Landscape and Urban Planning 271 (2026) 105635

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan

Research Paper

Unequal access to cultural ecosystem services across urban greenspaces

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HIGHLIGHTS

- Novel framework integrating social media and machine learning to assess unequal access to cultural ecosystem services (CES).
- Significant spatial and demographic disparities in CES accessibility revealed, underscoring environmental justice challenges.
- White and adult populations have greater local CES access; racial/ethnic diversity predicts accessibility at regional scale.
- Access to CES becomes more equitable as the service area of urban greenspace (UGS) expands to encompass larger populations.
- Evidence-driven policy recommendations proposed for a more just and sustainable UGS planning and transportation.

ARTICLE INFO

Keywords:
Urban greenspace
Accessibility
Cultural ecosystem service
Supply and demand

ABSTRACT

Urban greenspaces (UGS) provide essential cultural ecosystem services (CES) that support human health and wellbeing in developed landscapes. However, quantifying these intangible benefits and connecting them to environmental justice across demographic groups is challenging. In this study, we investigated accessibility disparities to CES in UGS across Broward County (Florida, USA), employing an innovative methodological framework integrating social media analytics with advanced machine learning methods. We extracted and quantified 10 distinct CES from online reviews across 426 urban greenspaces, using the diversity of these services as a measure of greenspace quality. We used an innovative two-step floating catchment area method to quantify CES accessibility across different demographic groups. Our results revealed substantial spatial heterogeneity in CES accessibility, with high-accessibility clusters concentrated in central urban areas and diminishing toward peripheries. Gini coefficient analysis quantified such inequity, showing it was most pronounced for the populations closest to UGS and decreased as broader proportions of the population were considered. We found that census blocks with higher proportions of White residents, adults, and males generally experienced enhanced CES accessibility. However, as the service radius of UGS expands to include larger proportions of the population, the predictive importance of racial diversity played an increasingly prominent role in CES accessibility patterns, although inequities still persisted. Our study provides an innovative research framework for assessing environmental justice in the distribution of diverse CES from UGS, moving beyond their quantity and proximity, and offers valuable insights and policy implications for developing more equitable and sustainable UGS in urbanizing landscapes.

1. Introduction

Urban greenspaces (UGS), defined as distinct land parcels designated and managed as publicly accessible parks or recreational areas (Miguez et al., 2025), represent critical environmental components in increasingly developed and populated urban landscapes, where natural experiences have become increasingly limited (Derdouri et al., 2025). Greenspaces deliver multiple ecosystem services, in particular cultural ecosystem services (CES), which, following the Common International Classification of Ecosystem Services framework (CICES), are defined as the physical, intellectual, and spiritual interactions between people and the environment (Haines-Young & Potschin, 2012; Hirons et al., 2016).

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https://doi.org/10.1016/j.landurbplan.2026.105635
Received 11 July 2025; Received in revised form 4 March 2026; Accepted 11 March 2026
Available online 18 March 2026

CES encompass non-material benefits such as cognitive development, stress reduction, and social cohesion (De Luca et al., 2024) and are essential for supporting human health and the wellbeing of urban residents (Pinto et al., 2022). Indeed, the significance of UGS has been extensively documented in the scientific literature in terms of their contributions to favorable physical health outcomes, mental well-being enhancement, and improved cognitive function (Shanahan et al., 2015; Tost et al., 2019). Despite their recognized importance, CES are challenging to quantify due to their inherently subjective and non-tangible nature (Fish et al., 2016). Unlike other ecosystem services, CES emerge as relational processes which are shaped by an individual's perceptions and actively created through human-nature interactions (Gould & Lincoln, 2017). This complexity makes their assessment and quantification particularly complex in the urban and landscape planning contexts.

Environmental justice is a prevailing issue and challenge in heterogeneous urban environment, and has become increasingly critical in understanding the persistent social disparities in the accessibility to UGS and their sustained ecosystem services (De Luca et al., 2024). Despite the existence of and progress in the United Nations Sustainable Development Goals, due to accelerated urbanization, historical development, and limitation of greenspaces, it remains difficult, if not impossible, for all urban residents to equitably benefit from the cultural, health, and well-being benefits that UGS delivers (Leng et al., 2023). Such access inequity, especially in countries like the United States, is deeply rooted in historical top-down urban planning and development and discriminatory policies and practices (e.g., "redlining" where racially biased housing policies from the 1930s have created lasting inequities in greenspace access that continue to be reproduced through contemporary greening efforts) (Nardone et al., 2021; Wood et al., 2024). Residents from Whiter and wealthier neighborhoods, for example, are found to consistently have greater access to parks than communities of color, though the specific form of relationship between proximity and race varies across urban contexts (Rigolon, 2016). Minority neighborhoods typically have 43% less access to urban parks, and similarly residents in the low-income neighborhoods have 42% less access compared to those in high-income neighborhoods (Larson et al., 2022). The contemporary theoretical framing of social-environmental justice encompasses multiple dimensions including distributive, procedural, and recognition justice (Schlosberg, 2007). While distributional equity just represents one aspect within the broader environmental justice movement, it has been primarily focused and often prioritized in the environmental policy and interventions, where normative principles are designed to guide the allocation of environmental benefits and burdens across relevant populations, communities, and space (Haque & Sharifi, 2024).

Accessibility to urban ecosystem services has been primarily examined and understood from the lens of distributional justice dimension (Haque & Sharifi, 2024). Such concerns are especially acute for CES which are "user movement related services" (Costanza, 2008), necessitating direct physical engagement with the service providing areas, which often involve UGS in the urban environment. For these CES, the service benefiting area often coincides with service providing areas (Ala-Hulkko et al., 2016), meaning that the actual realization of benefits is contingent upon individuals' ability to reach and use these UGS. Here we specifically focus on UGS as "contingent management units" distinct from linear vegetation and general greening (e.g., street trees, greenways), as these parcels explicitly aimed at supporting "human utility" through utilitarian, recreational, sport, and play functions (Miguez et al., 2025). Such distinction is critical for evaluating distributional equity as studied here, because equitable access to CES relies specifically on these managed spaces where individuals can actively and intentionally connect with nature and engage in social activities (Baró et al., 2019; Hunter et al., 2019). In other words, without such access to UGS, the potential CES remain largely untapped (Loos et al., 2023). Indeed, a recent critical review confirms that within the literature on equity in urban ecosystem services, CES are the most frequently emphasized category, followed by regulating services (Haque & Sharifi, 2024). However, this focus has often treated UGS as a monolith, using physical access to a greenspace, for example, as a simplified proxy for the entire suite of cultural benefits it might offer. Nevertheless, such assumption without considering the quality of UGS and their provided CES is highly questionable, and the actual quantification of the diverse and subjective CES that people experience has been less explored. For example, studies have demonstrated how the inequitable spatial availability of parks, key providing areas of urban CES, can affect various racial and socioeconomic groups differently, thereby shaping the distribution of cultural benefits and contributing to health disparities (Buckland & Pojani, 2023). Other examples of such distributional (in)justices include inequitable access to the cultural and well-being advantages of green schoolyards based on socioeconomic status (Baró et al., 2021), and the unjust distribution of street trees that limits access to regulating ecosystem services and associated cultural co-benefits (Afriyanie et al., 2020). Moreover, accessibility to CES from the European green regeneration projects has, in some cases, been influenced by ethnicity and racial segregation (Haase et al., 2022), while economic barriers like park entrance fees have restricted CES access for certain populations in some urban areas (Haque & Sharifi, 2024). This becomes especially significant as disadvantaged groups often face reduced access not only to the quantity of UGS but also quality greenspaces (e.g., related to the amount and kinds of CES provided), who are highly vulnerable (e.g., with physical and health issues) and ironically in a more dire need for the crucial CES these greenspaces provide (Benati et al., 2024).

