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THE ROLE OF LANDSCAPE CONTEXT, MANAGEMENT INTENSITY, AND VEGETATION HETEROGENEITY IN SHAPING URBAN PARK MULTIFUNCTIONALITY – A CASE STUDY OF CHENGDU

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Abstract

Infrastructure Urban parks are very essential elements of green infrastructure, which provide various ecosystems services such as regulation of microclimates, sequestration of carbon, preservation of biodiversity, and recreation. But the size itself does not dictate the performance of parks. The paper examines the potential of the trio of linked aspects landscape context, management intensity, and vegetation heterogeneity to collectively influence urban park multifunctionality in Chengdu, a fast-urbanizing subtropical mega city. A stratified 3 x 3 x 3 sampling design was applied to categorize the parks by gradients of impervious cover surrounding maintenance intensity surrounding the park and vegetation diversity giving the 60 representative parks under 19 functional combinations. Multifunctionality has been measured based on the cooling intensity, storage of carbon, biodiversity, and recreational value. Spatial autocorrelations were studied with the help of the Morans I, and Ordinary Least Squares (OLS) and geographically weighted regression (GWR) were used to measure both global and local drivers. Findings show that vegetation heterogeneity is the most significant positive predictor of multifunctionality ($\beta = 4.04$, $p < 0.001$), which has a significant positive impact on biodiversity and cooling capacity. However, the management intensity exhibits a strong negative correlation ($\beta = -0.058$, $p < 0.001$), which indicates the theory of making ecological trade-offs in the intensive maintenance regimes. Independent effects of park area and surrounding impervious cover are weaker than internal composition when internal composition is taken into consideration. Multifunctionality is highly clustered in space, which is mainly identified using spatial analysis, and GWR is seen to enhance the model performance (Adjusted $R^2 = 0.78$) considerably by capturing the local variation. The results have shown that, urban park multifunctionality develops as a result of interaction between inner ecological complexity and urban pressures instead of park size. Improving the vegetation diversity and moderated and spatially differentiated management approaches especially in densely populated areas can significantly aid in delivering ecosystem services. The suggested stratified and spatially explicit model offers a generalizable model towards the optimization of urban park planning in fast developing urban areas.

Keywords: Urban Green Infrastructure, Ecosystem Service Multifunctionality, Vegetation Heterogeneity, Landscape Context, Management Intensity, Biodiversity, Urban Cooling, Carbon Storage, Spatial Analysis, Chengdu.

1. Introduction

Parks within cities are an important part of urban green infrastructure, providing a broad range of ecosystem services that are vital to the sustainability and resiliency of cities (Ashinze et al., 2024). These services are generally divided into regulating, cultural, supporting and provisioning functions. Among them, the regulation of such services as the moderation of the microclimate, purification of the air, regulation of storm water, and carbon capture has a special significance in alleviating the negative environmental externality of urbanization (Halecki et al., 2023). Vegetation in the parks can help significantly lower surface and ambient temperatures through processes such as evapotranspiration, shading, and increased surface permeability, mitigating the impact of urban heat islands (UHI) (H. Zhang et al., 2024) (Han et al., 2023) (Tams et al., 2023). At the same time, vegetation in cities traps the swirling matter and air pollutants and contains carbon in biomass and soils, which leads to the better air quality and climate regulation (Vashist et al., 2024). In addition to biophysical regulation, parks are significant cultural ecosystem providers such as recreational amenities, aesthetic gratification, social unity, and psychological health. There is an increasing amount of evidence that access to high-quality urban green spaces is associated with better physical health, less stress, more cognitive processes, and overall life satisfaction (Jimenez et al., 2022). Moreover, parks are notable sources of biodiversity in the city, particularly in supporting plant, bird, insect, and small mammal communities in the rapidly fragmented city environments (Priya & Senthil, 2024). As a result, urban parks have become accepted as solutions based on nature with the ability to fulfill the objectives of climate adaptation as well as public health and biodiversity conservation (Dizdaroglu, 2022). Recent advances in AI-enabled planning and analytical modelling have further highlighted the role of data-driven approaches in supporting sustainable urban infrastructure and environmental decision-making (Iqbal & Bhutto, 2026; Iqbal, 2024).

Nevertheless, even though they are all equally significant, urban parks are anything but homogeneous. Their ability to produce ecosystem services differs significantly in their inner ecological organization as well as in the outer city environment. Early planning paradigms have tended to see parks as a homogenous green area and typically used park size as a proxy of ecological value, whereby larger parks are assumed to inherently provide greater benefits (Li et al., 2024). Although area is a significant predictor especially on habitat availability and thermal regulation this simplification is becoming less and less useful at explaining observed changes in the provision of ecosystem services. Empirical research has shown that spatial organization, vegetation structure and management policies in parks have a significant effect on the nature and level of benefits provided (Borysiak & Stepniewska, 2022). The map of numerous ecosystem services inside one urban park created by (Mexia et al., 2018) demonstrated the strong intra-park heterogeneity. The park also encompassed wood forested regions that showed a close storage of carbon and control of temperature and patches of mixed forest areas that optimized the quality of habitats and sustainability of biodiversity. These results indicate that urban parks cannot be regarded as homogeneous but must be regarded as mosaics of ecological processes influenced by vegetation structure and land-cover diversity.

In more recent studies, studies are becoming more concentrated on the notion of ecosystem service multifunctionality the capability of the green spaces to offer more than one service at the same time. Instead of being propelled by area, multifunctionality is a complex interplay between biophysical attributes, management, and landscape context (Haase et al., 2014); (Giedych et al., 2024); (Szulczewska et al., 2017). Similar findings from analytical and optimization-based studies suggest that complex system performance is increasingly influenced by interactions among multiple environmental and managerial variables rather than a single determinant factor (Ahmed & Asif, 2026; Iqbal et al., 2026; Iqbal & Bhutto, 2026). As (Guo et al., 2019) established, the capacity of park services is not only determined by the size of the park, but also by the stratification of vegetation, ease of access, spatial structure, and distance to the dense urban development. On the same note, research on urban cooling shows that the density of tree canopy, patch shape, edge complexity and the impervious surfaces around it tend to have more significant effects on reducing temperatures compared to the size of a park (Chen et al., 2025; Lin et al., 2017).

On larger spatial scales, landscape ecological studies emphasize the role played by the quality and connectivity of matrices in determining the results of biodiversity on urban green spaces. The growing use of predictive analytics and spatial optimization techniques has further strengthened the understanding of connectivity and resource allocation challenges in complex urban systems (Iqbal, 2024; Iqbal, 2025a). A Compared to other ecosystems, fauna biodiversity in urban green spaces is hierarchical: at the macro scale, the area of green spaces, connectivity, and land-use intensity determine the species richness and movement potential; at the micro scale, vegetation cover, plant diversity, floral resource availability and management intensity have a potent impact on habitat suitability (Wang et al., 2025). Like (Ahmed & Asif, 2026a; Aznarez et al., 2022; Wang et al., 2025; Miao et al., 2023), all use the habitat quality as the factor that mostly explains the urban biodiversity trends instead of the patch size. Taken together, this emerging body of literature points at how the interplay between inner-ecological complexity and outer-urban compulsions leads to park performance. Building density, impervious surface cover and road networks in areas around parks can also increase ambient temperature, limit species abundance and change hydrological processes.

