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Are Green Spaces More Available and Accessible to Green Building Users? A Comparative Study in Texas

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Abstract: Green buildings (GBs) and green spaces (GSs) play a key foundational role as important drivers of urban Sustainable Development Goals (SDGs). There have been many studies on the spatial distribution of GBs and GSs, but relevant studies exploring the spatial relationship between GBs and GSs are lacking. The research questions were: whether GBs are more likely to access GSs than nongreen buildings (NGBs) and whether GBs with higher certification levels are more likely to access GSs. In this study, we used Texas and its four major cities (Austin, Dallas, Houston, and San Antonio) as case studies to compare the availability and accessibility of GSs to GBs (certified by Leadership in Energy and Environmental Design, LEED by U.S. Green Building Council) and NGBs. The study was conducted using spatial analysis tools in a geographic information system (GIS) to explore the spatial distribution of GBs and quantify the availability and accessibility of GSs in a comparison of GBs and NGBs and different GB certification levels. The study found that GBs in each city showed uneven distribution with multicore distribution. In addition, the availability and accessibility of GSs for GBs are lower than for NGBs, and the ability to obtain GSs does not increase with higher GB certification levels. This is because many GBs are located in areas far from the city center or in small cities around large cities where there are few GSs available, resulting in a mismatch in the distribution of GBs and GSs. The study also reviewed the certification manuals and found that LEED has regulated GSs at the city and community levels, yet has ignored them at the building level, and thus further suggests specific improvements. This study provides references and suggestions for adding GSs to the certification content, helping policymakers to optimize future efforts to improve GB certification programs and contributing to the eventual greater role of GBs and GSs together in urban SDGs.

Keywords: green spaces; green buildings; LEED; certification levels; spatial distribution

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1. Introduction

The United Nations 2030 Agenda for Sustainable Development consists of 17 Sustainable Development Goals (SDGs) that humanity needs to achieve by 2030, which encompass three dimensions: economic growth, social inclusion, and environmental protection [1,2]. Cities are the places where the positive interlinkages among the SDGs are boosted [3]. At the city level, green buildings (GBs) and green spaces (GSs) can contribute significantly to the social, environmental, and economic scope of sustainable development, playing a key foundational role as important factors [4–8]. In the construction industry, GBs have shown great potential over the last few decades globally to reduce or eliminate negative impacts on our climate and natural environment during their design, construction, or operation, as well as to provide long-term positive benefits [9,10]. GSs also have high sustainability value in the natural environment [11]. The U.S. Environmental Protection Agency (USEPA) defines GS as land that is partly or completely covered with grass, trees, shrubs, or other vegetation, including parks, community gardens, and cemeteries [12]. GS provides ecosystem services that mitigate various hazards, such as flooding, urban heat, and air pollution [13–15], and it also provides residents with access to nature and encourages outdoor physical activity, thus promoting physical and mental health and wellbeing [16–18].

Given the importance of GBs and GSs in sustainable development, many studies have been carried out to explore their spatial distribution [19–21]. For GBs, Cidell and Beata [22] explored the differences in the spatial distribution of GBs across different regions, concluding that regional differences and aggregation characteristics have been reflected and that more spatially sensitive certification criteria are required. Zou et al. [23] analyzed the spatial distribution of GBs in China and examined their potential determinants, finding that GBs are not evenly distributed across provinces, that there are indeed regional quantity imbalances, and that local economic fundamentals and subsidy-based incentives can explain the presence of GBs. For GSs, Sathyakumar et al. [24] showed a spatiotemporal analysis of the distribution of urban GSs at the neighborhood level by applying geospatial methods in Mumbai, leading to the conclusion that urban GSs largely turned smaller, fragmented, and disaggregated. Zu et al. [25] provided a quantitative interpretation of the spatiotemporal patterns of service efficiency and distributional characteristics of community GSs in central urban areas of Beijing. The results showed that the measured values of the GS distribution coefficients showed a decreasing trend under the same conditions, and they further proposed an optimization strategy based on the empirical measurements.

In the urban development process, we should associate GBs with GSs and attach sufficient importance to their synchronization to enable efficient sustainable development, so it is important to explore the spatial relationship between GBs and GSs. For all buildings, including GBs and nongreen buildings (NGBs), GSs meet the landscape and outdoor activity needs of users and contribute to the recovery of individuals from physical and mental stress [26,27]. Buildings as properties in the market are composite commodities that reflect the value of comfort, and people are willing to pay to live near a comfortable local environment. For economic benefits, the advantages of GSs are also shown in real estate prices—there is a strong relationship between the selling price of a building and the distance of that building from GSs [28,29]. For example, Morancho [30] analyzed the link between housing prices and urban green areas using the hedonic technique and concluded that there is an inverse relationship between the selling price of buildings and their distance from a green urban area. Relative to NGBs, GBs could be more competitive in the real estate market because green attributes give them a higher value. Chun [31] investigated the price premium of GBs in Taipei and found that people would be willing to pay a higher price for buildings with green certification, and the higher the certification level, the higher the price people would pay. GSs are more likely to add value to GBs while meeting the basic needs and sustainability requirements of GBs. Therefore, GBs need GSs more to make them more attractive and consequently more superior, which requires a study of the spatial relationship between the two.

However, unlike the large number of studies on the spatial distribution of GBs and GSs, there are few studies that focus on the relationship between the two critical urban green infrastructures; only a few studies are found on the relationship between buildings and GSs. For example, Wang et al. [32] used multispectral remote sensing imagery to extract urban buildings and GSs and investigated the green visual index of buildings to estimate the green landscape of buildings. Mansour et al. [33] used geographic information system (GIS) technology and landscape metrics to study the spatial variation of green patches associated with other types of land use (mainly residential buildings) in arid urban areas, concluding that urban GSs are primarily positively correlated with population and residential density. We extend the scope to the relationship between GBs and GSs, which, to the best of our knowledge, has not been studied by previous researchers.

In addition, green building rating systems (GBRSs) have played a crucial role in the development of GBs through the definition of their attributes and the provision of tools to assess the environmental impact of buildings [34]. Since the publication of the first GBRS (Building Research Establishment Environmental Assessment Method, BREEAM) from the United Kingdom in 1990, GBs have been developed in tandem with the development of GBRSs [35]. Worldwide, Leadership in Energy and Environmental Design (LEED), published by the U.S. Green Building Council (USGBC), is one of the world's most popular and influential GBRSs, having covered 175 countries around the world and certified more than 90,000 buildings [36]. Since 1998, LEED has undergone seven revisions and continual improvements, from the original version 1.0 to the latest version 4.1 released in April 2019 [37,38]. LEED has made targeted changes based on the development of the building market, evolving from a sustainable assessment primarily for single buildings to a community-wide assessment and gradually expanding to citywide [39,40]. Based on the importance of specific issues in building-related sustainability, LEED certification scores are categorized into four levels: Certified (40–49 points), Silver (50–59 points), Gold (60–79 points), and Platinum (80 points and above), with higher levels indicating that more assessment items are met [41]. Typically, the certification level can be used as a result to reflect the greenness of a building and to motivate the continuous upgrading of existing buildings or the construction of new buildings to achieve higher levels of sustainability [42]. However, to our knowledge, the current GBRSs may ignore the obtaining of GSs in sustainability, and no previous studies have yet investigated the relationship between certification results and GSs. Considering that the certification results of GBRSs are an important reference for assessing the levels of GBs, it is necessary to explore the relationship between GBs and GSs under different certification levels.

