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Beyond the Backyard: GIS Analysis of Public Green Space Accessibility in Australian Metropolitan Areas

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Abstract: During times of stress and social pressure, urban green space provides social, cultural, and economic resources that help individuals and communities cope. Green space accessibility is, therefore, an important indicator related to people's health and welfare. However, green space accessibility is not even throughout urban areas, with some areas better served with green space than others. Green space patterning is, therefore, a major environmental justice challenge. This research uses GIS approaches to analyze and understand urban green space access of urban communities in the Australian metropolitan areas of Adelaide, Melbourne, Sydney, and Brisbane. We calculate indicators to describe green space access in relation to different green space patterns within different metropolitan zones, including the inner urban, suburban, and peri urban. We use the best available open data from the Australian census of 2017 to calculate green space accessibility. Our results describe the relationship between population density and green space distribution and patterning in the four metropolitan areas. We find that even cities which are generally thought of as liveable have considerable environmental justice challenges and inequity and must improve green space access to address environmental inequity. We also find that a range type of measures can be used to better understand green space accessibility. Accessibility varies greatly both within metropolitan areas and also from city to city. Through improving our understanding of the green space accessibility characteristics of Australian metropolitan areas, the result of this study supports the future planning of more just and equal green cities.

Keywords: environmental justice; green open space; accessibility; green infrastructure; environmental planning

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1. Introduction

Urban green space (UGS) provides important psychological and recreational resources for human wellbeing and health. Such benefits are particularly important to manage stress and social pressure, such as during the global COVID-19 pandemic [1–4]. The social and economic benefits of urban green space are well established and help individuals and communities deal, adapt, and cope with both daily and occasional urban stresses [5–7]. Green open spaces provide multiple services to human beings, including ecological, social, economic, and health benefits. Previous studies have demonstrated that green open space can provide a wide range of services such as the alleviation of urban heat [8,9], mitigating stormwater [10,11], conserving soil [12], enhancing biodiversity [13,14] and filtering pollutants [15,16]. Wu et al. [17] found that proximity to parks significantly increased real estate prices and led to economic growth.

Moreover, urban green spaces' direct contribution to human wellbeing has been confirmed in a wealth of literature. For instance, higher exposure to green open space has been connected with better social and health welfare [18–21]. Vienneau et al. [22] advised that well-planned environments, that integrate green open spaces in proximity to residential landscapes, can reduce the risk of mortality. Wolsink [23] emphasized the role of proximity to green space for outdoor environmental education. Nutsford et al. [24] revealed that higher accessibility to green space and a higher proportion of green space is associated with decreased anxiety. Further access to UGS can enhance physical and mental human well-being and both physical and mental health of citizens [25–27], which align with SDG 3 which aims to to ensure health and well-being for all, at every stage of life. Lorenzo-Sáez et al. [28] concluded that urban green space can directly contribute to SDG 11 "Sustainable cities and communities", SDG13 "Climate Action" and SDG 15 "Life and Land". Meanwhile, Opoku [29] also suggested that the conservation of urban green space can enrich biodiversity and therefore help us achieve the Sustainable Developmnet Goals (SDGs).

Unfortunately, within cities, urban green space is not always uniformly accessible amongst all residents [30–34]. Literature has pointed out various social-economic factors that cause inequal access to green space, including race [35,36], income [37,38], age [39,40], and education [41,42]. This inequality is, therefore, a significant environmental justice issue and tied to a broader range of injustices such as health and wellbeing disparities. Environmental justice focuses on the inequal access to green open space [32,43,44] and the ecosystem services they provide [45,46]. Schlosberg [47] has noted that there are three different dimensions of environmental justice in relation to green open space, including distributive, procedural, and recognition. Distributive justice perspectives focus on the uneven opportunities to access green spaces and the resulting welfare inequity [48]. Procedural justice perspectives focus on the unequal access to decision-making processes concerned with green space planning [49]. Recognition justice focuses on the different preferences and uses of green space by diverse social groups [50].

The focus on UGS accessibility has increased in recent years [51], due to the increasing recognition of the importance of UGS to health and wellbeing; however, little research focuses on Australian cities and environmental justice [52]. Previous empirical studies of UGS accessibility which were conducted in Europe found that higher UGS accessibility occurred in areas of lower population density [35,53,54]. On the other hand, in Asia and South America, studies show that higher UGS accessibility occurred in more densely populated areas [55,56]. The different results highlight that regional studies are essential, and there is a need for both regional studies to enable future cross-regional comparisons.

In this study, we focus on the distributive dimension of environmental justice, exploring the spatial inequality within and between Australian cities using GIS analyses of census based open data. The paper is structured in four parts. A brief critical background is provided on the measurement of green space accessibility in current literature. This is followed by a description of the adopted methodology for measuring green accessibility and the data sources used. Section three presents the results, including the analysis of the three green accessibility indicators used, along with a comparison of the different Australian Metropolitan areas analyzed. In Section 4, we reflect on the implications of our results and discuss the various types of green space patterns identified and the way such patterns affect green space access and environmental equity. The final section summarizes our findings and highlights areas for future research.

2. Background

Standards of Urban Green Space Accessibility (UGSA)

There are a variety of approaches used to measure urban green space accessibility (UGSA) [35,57]. For instance, one such approach, known as the container concept, evaluates accessibility by the total area green space located within a specific spatial unit, such as a census tract or neighborhood [42,58]. In contrast, the distance approach assesses the Euclidean distance or road network distance between residents and the closest UGS [59,60]. Some approaches also divide accessibility measures into "place-based" and "person-based" [61,62].