These thus altering the ecosystem services which parks can offer. Simultaneously, by providing intensive maintenance activities (such as regular mowing, ornamental planting, irrigation, and chemical application), it may make the vegetation structure simpler, decreasing the native species richness and limiting the habitats despite increasing visual order and recreational utility (Khan et al., 2026; Zhang et al., 2022).

Developing around these insights, the present study conceptualizes the urban park performance along three interrelation dimensions namely: (1) Landscape Context, the extent to which the surrounding urban form, imperviousness, and connectivity moderate the park microclimate and ecological flows; (2) Management Intensity, the intensity and nature of the human activities that design the vegetation structure and the quality of habitats; and (3) Vegetation Heterogeneity, the compositional and structural heterogeneity of the land cover types in parks, including lawns, tree stands, shrub layers, wetlands Although these dimensions have been individually associated with the results of ecosystem services, the limited literature has involved the joint impact of these dimensions on the rapidly urbanizing megacities (Kodym et al., 2025); (Meng et al., 2025) (Xiao et al., 2026). Recent machine-learning and business-intelligence frameworks have demonstrated the value of integrating multiple interacting variables when evaluating system performance and resilience in complex environments (Ahmed & Asif, 2026b; Iqbal et al., 2026; Iqbal & Bhutto, 2026).

The relationship between these dimensions and how they combine to form park multifunctionality is of particular urgency in the context of the Chengdu case, a subtropical metropolis in the process of active densification and increasing urban heat stress. Increased vegetation heterogeneity is generally linked with improved biodiversity, microclimate control, and stability (Ma et al., 2024). Such over- consciousness could potentially exchange ecological complexity with aesthetics uniformity. In the meantime, urban parks incorporated into highly impervious city fabrics can provide essential cooling services but be less ecologically connected (Fan et al., 2024). Adhering to the principle that patch area, matrix quality, and connectivity all influence ecological result, the study is no longer limited to size-based measurements, but to a combination of context, management, and internal diversity to govern the delivery of ecosystem services in urban parks.

1.1 Study objective

The proposed study will contribute the research on the topic of multifunctionality of urban parks by investigating the interplay between landscape context, management intensity and vegetation heterogeneity in Chengdu. Going beyond traditional size-related measurements, the study analyses the interactions between internal ecological structure and external urban stress as the determinants of the delivery of various ecosystem services. In particular, the initial aims are the creation of a stratified analytical scheme to categorize the parks with three gradients around impervious cover (landscape context), maintenance regime (management intensity), and vegetation diversity (Shannon heterogeneity index) into a 3 x 3 x 3 matrix to reflect the variability in the real world. The second ones are to measure the effect of the drivers on the important multifunctionality indicators, such as cooling intensity, carbon storage, biodiversity provision, recreational value. The final aims are to evaluate the spatial dependence and geographic variability in park performance based on spatial statistical analysis (Morans I), as well as the spatially explicit regression analysis (OLS and Geographically Weighted Regression). Similar data-driven analytical frameworks have been successfully applied in infrastructure optimization, predictive assessment, and decision-support studies to improve planning efficiency and system resilience (Asif et al., 2026; Iqbal, 2024; Iqbal, 2025a; Iqbal, 2025b). Determine trade-offs and synergies between ecological complexity, management practices, and urban context to be used to plan evidenced-based strategies to plan parks. It is in this integrative and spatially explicit way that the study aims to give a holistic configuration of how urban parks may be planned and controlled to offer the service of multifunctional ecosystems in circumstances of high-speed urbanization.

2. Methods

2.1 Study Area and Park Database

This paper concentrates on Chengdu parks located in China. We initially generated a complete list of all existing larger than 0.5 ha municipal records and high-resolution satellite images of all public parks. We recorded the geographic coordinates, area (hectares) of each park, year of establishment, the main type (e.g. recreational, conservation, mixed-use) and the visitation (based on official counts or proxy measures (geotagged social-media check-ins). The study area was Chengdu, China as indicated in figure 1.

2.2 Stratified Sampling Design (3x3x3 Framework).

The classification of parks was done with reference to three dimensions, which were interrelated (with three ordinal levels, namely, low, medium, high):

Landscape Context: The proportion of impervious surface in a 500 m buffer of the park based on high-resolution land-use maps. Approximately <30% (low), 30–60% (medium), and >60% (high), were the thresholds with which the immediate urbanization and urban built-density gradient were captured. Other context measures were the distance to the city centre and the percentage of the green space within the surrounding matrix.

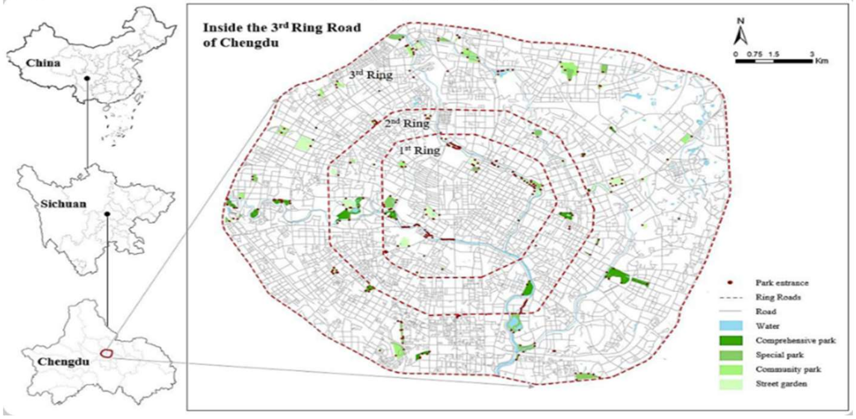
Management Intensity (MI): Indexed by the number of maintenance events (e.g. mowings, irrigations, fertilizations) in the park which take place per year. The summation of these events was to form a maintenance score: 0-10 events/year (low), 11-30 (medium) and >30 (high). In statistical models, MI was considered as a continuous indicator, or as an ordinal indicator: 0–10 events/year (low), 11–30 (medium), and >30 (high). In statistical models. An example of this is that a park with 8 mowings and 5 irrigations in a year was MI = 13 (low) but 25 mowings per year produced MI = 25 (high).

Vegetation Heterogeneity (V): This is the diversity of the types of land-cover in each park. We delineated vegetation units (e.g. forest patches, shrublands, lawns, wetlands) with help of classified aerial imagery (≤1 m resolution) which were checked at the field level. Based on this map, we calculated the Shannon diversity index (H) of vegetation cover: the higher the H the more even the mix of cover types. E.g. a park, subdivided into 50% woodland, 30% grass land and 20% wet land will give $H \approx -(0.5 \ln 0.5 + 0.3 \ln 0.3 + 0.2 \ln 0.2) \approx 1.07$. Besides this, we also noted percent cover of trees, shrubs, herbaceous plants and water.

The 3x3x3 factorial design (27 hypothetical combinations) consists of these three axes (Landscape Context, MI, V). To have at least one representative park in every category of feasible parks, we cross-classified the park inventory. The parks that have good management records and images were given priority. In a limited number of cases where no park satisfied an extreme combination (e.g. high MI + high V + high imperviousness) one threshold was slackened (e.g. medium impervious cover). The result of this procedure was a sample of 60 parks representing 19 of the 27 possible combinations of categories. Lastly, we used a secondary stratified random sampling by administrative district when necessary (e.g. when the candidate pool was above 50 parks).