To summarize, there are many studies related to the spatial distribution of GBs and GSs, respectively, but there is almost no research that specifically explores the spatial relationship between the two. To fill the gap, this study performed a comprehensive study of GSs for GBs, including a comparison of GBs and NGBs as well as different GB certification levels, using availability and accessibility as quantitative indicators. The questions of this study were: whether GBs are more likely to access GSs than NGBs and whether GBs with higher certification levels are more likely to access GSs. The purpose of this study was to spatially analyze the relationship between GBs and GSs with the following important implications: (1) to improve regulations for GBs in GBRSs in order to better make GBs serve people and (2) to make GBs and GSs echo each other so that they can potentially play a greater role together in urban SDGs.

2. Materials and Methods

2.1. Study Areas

Texas, USA, which is the second-largest state in the United States in terms of land area, after Alaska (Figure 1), was selected as the region for this study. In addition, it is the second-most populous state and has the second-highest gross domestic product (GDP) in the United States [43], making it significant to the nation. In terms of the development of GBs, Texas is ranked ninth in the 2020 LEED ranking for GBs and has the third highest total number of LEED professionals in the nation according to the USGBC [44]. These reflect the importance of GBs in the state, and the diverse profiles of its GBs are highly typical, and the number of GBs can satisfy the requirements of the analysis.

In addition to analyzing the whole of Texas, four cities within the state were selected for this study: Austin, Dallas, Houston, and San Antonio, with the aim of improving the precision of the analysis results and avoiding errors caused by coincidental factors. There are two reasons for choosing these cities: (1) they are the major cities of the state, with the highest level of population and economy [45], and (2) the four cities are on the list of the 50 cities with the most GS area per capita in the U.S., ranked 45th in Austin, 30th in Dallas, 10th in Houston, and 44th in San Antonio [46], which ensures that the data from the GSs are adequate.

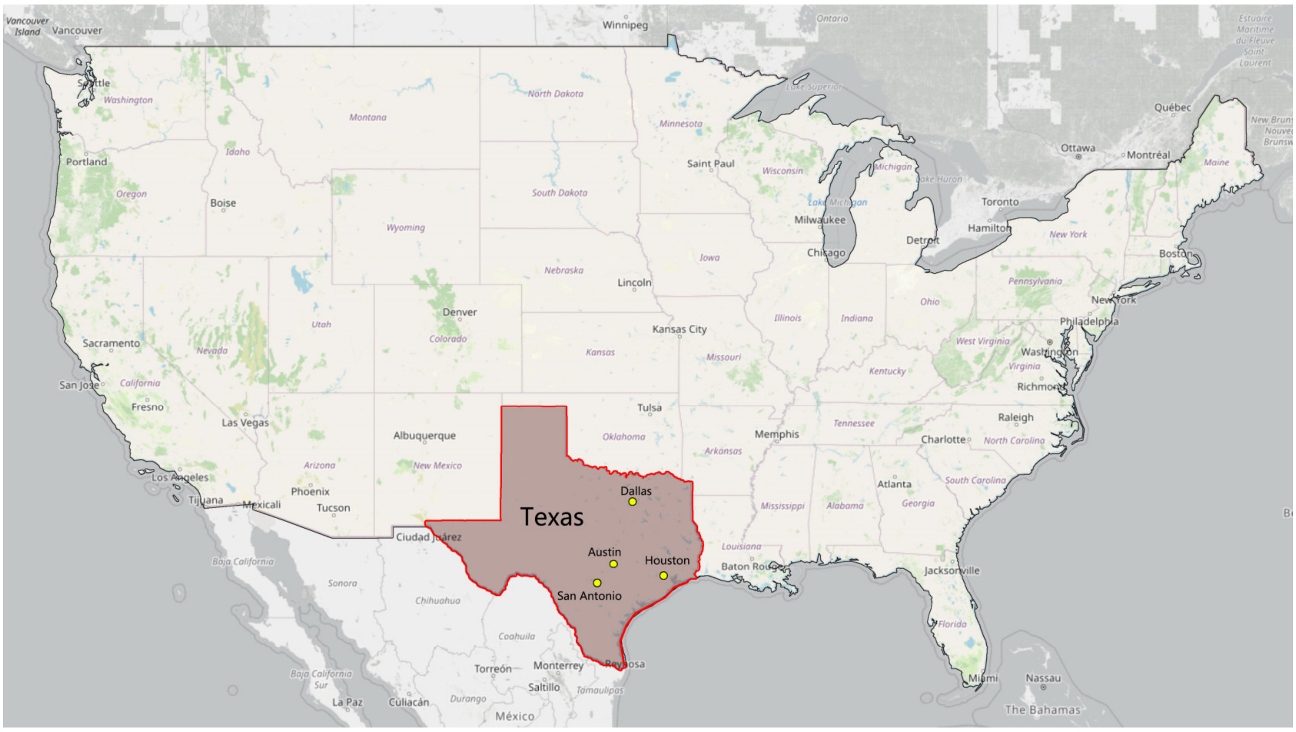


Figure 1. Location of Texas.

2.2. Data Collection and Processing

The data for the study was obtained from the official ArcGIS website and are thus reliable. Information on LEED certification levels and the geographic coordinates of individual buildings was available in the data for Texas's GBs and NGBs [47], and data for Texas's GSs came from data from American parks [48]. The two data sets were last updated in 2022, allowing the data to be temporally matched, and ensuring synchronization. The baseline map used in the study was taken from OpenStreetMap (https://www.openstreetmap.org, accessed on 1 November 2022), which is a mapping tool commonly used in geographic mapmaking [49].

In this study, GSs are specifically defined as public parks with high levels of open attributes, so private spaces such as the campus lawns of higher education institutions and golf courses are not considered. National parks and state parks were excluded from the park data because they tend to contain other land types, such as forests and wetlands, and ultimately, the county parks, regional parks, and local parks together make up the GSs in this study. Figures 2 and 3 represent the distribution of GSs in Texas and the four major cities, respectively. For the whole state, most of the GSs are concentrated in the four major cities that are the focus of this study, reflecting the rationality of the selection of these four cities. There are also numerous GSs distributed along the Gulf of Mexico in the southeast of the state. The four major cities show a great deal of heterogeneity in the shapes of the GSs: Austin is dominated by faceted GSs, Dallas shows a combination of point and linear distribution, and Houston and San Antonio show a point distribution because of the smaller area of each GS.

All of the building data collected for this study were filtered and screened to remove invalid data (blank or duplicate data), and the final data sample obtained is shown in Table 1. A total of 11,998 buildings in 237 cities were used in this study, including 9029 LEED-certified GBs and 2969 NGBs, and thus the sample size was adequate to ensure the trustworthiness of the study. The four major cities account for more than 25% and 45% of all GBs and NGBs, respectively, and are highly representative.