The former focuses on UGS as places with different spatial characteristics [63] while the latter focus on the person and their opportunities to reach UGS, which is more complex and requires individual activity and travel information [64]. The gravity-based concept accumulates all UGS in a study area and calculates the distance between each UGS and residents [65,66]. Floating catchment area concepts are also widely applied to measure green space accessibility. Studies often expand or modify such methodologies, for example the two-step floating catchment area [51,67,68] has been developed to assess UGS accessibility more precisely.

Over the past few decades, multiple standards have been applied to better measure and understand UGS accessibility [53,69–78]. Within Germany, national standards developed by the Federal Ministry for the Environment are calculated using the distance to the nearest UGS [70]; likewise, within the UK, Natural England set similar targets [73]. Moreover, the reports of English Nature also recommend accessing a minimum quantity of UGS within a certain radius zone of the place of residence, while in the Netherlands the Green City (De Groene Stad) project supported by the Ministry of Economic Affairs Agriculture and Innovation [75] set a minimum area of accessible green space within a certain radius around households. Australia and the European Union typically evaluate UGS by the proportion of UGS within an urban administrative area. The WHO, US, Singapore and European Environment Agency suggest that cities ensure people can access UGS within a certain walking distance [71,74,76,78]. In general, urban authorities and governments often have one or multiple methods and ways of measuring UGS accessibility [31,34]. Table 1 shows a range of global standards.

As is evident from Table 1, there are many ways to calculate metrics for green space accessibility and various standards or thresholds to evaluate the resulting metrics. A desktop web review of global urban authorities and environmental organizations revealed that there are multiple methods used to calculate green space accessibility [58,79,80].

Generally, the approaches can be classified according to the complexity of the metric and the contextual scale of the area used to calculate green space accessibility. Some urban and global agencies use either a simple metric or a compound metric. Some approaches calculate accessibility based on walking or travel catchment zones, and others focus on the spatial relation with residential areas. Residential metrics can be generally be categorized into two types, which are Proximity and Area, while the type of "area" can divide by Area-Based Provision and Population Share.

Table 1. Global urban green space (UGS) access standards [53,69–78].

No.	Method	Authorities and Organization	Metric Type	Metric Used in This Article
1	No person should live more than 300 m from their nearest area of green space [73]	Natural England of UK	Proximity	Distance to the nearest UGS (m)
2	The UK urban dwellers should have access to 20 ha of urban green space within a 300 m distance to the place of residence [73]	Natural England of UK	• Proximity • Area based provision	Accessible UGS within 500 m around SA1 boundary (km^2)
3	Can access any green site within 300 m of minimum administrative boundary [73]	Natural England of UK	• Proximity • Area based provision	Distance to the nearest UGS (m)
4	Provision should be made of at least 2 ha of accessible natural greenspace per 1000 population [73]	Natural England of UK	Population Share	UGS per capita (m^2)
5	Every resident should have access to UGS of a minimum of 0.5 ha within a 500 m distance from home [53]	Berlin's Department of Urban Development and the Environment	• Proximity • Area Based Provision	Accessible UGS within 500 m radius

Table 1. *Cont.*

No.	Method	Authorities and Organization	Metric Type	Metric Used in This Article
6	A minimum green provision of 60 m^2 per-capita within a 500 m radius around households [75]	Netherlands	• Proximity • Population Share	Accessible UGS per capita within 500 m of SA1 area (m^2)
7	Every household in Germany should have access to urban green space within walking distance [70]	National Strategy on Biological Diversity in Germany	Proximity	Distance to the nearest UGS (m)
8	The SDG indicator of urban greenness is the total amount of green area in square meters [76]	European Commission, Joint Research Centre of EU	Area Based Provision	UGS cover (%)
9	People should have access to urban green within 15 min walking distance, which is approximately 900–1000 m [77]	European Environment Agency (EEA)	• Green Space Catchment • Proximity	People living within 1000 m of UGS
10	Cities provide a minimum of 9 m^2 of green area per inhabitant [74]	World Health Organization	Population Share	UGS per capita (m^2)
11	Residents live within a 15 min walk of green areas [74]	World Health Organization	• Green Space Catchment • Proximity	• People living within 500 m of UGS • People living within 1000 m of UGS
12	Every household will be within a 10-min walk from a park [78]	Green Plan 2030, Singapore	• Green Space Catchment • Proximity	• People living within 500 m of UGS • People living within 1000 m of UGS
13	Create 20% more and better green space in urban areas in Australia by 2020 [69]	Program of Greener space better places, Australia	Area Based Provision	UGS cover (km^2)
14	A target of increasing urban green cover by 20% in metropolitan Adelaide by 2045 [72]	Government of South Australia	Area Based Provision	UGS cover (%)
15	Parkland thresholds per 1000 residents based on population density: Low for 20.3 acres; intermediate-low for 13.5 acres; intermediate-high for 7.3 acres; high for 6.8 acres [71]	U.S. Green Building Council	Population Share	UGS per capita (m^2)
16	Population located within a 1/2 miles or 10-min walk of public parkland: low for 70% and high for 85% [71]	U.S. Green Building Council	• Green Space Catchment • Proximity	• People living within 500 m of UGS (%) • People living within 1000 m of UGS (%)