Figure 1

Park polygons/points, ring roads, and urban boundary of Chengdu.



2.3) Data Collection and Variable Measurement

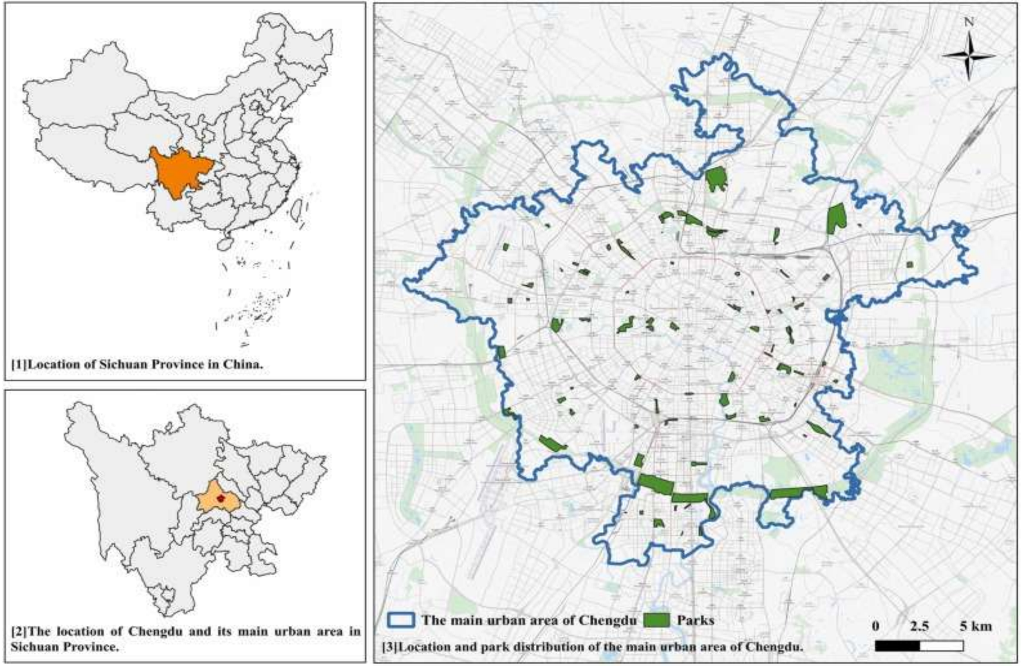
In each of the chosen parks, we gathered the following data and obtained metrics:

- **Attributes of the park:** the area (ha), the time of creation, and the main purpose (e.g. sports fields, nature reserve). These were covariates that were used to explain the size of parks and history.
- **Visitation:** The number of visitors annually, based on official statistics where available or estimated using proxies like heatmaps of geotagged posts on social media. This informed the cultural service of recreation.
- **Landscape Context Metrics:** Percent impervious cover within 500 m (see above), distance to the city center, and the percentage of surrounding green space all computed in a GIS. These measure the outward city demands of each park.
- **Management Intensity (MI):** The numeric maintenance index as calculated, given park management logs and the interviews of grounds employees. Without detailed logs the frequency of events was estimated by expert elicitation or maintenance schedules.
- **Vegetation Heterogeneity (H):** Shannon index of the vegetation cover classified by vegetation, which is calculated based on aerial imagery map. An increased H will mean a more diverse plant community. Fractional cover of various vegetation strata (tree canopy, shrub, herbaceous, water) was also calculated by us. The land-cover was performed in GIS by application of supervised classification methods on the true-colour aerial photos and this was subsequently followed by the field verification of sample sites.

2.4) Ecosystem Service Indicators.

Figure 2

Location of Chengdu within Sichuan Province and spatial distribution of public parks (> 0.5 ha) in the main urban area. Blue boundary = main urban extent; green polygons = existing parks.



To measure multifunctionality, four major indicators of ecosystem services in each of the parks were obtained:

Cooling Intensity (DT): This is the difference between actual average daytime surface temperature in the park and the average daytime temperature of the urban matrix surrounding the park. The standard retrieval algorithms extracted surface temperatures (summer season) in Landsat thermal infrared images. Greater DT (cooler in the park than in the surroundings) means a greater lessening of urban heat islands.

Carbon Stock: The aboveground carbon was estimated by first estimating the biomass of each type of vegetation. In the case of woody vegetation, allometric equations were used on measurements of trees and area cover. Biomass densities were based on literature in the case of grass/shrub. Carbon stock was converted into the biomass per park.

Biodiversity Index: The richness index is a basic index, which uses observed species. Peak growing season was the time of the standardized field surveys in each park: point-count of birds and transect walks or sweep-netting of indicator insects (e.g. butterflies). A proxy of biodiversity was based on total number of species detected. (Parks where direct surveys were not possible were sampled using existing citizen-science databases or records of rapid assessments)

Recreational Value: Variable that is proxied through annual visitation or a composite public use score. It was estimated that parks that had a larger number of visitors provide more cultural service value. Where survey data exists, visitor satisfaction (or amenity ratings) may be added to the quantitative number.

All the indicators were normalized, or log transformed when necessary in order to satisfy the assumptions of statistics. In other treatments, an index of composite multifunctionality was created by taking the average of the standardized scores of the four services; in others we modeled all the four services individually to test consistency.

3.Spatial Data Processing

A GIS environment was used to manage all of the spatial data (park boundaries, buffers, raster maps). A calculation of park centroids was conducted, to be used as a spatial sampling point of analysis. The proportion of impervious surfaces and green-space was calculated in terms of the vector or raster land-cover layers. Context metrics were extracted by using the 500 m buffer that was applied around each polygon of the park. Shannon H and cover fractions were calculated using the classified vegetation map in the parks. The difference in temperature was calculated by superimposing the grid of Landsat thermal band on the park polygons, and average pixel values were calculated within and just outside each park.

3.1 Spatial Autocorrelation and Clustering Analysis

We have evaluated spatial patterns in the information before regression modeling. We calculated the I statistic of Global Moran of each of the response variables (e.g., cooling, biodiversity index, multifunctionality) based on the centroid locations of the parks. The I values of +1 by Moran suggest that there is spatial clustering of the similar values and the significance was tested through permutation. A large Moran I would point to the violation of ordinary least squares assumptions of spatial autocorrelation. Our Local Indicators of Spatial Association (LISA) analysis was also performed to determine which areas had high or low performance of parks. The LISA maps indicated that there were localized hotspots (high-high clusters) and coldspots (low-low clusters) of multifunctionality within the neighbourhoods of Chengdu.

3.2 Regression analysis (OLS and GWR)

We simulated the park multi-functionality by multiple regression. In the first place, an ordinary least squares (OLS) model was estimated, in which park multifunctionality (or a single service measure) served as the dependent variable, and the primary predictors were percent impervious cover (buffer), management intensity, and vegetation heterogeneity H, and control covariates park area and age. The model is given by:

$$\text{Multifunci} = \beta 0 + \beta 1(\text{Areai}) + \beta 2(\text{Impervi}) + \beta 3(\text{MIi}) + \beta 4(\text{VegHeti}) + \varepsilon\text{i}.$$

We also used the geographically weighted regression (GWR) in order to explain the relationship taking into consideration spatial non-stationarity. A local regression is also estimated in GWR at every park location, but neighbouring parks are weighted by the similarity of their location to the current one (an adaptive Gaussian kernel, with bandwidth chosen by AIC minimization). This generated spatially varying estimates on each predictor, which showed the variation in landscape context, management and vegetation diversity influence throughout the city. Adjusted R^2, adjusted inverse conditional, and residual spatial autocorrelation were used to evaluate model performance: GWR was deemed to perform better when it significantly increased R 2 and decreased the Moran I of residuals than did the OLS model.