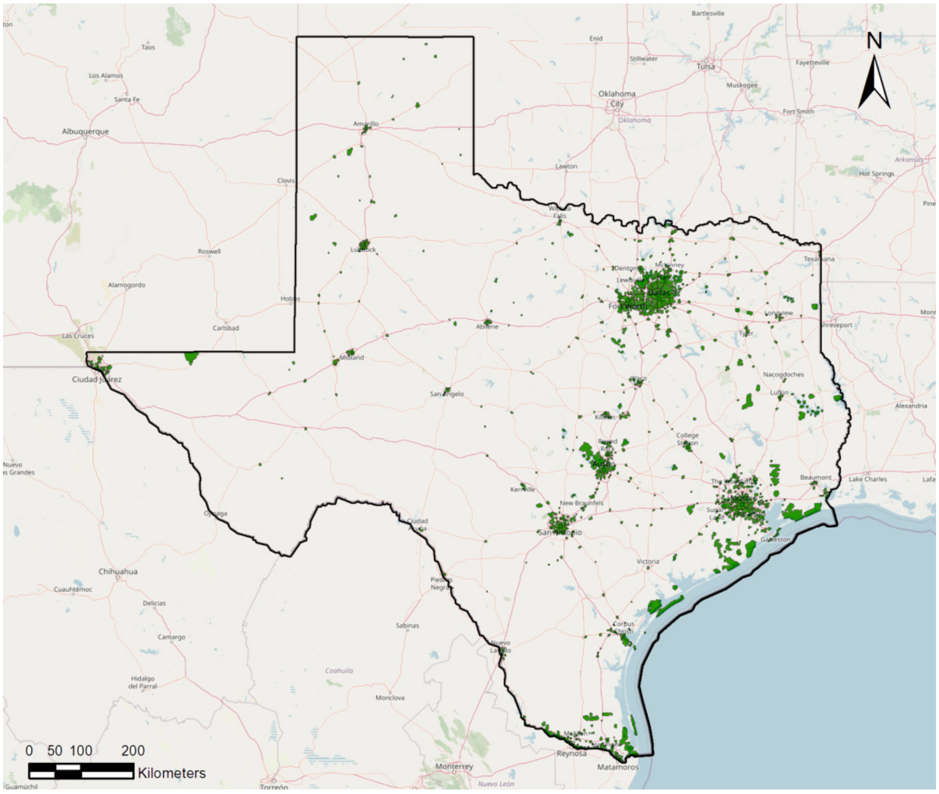
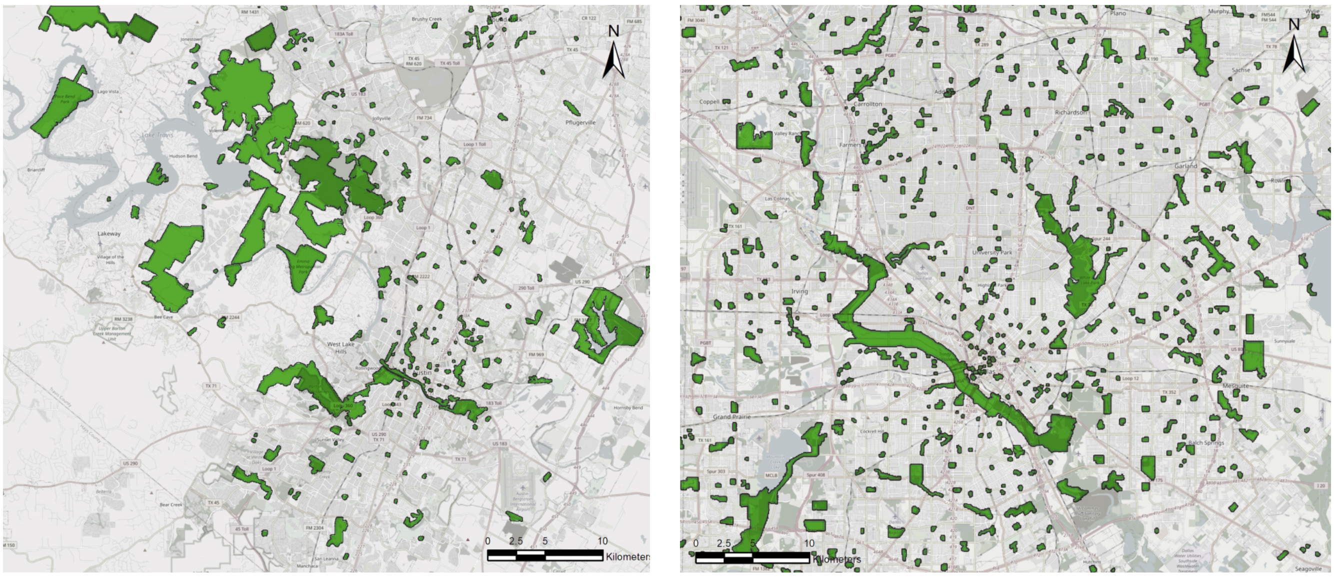


Figure 2. Distribution of green spaces in Texas.



(**a**) (**b**)

Figure 3. *Cont*.

(**c**) (**d**)

Figure 3. Distribution of green spaces in four major cities: (**a**) Austin, (**b**) Dallas, (**c**) Houston, and (**d**) San Antonio.

Table 1. Number of data samples.

Places	**GBs**					**NGBs**	**Total Buildings**
	Certified	**Silver**	**Gold**	**Platinum**	**Total**		
Austin	309	109	101	28	547	304	851
Dallas	548	172	118	19	857	371	1228
Houston	176	194	234	80	684	578	1262
San Antonio	242	43	31	3	319	118	437
Other 233 Cities	5444	602	500	76	6622	1598	8220
Texas	6719	1120	984	206	9029	2969	11,998

2.3. Data Analysis

For the data analysis in this study, GIS (ArcGIS 10.7 software, developed by Esri in Redlands, California, the U.S.) was used as a tool, which is a commonly used tool for spatial analysis [50]. Data analysis was compared under Texas and four major cities, and the study area of a city is determined by the locations of GBs within that city. The study consisted of three main parts:

1. Spatial distribution of GBs;
2. GSs for GBs and NGBs;
3. GSs for different GB certification levels.

In the first part of the analysis, we explored the spatial distribution using the kernel density estimation method, which has been widely used in similar studies [51,52]. Kernel density estimation is a spatial smoothing technique that uses a filtering window to define near-neighbor objects, where the closer the object is, the greater the weight is used to calculate the density of the element in its surrounding neighborhood, which results in the spatial distribution characteristics of the data. The method visualizes how elements are clustered in space, as it estimates the density around sample points based on the density of points per unit area, and produces a smooth surface with excellent visualization. It can be calculated using Equation (1):

$$F(d) = \frac{1}{nh} \sum_{i=1}^{n} k\left(\frac{d_i - d}{h}\right) \quad (1)$$

where $F(d)$ is the density calculation function at the spatial position d, k is the spatial weight function, h is the interval attenuation threshold, n is the number of sample points, and $d_i - d$ is the spatial distance from the sample point d to the sample point d_i.

To investigate the relationship between GSs and GBs, the second and third parts of the analysis compared the availability and accessibility of GSs to assess the ability of GBs to obtain GSs. The availability is determined by creating a buffer zone around the GBs at a certain distance and calculating the overlap area between that zone and the GSs (using the "intersect" function), and finally calculating the average availability of each GB for comparison. The larger the area is, the higher the availability is. The key to this part of the study lies in determining a reasonable buffer distance. Different criteria have been used in previous studies, but typically, 300 or 500 m is used as the distance. For example, Kabisch et al. [53] assessed the availability of GSs in 299 EU cities using 300 and 500 m as the distances, Kong et al. [54] proposed that a window of radius 500 m is more appropriate than 300 m to capture the effects of comfort when determining the percentage of urban GSs, Zhang et al. [55] set a 500 m buffer zone and calculated the availability of the supply of urban GSs in different communities in rapidly urbanizing Chinese cities, and Wüstemann et al. [56] defined a 500 m buffer zone around the center of mass of German households to determine the area of urban GSs within walking distance of residence to obtain urban GSs and environmental inequality. Based on the experience of previous studies, the buffer zone was set at 500 m in this study.

The accessibility is measured as the minimum distance between each building and the nearest geometric centroid of GS, and the distance between two points was used to explore accessibility in a similar study [55]. This was performed by using the "near" tool in ArcGIS 10.7, which is used to calculate the distance between any point in a layer and the nearest point in another layer. After getting the sum of the minimum distances of all buildings, the average distance of each building was calculated to compare the accessibility. The lower the calculated average distance, the higher the accessibility.