3. Materials and Methods

3.1. Study Area

We have used the Greater Capital City Statistical Area [81] as the boundary of the four Australian cities selected, which are Sydney, Melbourne, Brisbane and Adelaide (see Figure 1). We have selected these cities as each has recently been developing new green space policies [72,82–84], and therefore a comparative analysis is timely. The population data and the green open spaces data are collected from the open database of the Australian Bureau of Statistics. The basic data unit is the Mesh Block (MB), and there are four Statistical Area Levels from Level 1 (SA1) to Level 4 (SA4). The newest geography standard of the version Edition 2016 is applied. The latest available census data on population and housing by Mesh Block are from 2017 [85]. The majority of the populated Mesh Blocks contain between 30 to 60 dwellings. There are twelve land use categories of MB, which are Residential, Commercial, Industrial, Agricultural, Parkland, Educational, Hospital/Medical, Transport, Water, Shipping, No usual residence, and Other. Among those, Parkland is used to construct the urban green spaces dataset (see Figure 2). In this research, we focus mainly on the availability of publicly accessible green spaces and the spatial inequality among residents.

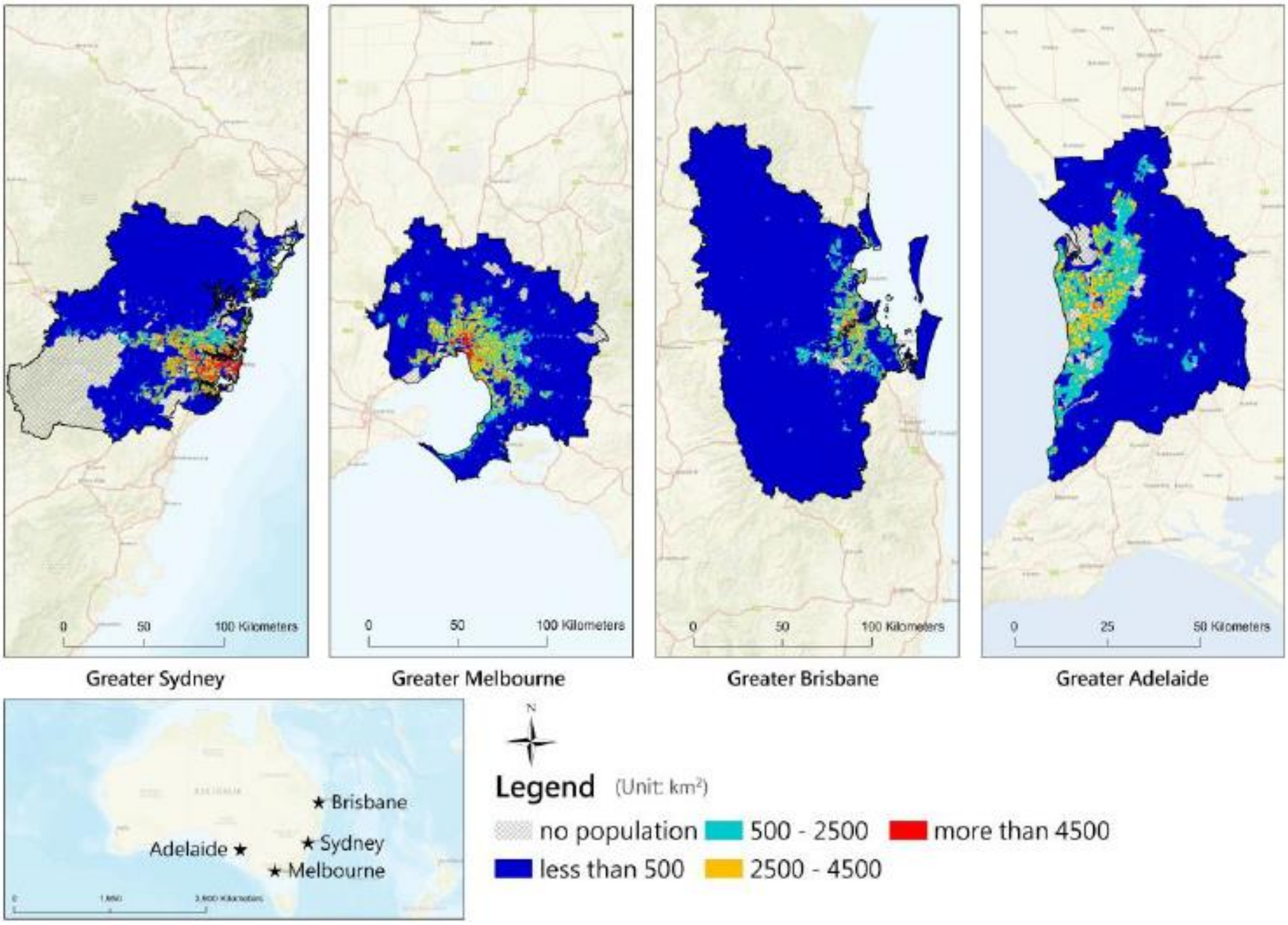

Figure 1. Area and location of the four Greater Cities: Population Density of Greater cities by Statistical Area Level 1 (SA1).

