the Sentinel study, exceeding the net urban-class gain. Some bare parcels may represent transitional development, disturbed land, or vacant plots rather than a stable land-use type. Before outward expansion consumes additional vegetated land, these already disturbed surfaces should be assessed for infill, adaptive reuse, or planned redevelopment. This sequencing principle can reduce pressure on remaining green areas while improving infrastructure efficiency. It should, however, be applied parcel by parcel because remote-sensing class labels do not reveal land ownership, contamination, legal restrictions, or microclimatic quality.

Water area declined by 0.3684 km² in the Sentinel study. Benghazi's urban lakes and water edges can contribute to ecological continuity, public-space quality, drainage, and local microclimate. Their observed contraction supports a precautionary planning principle: lake margins and connected open-space systems should be mapped as protected blue-green infrastructure, with development control based on hydrological and ecological surveys rather than on spectral classification alone.

7. Climate-Responsive Architectural Planning Framework

The evidence is translated into a five-part planning framework intended for municipal plans, district redevelopment studies, and the Libya engineering-data portal. First, establish a no-untracked-loss rule: every planning cycle should publish the area and share of green, water, bare, and built classes using a stable classification scheme and boundary. This does not require an arbitrary greenness target; it requires transparent accounting so that conversion is visible before cumulative loss becomes irreversible.

Second, prioritize disturbed-land infill. The mapped increase in bare land makes it possible to create a redevelopment screening layer that identifies parcels already lacking vegetation and compares them with infrastructure capacity, accessibility, ownership, and environmental constraints. Architecture and computer-science teams can jointly implement this as a spatial decision-support module: architects define suitability and urban-design criteria, while computer scientists implement the geodatabase, reproducible scoring logic, and web-GIS interface.

Third, protect and reconnect residual green infrastructure. The 3.943 km² net green-space loss and the decline in GUR justify treating remaining green patches as a connected system. Priority should be given to links between existing parks, institutional landscapes, street corridors, lake edges, and public facilities. At project scale, interventions can include shaded pedestrian routes, courtyard greening, vegetated setbacks, roof or façade greening where structurally and hydraulically feasible, and tree placement designed with solar exposure and urban-canyon geometry rather than simple planting counts.

Fourth, integrate blue-green safeguards into development control. Water-body contraction should trigger a dedicated review of lake edges, drainage corridors, and low-lying open spaces before building approvals. This is particularly important in coastal and semi-arid cities where the same open land may perform ecological, drainage, recreational, and thermal functions.

Fifth, institutionalize annual geospatial monitoring. CEMS demonstrates that Benghazi can be monitored with a combination of VHR imagery, Sentinel-2, settlement mapping, and night lights (CEMS, 2020). A municipal workflow should preserve raw imagery metadata, processing scripts, classification versions, and change logs. This converts GIS from a static mapping product into an auditable planning system and creates the data foundation required for later GeoAI models.

8. Limitations and Validity Controls

This study deliberately uses indicator-level fusion rather than pixel-level fusion. The main limitation is that the Copernicus and Sentinel study areas and class ontologies are not identical; their area values cannot be subtracted from one another, and their annualized rates are compared only for directional convergence. Second, the Sentinel land-cover figures are re-analyzed from a published classification rather than recomputed from raw Level-2A imagery in the present environment. The reported 92% classification accuracy comes from the source study (Bufarwa, 2022); without its full confusion matrix, uncertainty cannot be propagated to each class-change estimate.

Third, the study does not present a local Benghazi land-surface-temperature model. The architectural interpretation of green loss as a thermal-resilience concern is supported by a large external literature (Wang et al., 2025; Wan et al., 2026; Eneche et al., 2024; Y. Li et al., 2024; Beele et al., 2024; H. Li et al., 2024; Khan & Li, 2024), but no local °C effect is claimed. Fourth, a four-year or five-year observation window is short relative to urban-development cycles, and the 2017–2020 linear R^2 is descriptive only. Finally, satellite-derived land-cover classes cannot independently identify parcel ownership, legal status, irrigation reliability, vegetation species, building height, or social accessibility; these require municipal and field data before site-specific design decisions.

9. Registered GeoAI Thermal-Attribution Extension

To preserve the original computer-science research trajectory, this study specifies a reproducible extension that can be executed when raw Landsat Collection 2 and vector layers are locally available. The extension does not contribute any numerical result to Sections 5–8 and therefore cannot inflate the present evidence. It is structured as follows: (1) create a 250 m analysis grid over the common valid area; (2) derive Landsat surface temperature from the Collection 2 surface-temperature band and calculate NDVI, NDBI, and NDWI after QA_PIXEL cloud masking; (3) aggregate Urban Atlas morphology and spectral predictors per grid cell; (4) compare OLS, Random Forest, XGBoost, and LightGBM; (5) use spatially grouped cross-validation rather than a random train/test split; (6) interpret the best model with SHAP; and (7) test residual spatial autocorrelation before translating model relationships into design thresholds. The supplied analysis script implements this workflow, but the present paper intentionally withholds R^2, RMSE, MAE, and SHAP values until the raw rasters are processed.

This preregistered separation between completed evidence and planned inference is a methodological safeguard. Explainable machine learning is valuable for urban morphology because relationships with temperature are often nonlinear (Wang et al., 2025; Wan et al., 2026), while SHAP offers a consistent framework for feature attribution (Lundberg & Lee, 2017). However, explainability cannot compensate for spatial leakage, inconsistent acquisition dates, or missing provenance. The proposed extension therefore uses temporal matching and spatial validation as first-order requirements, not optional refinements.

10. Conclusions

Benghazi experienced measurable urban expansion during the late 2010s. Copernicus EMSN080 shows artificial surfaces increasing by 6.316 km^2 (3.89%) from 2017 to 2020, with growth in every annual interval. An independent Sentinel-2 assessment extends the diagnosis to 2021: urban and bare classes increased, while green space fell by 3.943 km^2 (32.50%) and water fell by 0.368 km^2. The green-to-urban ratio declined by 34.36%, showing that urban development was not accompanied by proportional green-space compensation.

The paper's main contribution is not a new satellite classifier but a defensible evidence-fusion logic for data-scarce urban planning. It demonstrates how heterogeneous official and published geospatial sources can be combined without erasing their differences, and how the resulting indicators can inform architectural priorities. For Benghazi, the immediate priorities are to preserve and reconnect remaining green infrastructure, assess bare/disturbed land for infill before outward expansion, protect blue-green edges, and establish annual versioned geospatial monitoring. These steps create both a stronger climate-responsive planning basis and the data architecture needed for the registered GeoAI thermal-attribution extension.

Data Availability and Reproducibility

Copernicus EMSN080 products are publicly documented through the CEMS On-Demand Mapping activation page and the EU data catalogue (CEMS, 2020; Joint Research Centre, European Commission, 2020). Sentinel-2 mission data are publicly available through Copernicus services (Copernicus Data Space Ecosystem, 2026). The Benghazi green-space values used here are taken from the published 2017/2021 Sentinel-2 study (Bufarwa, 2022). The accompanying supplementary files include the verified Copernicus annual-growth table, the derived-indicator table, and a GeoAI extension script. The Libya engineering-data portal was used as the application context; no portal value that could not be independently verified was used in the numerical results.

Conflict of Interest

The authors declare no conflict of interest.

Ethics Statement

The study uses remote-sensing and aggregated geospatial data and does not involve human participants, personal identifiers, or interventions.

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