In general, the specific analysis process of this study can be summarized in Figure 4. First, the various materials needed for the study were obtained, including the study area, data required, and analysis tools. Second, the three contents of the analysis were identified by organizing the data, and finally, reasonable research methods were chosen for analysis. After sufficient discussion, the conclusions of the study were reached.

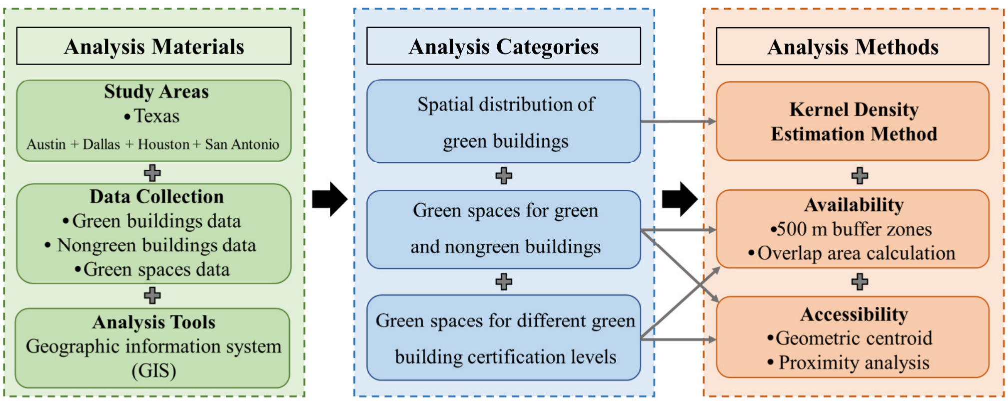


Figure 4. The flowchart of analysis.

3. Results

3.1. Spatial Distribution of Green Buildings

Figures 5–7 represent the spatial distribution of all GBs and GBs of different certification levels in Texas, as well as GBs in the four major cities after analysis using the kernel density estimation method, respectively. Across Texas, the most densely distributed areas of GBs are concentrated in and around the four cities of interest in this study. Among them, Dallas and Austin show the most densely distributed results, and Dallas is more extensive, while San Antonio and its surrounding areas are the least dense. In addition, LEED-certified projects are largely distributed in almost all urban areas. In Texas, while GBs of different levels are most distributed in the four major cities, the spatial distribution of the different GB certification levels varies: Certified is concentrated in Austin and Dallas, Silver is concentrated in Dallas and Houston, Gold is concentrated in Dallas and Houston, and Platinum is concentrated in Houston. In terms of the spatial distribution of GBs within each city, all four cities show the phenomenon of GBs having multiple cores, with Dallas having the largest number of cores and San Antonio having the fewest; in terms of sparsity, the distance between cores in Dallas and Houston is significantly smaller than that in Austin and San Antonio.

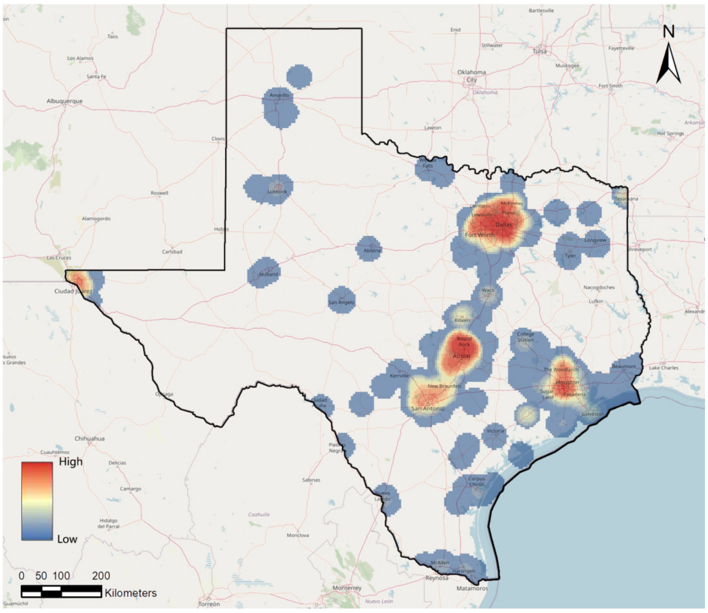


Figure 5. Spatial distribution density of green buildings in Texas.

3.2. Green Spaces for Green and Nongreen Buildings

3.2.1. Availability

Table 2 represents the quantitative results of the availability of GSs for GBs and NGBs within a radius of 500 m, where a larger available area indicates higher availability. In the comparison between GBs and NGBs, the availability of NGBs is higher than GBs in Austin, Houston, San Antonio, and Texas, while in Dallas, the availability of GBs is higher than NGBs. For GBs, the order of availability is Dallas > Austin > Houston > Texas > San Antonio, with only San Antonio below the statewide average of 9072.95 m^2. For NGBs, the order of availability is Austin > Houston > Dallas > San Antonio > Texas, with all four cities above the statewide average of 14,859.27 m^2.