Traditionally, studies relied on somewhat simplistic measures, like proximity (i.e., simply how close people lived to UGS; Benati et al., 2024), to quantify accessibility and justice, with the assumption of homogeneity in CES provided across UGS. But the evolvement of more advanced analytical methods, particularly the two-step floating catchment area (2SFCA) method and its variants, alongside the emergence of social media data analytics has allowed for an improved quantification and understanding of these relationships. New approaches such as the 2SFCA method allows for incorporating both spatial and non-spatial attributes, considering the interplay between supply (i.e., greenspace capacity and its provided services) and demand (i.e., human population size and composition) (Dony et al., 2015). These methods incorporate both objective measures of quality (e.g., the diversity and amount of provided ES) or subjective ecosystem service perceptions that influence greenspace attractiveness and usage, thereby offering advances to previous methods by capturing both the supply-side of greenspaces and the characteristics of human demands. This limitation has been even further addressed recently through the integration with social media data, which offers unique insights into the perceived quality and value of UGS from the lens of CES (Gugulica & Burghardt, 2023). While various social media platforms, including Flickr, Instagram, and X (formerly Twitter), have been employed in UGS studies to capture different dimensions of human-nature interactions, the choice of platform fundamentally shapes the type and quality of data available for CES analysis (Cao et al., 2022; Donahue et al., 2018). Geolocated data from review-oriented platforms (e.g., TripAdvisor and Google Maps) serve as valuable proxies for understanding human interactions with, and valuations of, environmental features (Cao et al., 2025), capturing the multi-dimensional benefits of UGS. When combined with traditional accessibility analyses, social media data provides a more complete and vivid picture of both physical access and perceived quality of UGS. Specifically, the integration of accessibility analyses with insights from social media data can be particularly valuable for understanding CES spatial flows, as social media comment texts can reflect users' perceived states and affective attitudes toward specific ecological infrastructures (Cao et al., 2024; Dang & Li, 2023). Research with such comprehensive approaches to quantify and evaluate the full spectrum of CES (rather than limiting to individual services) (Johnson et al., 2019) for a richer understanding of the extent and manners in which urban residents interact with and benefit from greenspaces remains scarce. Such a gap in the current literature therefore presents a clear need to employ these integrated approaches for a deeper examination of unequal access to the diverse cultural benefits of UGS.

2. Methods

Our overall aim in this research is to investigate the accessibility and quality of UGS from the angle of its CES by applying a semi-automatic methodology based on geotagged social media data to infer and unravel specific aspects of urban environmental (in)justice (see Fig. 1 of our overarching research workflow). The specific objectives of this study are three-fold: (1) To assess the CES provision of UGS and evaluate the accessibility to the most significant CES, notably through the application of an innovative population distribution-adjusted 2SFCA method that dynamically reflects how service provision and demand interact across varying spatial thresholds; (2) To evaluate how equity in CES accessibility differs when assessed at different spatial scales, specifically by comparing distributional outcomes across these varying thresholds to test the sensitivity of equity assessments to the spatial extent of greenspace service provision; (3) To examine CES accessibility of UGS among different demographic groups, including race and ethnicity, gender, and age. We conduct this research in South Florida, where CES are highly valued by the general public, particularly community-level services such as connecting people with community and nature (Zhao et al., 2024), underscoring the regional importance of these services for urban residents. Together, we synthesize these findings into a roadmap to identify areas with limited access to critical CES from UGS, thereby offering insights into more equitable and sustainable urban planning and policy interventions.

2.1. Study area

Our research was centered on Broward County, Florida, USA (Fig. 2a), a location selected for its specific urban characteristics. The county represents a highly urbanized, subtropical landscape where UGS are under pressure from development, yet are essential for the community. It also serves as an example of a subtropical/tropical urban system that is less commonly explored in existing literature but is presumed to host significant urban biodiversity. As the second-most populous county in Florida and one of the top 20 in the United States, Broward County is home to approximately 1.9 million people. Its landscape is characterized by a stark contrast between the densely populated urban corridor in the east and the expansive Everglades Wildlife Management Area in the west. This division accentuates the need for well-distributed greenspaces within the urban matrix to serve both ecological functions and human well-being. Broward County's built environment was largely shaped by land use plans from the 1970s and 1980s that prioritized low-density, auto-oriented suburban development, which subsequently drove public initiatives (e.g., the 2000 Safe Parks and Land Preservation Bond Referendum) to acquire and preserve remaining natural lands (Parks & Division, 2023). This development trajectory, characterized by suburban expansion followed by reactive land preservation, is common across many metropolitan regions, making Broward County a representative case for examining scale-dependent inequities in urban greenspace accessibility (Meentemeyer et al., 2013). The county's total area is 342,655 ha, with 110,799 ha comprising urbanized areas across 31 municipalities. For this study, we utilized a dataset of 639 UGS whose spatial boundaries were previously delineated by Miguez et al. (2025). Specifically, these UGS vary considerably in size (0.03 to 376 ha, average of 8.0 ha) and composition, encompassing a range of physical attributes such as children's playgrounds, walking paths, and nature preserves (median of three distinct

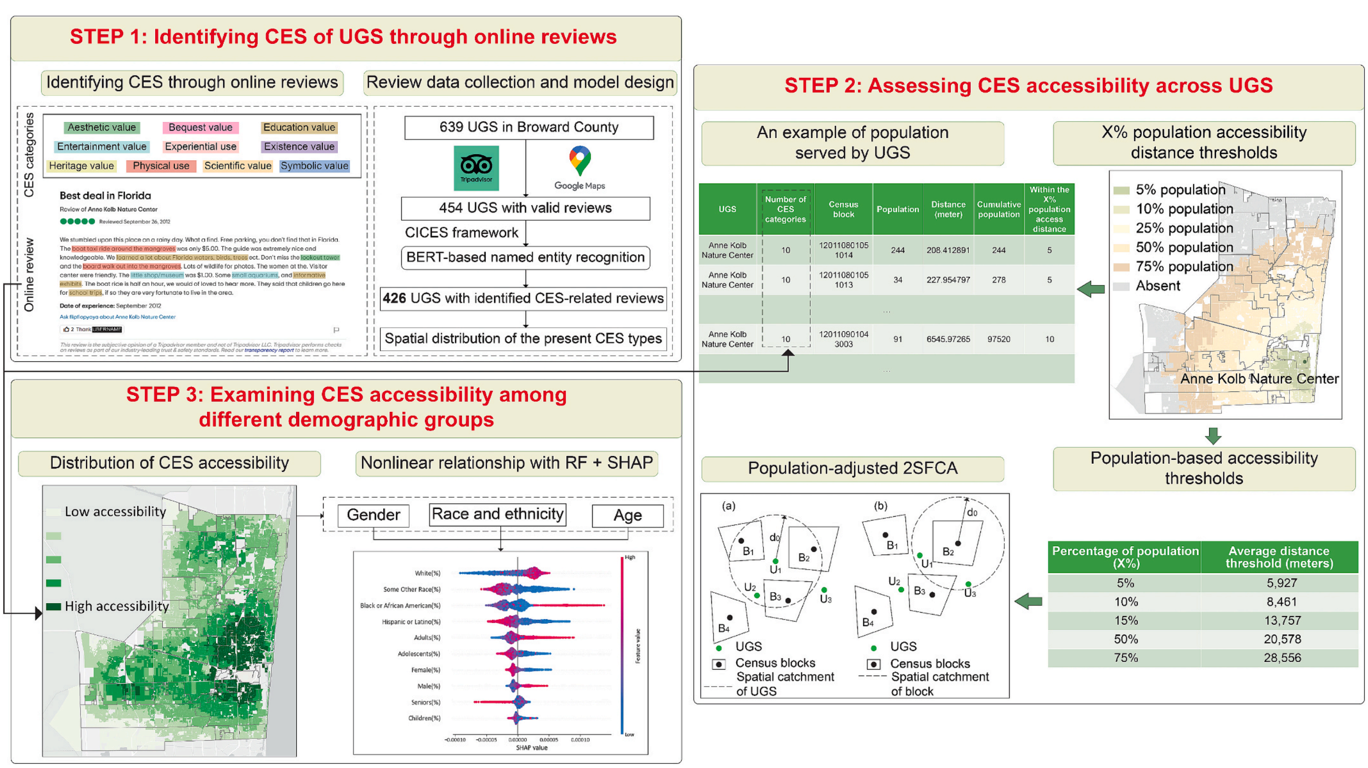


Fig. 1. Schematic diagram of overall research workflow. Our three-step approach to assess cultural ecosystem services (CES) accessibility across urban greenspaces (UGS): (1) Identification of CES from online reviews using a BERT-based named entity recognition model (methodology and results detailed in Cao et al. (2025); (2) Implementation of a population-adjusted Gaussian two-step moving search method (G2SFCA) model to quantify CES accessibility across UGS; and (3) Application of random forest with SHAP (SHapley Additive exPlanations) explainable analysis to examine nonlinear relationships between greenspaces CES accessibility and social-demographic factors.

