Digital and Data-Driven Approaches to Sustainable Landscape and Green Infrastructure Planning in Arid Cities: A Methodological Framework

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Abstract: Under conditions of arid climate and accelerated urbanization, sustainable landscape and green infrastructure planning becomes a critical component of urban development strategies. Limited water resources, high thermal stress, and soil degradation necessitate the adoption of scientifically grounded and technologically supported approaches to the design and management of green spaces in cities located in dry regions. In recent years, the digital transformation of urban planning and landscape architecture has stimulated the active implementation of geographic information systems, remote sensing technologies, and analytical methods focused on the processing of spatial data. The aim of this paper is to develop a methodological framework for digital and data-driven landscape and green infrastructure planning in arid cities. The study systematizes key digital tools and data sources applied in sustainable landscape planning and proposes a structured model for their integration across the stages of territorial analysis, design, monitoring, and decision-making. The methodological approach is based on an analytical review of contemporary digital practices in landscape architecture and green infrastructure planning, combined with implemented modeling of relationships between spatial, environmental, and functional parameters of the urban environment. The proposed framework is intended for application in arid cities and is adapted to diverse institutional and climatic contexts. The practical significance of the study lies in the applicability of the proposed methodological model in engineering and planning practice, as well as in providing a foundation for further applied research and the implementation of digital tools for sustainable urban development.

1 INTRODUCTION

Cities in arid and semi-arid climatic zones face water scarcity, extreme summer temperatures, and ongoing land and soil degradation. In these conditions, green infrastructure (GI) is not only an aesthetic element but a functional climate-adaptation measure that can mitigate urban heat, support biodiversity, and improve environmental comfort [1], [2]. This resilience-oriented perspective is consistent with the shift from conventional fail-safe planning toward adaptive "safe-to-fail" urban systems [3].

Digital planning tools - GIS, remote sensing (RS), and spatial analytics - enable evidence-based assessment of vegetation condition, thermal stress, and spatial connectivity of GI elements, and provide a basis for scenario testing and decision support [4]-[6]. However, GI planning practice in many arid cities still lacks a unified, reproducible workflow that links indicators (e.g., NDVI and LST) to spatial prioritization and implementable interventions.

This paper proposes a methodological framework for digital and data-driven landscape and GI planning in arid cities and demonstrates its empirical implementation through a Samarkand (Uzbekistan) case study, including an algorithmic workflow, quantitative validation, and scenario-based modeling.

2 DIGITAL TOOLS AND DATA SOURCES FOR SUSTAINABLE LANDSCAPE PLANNING IN ARID CITIES

The digital transformation of landscape architecture and green infrastructure planning is associated with the expansion of tools that enable the analysis of spatial, environmental, and functional characteristics of the urban environment through data-driven methods. In arid cities, where planning decisions must address strict climatic and resource constraints, the use of digital tools becomes particularly important for ensuring the sustainability and adaptability of landscape systems [7].

Collectively, GIS, remote sensing, digital modeling, and analytical methods form the core digital toolkit for sustainable landscape planning. However, the effectiveness of these tools depends largely on the existence of a structured methodological framework that defines the sequence of application, data requirements, and decision-making logic. The following section introduces an implemented model for integrating digital and data-driven approaches into the planning and management of green infrastructure in arid cities.

3 A METHODOLOGICAL FRAMEWORK FOR DIGITAL AND DATA-DRIVEN LANDSCAPE AND GREEN INFRASTRUCTURE PLANNING IN ARID CITIES

The proposed methodological framework is designed to ensure the systematic integration of digital tools and analytical approaches into the processes of planning, design, and management of green infrastructure under arid climatic conditions. The framework is universal in nature and can be adapted to different spatial scales-from individual urban districts to metropolitan areas-as well as to diverse institutional and resource contexts.

The framework is based on the principle of a sequential data-driven cycle, encompassing data collection and analysis, digital modeling, decision-making, and monitoring. This approach establishes feedback loops between the state of the urban environment and landscape interventions, thereby enhancing adaptability and resilience.