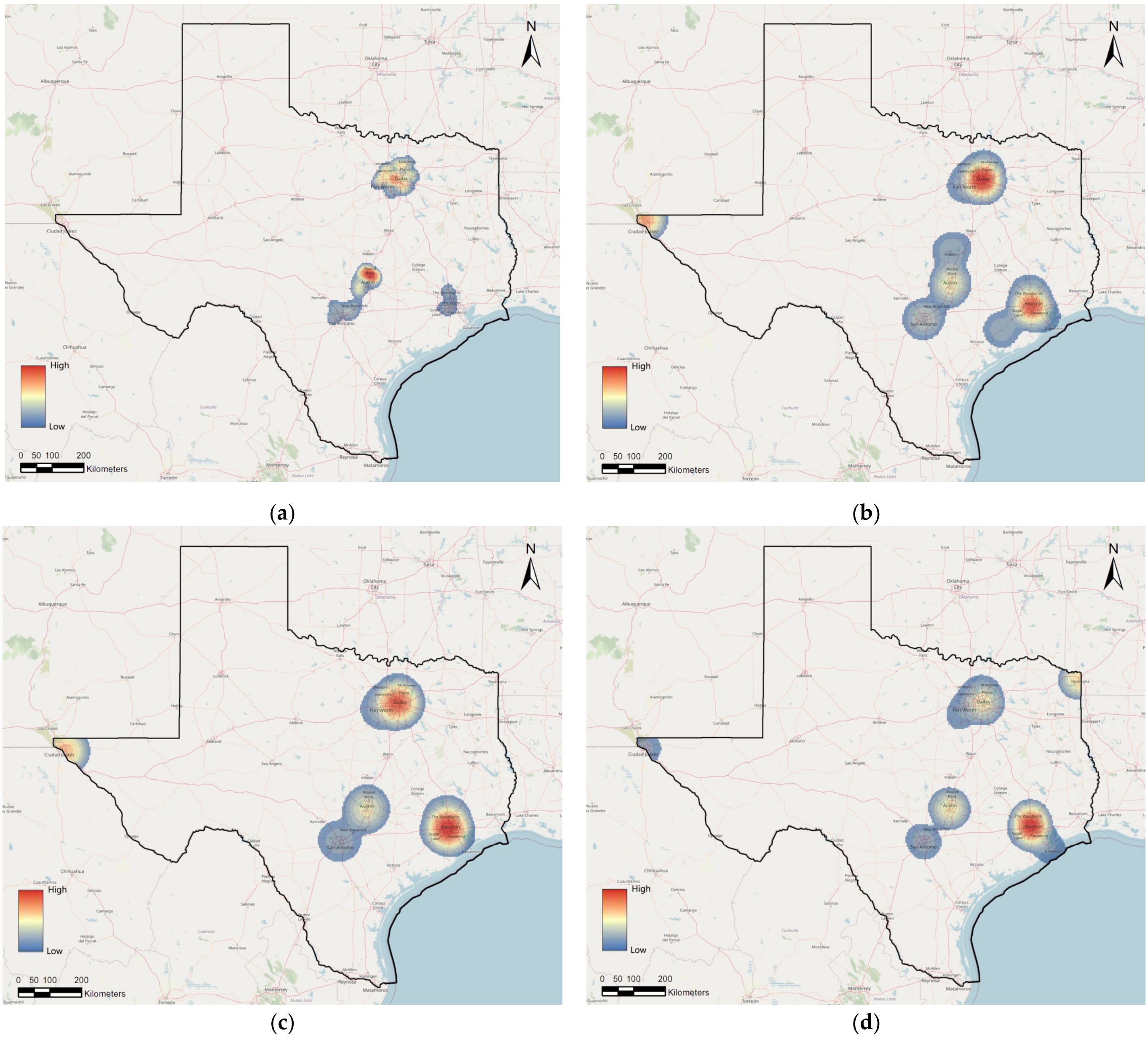


Figure 6. Spatial distribution density of different green building certification levels: (**a**) Certified, (**b**) Silver, (**c**) Gold, and (**d**) Platinum.

3.2.2. Accessibility

Table 3 represents the quantitative calculation of accessibility of GSs for GBs and NGBs, where a smaller distance from the building to the nearest GS indicates higher accessibility. For Texas and the four cities, the level of accessibility for NGBs is higher than that for GBs. For GBs, the order of accessibility is Dallas > Houston > Texas > Austin > San Antonio, with Austin and San Antonio below the statewide average of 3081.47 m. For NGBs, the order of accessibility is Dallas > Houston > Austin > Texas > San Antonio, with only San Antonio below the statewide average of 3079.95 m.

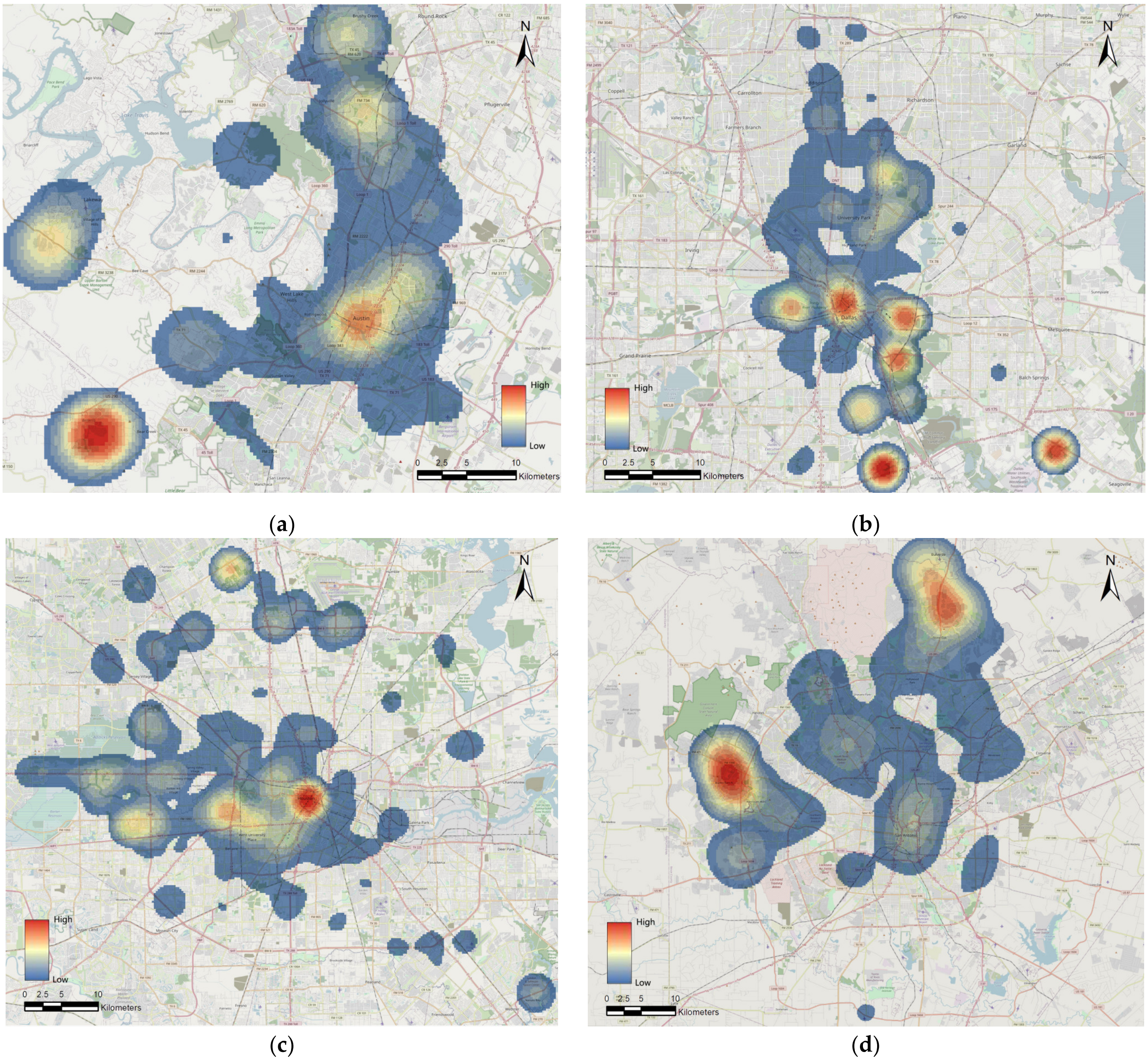


Figure 7. Spatial distribution density of green buildings in four major cities: (**a**) Austin, (**b**) Dallas, (**c**) Houston, and (**d**) San Antonio.

We expressed the distance between each GB reaching the nearest GS by visualizing the accessibility data, and Figures 8 and 9 represent Texas and the four cities, respectively. The radius of the circle represents the length of the distance, and the larger the radius, the larger the distance, reflecting that the GB is less accessible to GSs. For Texas as a whole, the radius of the circle is generally larger in cities other than the four major cities. As can be seen in the four cities, for the GBs in Austin, Houston, and San Antonio, the radius of the circle basically becomes larger and larger from the center outward, so the closer to the city center, the higher the accessibility, showing a significant difference; in the case of GBs in Dallas, the accessibility is more evenly distributed, and the radius of the circle does not vary much.

Table 2. Availability of green spaces for green and nongreen buildings.

Categories		Min (m^2)	Max (m^2)	Sum (m^2)	SD (m^2)	Number	Average Availability (m^2)
Austin	GBs	0.62	564,579.23	1,1242,110.08	18,165.85	547	20,552.30
	NGBs	0.03	440,950.74	12,158,302.98	28,246.74	304	39,994.42
Dallas	GBs	0.01	302,092.00	27,658,928.87	10,442.58	857	32,274.13
	NGBs	0.26	387,237.72	7,370,672.23	24,184.19	371	19,867.04
Houston	GBs	0.01	785,398.16	13,711,593.43	13,691.49	684	20,046.19
	NGBs	0.01	438,327.32	12,056,701.41	12,823.46	578	20,859.35
San Antonio	GBs	11.24	147,740.51	1,546,658.81	19,321.20	319	4848.46
	NGBs	3.31	288,107.71	2,227,217.70	44,458.41	118	18,874.73
Texas	GBs	0.25	785,398.16	81,919,670.94	9756.04	9029	9072.95
	NGBs	0.01	446,470.07	44,117,176.66	23,974.33	2969	14,859.27

Min means minimum, Max means maximum, and SD means standard deviation.