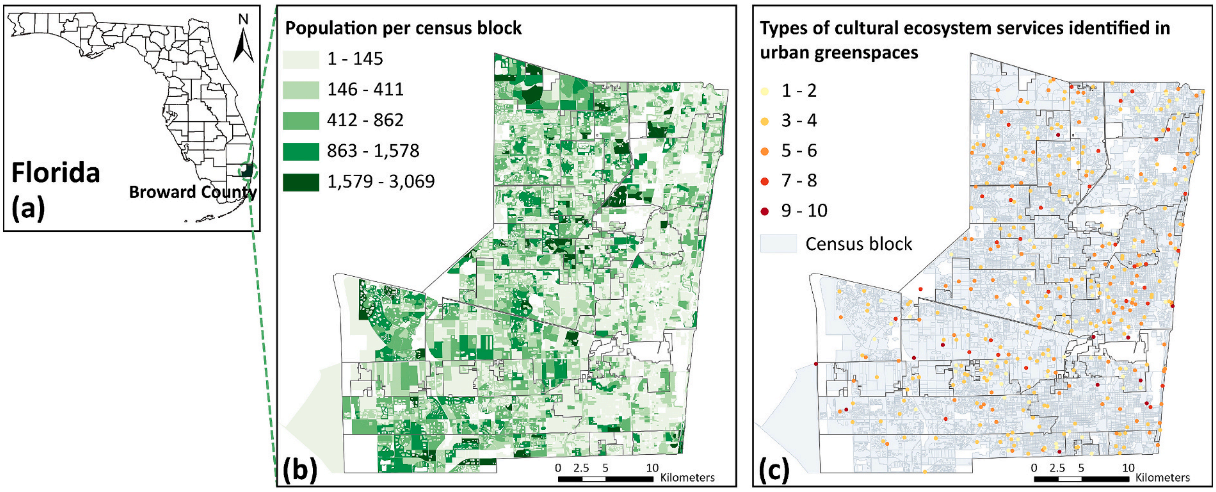


Fig. 2. (a) Geographic location of our study sites in Broward County, Florida, USA. (b) Population of individual census block at the Broward County. (c) Total number of present categories of identified CES for all the major UGS mapped for this study region.

attributes per greenspace), as well as differing proportions of tree canopy cover, non-tree vegetation, and impervious surface (Miguez et al., 2025).

2.2. Online reviews collection and processing and CES quantification

To assess the CES provided by UGS, we analyzed user-generated online reviews. Our approach of CES classification and quantification was directly guided by the established CICES framework (Hirons et al., 2016). We adopted their full typology to derive 11 distinct CES categories, mapping them to the two first-order divisions identified in their framework (Table 1) by systematically identifying them using the textual data. Specifically, we categorized services into two divisions: physical and intellectual interactions, and spiritual and symbolic interactions.

Data were sourced from two major online review platforms, Google Maps and TripAdvisor, which provide complementary, globally scalable, and spatially specific user-generated content ideal for studying human-ecosystem interactions and CES perceptions (Kong & Sarmiento, 2022). Our platform selection was guided by three key considerations: First, both Google Maps and TripAdvisor specialize in rich, text-based narratives about place-based experiences but with slightly different user groups, where TripAdvisor attracts users motivated to detail recreational and cultural experiences and Google Maps integrates location-based reviews into daily navigation, capturing more spontaneous UGS interactions (Cao et al., 2025; Kong & Sarmiento, 2022). Second, these platforms demonstrate high spatial precision in linking user experiences directly to specific UGS boundaries, as reviews are explicitly attached to

Table 1
Definition of cultural ecosystem services (CES) focused on this study and example of CES-related online review entities for model training. Complete methodology details can be found in Cao et al. (2025).

CICES division	CES category	Definition	Example of entities
Physical and intellectual interactions	Experiential use	Experiential use of plants, animals, and land-/seascapes in different environmental settings.	"…Very nice camp site. not a lot of activities. great for **dog walking**…"
	Physical use	Physical use of land-/seascapes in different environmental setting.	"…The boardwalks are in good shape for **a walk through the mangroves**…"
	Scientific value	Subject matter for scientific research.	"…This small park was **one of the last areas of undisturbed cypress swamp** in the county, and it was preserved, apparently, through the efforts of a group of local high school students…"
	Educational value	Subject matter of educational value.	"…A great place to **understand the importance of the wildlife** and a history of the area both ecologically as well as architecturally…"
	Heritage value	Historic records of a place; cultural heritage preserved in different environmental settings.	"…He was very **informative about the history of the glades and the Seminoles**. We saw lots of birds which he told us interesting things about…"
	Aesthetic value	Artistic representations of nature.	"…You can **see the beautiful green leaves of the red mangroves**; it is a bridge who brings you in the middle of the groves with a tower to observe the panorama…"
	Entertainment value	Benefits arising from various outdoor recreational activities.	"…This is a great place to **hold a picnic**, even in the evening…."
Spiritual and symbolic interactions	Symbolic value	Emblematic plants and animals; national symbols.	"…This is **a great hidden little gem**. Very peaceful to walk the raised boardwalks in between lots and lots of spiders…"
	Religious value	Holy or spiritual places important to spiritual or ritual identity.	"…A beautiful spot to **meditate, relax**, and commune with the birds and nature…"
	Existence value	Enjoyment and philosophical perspective provided by the knowledge of, and reflections on, the existence of wild species, wilderness, or land-/seascapes.	"…Also enjoyed walking on their board walk and **feeling like being in the middle of the Everglades** and forgetting that I was just 10 min away from I to 95 and all the hub bub…"
	Bequest value	Willingness to preserve plants, animals, ecosystems, and land-/seascapes for the experience and use of future generations.	"…Very happy to see Florida residents felt it was important in the 1970's to **preserve a little nature** so close to its popular beaches…"

discrete locations rather than simply geotagged within broader areas (Ghermandi et al., 2023). Third, combining data from both platforms ensures a more comprehensive dataset that captures a wider demographic and culture of users. Using the Python-supported browser automation tool "Selenium," we scraped all reviews posted between December 2010 and October 2023 to capture a long-term average of UGS use. The collection was conducted for research purposes under fair use principles, and all data were anonymized and aggregated to protect user privacy. Our initial dataset consisted of 69,084 reviews (60,552 from Google Maps; 8,532 from TripAdvisor) corresponding to 454 of the 639 delineated UGS. The remaining 193 UGS were excluded from the analysis as they had no reviews on either platform. To classify and extract CES-related content, we employed a BERT-based named entity recognition model. This model was trained on a custom corpus of reviews annotated for 10 CES types; a proposed eleventh category, "religious values," was omitted from further analysis due to its extremely low frequency (four occurrences). A full description of the data collection, processing, and CES classification methodology is detailed in our previous work (Cao et al., 2025).

Following the automated classification, we identified 60,156 textual entities related to CES within 30,599 reviews. This process revealed that 28 of the 454 UGS with reviews did not contain any identifiable CES content, leading to their exclusion. The final analysis was therefore conducted on a dataset of 426 UGS, which exhibited substantial variability in both natural landscape cover (e.g., tree cover ranging from 0% to 37%, mangrove cover from 0% to 68%) and greenness conditions (mean NDVI ranging from 0.06 to 0.54), alongside a diversity of physical attributes (detailed descriptive statistics are provided in Table A1 in the Supplement;. see also Cao et al., 2025). To quantify the breadth of services offered, we used the total number of unique CES categories identified for each UGS as a numeric indicator of CES diversity (Fig. 2c). This approach acknowledged that a single review could express appreciation for multiple CES simultaneously.