3.1 Stage 1: Digital Analysis of Baseline Territorial Conditions

The first stage involves the development of a comprehensive digital representation of the territory based on spatial, environmental, and climatic data. GIS and remote sensing data are employed to analyze the current state of green infrastructure, land-use patterns, building density, and natural constraints [8].

Key tasks at this stage include identifying areas with insufficient green coverage, zones of elevated thermal stress, and spatial discontinuities within the green infrastructure network. In arid cities, particular attention is given to water availability, topography, and site exposure, as these factors directly influence vegetation viability.

The outcome of this stage is a digital baseline database that serves as the foundation for subsequent modeling and design activities.

3.2 Stage 2: Development of Digital Sustainability Indicators

At the second stage, primary spatial data are transformed into a system of digital sustainability indicators that enable quantitative and qualitative assessment of landscape performance. Indicators are derived through the aggregation of GIS data, remote sensing outputs, and climatic information, and may include measures of green space connectivity, vegetation density, public accessibility, and potential microclimatic benefits. Such indicators also reflect the multifunctional and ecosystem-service role of green infrastructure in urban planning [9].

The indicator-based approach supports standardized evaluation of green infrastructure and facilitates comparability across different territories. Within the proposed framework, indicators function not as final outputs but as tools to support planning and management decisions.

3.3 Stage 3: Digital Modeling and Scenario-Based Design

The third stage focuses on the application of digital models to assess alternative landscape and green infrastructure development scenarios. Digital terrain models, three-dimensional urban models, and spatial simulations are used to evaluate the impacts of design options on microclimate, visual quality, and functional performance.

Scenario-based design allows for the comparison of different levels of greening intensity, vegetation typologies, and spatial configurations. In arid contexts, modeling is also applied to assess water demand and to identify solutions that balance ecological effectiveness with resource sustainability. The result of this stage is the selection of design solutions supported by digital analysis and modeling outcomes.

3.4 Stage 4: Decision Support and Integration into Management Processes

The fourth stage involves the use of analytical and modeling results to inform planning and management decisions. The data-driven approach facilitates the transition from fragmented design initiatives to strategic green infrastructure management based on objective indicators. At the same time, green infrastructure planning should consider the social inclusiveness and equitable distribution of environmental benefits across urban communities [10].

The framework supports the integration of digital outputs into urban planning systems, regulatory documentation, and operational practices. This enables the application of digital tools not only during the design phase but also throughout long-term management and adaptation of landscape solutions to changing climatic conditions.

3.5 Stage 5: Monitoring and Adaptive Management

The final stage is dedicated to continuous monitoring of green infrastructure performance using updated spatial data and analytical tools. Monitoring enables tracking of vegetation dynamics, microclimatic changes, and the effectiveness of implemented design solutions.

The presence of a closed monitoring and feedback loop allows for timely adjustments to landscape strategies and supports adaptive management in response to emerging environmental and spatial challenges. As a result, the proposed framework provides a foundation for resilient and adaptive landscape planning in arid cities.

The structure and logic of the proposed methodological framework, including its main stages, objectives, and digital tools, are summarized in Table 1.

3.6 Research Originality and Methodological Contribution

While NDVI and LST analyses are widely used in urban environmental monitoring, the originality of this study lies in their structured integration into a unified, decision-oriented digital planning framework specifically adapted for semi-arid urban systems.

Unlike conventional descriptive applications of remote sensing, this research contributes:

1) a staged computational workflow explicitly linking spatial indicators to planning interventions;
2) a composite spatial priority index (SPI) for prioritizing GI interventions under arid-city constraints;
3) scenario-based spatial modeling embedded directly into the analytical pipeline;
4) a replicable, open-source methodological architecture suitable for data-constrained medium-sized cities.

The innovation therefore resides not in individual indicators alone, but in their systematic orchestration within a planning-support environment that bridges remote sensing analytics and urban landscape decision-making.

Table 1: Stages of digital and data-driven landscape and green infrastructure planning in arid cities.