Table 3. Accessibility of green spaces for green and nongreen buildings.

Categories		Min (m)	Max (m)	Sum (m)	SD (m)	Number	Average Accessibility (m)
Austin	GBs	66.71	14,223.53	2,622,342.71	4763.28	547	4794.05
	NGBs	66.19	13,053.25	625,936.54	2911.66	304	2059.00
Dallas	GBs	15.18	2583.00	793,169.58	568.13	857	925.52
	NGBs	56.74	2184.63	293,510.90	456.41	371	791.13
Houston	GBs	61.37	5808.65	949,828.74	1030.94	684	1388.64
	NGBs	56.18	4995.75	725,476.38	1010.99	578	1255.15
San Antonio	GBs	125.57	11,487.43	1,630,143.58	2664.36	319	5110.17
	NGBs	70.76	10,628.28	384,650.46	2643.43	118	3259.75
Texas	GBs	5.64	48,959.59	27,822,599.99	3308.42	9029	3081.47
	NGBs	39.33	117,330.49	9,144,371.18	5169.99	2969	3079.95

Min means minimum, Max means maximum, and SD means standard deviation.

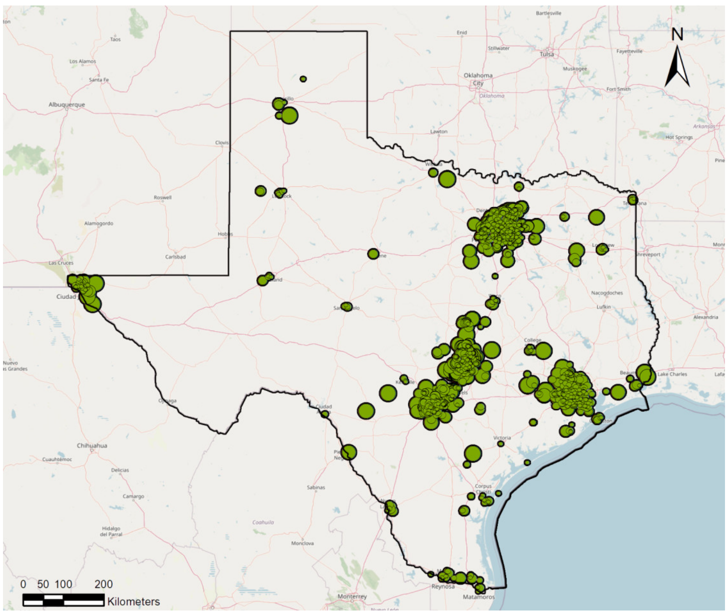


Figure 8. Accessibility of green spaces for green buildings in Texas by visualization.

(**a**) (**b**)

(**c**) (**d**)

Figure 9. Accessibility of green spaces for green buildings in four major cities by visualization: (**a**) Austin, (**b**) Dallas, (**c**) Houston, and (**d**) San Antonio.

3.3. Green Spaces for Different Green Building Certification Levels

3.3.1. Availability

Table 4 reflects the differences in availability between different GB certification levels in Texas and the four cities. The results for each location are inconsistent: Gold > Silver > Platinum > Certified in both Austin and Texas, Gold > Silver > Certified > Platinum in Dallas and Houston, and Platinum > Silver > Gold > Certified in San Antonio. Specifically for each city compared with statewide availability, in Certified, Silver, and Gold, only San Antonio is below the Texas average; in Platinum, Dallas and Houston are below the state average of 13,521.16 m^2, while Austin and San Antonio show the opposite results.

Table 4. Availability of green spaces for different green building certification levels.

Categories		Min (m^2)	Max (m^2)	Sum (m^2)	SD (m^2)	Number	Average Availability (m^2)
Austin	Certified	4.50	184,107.21	2,349,172.00	29,211.92	309	7602.50
	Silver	6.52	564,579.23	3,798,874.24	52,269.39	109	34,852.06
	Gold	0.62	190,000.16	4,174,033.64	22,213.88	101	41,327.07
	Platinum	1.25	158,206.29	920,030.20	39,099.86	28	32,858.22
Dallas	Certified	0.05	177,957.83	13,004,054.62	9463.06	548	23,730.03
	Silver	0.01	211,134.86	8,255,115.62	9773.06	172	47,994.86
	Gold	0.34	302,092.00	6,233,719.32	43,057.78	118	52,828.13
	Platinum	69.66	49,520.62	166,039.31	15,683.97	19	8738.91
Houston	Certified	0.01	785,398.16	2,759,850.60	62,917.07	176	15,680.97
	Silver	0.18	285,721.16	3,631,084.50	33,136.14	194	18,716.93
	Gold	0.01	625,763.31	6,541,362.21	14,138.63	234	27,954.54
	Platinum	325.08	91,393.07	779,296.12	19,495.37	80	9741.20
San Antonio	Certified	1973.45	147,740.51	271,909.35	33,455.92	242	1123.59
	Silver	11.24	126,770.21	629,578.49	30,961.93	43	14,641.36
	Gold	38,849.47	109,710.87	356,412.73	24,185.77	31	11,497.18
	Platinum	1973.45	139,091.96	288,758.24	45,503.09	3	96,252.75
Texas	Certified	0.01	785,398.16	36,440,640.07	6963.33	6719	5423.52
	Silver	0.01	564,579.23	20,235,087.66	19,997.87	1120	18,067.04
	Gold	0.01	625,763.31	22,458,583.99	24,762.82	984	22,823.76
	Platinum	1.25	325,722.01	2,785,359.22	41,902.21	206	13,521.16

Min means minimum, Max means maximum, and SD means standard deviation.

3.3.2. Accessibility

This study investigated the differences in accessibility between the different GB certification levels, and the results are reflected in Table 5. The accessibility of different certification levels varies greatly in each location: in Austin, Silver > Platinum > Gold > Certified; in Dallas, Gold > Silver > Platinum > Certified; in Houston, Gold > Platinum > Silver > Certified; and in San Antonio and Texas, Platinum > Silver > Gold > Certified. For each city versus the statewide average accessibility level, in Certified, Dallas and Houston are above the state average, but Austin and San Antonio are below average; in Silver, Austin and Dallas are above the state average, but Houston and San Antonio are the opposite; in Gold, only Dallas is above the state average, and the other three cities are the opposite; and in Platinum, all four cities are above the state average of 1657.40 m. In addition, Figure 10 provides a visual representation of the accessibility of the different certification levels, and it can be seen that the levels in general follow the characteristics of Texas as a whole; that is, the accessibility of GSs for GBs is lower in cities other than the four major cities. There is no significant difference in the distribution of accessibility across the four cities as shown by the different certification levels, and only quantitative differences.

Table 5. Accessibility of green spaces for different green building certification levels.