2.3. Demographic and geographical data processing

We used the most updated U.S. Census Bureau's 2020 Demographic and Housing Characteristics data at the census block level to assemble measures of age, gender, race and ethnicity. Census blocks were chosen as the zonal system because these spatial units are the smallest geographical unit at which data on population-level demographics are publicly available. After filtering populated census blocks (Fig. 2b), there were 15,536 blocks accounted for in further analysis. The sex by age dataset (titled "P12 – Sex by age for selected age categories") includes the number of residents broken down by gender and age groupings (including under 5 years and by 5-year up to 85 +). Race and ethnicity data were sourced from the dataset "P9 – Hispanic or Latino, and not Hispanic or Latino by race." For our analysis, we created a composite group labeled "Other", which includes individuals who identified as "American Indian and Alaska Native," "Asian," "Native Hawaiian and Other Pacific Islander," and "Some Other Race." Regarding age structure, we categorized the population into four distinct groups to capture life-stage-specific demands: children (5–9), adolescents (10–17), working-age adults (18–64), and seniors (65–85). Specifically, since toddlers (age $\leq$ 4) rarely go to the park alone but go out with their families (Cronin-de-Chavez et al., 2019), this study does not consider the competition for greenspace resources from toddlers. Moreover, drawing on recent literature highlighting differential UGS access patterns between older populations and younger adults (Ho et al., 2022; Li & Wang, 2024), we utilized 65 years as the age threshold to distinguish seniors from the working-age adult population. We then calculated each demographic grouping factor ratio of each census block unit (Table 2). Overall, the county's population shows a balanced gender distribution, with adults (18–65) comprising the largest age group (~66.7%). Notable racial and ethnic groups include White (~33.3% of the population) and Hispanic or Latino (~28.6%) residents. Road network for Broward County extent was processed using the 2022 U.S. Census Bureau's TIGER/Line roads shapefiles. The locations of UGS and census blocks were assigned to the nearest points on the road network.

Table 2
Descriptive statistics of demographic characteristics and population-adjusted CES accessibility index for census blocks in UGS of Broward County.

Variable	Min	Median	Max	SD
Gender				
Male	0	48.8%	1	15.4%
Female	0	51.2%	1	15.4%
Age				
Children (5–9)	0	5.1%	1	6.0%
Adolescents (10–17)	0	10.0%	1	8.4%
Adults (18–65)	0	66.7%	1	15.6%
Seniors (over 65)	0	14.7%	1	15.7%
Race-ethnicity				
White	0	33.3%	1	25.8%
Black or African American	0	15.2%	1	27.0%
Other	0	5.3%	1	7.5%
Hispanic or Latino	0	28.6%	1	19.4%
Population-adjusted CES accessibility scores				
For 5% population	0	$8.8'10^{-4}$	$8.3'10^{-3}$	$5.4'10^{-4}$
For 10% population	0	$8.9'10^{-4}$	$2.2'10^{-3}$	$3.7'10^{-4}$
For 25% population	0	$9.3'10^{-4}$	$1.5'10^{-3}$	$2.2'10^{-4}$
For 50% population	0	$9.6'10^{-4}$	$1.3'10^{-3}$	$1.9'10^{-4}$
For 75% population	0	$9.4'10^{-4}$	$1.3'10^{-3}$	$1.9'10^{-4}$

2.4. CES accessibility assessment

To better reflect the mobility patterns of urban residents accessing greenspaces (**Objective 1**), the Gaussian two-step floating catchment area (G2SFCA) method enhances the traditional 2SFCA approach by incorporating a distance decay function, thereby improving the sensitivity of accessibility assessments to travel behavior. This method has been widely applied in contexts ranging from local-scale analyses, such as evaluating walking accessibility to urban parks for elderly populations to explore age-specific needs (Li & Wang, 2024), to city-level (in)equity assessments that highlight disparities in greenspace access (Williams et al., 2020). On a broader scale, it has been utilized in national evaluations spanning hundreds of Chinese cities over past decades, offering insights into long-term accessibility trends (Huang et al., 2022). Beyond UGS, its applications extend to suburban forests and natural areas (Dony et al., 2015), demonstrating its transferability for accessibility analyses across different greenspace types.

Specifically, the G2SFCA method operates in two steps: First, for each UGS (supply point j), we calculate a supply–demand ratio by dividing the UGS's service capacity by the population within its search radius, weighted by a Gaussian distance decay function. Second, for each census block (demand point i), we sum the weighted supply–demand ratios of all accessible UGS within its search radius to derive an accessibility index. In this study, the supply capacity (S_j) represents the number of CES categories at each UGS (defined as CES diversity), and population size (P_i) represents demand at each census block. The Gaussian distance decay function ensures that nearby greenspaces contribute more to accessibility than distant ones, with weights decreasing exponentially beyond the search radius threshold (d_0). This calculated accessibility index, unlike simple proximity measures, comprehensively considers the quantity and quality of UGS (in terms of provided CES), human demand, and geographic distance, where higher values indicate better access to diverse CES (Fu et al., 2024).

Traditional metrics such as fixed catchment areas defined by "X-minute walks" (e.g., 10-minute or 15-minute; Logan et al., 2022), or Xkilometer distances (Kimpton, 2017) were often used in the greenspace accessibility assessment. However, these measures may not adequately reflect the diverse socioeconomic and demographic characteristics that could influence greenspace utilization preferences within different urban contexts in the United States. For example, studies in areas as Atlanta, Georgia, USA (Dai, 2011), characterized by extensive urban sprawl and an automobile-dependent culture, have highlighted the limitations of pedestrian-centric access metrics. According to the 2023 ParkScore Index created by the Trust for Public Land (https://www.tpl.org/parkscore), 84% of residents in Fort Lauderdale, the most populous city in Broward County, can access nearby parks within 10 min. In comparison, in the median city across all urban cities and towns in the U.S., only 55% of urban residents can access parks within this timeframe. Thus, to address and better characterize how well UGS serves different proportions of the population in study areas, we conducted a multi-step accessibility assessment. First, we used ArcGIS Pro 3.3.0's Closest Facility function to measure and rank the actual road network distances between each UGS and surrounding census blocks. We then determined how many residents each UGS could serve by calculating the cumulative population within these ranked distances. From this analysis, we defined a series of service radius for each UGS, with each radius representing the network distance needed to encompass a specific cumulative percentage of the population. We thus applied dynamically adjusting catchments based on population in this study rather than fixed distances estimated by transportation modes and time cost of greenspace accessing. The choice of following specific percentages reflects a balance between statistical rigor and practical utility proved by prior similar studies (Song et al., 2022; Supak et al., 2015), providing a range that captures both local and regional dynamics and allowing us to model a range of realistic greenspace-use scenarios. We identified five key distance thresholds representing scenarios with increasing percentages of population coverage, where smaller radius of UGS like 5,927 m (serving the nearest 5% of the population) and 8,461 m (10%) represent access to local or neighborhood greenspaces for daily recreation. In contrast, larger radius such as 20,578 m (50%) and 28,556 m (75%) represent access to community or regional destination greenspaces that residents are willing to travel farther to visit. These scenarios of different distance thresholds, therefore, range from representing access for the fewest residents (the nearest 5% of the population served by the smallest service radius) to access for the majority of residents (the nearest 75% of the population served by the largest service radius).

The Gini coefficient of CES accessibility index and associated Lorenz curve are widely adopted in horizontal equity analysis since they can measure whether the resources are evenly distributed among populations. Its application has been expanded into various disciplines, including the assessment of disparities in access to UGS and CES they provide (Martin & Conway, 2025). The Gini index produces values that range from 0 to 1; higher Gini coefficients signify a greater imbalance in the distribution of CES from UGS. In this study, we calculated Gini coefficients for each of the five population-adjusted distance threshold scenarios (5%, 10%, 25%, 50%, and 75%) to compare how equity in CES accessibility varies across different spatial scales of greenspace service provision.