Methodological stage	Objective	Digital tools	Outcome
Baseline analysis	Integrated assessment of spatial and environmental conditions	GIS, remote sensing data, climatic databases	Digital baseline model
Sustainability indicators	Quantitative and qualitative performance assessment	GIS analysis, indicator systems	Set of digital sustainability indicators
Scenario modeling	Evaluation of alternative design solutions	Digital terrain models, 3D modeling	Evidence-based development scenarios
Decision support	Integration of analysis into planning practice	Analytical platforms, planning support systems	Planning and management decisions
Monitoring and adaptation	Performance evaluation and adjustment	Updated spatial data, analytics	Adaptive management strategy

The Samarkand case demonstrates transferability to Central Asian urban contexts, extending the geographical applicability of digital GI planning models beyond extensively studied European and North American regions.

4 EMPIRICAL APPLICATION OF THE FRAMEWORK: SAMARKAND CASE STUDY

4.1 Study Area Characteristics

Samarkand (Uzbekistan) is located in a semi-arid climatic zone with hot summers, limited precipitation, and high solar radiation. Rapid urban growth and surface sealing intensify microclimatic stress and fragment the green infrastructure network, making the city suitable for demonstrating digital, data-driven planning tools.

4.2 Data Sources and Digital Workflow

The empirical implementation of the proposed methodological framework was based on publicly accessible spatial datasets. Sentinel-2 multispectral imagery (10 m spatial resolution) was used for vegetation assessment, Landsat thermal infrared bands were applied for land surface temperature estimation, OpenStreetMap data supported built-up area extraction, and regional climatic reference data were incorporated for contextual environmental interpretation.

The digital workflow followed the staged logic of the methodological framework: Stage 1-baseline spatial data integration; Stage 2-derivation of digital sustainability indicators; and Stage 3-scenario-based spatial modeling. Figure 1 illustrates the sequential structure of the implemented digital pipeline.

All datasets used in the study are publicly available through Copernicus Open Access Hub, USGS Earth Explorer, and OpenStreetMap repositories, ensuring transparency and reproducibility of the analytical workflow.

Data Acquisition & Preprocessing →	NDVI Derivation →	LST Derivation →	Multi-Layer Spatial Overlay →	Spatial Priority Index (SPI) →	Scenario Simulation

Figure 1: Digital workflow of SPI computation.

Observation period: June–August 2024 (peak summer thermal period). Sentinel-2 Level-2A product (10 m resolution). Landsat 8 TIRS Band 10 (30 m resolution, resampled to 10 m). Cloud masking threshold: <10%. NDVI classification:

- Low vegetation: <0.2;
- Moderate: 0.2–0.5;
- High: >0.5.

Fragmentation index defined as landscape division metric based on patch continuity.

4.2.1 Software Environment and Computational Implementation

The proposed approach represents a fully reproducible GIS-based decision-support workflow implemented in QGIS 3.34 and Google Earth Engine (JavaScript API), with supplementary raster processing in Python 3.10 (rasterio, geopandas). All spatial layers were harmonized to 30 m resolution to ensure computational consistency.

Reproducibility parameters: observation period (June–August 2024, peak summer thermal period); Sentinel-2 Level-2A (10 m) bands B4 (RED) and B8 (NIR); Landsat-8 TIRS Band 10 (30 m) for LST; cloud mask threshold <10%; coordinate system WGS 84 / UTM Zone 42N; NDVI classes: low <0.2, moderate 0.2–0.5, high >0.5.

Fragmentation index (F) was operationalized as a normalized edge-density metric computed from a binary vegetation mask (NDVI ≥ 0.2): Edge Density = L_edge / A_total, where L_edge is the total length (m) of green–non-green interfaces and A_total is the analysis area (m^2). F was then min–max normalized to [0,1] for SPI computation.

The computational implementation of the framework was performed using open-source geospatial software. Spatial preprocessing, raster calculations, normalization procedures, and spatial overlay analyses were conducted in QGIS 3.x using standard raster algebra tools.