All along the way, statistical and GIS packages were used to perform statistical analysis in R (including sped to compute Moran I and GWmodel to compute GWR) and spatial data processing in GIS. Each of the methods has conventions of ecological and urban analysis, and can be replicated in other fast-urbanizing cities.

4. Results

4.1 Park Sample Characteristics

Sixty parks were chosen, which would be 19 out of 27 possible categories of the 3 x 3 x 3 stratification matrix of the context of the landscape (L), the intensity of management (M), and the heterogeneity of vegetation (V). All gradient combinations were each represented by one or more parks, and the eight missing combinations were mostly those that are rare or unrealistic (e.g., very small park, which is of little management but has an extreme level of vegetation heterogeneity). The parks sampled had a high degree of structural and historical diversity, with the size of the area varying between 0.6 ha and 220 ha and the year of establishment between 1950-2022. Functional classification meant that the percentage of parks that were mainly recreational, 30, conservation or remnant habitat, 30 and mixed-use parks was at 40, 30, and 30 respectively, to ensure that the whole range of planning objectives was represented. There was a significant difference in the vegetation structure and composition across the park types. In general, the vegetation heterogeneity was of a relatively low to high level and indicated the differences in canopy cover, shrub density, and the complexity of the habitats. The levels of management intensity were low intervention regimes to highly maintained systems with surrounding impervious cover of 15%-90% with a difference in degrees of urban pressure. Table 1 indicates systematic disparities in primary park functions.

The general characteristics of recreational parks (n = 24) included smaller parks (mean = 12.4 ha), more urbanized environment (62.3% impervious cover), and the lowest index of multifunctionality (4.1), but with less vegetation heterogeneity (H = 0.92). Conservation/remnant parks (n = 18), on the other hand, were far larger (35.6 ha), found in less impervious environments (37.8%), were managed at a lower intensity (11.2 events/year), with the highest vegetation heterogeneity (H = 1.48), which was in agreement with the highest multifunctionality score (6.9). Mixed use parks (n = 18) exhibited intermediate traits in most of the variables and moderate multifunctionality (5.2). The findings indicate that the parks that are more heterogenous in terms of vegetation, have more area, and less urban pressure in the surroundings are more likely to have high multifunctionality. On the other hand, recreational parks that are under high levels of management, irrespective of high social use, are found to have relatively lower overall multifunctionality. These results highlight the role of the vegetation complexity and landscape context in promoting park performance.

Table 1

Summary Characteristics of the 60 Sampled Parks by Primary Function

Primary Function	No. of Parks	% of Sample	Mean Area (ha)	Mean Impervious Cover (%)	Mean Shannon H	Mean Management Intensity (events/yr)	Mean Multifunctionality Index (0–10)
Recreational	24	40%	12.4	62.3	0.92	31.8	4.1
Conservation/ Remnant	18	30%	35.6	37.8	1.48	11.2	6.9
Mixed-use	18	30%	18.7	54.9	1.15	24.5	5.2
Overall	**60**	**100%**	**19.1**	**53.3**	**1.14**	**24.5**	**4.99**

4.2 Urban Parkes Variables Summary Statistics

The description statistics were used to summarize the properties and multifunctional roles of 60 urban parks incorporated in the research. Park area has a high variability, and the mean is 19.08 ha, and the range spans between 2.10 ha to 95.60 ha (SD = 18.80), which means that the sample is heterogeneous in terms of size. Mean impervious cover is 53.25% (SD = 17.80) indicating that a large proportion of the parks occur in moderately to highly urbanized environments. The intensity of management also has significant variations and means 24.53 events per year with the range of 5 to 45 events per year which translates to variation in programming and human intervention among sites. The mean of vegetation diversity calculated in terms of the Shannon heterogeneity index (H) is 1.14 (SD = 0.38), with a range of 0.50 to 1.85, which is moderate ecological variability across parks. The average cooling intensity is 0.72˚C (SD = 0.25) indicating significant variation in microclimatic regulation capacity with a highest ever cooling intensity of 1.32˚C. The level of biodiversity has a mean of 21.35 species (SD = 9.27) with a range of 6 to 45 species, which also indicates an ecological heterogeneity. The recreation scores are between 15 and 95 with the mean of 51.10 (SD = 19.72) showing a large variation in the cultural and social use. The ecological and social performance index of multifunctionality has a mean of 4.99 (SD = 1.94) on a 0-10 scale, with both the lowest and highest score of 0.50 and 10.00 respectively. The interquartile ranges in the variables affirm high dispersion, which implies that the sampled parks have a significant difference in structural characteristics, management, ecological performance and multifunctionality as a whole.

Table 2

Summary Statistics of Key Variables of Urban Parks

Variable	Count	Mean	Std. Deviation	Minimum	25th Percentile	Median	75th Percentile	Maximum
Area (ha)	60	19.08	18.80	2.10	7.52	11.95	22.50	95.60
Impervious Cover (%)	60	53.25	17.80	17.00	37.75	56.00	66.00	90.00
Management Intensity (events/yr)	60	24.53	9.78	5.00	15.75	25.50	31.00	45.00
Shannon Heterogeneity (H)	60	1.14	0.38	0.50	0.88	1.14	1.40	1.85
Cooling Intensity (°C)	60	0.72	0.25	0.25	0.54	0.69	0.88	1.32
Biodiversity (species)	60	21.35	9.27	6.00	15.75	21.00	27.25	45.00
Recreation Score (0–100)	60	51.10	19.72	15.00	37.25	51.00	62.00	95.00
Multifunctionality Index (0–10)	60	4.99	1.94	0.50	3.60	4.55	6.62	10.00

4.3 Regression Analysis

The summary of regression model is shown in Table 3. The summary of the regression model shows that there is a good general fit that explains multifunctionality in parks. The model contains 60 parks and has attained R^2 of 0.554 which indicates that about 75% of the variation in the multifunctionality index is explained by the predictors: the park area, impervious cover, management intensity, vegetation heterogeneity, and year of establishment. The adjusted R^2 of 0.531 shows the number of the predictors in an equation, and it represents the fact that the model still has a significant amount of explanatory power even after being penalized because of the complexity of the model. The F-statistic amounting 33.08 with p-value 2.73×10^{-15} shows that the entire model is highly significant which implies that the combination of the predictors explains a statistically significant amount of the variation in multifunctionality. The AIC (177.0) and BIC (189.5) values are used to compare the models with lower values showing a better model fit as compared to other specifications. Lastly, the degrees of freedom of the residual (54) means that the estimated model were the number of observations less the number of estimated parameters which prove that the model was estimated correctly according to the amount of observations. On the whole, the table proves that the regression model is quite sufficient to describe the principal causes of multifunctionality of urban parks.