To investigate the spatial distribution of CES accessibility across census blocks within the study area (**Objective 1**), we employed hot and cold spot analyses to reveal underlying spatial patterns and provide a clearer understanding of the spatial heterogeneity across the urban landscape. This method is highly effective for identifying statistically significant geographical concentrations of high values (hot spots) and low values (cold spots). The hot spots analysis was carried out in ArcGIS Pro 3.3.0 using the "Getis-Ord Gi*" tool. In our case, we specified queen contiguity, called "contiguity edges corners", presuming that if two blocks share a boundary or corner, spatial interaction between them is high (i.e. vacancy in one tract is likely to spread to adjacent blocks first).

2.5. Identifying nonlinear relationships between CES and social-demographic factors

We used random forest model to examine the relationship between CES accessibility and demographic factors (**Objective 2)**. The training set and test set of the census block dataset, according CES accessibility, were divided into a commonly occurring ratio of 8:2. The optimal hyperparameters (Table A2 in the Supplement) for the five random forest models were determined through RandomizedSearchCV using 5-fold cross-validation derived from the "sklearn" package of Python. Three metrics were applied to measure fitting performance: root mean squared error (RMSE), mean absolute error (MAE), and R-squared (R^2). RMSE and MAE are negatively-oriented scores, while R^2 is positive with a range of 0——1. Detailed results can be found at the Table A2 in the Supplement.

After establishing the random forest regression model, the specific contributions of different demographic input parameters to CES accessibility remained quantitatively undefined, with unclear directional effects (positive/negative) of those demographic variables. To address this, the SHAP (SHapley Additive exPlanations) method (Lundberg & Lee, 2017) was applied to interpret the tuned random forest using game-theoretic principles. SHAP quantifies the marginal contribution of the input parameters (demographic variables) as "players" to the model's predictions (CES accessibility scores) as the "game", where contributions are calculated through Shapley values derived from cooperative game theory. The SHAP interpretation model, f, is expressed as a linear function of these contributions:

$$f(z') = \phi_0 + \sum_{i=1}^{M} \phi_i z'_i \tag{1}$$

where f is the interpretation model; z' is a simplified binary representation of the input features where $z'_i = 1$ if the i^{th} feature is present and 0 otherwise; M is the total number of demographic features; and ∅ is the Shapley value, or attribution, for each feature.

The contribution of any single input feature is determined by comparing the output of a prediction model, g, when the feature is included $g_{H\cup\{i\}}$ versus when it is excluded g_H. The Shapley value is the weighted average of these differences across all possible combinations of features, as shown in Eq. (2).

$$\phi_i = \sum_{H\subseteq P\setminus\{i\}} \frac{|H|!(|P|-|H|-1)!}{|P|!}\left[g_{H\cup\{i\}}(H\cup\{i\}) - g_H(H)\right] \tag{2}$$

where P is the set of all input demographic parameters; H is a subset of all parameters excluding the i^{th} feature. The aforementioned steps of SHAP model were performed in a Python library named "SHAP". The SHAP values were calculated for all census blocks to quantify the impact of each demographic factor on the model of CES accessibility's prediction.

3. Results

3.1. CES accessibility of UGS

We found that the CES accessibility of UGS varies with different population scenarios, as determined by the distance thresholds for characterizing various dynamic catchments (Table 2). For example, as the percentage of the population with access to CES increased (i.e., from 5% to 75%), the median accessibility index also increased accordingly. There was a noticeable difference between the maximum and minimum values of accessibility, with higher values of standard deviation. Specifically, for the 75% of the population threshold to access CES at UGS, we found a lower standard deviation of accessibility score, indicating that accessibility disparities diminished when considering larger service radii of UGS.

Geographically, the spatial distribution of accessibility presented an overall high accessibility in the center of the study region, with lower accessibility around it (Fig. A1). Areas with high accessibility were clustered around the County's center. The value of accessibility gradually decreased around those areas and outward. The more the population could access the CES of UGS, the more noticeable it was that centers with higher accessibility were.

There were varying levels of equity depending on the proportion of the population considered, reflecting the significant influence of scale on CES equity assessments (Fig. 3). While it is analytically expected that inequality measures compress as larger population proportions are included, as evidenced by the Gini coefficient decreasing to 0.16 at the 75% threshold, this pattern highlights the tendency of such broader analyses to mask local disparities. Our analysis reveals that inequities are most severe at the local scale, where the Gini coefficient peaked at 0.35 for the nearest 5% of the population, but these disparities become increasingly obscured as the service radius expands. Consequently, the observed Gini coefficient changes from 0.35 (local) to 0.16 (regional), demonstrating that accessibility assessments conducted solely at regional levels may risk overlooking severe localized injustices in CES access, as the data smooths out significantly when the service radius narrows to the nearest 10% (0.30) and 25% (0.23) of the population.

The spatial analysis of CES accessibility (Fig. 4) revealed significant local clustering into hot spots and cold spots. Hot spots, which pinpoint census blocks where accessibility to CES is statistically significantly higher than the local average of their surrounding areas, were mainly concentrated in central Broward County, including municipalities such as Fort Lauderdale, Davie, and Weston, where they were surrounded by more greenspaces with less population density and generally had high levels of accessibility. In contrast, cold spots, which indicate census blocks with CES accessibility statistically significantly lower than their local neighborhood average, were mainly clustered in the fringe areas of the central county. These areas were often characterized by fewer greenspaces, or by a large number of high-rise residential communities and high population density, which contributed to their significantly low levels of local CES accessibility. We also measured the trends of cold and hot spots for accessing CES in response to population thresholds. As our analysis shifted from scenarios where fewer residents had access (i.e., 5% of the served population) to scenarios where most residents had access (i.e., 75% of served population), the percentage of cold spots among all blocks decreased from 25.3% to 20.1%, while hot spots decreased from 27.9% to 19.7%. In summary, there was substantial spatial heterogeneity in the accessibility of CES in Broward County, with an unbalanced distribution of UGS resources and the provided CES. Overall, accessibility remained low, and existing UGS failed to adequately meet the various CES demands of the majority of residents in their respective areas.

3.2. Effects of social-demographic factors on UGS CES accessibility

Fig. 5 illustrates the locality-specific importance of demographic factors on CES accessibility of UGS. Analysis of the less accessible scenarios (5%, 10% and 25% population access) in Broward County revealed that White, adults, and female individuals had the most significant effects on predictions of CES accessibility within their respective demographic groups. For example, the SHAP value for White residents was the most variable and shifted from a slightly negative mean toward near-zero values at 25%, indicating heterogeneous yet consistent influence. In these less accessible scenarios, both the White and adult populations showed wider spreads, indicating greater variability in how these demographic groups affected CES accessibility. Moreover, high percentages of White, adult, and male populations generally correlated with shifts towards positive values, potentially indicating increased accessibility to CES compared to other demographic groups in the less CES accessible scenarios. However, the more accessible scenarios (50%