3.2. Population

Figure 1 reveals various patterns of population density in the four study cities. All four cities are situated on the coast and are port cities. Sydney and Melbourne have total populations of over four million, while Greater Brisbane has around two million, and Adelaide has a population of over one million. Regarding the density, Melbourne has the highest of around 449 people per square kilometer; Adelaide and Sydney have around 390 people per square kilometer, and Brisbane is the least dense with only about 144 people per square kilometer.

3.3. Urban Green Space within Each of the Four Study Cities

Each of the four study areas has a contrasting distribution of green space, as is shown in Figure 2, Brisbane has a considerable area of parkland both at the centre and beyond the administrative limits of the city, while Adelaide has a much more fragmented pattern of parkland around the city with the greatest concentration in the Adelaide Hills district of the city which is made up of a cluster of reserves and national parks such as Belair National Park and Sheperds Hills Reserve. Melbourne has a large patch of Parkland at the northeast boundary of the city, most of it belonging to the Dandenong Ranges National Park. Sydney has a wealth of substantial green space contained within the various National Parks that surround the city to the north, west, east, and south. The green space cover rate of Sydney is around 57%, and Melbourne takes second place at around 20%. Brisbane follows closely with about 18%, while Adelaide has the least at about 10%.

Figure 2. UGS area of the research sites.

As is evident from the above overview, Australian metropolitan areas are spatially extensive with a low-density distribution of populations. However, this low-density distribution is not even, but rather it is heterogeneous and patchy. Nevertheless, Australian metropolitan areas can be divided into higher density inner urban zones, more low-density suburban zones, and peri-urban or semi-rural zones of very low density. To better understand green space accessibility within Australian metropolitan areas, it is helpful to identify the different green space relationships within each of these zones. To achieve this, we first applied Hot Spot Analysis to using the Getis-Ord Gi* algorithm within the ArcGIS software environment. This permitted the development of a three-part population density classification for each city. Data from the Australian Census SA2 and Mesh Block administrative zones were used to complete this calculation.

As mentioned above, cities were then statistically classified according to the three density classes of inner urban, suburban, and peri urban by hot spot area, insignificant area, and statistically cold spot area. See Section 4.1 for the results of detailed population and land cover area information. Accordingly, the urban green space accessibility analyses are calculated for the three metropolitan zones. We then outline the 11 mapping approaches and associated metric types that can be used to build up a contextual picture of urban green space accessibility in the table below. Table 2 collates metrics that can be applied to assess equality in urban green space accessibility of different types (green space catchment, proximity, area-based provision, population share).

Table 2. Urban green space (UGS) accessibility metrics by types in this study.

	Metric Type	Metric	References	Calculation Method for Maps	Formula Applied
1	Area based provision	UGS cover (km^2)	[69,86,87]	Total green space area in a SA1	$A_i^{m1} = \sum_{b \in i} g_b$
2		UGS proportion (%)	[72,76,87]	Proportion of green space area in a SA1	$A_i^{m2} = \frac{\sum_{b \in i} g_b}{a_i}$
3	Population share	UGS per capita (m^2)	[53,71,73,74]	Total green space area in a SA1 divided by the total population of a SA1	$A_i^{m3} = \frac{\sum_{b \in i} g_b}{P_i}$
4	Green space catchment	People living within 500 m of UGS	[74,78,88]	Population which located in the 500 m catchment of total green space	$A_i^{m4} = \sum_{R_G \in i} P_{r_G}$
5		People living within 500 m of UGS (%)	[35,71]	Proportion of population in a SA1, which located in the 500 m catchment of total green space	$A_i^{m5} = \frac{\sum_{R_G \in i} P_{r_G}}{P_i}$
6		People living within 1000 m of UGS	[74,77,78,88]	Population located in the 1000 m catchment of total green space	$A_i^{m6} = \sum_{R_G \in i} P_{R_G}$
7		People living within 1000 m of UGS (%)	[35,71]	Proportion of population in a SA1, which located in the 1000 m catchment of total green space	$A_i^{m7} = \frac{\sum_{R_G \in i} P_{R_G}}{P_i}$
8	Proximity	Distance to the nearest UGS(m)	[54,70,73,89]	Average of the distance from the centre of census mesh block to the nearest green space in SA1.	$A_i^{m8} = \frac{\sum_{b \in i} (min\|d_{C_b G}\|)}{n_{b \in i}}$
9	• Proximity • Area based provision	Accessible UGS within 500 m radius	[53,90,91]	Average green space area within 500 m around the centroid point of Mesh Block in each SA1	$A_i^{m9} = \frac{\sum_{b \in i} g_{r_{C_b}}}{n_{b \in i}}$
10		Accessible UGS within 500 m of SA1 area (km^2)	[19,73,75,90,91]	Green space area located at 500 m around the boundary of SA1.	$A_i^{m10} = g_{r_i}$
11	• Proximity • Population share	Accessible UGS per capita within 500 m of SA1 area (m^2)	[92,93]	Green space area per capita of 500 m around the boundary of SA1.	$A_i^{m11} = \frac{g_{r_i}}{P_i}$

Note: A_i^{m1} is the accessibility of metric 1 for SA1 i. Where g_b is the green space area of Mesh Block b, a_i is the area of SA1 i, and P_i is the population of SA1 i. r_G and R_G are respectively defined as 500 m radius zone and 1000 m radius zone of the urban green space G of the study area. While $d_{C_b G}$ is the distance between urban green space G and the centroid point C of Mesh Block b. Finally, $\sum_{b \in i} n_b$ is the number of Mesh Block b of SA1 i.