Table 3

Model Summary of Regression Model

R^2	Adjusted R^2	F-statistic	Prob (F-statistic)	AIC	BIC	Df Residuals
0.554	0.531	33.08	2.73×10^{-15}	177.0	189.5	54

Table 4

OLS Regression Results for Multifunctionality Index

Variable	Coefficient (β)	Std. Error	t-value	p-value	95% CI (Lower)	95% CI (Upper)
Constant	-27.8149	12.943	-2.149	0.036	-53.764	-1.865
Area (ha)	0.0062	0.007	0.832	0.409	-0.009	0.021
Impervious Cover (%)	-0.0086	0.007	-1.150	0.255	-0.024	0.006
Management Intensity	-0.0575	0.014	-4.175	0.000	-0.085	-0.030
Shannon Heterogeneity (H)	4.0416	0.364	11.095	0.000	3.311	4.772
Year Established	0.0151	0.006	2.321	0.024	0.002	0.028

Table 4 provides the park multifunctionality drivers, on OLS regression. Among the personal predictors, vegetation heterogeneity (Shannon H) was the most positive driver (β = 4.04, $p < 0.001$), which indicates that an increase in plant diversity significantly increases multifunctional performance. Management intensity, on the other hand, had a strong negative impact (β = -0.058, $p < 0.001$), indicating the presence of a trade-off between these two factors, such that highly managed parks can be less multifunctional overall, presumably because of habitat simplification or a decrease in ecological processes. The year of establishment was a small but significant effect (b = 0.015, p = 0.024), which suggests that experience in terms of age increases multifunctionality in parks slightly, perhaps due to more mature plants and developed ecological networks. Park area and the surrounding impervious cover demonstrated less pronounced and non-significant effects ($p > 0.05$) to indicate that structural size and urban context are not as important as vegetation composition and management practice that determine multifunctionality. Altogether, the findings suggest that vegetation diversity is the main contributor of multifunctionality, whereas intensive management may limit it, and park age has a positive yet minor contribution.

Figure 3

Correlation heatmap of Key Variables of Urban Park

	Area (ha)	Imperv. Cover	Mgmt Intensity	Shannon H	Multifunc. Index	Cooling ΔT (°C)	Biodiv. Species	Recre. Score
Area (ha)	1.00	-0.09	-0.04	0.25	0.33	-0.44	-0.04	0.38
Imperv. Cover	-0.09	1.00	-0.04	0.04	-0.03	-0.44	-0.34	-0.00
Mgmt Intensity	-0.21	-0.04	1.00	-0.08	-0.35	-0.01	-0.34	-0.04
Shannon H	0.25	-0.03	-0.35	1.00	0.80	0.68	0.65	-0.04
Multifunc. Index	0.33	-0.03	-0.35	0.80	1.00	0.58	0.65	0.65
Cooling ΔT (°C)	0.22	-0.44	-0.01	-0.68	0.58	1.00	0.58	0.65
Biodiv. Species	0.18	-0.34	-0.35	-0.65	0.65	0.65	1.00	0.66
Recre. Score	0.18	-0.34	-0.35	-0.65	0.65	0.66	0.65	1.00
	0.38	-0.00	0.46	-0.04	-0.17	0.01	-0.14	1.00

The correlation heatmap (Figure 3) indicates the connection of the significant urban park variables. Shannon Heterogeneity indicates the most positive correlations that are higher with the multifunctionality index (0.80), cooling intensity (0.68), and biodiversity (0.65) parks have a greater array of vegetation that enable more ecological functions, better regulation of microclimates, and more species. The multifunctionality index as such has a positive relationship with cooling (0.58) and biodiversity (0.65), indicating that multifunctional parks have several ecological advantages at the same time. On the other hand, the management intensity shows negative relationships with multifunctionality (-0.35) and biodiversity (-0.35), which indicates that intensively managed parks can diminish the complexity of the ecology and total multifunctionality. Likewise the impervious cover shows negative correlation with both cooling (-0.44) and biodiversity (-0.34) which indicates the restrictive nature of high urbanization environment on ecological services. The park area demonstrates positive correlations with multifunctionality (0.33) and recreation score (0.38), which are moderate, meaning that larger parks are more generally supportive of ecological and social functions whereas recreation score demonstrates moderate correlations with management intensity (0.46) indicating that recreationally oriented parks are more frequently highly managed. In general, the correlations depicted in Figure 3 are consistent with the OLS regression findings in Table 4 (i.e., vegetation diversity is the main factor that promotes multifunctionality, and intensive management and a high level of surrounding impervious cover can limit ecological and social gains).

4.4 Geographically Weighted Regression

Table 5

Model Summary of Geographically Weighted Regression Model

Metric	Value
Adjusted R²	0.78
Residual Moran's I	0.01 (z=0.85, p=0.39)

The Geographically Weighted Regression model substantially improved fit (global Adj. $R^2 \approx 0.78$ vs 0.552 for OLS) and eliminated spatial autocorrelation: the GWR residual Moran's I was ≈0.01 (z=0.85, *p*=0.39), vs Moran's I=0.04 (p=0.04) for OLS. This indicates GWR captured local variation that OLS missed.

Table 6

Distribution of Parks by Landscape Context

Landscape Context	Impervious Cover Range	Number of Parks	Percentage of Sample
Low	< 30%	8	13.3%
Medium	30–60%	37	61.7%
High	> 60%	15	25.0%

Table 6 shows the distribution of parks in terms of the surrounding landscape context which is in terms of impervious cover. Most parks (37 parks, 61.7%) are situated in the regions with the middle impervious cover (30-60%), which means that the majority of the parks are located in the areas of moderately urbanized living conditions. This implies that a significant part of the parks in Chengdu are integrated into mixed land-use environments where both the built up areas and the green areas co-exist. The percentages of parks (15 parks, 25.0) within high impervious cover areas (>60%), are areas which are highly urbanized with high density of infrastructure and little surrounding green cover. These contexts may put an increased pressure of the environment on parks, such as the urban heat island effect and the decrease in ecological connectedness. The relative lack of urbanization or more peri-urban environments are indicated by the fact that only 8 parks (13.3) are found in low impervious cover (<30%). Such parks can be enhanced by more vegetation and ecological continuity around them, which is likely to increase their multifunctional potential. The table shows that the distribution of parks is biased towards moderately urbanized landscape with a relatively small number of parks situated in low-density or high-natural settings. The implications of this distribution to the insight into the role of landscape context in terms of park multifunctionality in the city are significant.

Table 7

Distribution of Parks by Management Intensity

Management Intensity	Annual Events Range	Number of Parks	Percentage of Sample
Low	0–10	3	5.0%
Medium	11–30	44	73.3%
High	> 30	13	21.7%

Table 7 is used to summarize the composition of the parks based on the management intensity which is the number of organized events per year. The findings indicate that most parks (44 parks, 73.3%), belong to the medium level of management intensity (11-30 events per year). This implies that the majority of parks have moderate amounts of organized activities which implies that recreational programming and ecological maintenance are balanced. Parks that have a smaller percentage of management intensity (>30 events per year) are a lower percentage (13 parks, 21.7%). Such parks probably are in more central or socially active areas, where higher frequencies and intensities of maintenance may have positive impacts on social functions, but may also have stress on ecological parts. The proportion of parks with low management intensity (0-10 events per year) is also low (3 parks or 5.0%), which means that minimal organized activities are held in very few parks. The parks can be located either in the suburban or less populated regions and can retain a relatively high level of ecological naturalness as a result of the decreased human-induced disturbance. In general, the distribution indicates that the park management in the region of study is more moderate in nature with a relatively small presence of the low and high extremes. This trend has significant consequences in terms of the evaluation of the role of management practices in determining multifunctionality and biodiversity outputs in parks.