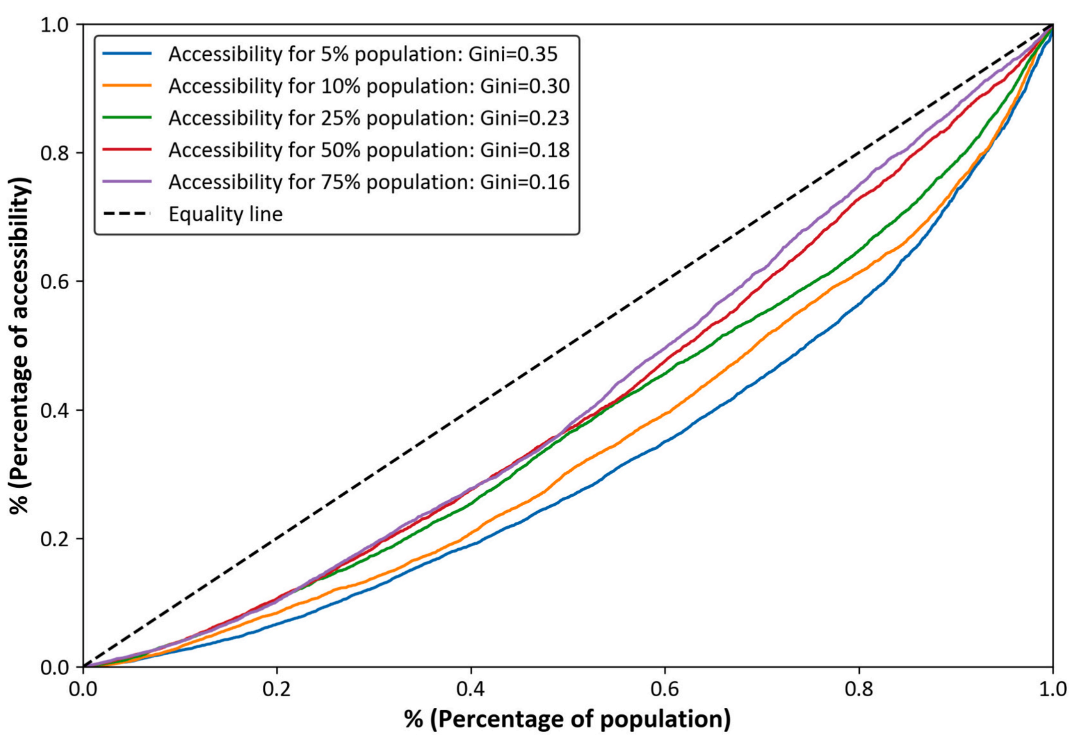


Fig. 3. Lorenz curve and the Gini coefficient values representing the dissimilarity in CES accessibility and different population distribution scenarios. The x-axis represents the cumulative percentage of the total population, ordered from the individuals with the lowest accessibility to those with the highest. The y-axis represents the cumulative percentage of the total CES accessibility experienced by that population. The "Equality line" represents a scenario of perfect equality where x% of the population would have access to x% of the total CES accessibility. The colored curves show the actual distribution of accessibility under five different scenarios, where the service radius of UGS is set to reach the nearest 5%, 10%, 25%, 50%, and 75% of the population, respectively. Curves that bow further away from the Equity line indicate greater inequality. The Gini coefficient quantifies this inequality (0 = perfect equality, 1 = perfect inequality).

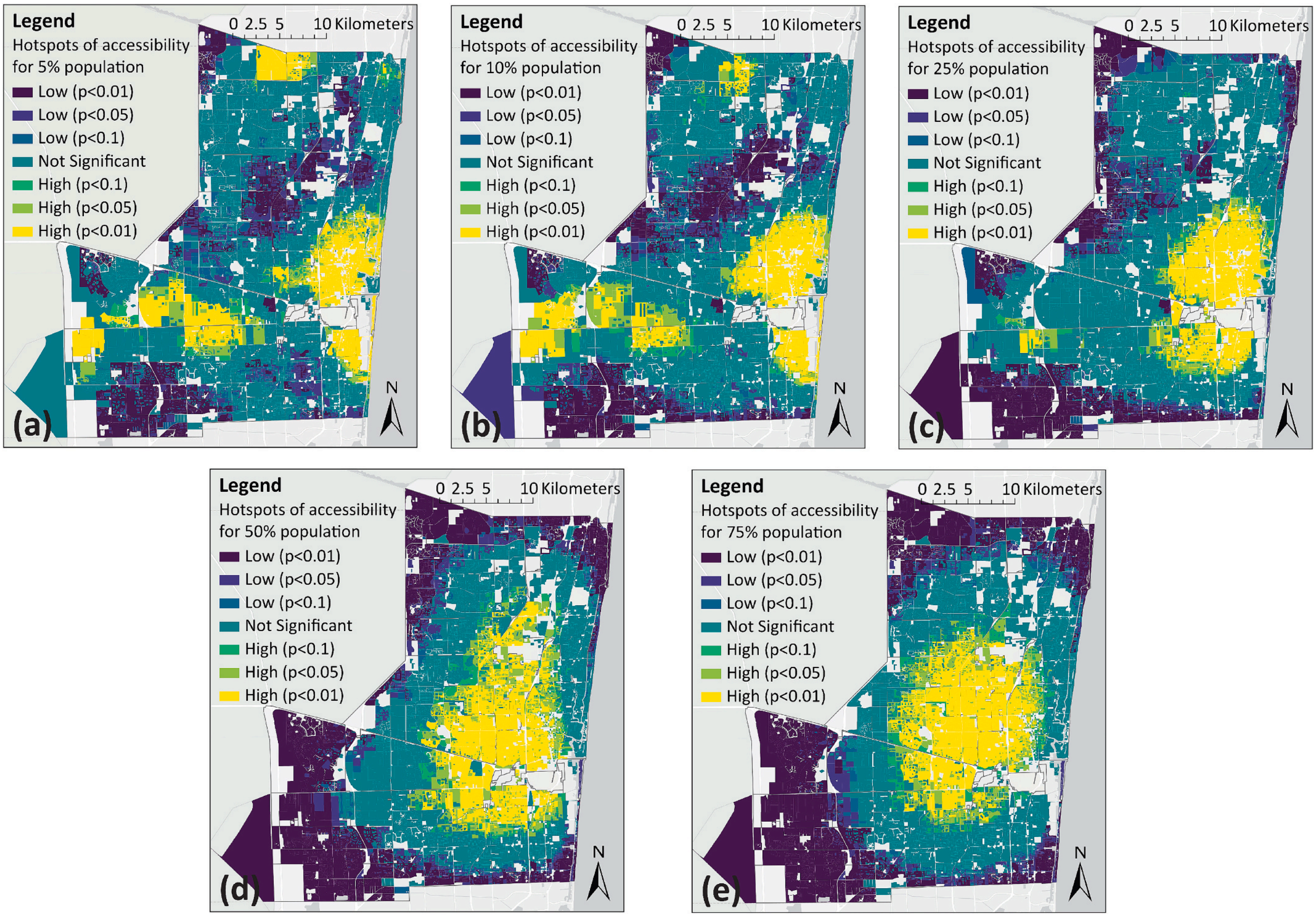


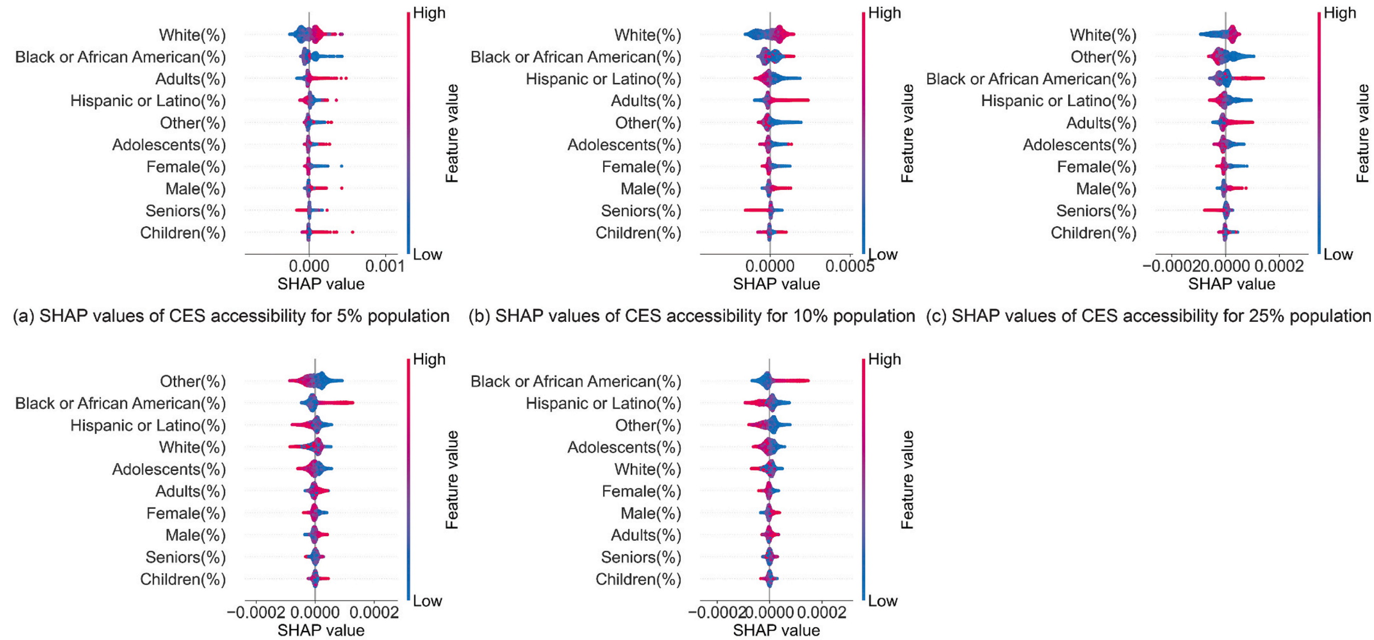
Fig. 4. Hot and cold spots among census blocks for accessing CES in UGS under different population-adjusted distance thresholds. The hot and cold spots were clustered according to Z-scores: hot spot (99% significant), hot spot (95% significant), hot spot (90% significant), not statistically significant, cold spot (90% significant), cold spot (95% significant), and cold spot (99% significant).