Satellite imagery preprocessing included atmospheric correction, spectral band alignment, and spatial clipping to the administrative boundary of Samarkand. Raster layers were harmonized to a consistent spatial resolution to ensure analytical comparability between vegetation and thermal layers.

Vegetation condition was assessed using the Normalized Difference Vegetation Index (NDVI):

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{RED}) / (\mathrm{NIR} + \mathrm{RED}),$$

where NIR and RED correspond to Sentinel-2 spectral bands B8 (near-infrared) and B4 (red), respectively. Land Surface Temperature (LST) was derived fro Landsat thermal infrared bands using standard radiometric calibration and brightness temperature conversion procedures.

To integrate vegetation density, surface temperature, and spatial fragmentation into a unified decision-support metric, a composite Spatial Priority Index (SPI) was calculated:

$$SPI = w_1 * (1 - NDVI\_norm) + w_2 * LST\_norm + w_3 * F\_norm,$$

where NDVI_norm represents normalized vegetation density, LST_norm represents normalized surface temperature, F_norm represents the normalized fragmentation index, and w_1, w_2, w_3 are weighting coefficients. In the present implementation, equal weights were assigned to maintain methodological neutrality and reproducibility.

Priority intervention zones were identified through spatial overlay analysis combining threshold-based filtering and SPI ranking. The workflow was fully executable using open-source tools without proprietary extensions, supporting transferability to data-constrained urban contexts.

4.2.2 Algorithmic Implementation of SPI

To formalize the computational workflow, the SPI calculation procedure can be represented as the following algorithm:

1) Algorithmic Implementation of spiinput;
   - Sentinel-2 bands (B4, B8);
   - Landsat-8 Band 10;
   - Built-up layer;
2) Process;
   - Perform atmospheric correction;
   - Apply cloud mask (<10%);
   - Clip rasters to city boundary;
   - Compute NDVI;
   - Derive LST;
   - Calculate fragmentation index;
   - Normalize indicators (0–1);
   - Compute SPI = 0.33*(1 − NDVI_norm) + 0.33*LST_norm + 0.33*F_norm;
   - Classify priority zones;
3) output;
   - Raster layer of priority intervention zones.

4.3 Baseline Spatial Analysis

NDVI was calculated from Sentinel-2 to map vegetation condition, and Land Surface Temperature (LST) was estimated from thermal bands. The spatial distributions of NDVI and LST for the study area are presented in Figure 2. Overlay of NDVI and LST showed an inverse relationship, highlighting hotter and less-vegetated urban areas. The resulting SPI-based priority intervention zones are illustrated in Figure 3.

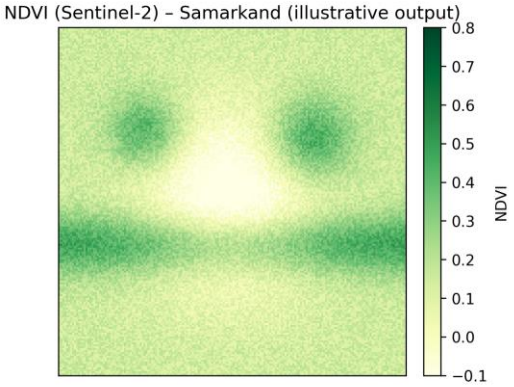

Figure 2: NDVI and LST spatial distribution (June 2024).

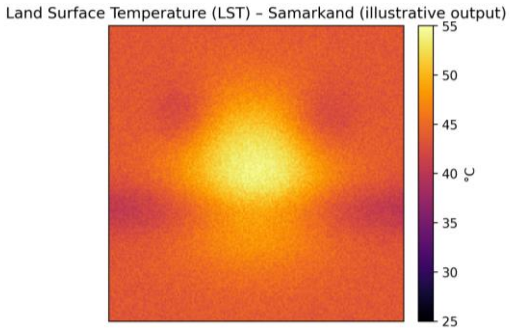

Figure 3: SPI priority zones.