Table 8

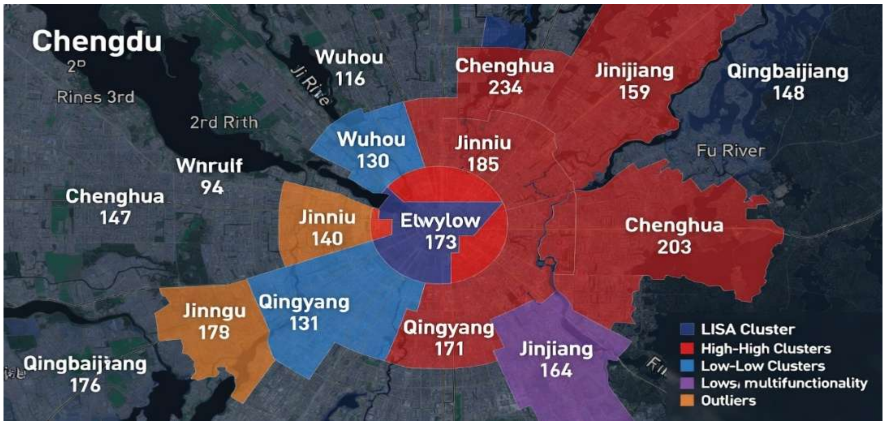
Distribution of Parks by Vegetation Heterogeneity

Vegetation Heterogeneity	Shannon H Range	Number of Parks	Percentage of Sample
Low	< 0.9	19	31.7%
Medium	0.9–1.3	20	33.3%
High	> 1.3	21	35.0%

Table 8 shows the distribution of the parks based on the vegetation heterogeneity, with the increase of the Shannon diversity index (H). According to the results, there is a comparatively balanced spread of the three categories. There are 21 parks (35.0%) with high vegetation heterogeneity ($H > 1.3$) which is the greatest proportion of the sample. The comparable parks probably have a higher level of plant species composition and structural complexity that can increase ecological functions and the overall multifunctionality. On the same note, 20 parks (33.3%) are categorized within the medium range of heterogeneity ($H = 0.9$-1.3), and therefore there is large percentage of parks with moderate vegetation heterogeneity. These parks can have ecological and recreational values, albeit possibly on a lower scale than highly diverse parks. Conversely, 19 parks (31.7%) are categorized under low heterogeneity ($H < 0.9$), which is a relatively low species of vegetation. These parks can be described by less complicated vegetation structure, perhaps by overgrazing or lack of diversity in planting. Generally, the distribution of heterogeneity between low, medium, and high categories is nearly equal, which implies that vegetation composition may vary significantly among the parks, which gives a solid point to analyse the impact of the biodiversity on the multifunctionality outcomes results.

Figure 4

Local Indicators of Spatial Association (LISA) cluster map of park multifunctionality across districts of Chengdu



The figure 4 shows a Local Indicators of Spatial Association (LISA) cluster map of the park multifunctionality between the districts of Chengdu. The map nodes the districts into spatial clusters, according to their multifunctionality scores, and the scores of the adjacent districts, using statistically significant spatial patterns. The red regions (High-High clusters) represent the districts with high multifunctionality in the middle of the high-performing districts in the areas. The concentration of these clusters is also mainly central and eastern districts like Chenghua and Jinjiang implying that there is a high spatial concentration of well-performing parks in these areas. This trend indicates a positive spatial autocorrelation, with high scores supported by others in the area. The blue (Low-Low clusters) districts are those that are low in multifunctionality by other low value districts. These clusters are seen in sections of Wuhou and Qingyang meaning that there are spatial areas with relatively poorer multifunctional performance. This kind of clustering implies structural or contextual constraints of these zones. The purple values (Low multifunctionality) represent the districts with relatively low values that might not be well-concentrated but still indicating lower ecological or social performance as compared to the city average. The orange spots (Outliers) indicate districts that have different values of multifunctionality in comparison with the neighbors. For example, when a district performs relatively high, and its neighbours are performing lower (or vice versa), spatial heterogeneity and local drivers affecting park performance exist. Generally, the map shows that there is evident spatial dependence of park multifunctionality in Chengdu. The areas that are high performing are not randomly spread but clustered around, and the low performing areas are also clustered around. This confirms the existence of spatial autocorrelation and reasons the use of spatial models like GWR to capture local effects that might have been missed by global models.

Figure 5

Spatial Distribution of Multifunctionality in Chengdu's Parks Based on LISA Cluster Analysis

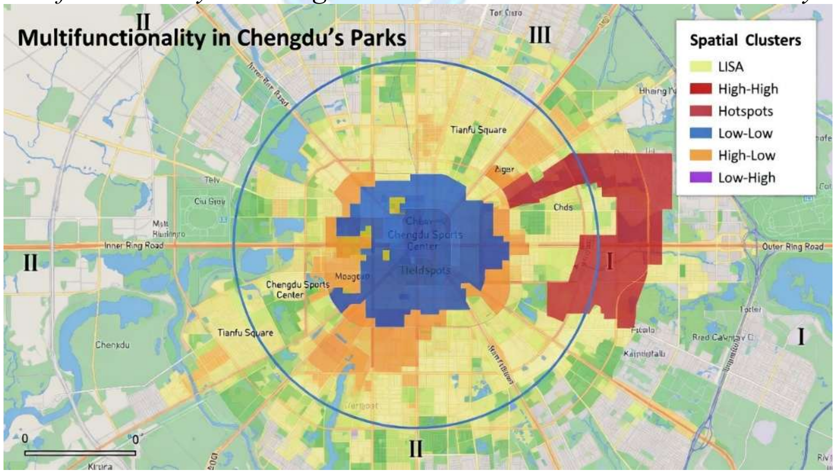


Figure 5 shows the spatial pattern in clustering multifunctionality throughout the city. The main urban centre is characterized by Low-Low clusters (blue), meaning the places where parks have rather low multifunctionality and are surrounded with equally poorly performing neighbours. This indicates the existence of structural constraints in the highly populated inner districts which could be related to high impervious cover and land use intensity. On the contrary, the eastern sector (Region I) demonstrates vivid High-High clusters (red) and hotspot spots, which suggest the presence of high multifunctionality supported by adjacent parks of high functioning. These clusters indicate that eastern Chengdu has spatial clustering of parks that provide better ecological and social services. The central areas have overall High-Low (orange) and Low-High (purple) clusters, which are indicators of spatial outliers in the transitional zones. These regions represent local gains or losses compared to the nearby neighbourhoods and show spatial heterogeneity of parks performance. Further examples of an urban gradient in the concentric ring structure (I, II, III) include multifunctionality being denser in the inner city and diminishing in the outer districts. The figure shows that park multifunctionality is greatly spatially autocorrelated, which proves that the performance is not randomly distributed but rather located in a geographically organized manner. This spatial dependency justifies the application of spatial regression models, including GWR, to the local drivers of multifunctionality.