and 75% population access) revealed a more inclusive CES access landscape, where racial diversity, especially "Other" race, Black or African American, and Hispanic or Latino populations, played a larger role in predicting access to CES, while the influence of age and gender demographics diminished. The SHAP value for the Black or African American population increased from a negative to a positive mean across the 5% to 75% scenarios, while the value for "Other" race exhibited a similar positive shift. In contrast, the SHAP value for the Hispanic or Latino population indicated a non-linear effect, peaking at the 10% access scenario before it declined. Altogether, our analyses illustrated that underrepresented groups often experienced significantly lower CES accessibility. In Figs. A2–A6 in the Supplementary Material, we further mapped the SHAP values for each demographic factor for predicting different CES accessible scenarios of individual blocks. We found that SHAP values increased for most demographic classes as population coverage expanded, indicating improved and more equitable CES access when the proportion of population that UGS can serve increases.

4. Discussion

4.1. Key findings

Our study introduces a novel approach to examining the (in)equality that exists in UGS access and their provided CES across social-demographic groups through crowdsourcing online review data and advanced machine learning methods. Key findings of our research include: (1) an overall low level of accessibility to CES from UGS, suggesting that the current supply and spatial distribution of greenspaces may be inadequate to meet the CES demands of urban residents, particularly given the observed demographic disparities; (2) substantial spatial heterogeneity of CES accessibility, which our hot spot analysis confirmed by identifying distinct clusters of high accessibility in central Broward County and "cold spots" in urban fringe areas. This moves beyond the county-wide average of the first finding to reveal a more nuanced geographically uneven distribution, where urban fringe areas, often characterized by high-rise residential communities and high population density, are significantly underserved; (3) accessibility varies across population-adjusted distance thresholds – from highly variable access for 5% of the population to more equitable access for 75% of the population, reflecting the significant scale effects on CES equity; and (4) demographic factors emerged as significant predictors of accessibility patterns. Specifically, the proportion of White and adult residents were the most dominant predictors, correlated with higher, albeit more variable, CES accessibility. This points to persistent systemic disparities where underrepresented groups experience significantly lower CES access of UGS at the local scale. However, the predictive importance of racial and ethnic diversity (particularly the proportions of Black or African American and Hispanic or Latino populations) increased under scenarios of broader regional access (i.e., 50–75% of the population), suggesting that the dynamics of access become more complex at a regional scale, moving beyond the stark divides seen at the local level.



(a) SHAP values of CES accessibility for 5% population (b) SHAP values of CES accessibility for 10% population (c) SHAP values of CES accessibility for 25% population

(d) SHAP values of CES accessibility for 50% population (e) SHAP values of CES accessibility for 75% population

Fig. 5. Locality-specific importance and impact of demographic factors on CES accessibility of UGS. The panels represent five accessibility scenarios calculated using a G2SFCA model with dynamically adjusted service radius designed to serve (a) 5%, (b) 10%, (c) 25%, (d) 50%, and (e) 75% of the Broward County population. Within each panel, features are ranked by their global importance (mean absolute SHAP value) from top to bottom. Each dot represents a single census block. The dot's horizontal position on the x-axis indicates the SHAP value – the impact of that feature on the model's output, with positive values indicating a push towards higher CES accessibility and negative values indicating a push towards lower accessibility. The color of the dot represents the feature's value for that census block, from low (blue) to high (red), revealing the directionality of the relationship. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.2. Interpreting CES accessibility across social-demographic groups

Our findings both align with and diverge from previous research on environmental justice and CES accessibility. Similar to studies in Chicago (Liu et al., 2021), Los Angeles (Wang et al., 2025) and other regions, our results demonstrate persistent disparities in CES accessibility of UGS across racial and ethnic groups, with White populations generally experiencing improved access. This is unsurprising, as communities with lower social and economic power tend to have reduced access to environmental amenities (Dai, 2011; Nesbitt et al., 2019). However, unlike previous studies where underrepresented group-clustered areas showed the lowest accessibility despite having relatively lower internal inequity (Liu et al., 2021), our results' accessibility patterns exhibit more complex and nuanced spatial variations. Such findings that central areas have higher accessibility while peripheral areas experience lower access suggest that geographic location and urban development patterns also play important roles beyond purely demographic factors. In addition, our demographic analysis reveals interesting parallels with studies exploring age-based disparities. Similar to findings from Auckland, New Zealand (Zhang et al., 2024), where senior adults and children had fewer opportunities to access different UGS in their neighborhoods, our results suggest that demographic factors significantly influence CES accessibility patterns. However, while the Auckland study found no gender-based inequalities, our analysis showed that male populations were more likely to have higher CES accessibility of UGS. Similarly, research on ecosystem services from urban agriculture in the Miami Metropolitan Area revealed that age and race were significant demographic predictors of CES perception, with White respondents showing stronger perceptions than Black or African American respondents, while personal agriculture experience and neighborhood presence of urban agriculture sites enhanced perceptions across demographic groups (Zhao et al., 2024). Moreover, this study also connects with broader discussions about methodological approaches to measuring UGS accessibility. This study's employment of various population distribution (5% to 75%) scenarios for determining catchment distance thresholds of 2SFCA methods provides a more comprehensive understanding of accessibility patterns that account for the spatial extent of UGS service radius. Offering important insights into urban planning and policy interventions, the finding that accessibility becomes more equitable with increased population coverage suggests that enabling UGS to serve populations residing farther away can reduce overall inequity in access to CES.

4.3. Policy implications

Our findings highlight significant spatial disparities in CES accessibility of UGS, particularly between central and peripheral areas of Broward County. To address these disparities, urban planners should implement a hierarchical network of greenspaces that prioritizes equitable distribution while mitigating gentrification risks (Bressane, Pinto, et al., 2024). In central areas where accessibility is already high, the focus should be on maintaining and enhancing existing greenspaces without triggering further displacement pressures (Wang et al., 2025). For peripheral areas identified as cold spots, planners could prioritize developing networks of smaller, interconnected greenspaces to enhance accessibility and reduce inequality. This aligns with findings that small-scale green infrastructures present lower gentrification risks than large-scale projects (Chen et al., 2021), while areas with high baseline greenness, such as those resulting from these distributed greenspace networks, exhibit reduced susceptibility to gentrification effects. This could include converting vacant lots into pocket parks, establishing green corridors, and rehabilitating brownfield sites (Kim, 2018). Such a network approach (e.g., using Geodesign planning process) can help create a more spatially balanced provision of CES from different UGS across the urban landscape while acknowledging the practical constraints of land availability in developed areas (Huang et al., 2024).

Secondly, our findings regarding demographic disparities in CES accessibility of UGS call for more targeted interventions. Urban planners should prioritize areas with high concentrations of underrepresented groups who currently experience lower CES accessibility. This includes developing specific design guidelines that consider the needs of different age groups, particularly seniors and children, who show distinct patterns of and benefits from greenspace usage (Ward Thompson, 2013). Master planning in urban development should be incorporated to ensure equitable access across gender groups (Calderón-Argelich et al., 2023), addressing the identified gender-based accessibility disparities. Additionally, planners should consider cultural preferences and usage patterns when designing new UGS or renovating existing ones to ensure they meet the diverse needs of different demographic groups (Elbakidze et al., 2022). This involves developing robust mechanisms for community engagement in greenspace planning and design, particularly in underserved areas (Bressane, Cunha Pinto, et al., 2024). Community-driven nature-based solutions, such as community gardens can act as catalysts for social cohesion while mitigating green gentrification risks and averting marginalization of vulnerable populations when designed with meaningful local governance structures (Bressane, Pinto, et al., 2024). Regular monitoring and evaluation of CES accessibility across demographic groups should be also conducted, with results made publicly available in a timely manner. To ensure the success of these interventions, stakeholders must prioritize procedural justice mechanisms in planning and implementation, coupling greenspace interventions in underserved areas with explicit anti-displacement policies (Qiu et al., 2025).