Categories		Min (m)	Max (m)	Sum (m)	SD (m)	Number	Average Accessibility (m)
Austin	Certified	66.71	14,223.53	2,350,017.19	4588.87	309	7605.23
	Silver	91.48	4849.74	104,723.01	821.06	109	960.76
	Gold	106.55	4025.16	133,208.40	1274.78	101	1318.90
	Platinum	133.45	5941.11	34,394.11	1295.48	28	1228.36
Dallas	Certified	15.18	2583.00	54,6248.50	532.14	548	996.80
	Silver	57.53	2253.40	148,503.79	666.31	172	863.39
	Gold	43.23	2204.71	80,413.57	508.12	118	681.47
	Platinum	152.63	1876.74	18,003.72	465.87	19	947.56

Table 5. *Cont.*

Categories		Min (m)	Max (m)	Sum (m)	SD (m)	Number	Average Accessibility (m)
Houston	Certified	89.69	5284.97	280,508.16	1116.62	176	1593.80
	Silver	61.37	5604.08	268,715.64	1079.52	194	1385.13
	Gold	72.20	5808.65	291,291.96	1017.15	234	1244.84
	Platinum	105.49	3731.76	109,312.98	581.69	80	1366.41
San Antonio	Certified	194.89	10,677.39	1,448,923.36	2217.04	242	5987.29
	Silver	125.57	11,487.43	102,649.82	2182.53	43	2387.21
	Gold	261.14	9544.20	76,463.10	1702.13	31	2466.55
	Platinum	205.79	1149.03	2107.30	386.70	3	702.43
Texas	Certified	15.18	37,204.49	24,745,786.56	3420.91	6719	3682.96
	Silver	57.53	48,959.59	1,540,611.41	2137.57	1120	1375.55
	Gold	23.78	38,375.47	1,194,778.04	2145.83	984	1214.21
	Platinum	5.64	23,796.12	341,423.98	2215.26	206	1657.40

Min means minimum, Max means maximum, and SD means standard deviation.

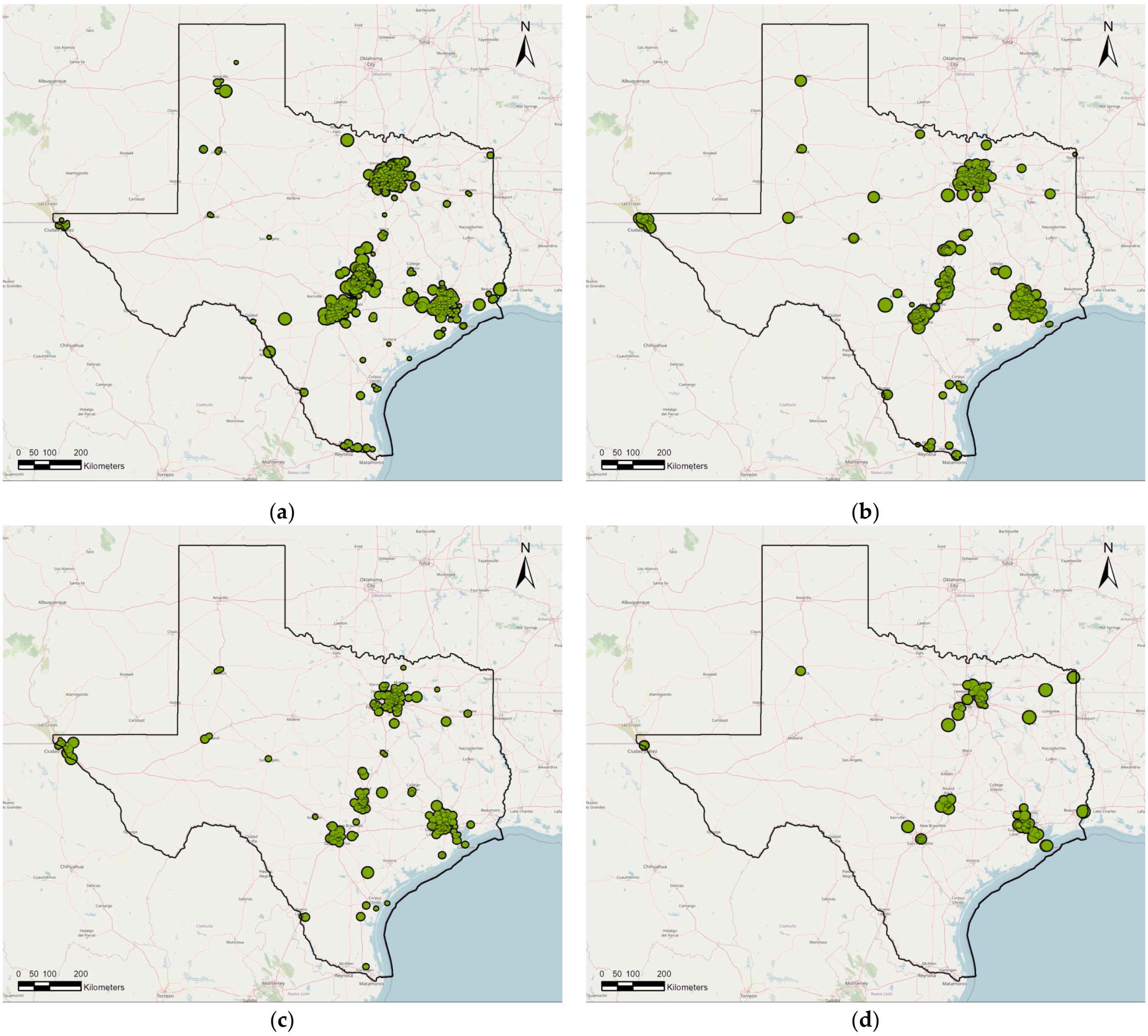


Figure 10. Accessibility of green spaces for different green building certification levels by visualization: (**a**) Certified, (**b**) Silver, (**c**) Gold, and (**d**) Platinum.

4. Discussion

4.1. Findings of the Study

The results of the spatial distribution of GBs show that Texas, as one of the most important states for the development of GBs in the whole United States, has a distribution of LEED-certified projects in almost all urban areas, which indicates the high popularity of GBs. It has been shown that economic factors such as residential income, financial support, and real estate market all have a significant positive impact on the spatial clustering of GBs [19]. The four cities in this study are listed in the ranking of the 15 most economically robust metropolitan economies in the United States [57], and the results of the kernel density estimates indicate that they also have the highest concentration of GBs statewide, which is consistent with the findings of existing studies. In addition, there is great heterogeneity in the spatial distribution of different certification levels, a phenomenon that is likely to be strongly associated with social factors such as economic factors as well. In terms of the spatial distribution of GBs within each city, it is not the case that the closer the city center is, the denser the GBs are, but each city shows an uneven result of the multicore distribution, which is closely related to the polycentric urban development model, which is considered to be an ideal urban form because it can generate greater agglomeration externality and achieve greater market integration and environmental goals [58].

In order to protect the environment and improve the quality of human life, GBs have been considered a sustainable alternative to conventional buildings (NGBs) as a tool to attenuate the negative impacts of buildings on the natural environment [59]. For example, GBs produce 50%, 48%, and 5% fewer greenhouse gases related to water consumption, solid waste management, and transportation, respectively, compared with NGBs [60]. GBs are usually more responsive to occupants' needs than NGBs and, therefore, have higher occupant satisfaction after use [61]. Given the friendly relationship between GBs and the environment and better usage experience, it is reasonable to assume that GBs would also be more capable of acquiring GSs than NGBs in order to generate more pronature opportunities. However, the results are the opposite, with both availability and accessibility of GSs for GBs being lower than for NGBs, suggesting that in terms of affinity with GSs, GBs do not make GSs more available and accessible to users because of their ecological attributes as an innovative building product. Furthermore, the results of comparisons of availability and accessibility are not the same across cities, and there is no consistency.

For GBs, the certification level is set to effectively determine the greenness of the building, and in general, GBs with higher certification levels provide better performance. For example, Gui and Gou [62] analyzed the association between GB certification level and postoccupancy performance and revealed a linear relationship between performance data and certification level—a one-level rise reduced energy use, emissions, and water consumption. In comparing the availability and accessibility of different certification levels of GBs, the study found that the ability of buildings to obtain GSs did not increase with increasing levels. For availability, Gold and Silver generally performed better than Certified and Platinum; for accessibility, performance varied by certification level from place to place, with no clear pattern.