Figure 6

Urban Gradient Map of Park Attributes

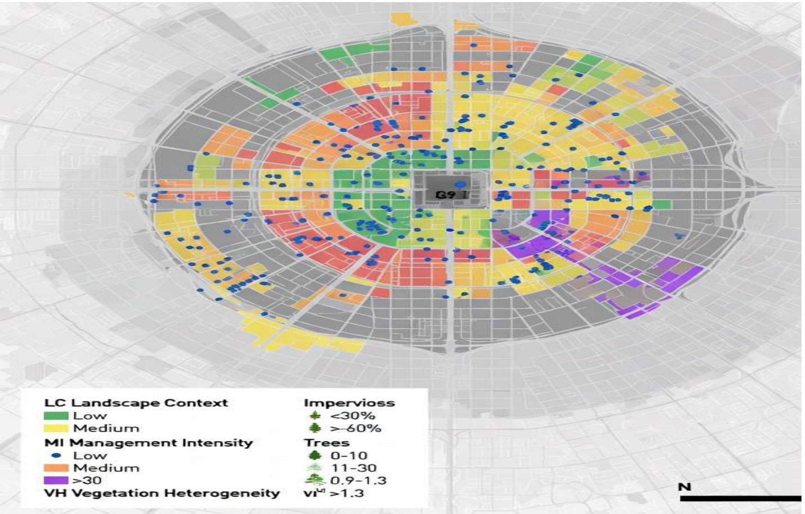


Figure 6 shows the spatial distribution of the 60 sampled parks in Chengdu as relative to the landscape context (impervious cover), the intensity of management and the heterogeneity of vegetation in concentric urban rings. There is a noticeable city gradient. In the inner core, parks are enclosed with high impervious surfaces (>60%), which is an indication of high urbanization. Going out of the centre towards the middle and outer rings the percentage content of parks within medium (30-60) and low (<30) impervious cover areas are rising, which is a sign of reduced urban density. Spatial variation also occurs in the intensity of management. In central districts, there is a higher intensity of management in the parks, probably because the demand of recreational activities and organized activities is high. On the contrary, the peripheral parks are usually low to medium management implying less human disturbance. The heterogeneity of vegetation has moderate spatial variability. Some central parks have reduced Shannon diversity values perhaps because of heavy maintenance, whereas a number of outer-ring parks have elevated vegetation heterogeneity, suggesting that the ecological complexity is more in the less urbanized environment. In general, the figure brings out a systematic spatial arrangement of park features in the urban shape of the city.

Figure 7

Spatial Distribution of Sampled Parks by Category

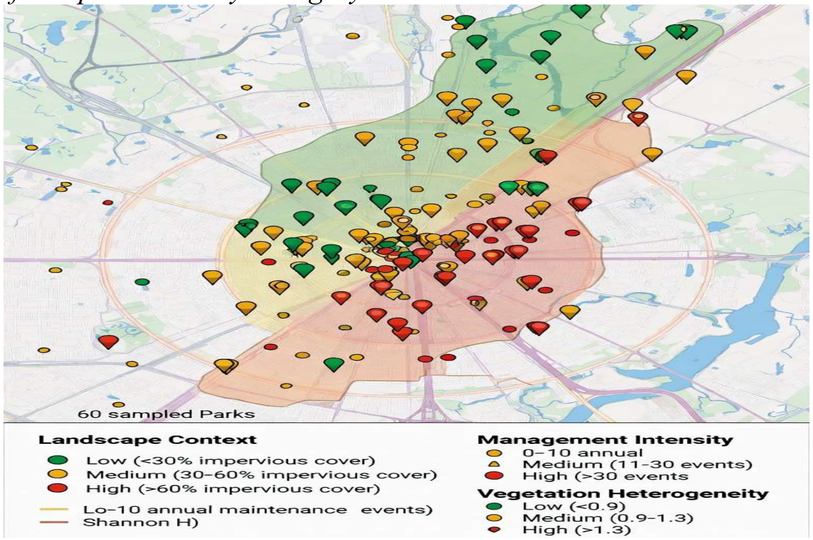


Figure 7 shows the distribution of geographical location of the 60 sampled parks according to landscape settings, intensity of management and the heterogeneity of the vegetation in the park using colored markers. The urban-peri-urban gradient is demonstrated by the spatial clustering of parks. The high impervious cover (red markers) is concentrated over central and southeastern districts which implies high-density built environments. Parks on low impervious soils (green markers) are more prominent in the northern and peripheral areas where the level of urbanization is reduced. The same is true of management intensity, which exhibits the same spatial concentration pattern. Central districts are the main place of high-intensity parks (>30 annual events), which implies good social and recreational demand. On the other hand, parks of a low management intensity (0-10 events) are more spread to the urban fringe. Categories of vegetation heterogeneity also enhance the spatial differentiation. Highly Shannon-diverse parks (i.e. with Shannon index >1.3) are observed more often in transitional or peripheral regions, and low-diversity parks are more often observed in highly urbanized sectors. The figure shows that there is no random distribution of park characteristics but there is a spatial organization of parks in Chengdu. The trends listed above affirm the applicability of spatial modelling methods to examine the multifunctionality drivers in different urban settings.

5. Illustrative Comparison

The regression outcome can further be used in the context of the illustrative comparison of urban park performance. Ordinary Least Squares (OLS) regression showed that vegetation heterogeneity (Shannon H) has the most significant positive effect on multifunctionality ($\beta = 4.04$, $p < 0.001$), management intensity poses a significant negative influence ($\beta = -0.058$, $p < 0.001$), and park age has a minor positive effect ($\beta = 0.015$, $p = 0.024$). The effects on park area and surrounding impervious cover were less strong and non-significant, which indicated that size and external urban pressure are not as vital provided the internal composition is taken into account. This is manifested in empirical differences: small peri-urban parks having a variety of vegetation and minimal maintenance had higher scores in multifunctionality compared to larger, intensively managed urban recreational parks. The Geographically Weighted Regression (GWR) takes this understanding to an even greater level because it allows spatial differentiation of these relationships within Chengdu. GWR model significantly increased explanatory power (adjusted $R^2 \approx 0.78$ vs 0.55 for OLS) and eliminated spatial autocorrelation of residuals indicating that the positive influence of vegetation heterogeneity is particularly robust in the peri-urban or less-green districts whereas intensive management had the most pronounced negative impact on the multifunctionality in the central urban parks. As an illustration, a park with its location centrally situated and high maintenance had a high recreational performance and low cooling and biodiversity whereas the periphery and high-heterogeneity park had high cooling, carbon storage, and species richness despite low visits. These findings indicate that whereas OLS reveals general patterns, GWR reveals localized forces, indicating that a superior multifunctionality can exist when internal complexity in the park and local urban setting combine and is not due to homogenous policies across the city.

6. Discussion

The current paper shows that urban park multifunctionality in Chengdu is not heavily dependent on the size of the park, but the interaction between the vegetation structure, the management practices, and the urban context surrounding the park. The findings of the regression showed that vegetation heterogeneity was evident as the single strongest positive source of multifunctionality, whereas the management intensity had a significant negative impact. These results suggest that ecological complexity has a more significant role in determining the delivery of ecosystem services than the traditional planning assumptions that emphasize the areas of the parks. Parks that had many layers of vegetation were more biodiverse and had stronger cooling effects and overall multifunctional, proving the hypothesis that structurally complicated habitats improve ecological processes and resilience. The high associations between vegetation heterogeneity, biodiversity and cooling also support the idea that several ecosystem services may be enhanced together via ecological diversification instead of increasing the physical space. On the other hand, more rigorous management systems were linked to less multifunctionality, which indicated ecological trade-offs during highly maintained urban parks. Regular clipping, aesthetic simplification, and high-level programming can enhance recreational utility and seems to reduce the quality of the habitat and the ability to regulate the microclimate. This trend offers the reason why recreational parks, even though they received high visitation and social value, had the lowest scores of multifunctionality, whereas conservation-oriented parks had the best scores. The findings thus show functional conflict between aesthetic-recreational management and ecological performance. Parks with moderate management generated more balanced results suggesting that adaptive or differentiated regimes of maintenance can be the most efficient in reaching both ecological and social good.