3.4. Urban Green Space Area within the Four Cities

The first measure of green space accessibility we use assesses green space distribution within inner urban, suburban and peri-urban areas or metropolitan zones. The census mesh block dataset was used to calculate the distribution of the green space across the metropolitan area. The area of green space in each metropolitan zone for the respective cities is then calculated, by (1) total area of Green Spaces, (2) Green Spaces proportion, and (3) the area of UGS per capita. Our approach consist with the container concept [80].

3.5. Urban Green Space Catchments

The second measure calculates the service area for green space using buffer zones [91,94]. Calculations for populations that live within different walkable buffer zone areas was calculated, including for both 500 m and 1000 m buffer zones. This metric is important to help identify the amount and proportion of people located in the green space catchment zone of a certain location, as well as identifying the area that is excluded from the catchment zones.

3.6. Residential Accessibility to Urban Green Space

In addition, we also calculated UGS accessibility within particular residential (census catchment) areas to gain a picture of what accessibility is like for different inhabitants [53,60,70,73]. We first calculate the average distance to the nearest Green Space for each SA1 [80]. Then, we calculated the average accessible UGS within a 500 m radius from the centroid of each census tract Mesh Block for each SA1 zone [60]. Furthermore, accessible UGS per capita within 500 m buffer zone of each SA1 indicates the UGS shared by residents. SA1 was used as the smallest statistic area to emphasise the geospatial statistical variation. The results are presented next and illustrated through maps and a summary table.

4. Results

Using a range of spatial analyses, we have generated three sets of metrics on Urban Green Space accessibility. Hot spot analysis were applied to classify the cities into Metropolitan Zones (see Table 3 for detailed information of different zones). The results of our research are collated in Table 4 and summarized in four parts, 1. Urban structure classification 2. Urban green space area, 3. Green space service catchment, and 4. Residential green space accessibility. The values can be easily read and compared between the metropolitan areas and between related zones. We then examine the results from the different contexts using maps and figures.

4.1. Urban Structure Classification: Inner Urban, Suburban and Peri Urban

The first set of analyses used hot spot analysis (Getis-Ord Gi*) of population density to classify each study metropolitan area into three zones: inner urban, suburban and peri urban. Cold spots of over 90% confidence level were classified as peri urban areas, while the hot spots of over 90% confidence level were classified as inner urban areas, and areas with no significant statistical result were classified as suburban areas. In general, inner urban are where high-density clusters are concentrated; and peri urban areas integrate low-density area clusters. The population density of each urban structure is summarized in Table 3. Sydney has the highest density inner urban areas with 5241 people per km^2, and Melbourne has the second highest density inner urban areas with 3671 people per km^2 (see Figure 3a,b). Figure 3c,d show that Brisbane and Adelaide present similar Inner Urban population densities with, respectively, 2991 and 2148 people per km^2. In regards to the peri urban area, Melbourne has the highest density whilst Brisbane has the least dense peri-urban area. Figure 3 shows the spatial pattern and distribution of three-part urban structure classifications which will be used to guide the green space accessibility analysis communicated in the following results sections from Section 4.1 to Section 4.4.

4.2. Green Space Area: The Analysis of Green Space in the Four Selected Cities

Our initial analyses involved basic calculations regarding density and green space coverage within the four metropolitan areas. These simple calculations demonstrate the spatial mismatch between population density and urban green space distribution. As expected, in the four cities, the urban green space is greatest in peri urban areas, followed by suburban and inner urban. However, the suburban area of Brisbane showed a relatively high rate of around 39%, which, for example, is two times more than that of Melbourne. The peri urban area of Brisbane, on the contrary, had a similar coverage of green space as its inner urban area, which is 14%. This is only a quarter of that of Sydney. Regarding the green space coverage of peri urban areas, Adelaide showed a very low rate of only 6% green space coverage (see Figure 4).

With regard to the population share area of UGS, in general, people in peri urban areas share more green spaces, while inner urban areas have less. From the metropolitan area level, Sydney and Brisbane's area is 1000 m^2 of green space per person. In contrast, people in Melbourne share only 458 m^2 on average per person. Adelaide has the least share of urban green space per person at only 272 m^2. However, this pattern is not always consistent. For example, in the case of inner urban areas, Adelaide performs the best with around

56 m^2 per person. On the contrary, residents living in the inner urban area of Sydney share only 27 m^2 per person. With regard to a suburban area, Brisbane has the largest share of around 572 m^2 per person, and Melbourne has the least with less than a quarter of that (see Figure 5).