To explain the poor performance of GSs for GBs, we studied the spatial distribution density of GBs in four cities overlapped with the GS distribution map. It was found that where GBs were more distributed, GSs were rather less distributed, and the two were extremely mismatched. For example, Austin has the highest concentration of GBs in the southwest corner of the city, but GSs are widely distributed in the northwest corner of the city. In addition, San Antonio's GBs are concentrated in the north and west of the city, while the more distributed GSs in the city are located in the northwest corner and downtown. Although GBs show a multicore distribution in urban areas, more GBs are located in areas far from the city center or in smaller cities around larger cities, such as the new headquarters of the American Professional Golf Association (PGA), which recently (December 2022) received LEED certification, located in Frisco, 30 miles north of Dallas [63]. These locations themselves have few available GSs, thus contributing to the poor performance of GSs for GBs.

The results of the study illustrated that obtaining GB certification does not mean that buildings are more likely to obtain GSs and that the ability to obtain GSs in GBs does not increase with the certification levels. Although there are different definitions and rating systems for GBs around the world, several major factors are generally considered, including efficient use of energy, water, and materials; improvement of indoor environmental quality; and minimization of negative impacts on the environment [64]. The current focus on buildings is mainly on achieving SDGs through strategies that integrate whole life cycle activities, which are considered at the level of the building itself. The existing GB system requirements for buildings may ignore the affinity of buildings with their environment, including at least the relationship between GBs and GSs in nature in this study. The evaluation of buildings would be more comprehensive if the certification criteria were developed regarding both the satisfaction of users in the building and the opportunity for the users to be close to nature.

Meanwhile, we should not overlook the impact of the selected cases on the findings. In Texas; a significant reason for leading the GB development is the state's ambitious goals in sustainability. The USGBC (U.S. Green Building Council) notes that Texas's progress in sustainable design, construction, and transformation relies on multilayered impetus, including economic, social, and environmental factors [65]. As early as 2018, LEED buildings supported 244,000 jobs in Texas and had a USD 21.39 billion impact on the state's GDP. On the social level, sustainability advocates, research institutions, academics, and architects in Austin, Dallas, Houston, and San Antonio are joining forces with different unions and working with city officials to build "green" into the infrastructure of their urban communities. Texas, which naturally faces greater environmental risks due to its extreme and diverse weather patterns, is also more actively seeking opportunities to apply technology to improve the reliability of urban environmental systems and environmental management. Against the background of such a strong emphasis on SDGs and a strong promotion of green development in the state, this study conducted the above analysis and found that the state still overlooks the priority of GBs in obtaining GSs, reinforcing the deficiencies in the GB certification process. There is a reasonable expectation that the same analysis, when applied in other states or cities, would likely find that GBs perform even worse than Texas in terms of accessing GSs. Therefore, this study not only urges Texas to revisit their GB development, but also addresses some general issues about locating GBs and planning GSs in cities.

4.2. Improvements of Certification

The development status of GBs is related to external factors, including policy support, economic benefits, and certification programs, where GBRSs, as a major component of certification programs, are a direct tool to guide the development of GBs [35]. Therefore, we reviewed the latest LEED certification manuals (LEED v4.1) to explore whether GSs are considered an element in the green certification process for buildings. Furthermore, if this element was not considered, it allowed us to identify where this element could be added to the score to make the evaluation more comprehensive. The certification manuals are derived from the official LEED website and are therefore accurate [66]. LEED v4.1 has five subsystems, namely, Building Design and Construction (BD + C), Interior Design and Construction (ID + C), Operations and Maintenance (O + M), Residential (including Single Family Homes, Multifamily Homes, and Multifamily Homes Core and Shell), and Cities and Communities (C + C, including Plan and Design and Existing), for a total of eight manuals.

Through a careful review of all manuals, the study found that only the Natural Systems and Ecology evaluation item in the two manuals of C + C has explicit requirements for GS, with two credits assigned in Plan and Design as a prerequisite and two credits in Existing. LEED v4.1 C + C: Plan and Design specifies the following: (1) provide a minimum of

11.25 m^2 per person of GS within the city; (2) 90% of the dwelling units must have a GS within 800 m of walkable distance. These two points correspond to the availability and accessibility elements of this study, respectively. In addition, LEED v4.1 C + C: Existing requires a minimum of 70% of the dwelling units having a GS within 800 m of walkable distance, with one point for achieving 11.25 m^2 per person of GS and two points for achieving 13.5 m^2 per person. Among other manuals, Open Space in LEED v4.1 BD + C's Sustainable Sites program addresses the requirement for GS, but only at the landscape level: a landscape area with two or more types of vegetation that provide opportunities for year-round visual interest.

From the above results, we found that LEED has specified GSs at the city and community scales and specifically requires minimum distances from residential buildings to GSs. However, there is no corresponding criteria item in the building certification process, even for residential buildings (LEED v4.1 Residential), which indicates that LEED does ignore the relationship between GSs and GBs in the building scale, and the developers should consider this to make the certification more comprehensive. According to the classification of USEPA, GSs are part of open space [12], and in LEED v4.1 BD + C and LEED v4.1 Residential, the evaluation of Sustainable Sites includes detailed provisions for open space, so it is reasonable to add GSs to this section in future work.

4.3. Limitation

Although this study provides an innovative and inspiring comparative study of GSs for GBs, it also has some limitations. First, due to the differences in the distribution of sample sizes, the sample sizes under certain classifications are smaller in number, although they are available. Second, due to the limitation of data availability, only some preliminary comparative studies have been conducted on spatial distribution, which have not yet involved the investigation of the specific effects of social factors such as economy and natural factors such as climate. In addition, different building types may have an impact on the availability and accessibility of GSs; for example, commercial and residential buildings have different requirements for GSs. Therefore, the differences due to different building types need to be more deeply analyzed in subsequent studies. Finally, Texas serves as a typical case study, and although it is more comprehensively described in this study, future studies can expand the selection of cases to the whole U.S. or even other countries to make the results more generalizable.

5. Conclusions

Using data on GBs, NGBs, and GSs in Texas, USA, this study explored the spatial distribution of GBs statewide and within four major cities, Austin, Dallas, Houston, and San Antonio. This study used spatial analysis tools, such as the kernel density estimation method in ArcGIS software, and quantified the specific situations on the availability and accessibility of GSs for GBs. It was found that the spatial distribution of GBs in Texas was concentrated in the four major cities, and each city showed uneven results with a multicore distribution of GBs. In GBs, there is a great heterogeneity in the spatial distribution of different certification levels. In addition, obtaining GB certification does not mean that buildings are more likely to have access to GSs; instead, both availability and accessibility of GSs for GBs are lower than for NGBs, and the ability to obtain GSs in GBs does not increase with the higher certification levels. An overlap study of the distribution maps of GBs and GSs in the four cities found that where GBs are more distributed, GSs are instead less distributed, as more GBs are located in areas farther from the city center or in smaller cities around larger cities where there are few GSs available themselves. A review of the certification manuals found that LEED already provides for GSs at the city and community scales. However, there is no corresponding criteria item at the building level. The study suggested that future work should add GSs to the open space section of the Sustainable Sites evaluation item.

This study innovatively compared the ability of GBs to obtain GSs, revealing what is currently overlooked at the building level in the GB certification process. In addition, this study provided references and recommendations for adding GSs to the certification content, helping policymakers to optimize future efforts to improve GB certification programs and make the concept of GB more comprehensive. The findings of the study contributed to the eventual greater role of GBs and GSs together in urban SDGs.

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