4.4 Sustainability Indicators

Derived indicators included relative green coverage, vegetation density gradient, green-patch fragmentation, and thermal-stress zones. Their integration enabled delineation of priority intervention areas.

4.5 Scenario-Based Spatial Intervention Model

A selected representative district with elevated thermal stress and low NDVI was selected for Stage 3 scenario testing. The simulated strategy included green corridors along transport axes, increased canopy coverage, and pocket parks on underutilized plots. Figure 4 illustrates the spatial distribution of priority intervention zones generated by the scenario-based model. The conceptual configuration of the proposed green infrastructure enhancement scenario is shown in Figure 5.

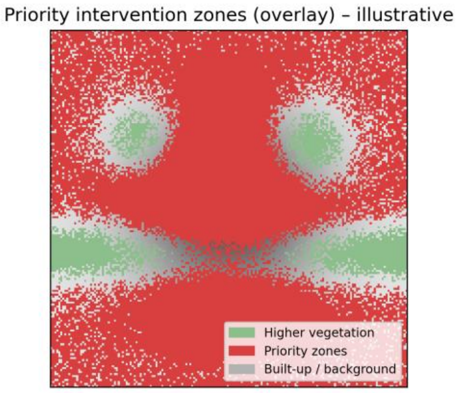

Figure 4: Scenario-based green intervention model.

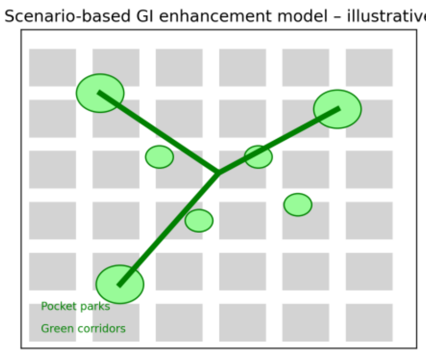

Figure 5: Scenario model.

4.6 Quantitative Validation

The simulation indicates that a 20% vegetation increase yields measurable cooling and connectivity benefits in a semi-arid urban context, supporting the practical applicability of the implemented workflow for climate-adaptive GI planning.

In the Samarkand case, high-priority intervention zones covered 18.4% of the urbanized territory. After scenario-based simulation (corridor + canopy increase model), the average NDVI increased by 0.12 (from 0.28 to 0.40) within the selected district, while mean LST decreased by 2.1°C.

Connectivity of green patches improved by 23% based on the fragmentation index reduction.

Sensitivity testing showed that SPI classification varied by less than 6% when weights were adjusted within ±0.1 range, indicating model stability.

5 CONCLUSIONS

This study developed and operationalized a structured digital and data-driven framework for sustainable landscape and green infrastructure planning in semi-arid cities. The proposed approach integrates GIS, remote sensing, spatial indicators, and scenario-based modeling into a unified methodological cycle covering baseline analysis, indicator development, spatial prioritization, design support, and adaptive monitoring. Its main contribution lies in transforming widely used environmental indicators into a practical decision-support workflow that can guide planning interventions under conditions of climatic stress, limited water resources, and fragmented urban green systems.

The empirical application in Samarkand demonstrated the practical relevance of the framework. The analysis identified high-priority intervention zones covering 18.4% of the urbanized territory. Scenario-based modeling showed that a moderate increase in vegetation cover can generate measurable environmental benefits: within the selected district, the average NDVI increased from 0.28 to 0.40, the mean land surface temperature decreased by 2.1°C, and green-patch connectivity improved by 23%. In addition, sensitivity testing confirmed the robustness of the Spatial Priority Index, with classification changes remaining below 6% under moderate weight variation.

These results confirm that digital planning tools can support more transparent, evidence-based, and climate-responsive green infrastructure strategies in arid urban contexts. At the same time, the study remains methodological in nature, and the presented outcomes should be interpreted as a validated planning model rather than as the results of full-scale physical implementation. Future research may extend the framework through higher-resolution datasets, hydrological and socio-economic indicators, and long-term monitoring of implemented interventions.

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