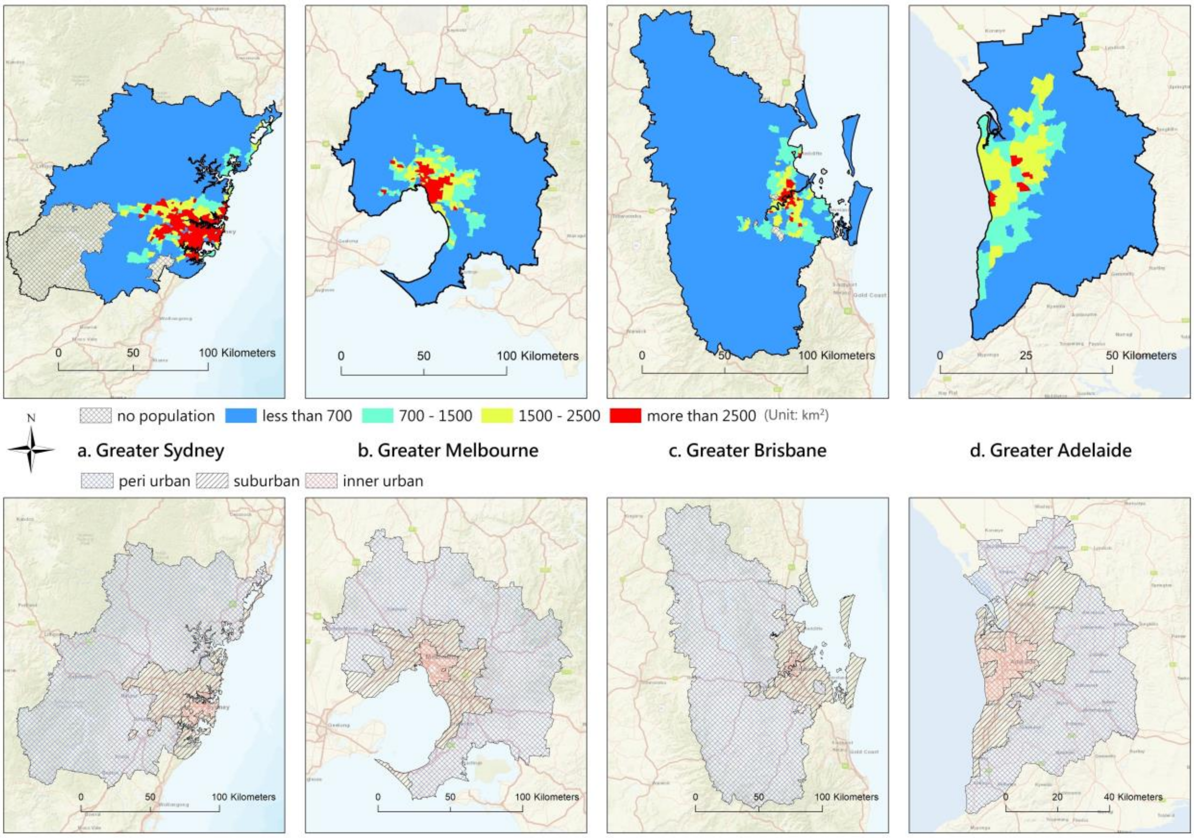

Figure 3. Population Density and classification of metropolitan zones. Inner urban zones have more than 2500 people per km^2. Suburban zones have 700 to 2500 people per km^2, whilst peri urban zones have less than 700 people per km^2.

Table 3. Population density of inner urban, suburban and peri urban.

City Overview (Figure 3) Metropolitan Zones	Area (km^2)	Population	Population Density (People/km^2)
Greater Sydney	12,367.542	4,822,739	389.951
Inner urban	200.435	1,050,552	5241.360
Suburban	1643.621	2,981,318	1813.872
Peri urban	10,527.638	790,869	75.123
Greater Melbourne	9991.464	4,484,394	448.823
Inner urban	286.944	1,053,515	3671.499
Suburban	2006.511	2,608,332	1299.934
Peri urban	7698.008	822,547	106.852
Greater Brisbane	15,829.990	2,270,743	143.446
Inner urban	123.973	370,750	2990.566
Suburban	2274.882	1,563,451	687.267
Peri urban	13,431.135	336,542	25.057
Greater Adelaide	3260.732	1,295,649	397.349
Inner urban	204.728	439,819	2148.312
Suburban	913.294	698,958	765.315
Peri urban	2142.710	156,872	73.212