Thirdly, our analysis of accessibility across different population thresholds reveals the critical role of transportation infrastructure in determining CES access, especially in urban areas such as our study region that lacks public transportation infrastructure. Urban planners should focus on developing integrated transportation networks that allows residents to access distant UGS and thus enhance overall greenspace accessibility. This includes expanding public transit routes (and their frequencies) to major greenspaces, developing safe and convenient pedestrian and cycling infrastructure (e.g., rental of electric scooters) for last-mile transportation, and implementing traffic calming measures in residential areas (Chen & Chang, 2015). The goal should be to ensure that residents can access at least one quality greenspace within a 15-minute walk or ride (Logan et al., 2022; Mansur et al., 2022), aligning with contemporary urban planning principles of the "15-minute city". This framework transforms the abstract goal of "enhancing CES accessibility" into a tangible, measurable target. By applying our population-threshold research framework as a baseline, urban planners can track progress toward creating a truly connected and equitable urban ecosystem, moving beyond a landscape of isolated green "islands".

Lastly, while quantitative measures of simply UGS accessibility (e.g., based on proximity and distance) are important, our findings suggest that the quality and diversity of CES within UGS are equally if not more crucial. Parks departments should implement regular assessment protocols to evaluate and enhance CES diversity within existing greenspaces, since ultimately, it is what services provided by UGS matter to the wellbeing of residents, rather than UGS *per se*. This includes maintaining high-quality facilities, conserving natural ecosystems, ensuring safety through proper lighting and design, and developing multi-functional spaces that can accommodate various cultural and recreational activities (Krellenberg et al., 2021). Special attention should be paid to underserved areas where both accessibility and quality improvements are needed.

4.4. Limitations and future research needs

This research alludes to several promising avenues of future research to advance our understanding of CES accessibility and environmental justice in UGS. First, the integration of multiple platforms and types of data sources beyond social media data could provide a more comprehensive assessment of CES perceptions and usage patterns. Specifically, the incorporation of crowdsourcing online review platforms and advanced natural language processing techniques could offer deeper insights into public preferences and temporal dynamics of UGS utilization. Second, future studies could benefit from employing a strong sustainability framework that integrates diverse disciplines and methodologies to examine the interplay between social, built, and natural environments in shaping neighborhood perceptions and CES accessibility (Huang et al., 2024; Liao et al., 2020; Wilson & Wu, 2017; Wu, 2013). This approach would encompass demographic and socioeconomic features (e.g., age, gender, income, education), alongside environmental stressors such as temperature, rainfall, and air pollution, providing a multi-dimensional understanding of perception-environment relationships in the context of urban sustainability (Hunter et al., 2019). Third, the development of longitudinal studies based on historical street view images and social media data could enable the simulation and prediction of changes in visual built environments and CES distribution patterns (Zhao et al., 2025). Such temporal perspectives and analyses could be particularly valuable for understanding how urban development impacts CES accessibility across different demographic groups over time and examining the effectiveness of policy interventions. Additionally, the application of advanced AI techniques could help synthesize realistic urban scenarios and fill data gaps (Bibri et al., 2024), facilitating more proactive planning and policy interventions. Last but not least, future research could differentiate CES identification based on local versus tourist perspectives, potentially revealing different patterns of greenspace utilization and perception across user groups (Jones et al., 2020).

However, there are also several methodological constraints worth discussion. Although social media data provides valuable insights into CES perceptions and quantification, it presents inherent biases in user representation, potentially excluding important demographic groups such as children and elderly people (Busch et al., 2024). The uncertainty regarding user demographics and whether posts originate from locals or tourists could skew results in unpredictable ways, even though we have strived to minimize such uncertainties in our analysis. Our reliance on social media data might lack essential contextual information about the historical, social, and political dimensions of greenspaces (Benati et al., 2024), which are crucial for environmental justice research. Understanding these contexts is vital for identifying past injustices, discriminatory practices, and patterns of unequal resource distribution. Additionally, our use of CES diversity as a proxy for UGS quality, while advanced compared to monolith approaches, still represents a simplification of the complex, multi-dimensional nature of greenspace quality. Moreover, certain CES categories, particularly those of a more intangible nature (e.g., symbolic value, scientific value, existence value, and bequest value), proved difficult to detect through social media analysis, potentially resulting in an incomplete picture of CES analysis. Addressing this limitation might require integration of other social science approaches (e.g., surveys and questionnaires, participatory mapping, community-based focus groups and workshops, choice experiments, semi-structured interviews, contingent evaluation, social network analysis) to help ground-truth our findings and provide more robust CES-metric for USG quality.

Beyond data quality concerns, our study also faces limitations related to data coverage. The exclusion of some UGS (approximately 30% of all identified greenspaces in this study) that had no reviews on either platform represents a potential limitation. These review-absent UGS may serve distinct populations or provide different types of CES that are not readily captured through online review platforms. Their exclusion could systematically bias our accessibility assessments, particularly if these greenspaces are disproportionately located in underserved communities where residents may have lower rates of digital engagement. Future research should investigate the characteristics and service populations of these excluded UGS through alternative data collection methods (e.g., those stated above) to ensure a complete understanding of CES accessibility patterns. Furthermore, our data covers a period of over 13 years of accumulated reviews. We acknowledge that both the physical characteristics of greenspaces (e.g., facility improvements, vegetation maturation, management changes) and cultural values toward nature may have evolved during this period. However, several factors could support our aggregated temporal approach: (1) fundamental CES categories (e.g., aesthetic appreciation, physical activity, social connection) represent relatively stable human-nature interactions characterized by enduring trait-like qualities that persist across time, rather than rapidly shifting preferences and behaviors (Colléony et al., 2020); and (2) our focus on CES diversity across multiple categories likely captures persistent service qualities rather than temporal anomalies. Nevertheless, future research incorporating explicit temporal analysis could reveal how greenspace quality perceptions and environmental justice patterns evolve over time, particularly in response to urban development pressures or targeted interventions.

5. Conclusion

Our study introduces a novel research framework to characterizing CES accessibility of UGS in urbanizing landscapes and quantifying their relationship with social-demographic characteristics, using crowd-sourced social media data and machine learning methods. Our findings reveal a substantial spatial heterogeneity in CES accessibility of UGS, and importantly, demonstrates that accessibility patterns are driven by demographic factors whose influence is fundamentally scale-dependent. While the proportion of White and adult residents are the most dominant predictors of CES accessibility at the local scale, the predictive importance of broader racial and ethnic diversity increases at the regional scale. Ultimately, achieving environmental justice in CES access requires a shift towards an integrative, sustainability-focused, and justice-centered approach that addresses not only physical proximity but also ensures the quality and cultural relevance of services for diverse communities.

CRediT authorship contribution statement

Haojie Cao: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Hui Zhao:** Conceptualization, Writing – review & editing. **Corey T. Callaghan:** Writing – review & editing, Data curation, Conceptualization. **Jiangxiao Qiu:** Writing – review & editing, Supervision, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was partially funded by the Swedish government research council for sustainable development (Formas), 'Inequality and the Biosphere: Achieving the Sustainable Development Goals in an Unequal World' project (#2020-00454). Qiu also acknowledges the financial support from School of Natural Resources and Environment, University of Florida, and USDA National Institute of Food and Agriculture (FLA-FTL-006277; FLA-FTL-006371) and AFRI Foundational and Applied Science Program (2021-67013-33617; 2023-67019-39728).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2026.105635.

Data availability

Data will be made available on request.

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