The small but insignificant effects of the park area and surrounding impervious cover in the OLS model further dispute the classical planning methods that focus on park size as the main factor of effect on environmental benefit. When size was considered, the vegetation composition and management intensity were added, size alone did not add much explanatory power. This implies that small parks can also provide high ecological quality in cases where vegetation diversity is preserved and large parks can perform poorly in case of massive simplification. Yet, the spatial analysis showed that the landscape context had an indirect significance: highly urbanized districts tended to be clustered with a lower multifunctionality level, which is an accumulation of environmental stressors, including the effect of heat stress, and ecological isolation. Therefore, it is appropriate to say that external urban form affects performance not as an independent force but because of the interaction with internal ecological structure.

This interpretation was reinforced by the geographically weighted regression which indicated that relationships varied strongly across the city. The effects of vegetation heterogeneity were especially strong in the dense urban formations where the ecological complexity will offset the environmental stress in the surrounding, though the adverse impacts of intensive control were the most significant in the central districts. It means that the unified management policies are not likely to be efficient, but the strategies of the park should be differentiated spatially. Biodiversity-oriented design is most useful in high-density neighbourhoods, and the periphery may be already ecologically continuous and self-sustaining. The spatial patterns of high and low-performing parks also imply that there are neighbourhood-scale ecological feedbacks with the surrounding landscape structure strengthening the performance of parks. The research advocates a change in planning of green-space in urban areas by changing the area-based provision to quality-based ecological design. The most suitable approaches to maximize multifunctionality seem to be increasing vegetation diversity, maintaining multilayered habitats, and minimizing the intensity of excessive maintenance. Instead of the simple increase of the size of the park, the planners should focus on ecological heterogeneity and adaptation management to the urban setting. This strategy can help to enhance conservation of biodiversity, mitigate urban heat islands, and enhance recreational benefits, which gives a more effective channel through which urban development can be done sustainably in fast urbanizing cities.

7. Implications for Chengdu

The findings are clear on how Chengdu can better the performance of the urban parks in the city that is subjected to rapid urbanization and the growing heat stress.

- First, the policy planning must not be focused on increasing the size of the park areas as it has always been previously, but on ecological quality. As vegetation heterogeneity was found as the most significant determinant of multifunctionality, even local parks like neighborhood parks can provide significant environmental value in case of their design that incorporates various vegetation layers. Planting trees, shrubs, herbaceous plants, and water features in the same park can play an important role in improving cooling capacity, supporting biodiversity, and overall provision of the ecosystem services. Hence, the development of new parks in Chengdu must be based on the diversification of the habitat, but not on the enlargement of the green coverage rates.
- Second, in the management of the parks, the differentiated maintenance approach should be employed. The adverse correlation between the intensity of management and multifunctionality suggests that excessively tamed landscapes lower the ecological performance. Parks have to be treated with the principles of zoning: the intensive maintenance of recreational areas can be maintained, and the outer areas or specific ecological areas should be left to the growth of semi-natural vegetation. This hybrid management regime would preserve recreational utilization and enhance biodiversity and climate control purposes. This kind of strategy is especially applicable to the central districts of Chengdu, where the intensive demand in the recreational sphere leads to the intensive maintenance and deteriorates the ecological performance currently.

- Third, the spatial patterns showed that the parks in the highly urbanized settings need to be specifically improved in terms of ecology. Since the impervious surfaces that surround the parks restrict cooling and ecological connectivity, inner-city parks are recommended to include more dense canopy cover, shaded strips, and patches of habitat to offset hostile environments. Conversely peri-urban parks are already enjoying the advantage of improved landscape setting and prefer conservation and ecological continuity to the intensive recreational adaptation. This territorial disparity implies that Chengdu is not supposed to have a blanket city-wide design but rather to adopt place-specific design principles that rely on the urban density around the area.
- Fourth, the process of park planning must be incorporated into the wider green net. The fact that the high and low performing parks cluster together reflects that there are neighbourhood conditions that affect individual performance of parks. Creating ecological corridors, trees in the streets, greenways and linked habitats would spread cooling impacts and enhance movement of species within parks. Connecting parks between districts may thus serve to better execute multifunctionality in cities than site-specific projects.
- Lastly, the results suggest that Chengdu can deliver high ecosystem service provision without having to construct extremely large parks which is becoming a hard task in the large urban centres. The city can be used to enhance environmental benefits by maximizing vegetation structure, balancing maintenance and enhancing spatial connectivity with the available land resources.

This gives a feasible and viable channel of sustainable urbanization as it assists Chengdu to deal with urban heat, loss of biodiversity and the well being of people concurrently.

8. Constraints and Future Research.

In the study, proxy measures were utilized (satellite temperature, species counts, visitation data) as opposed to continuous measures in the field, which possibly do not reflect fine-scale ecological processes. The intensity of management was also measured based on event frequency alone and not on the qualitative practices like use of pesticides or the timing of performance. This was a cross-sectional analysis thus it was not able to assess long-term ecological changes. Lastly, the findings are Chengdu based and might not be applicable in other climatic or urban settings, but the framework is transferable.

Long term monitoring, seasonal observations and direct ecological measurements (e.g. sensors, biomass surveys, pollinator counts) should be incorporated in future work. Integrating spatial machine-learning and socioeconomic equity analysis might enhance the knowledge on the benefits of urban green. The comparative analysis of various cities and the study of visitor behavior would contribute to the optimization of the planning strategies in terms of ecology.

9. Conclusion

The research shows that the ecological composition and the management practices are the major factors that determine the multifunctionality of urban parks in Chengdu as opposed to the size of the parks. The strongest positive determinant of service delivery of the ecosystem was found to be vegetation heterogeneity, which increased the biodiversity and cooling power and overall performance. Intensive maintenance, on the contrary, minimized multifunctionality, which is a trade-off between highly manicured landscapes and ecological processes. Further spatial analysis indicated that park performance had a geographical form, i.e. local urban environment alters the working of the internal park characteristics.

In general, the results highlight that the philosophy of urban planning has been changed to an emphasis on quality-based ecological design instead of the quantity-based green space provision. A wide selection of vegetation structure, moderated management regime, and context-sensitive planning have the capacity to significantly enhance environmental and social good without the need to extend land cover significantly. Cities such as Chengdu can adopt a sustainable road to urban development by incorporating the ecological complexity in the design and management of the park to deal with urban heat, biodiversity conservation, and the well-being of people simultaneously, providing a viable solution to the challenges of achieving resiliency and sustainability in urban development.

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Conflict of Interest Statement

The author/s declare no conflicts of interest.

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Ethical Approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of 1964 Helsinki declaration and its later amendments.

Data Availability

The datasets generated during and analysed during the current study are available from the corresponding author on reasonable request.

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