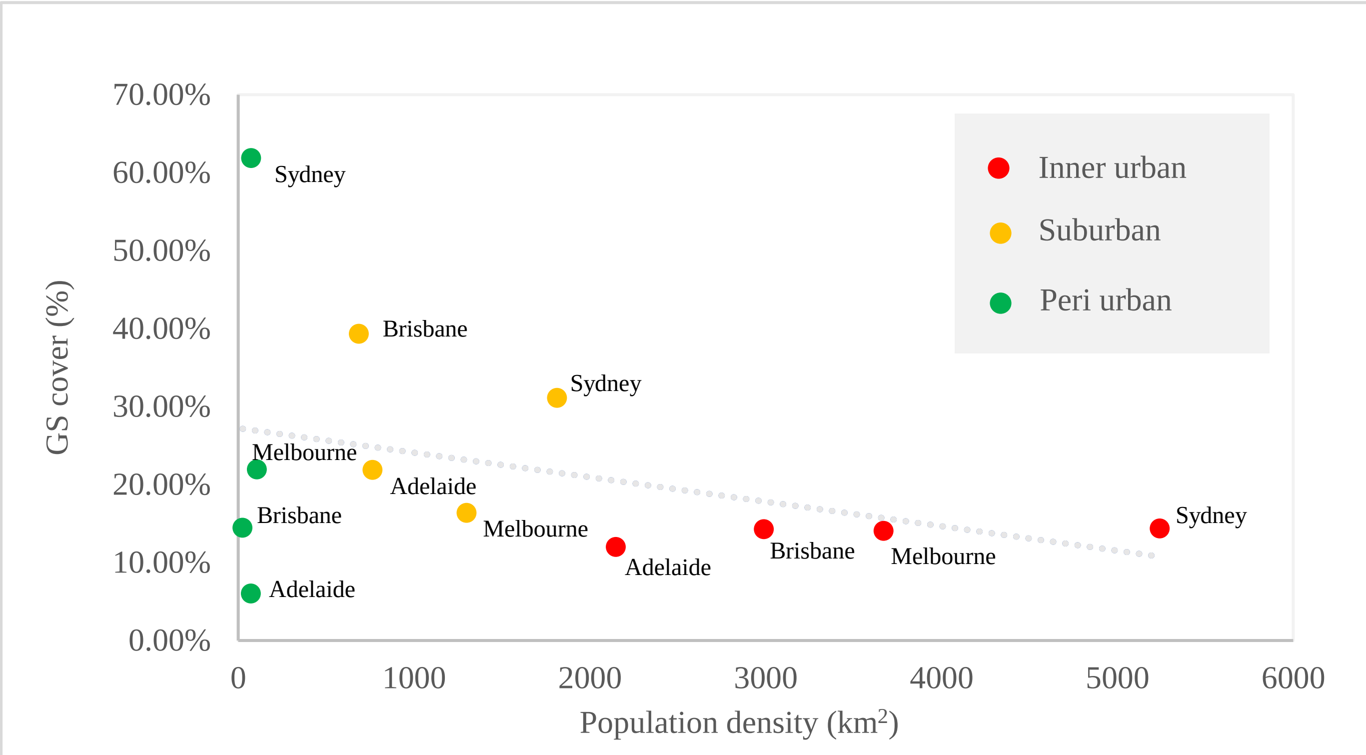

Figure 4. Proportion of green spaces to all land and population density.

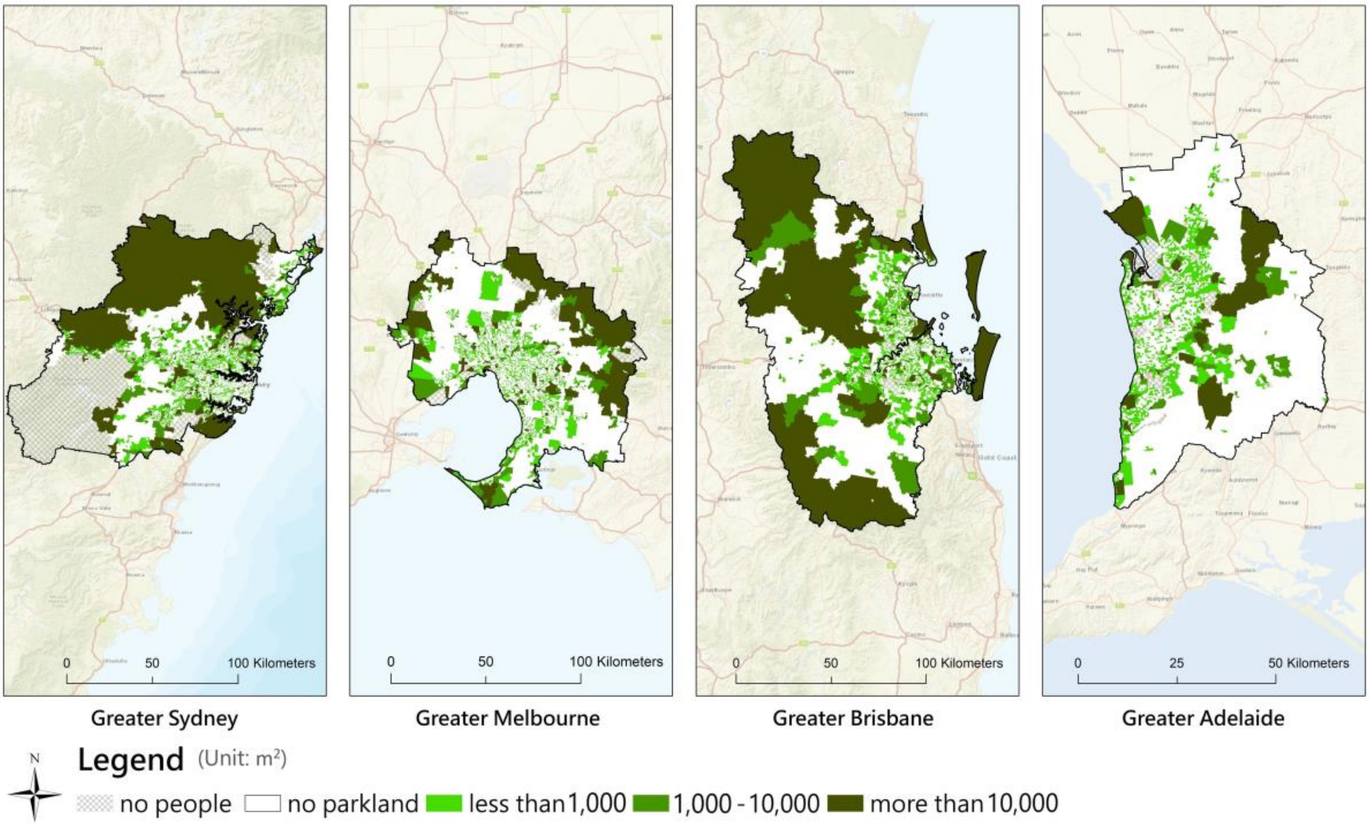

Figure 5. Visualization of UGS per capita (m^2) in four selected cities in Australia.

Table 4. Green Space Accessibility of Metropolitan Areas in Australia. (* UGS = Urban Green Space).

Urban Structure		Greater Sydney				Greater Melbourne				Greater Brisbane				Greater Adelaide			
			Inner Urban	*Suburban*	*Peri Urban*		*Inner Urban*	*Suburban*	*Peri Urban*		*Inner Urban*	*Suburban*	*Peri Urban*		*Inner Urban*	*Suburban*	*Peri Urban*
Green Space Cover (Figures 4 and 5)	UGS cover (km^2)	7049.850	28.751	505.999	6515.100	2054.637	40.263	328.201	1686.173	2849.958	17.671	894.020	1938.267	352.688	24.532	199.538	128.618
	UGS cover (%)	57.003%	14.344%	31.101%	61.842%	20.564%	14.032%	16.357%	21.904%	18.004%	14.254%	39.300%	14.431%	10.816%	11.983%	21.848%	6.003%
	UGS per capita (m^2)	1461.794	27.367	171.463	8232.122	458.175	38.217	125.828	2049.941	1255.077	47.663	571.825	5759.361	272.210	55.778	285.479	819.893
Green Space Catchments (Figures 6–8)	People live within 500 m of UGS	4,428,250	988,162	2,818,902	621,186	3812,694	953,760	2,303,062	555,872	1,953,895	334,132	1,442,754	177,009	1,081,121	355,486	643,451	82,184
	People live within 500 m of UGS (%)	91.820%	94.061%	94.772%	78.856%	85.021%	90.531%	88.296%	67.579%	86.047%	90.123%	92.280%	52.596%	83.442%	80.826%	92.059%	52.389%
	People live within 1000 m of UGS	4,731,474	1,050,552	2,977,321	703,601	4353,962	1,052,958	2,589,854	711,150	2,160,867	370,709	1,553,480	236,678	1,233,855	431,077	692,349	110,429
	People live within 1000 m of UGS (%)	98.108%	100.000%	99.866%	88.966%	97.091%	99.947%	99.292%	86.457%	95.161%	99.989%	99.362%	70.326%	95.231%	98.012%	99.054%	70.394%
Residential Green Space Accessibility (average of SA1) (Figures 9–13)	Distance to the nearest UGS (m)	242.162	220.692 (0~843.061)	195.174 (0~2136.714)	432.072 (0~5296.344)	330.489	246.024 (0~1069.563)	260.308 (0~5149.360)	662.025 (0~9517.016)	365.952	247.957 (0~923.522)	220.839 (0~2371.375)	1207.710 (0~11,133.712)	387.511	315.634 (0~1485.218)	234.318 (0~3996.420)	1199.498 (0~9753.489)
	Accessible UGS within 500 m radius	113,663.87 14.48%	73,524.449 9.37%	113,242.299 14.43%	163,690.623 20.85%	83,123.345 10.59%	78,632.628 10.02%	85,993.825 10.95%	80,245.694 10.22%	105,276.26 13.41%	78,140.159 9.95%	114,905.745 14.64%	93,598.745 11.92%	91,501.032 11.66%	67,888.989 8.65%	109,812.515 13.99%	75,235.85 9.58%
	Accessible UGS within 500 m of SA1 area (km^2)	1.033	0.155 (0~2.643)	0.392 (0~147.472)	4.318 (0~2307.482)	0.484	0.184 (0~2.916)	0.317 (0~67.804)	1.395 (0~252.911)	0.917	0.202 (0~1.919)	0.567 (0~268.124)	3.420 (0~714.573)	0.383	0.186 (0~2.629)	0.439 (0~32.163)	0.637 (0~32.836)
	Accessible UGS per capita within 500 m of SA1 area (m^2)	12,990.541	964.854	6064.699	51,509.332	14,435.050	2088.205	3487.059	65,144.232	16,834.445	1468.99	10,696.811	63,862.693	5228.744	1654.13	7829.983	3376.823

4.3. Green Space Service Catchments in the Four Selected Cities

The next set of analyses permits us an insight into the concentrations of green space in the different parts of the metropolitan area. Thus, we analyzed the distribution of people living within a 500 m and 1000 m radius catchment from the edge of green spaces. Our results show that within a 500 m radius catchment, a greater proportion of the suburban population live within the catchment radius of green space and a smaller proportion of peri-urban populations live in close proximity to green space. Melbourne performs differently, however, with inner urban green space areas containing a greater population within its catchment than any other urban spatial class. As for 1000 m catchments, inner urban areas cover the largest proportion of the population, and peri urban areas cover the least. Adelaide suburban areas performed the best using this metric.

Within the entire Sydney metropolitan area, almost 92% of people live within green space catchment service areas of 500 m, while Brisbane and Melbourne, respectively, have 86% and 85%, whereas within Adelaide only around 83% of the population live within 500 m of green space catchments. It is notable that altogether over 95% of the metropolitan populations of the four cities can access UGS within 1000 m. The figures also show that around 12% of the population in Adelaide and Melbourne live in the zone of 500 to 1000 m, in contrast to 9% of Brisbane and 6% of Sydney (see Figure 6).

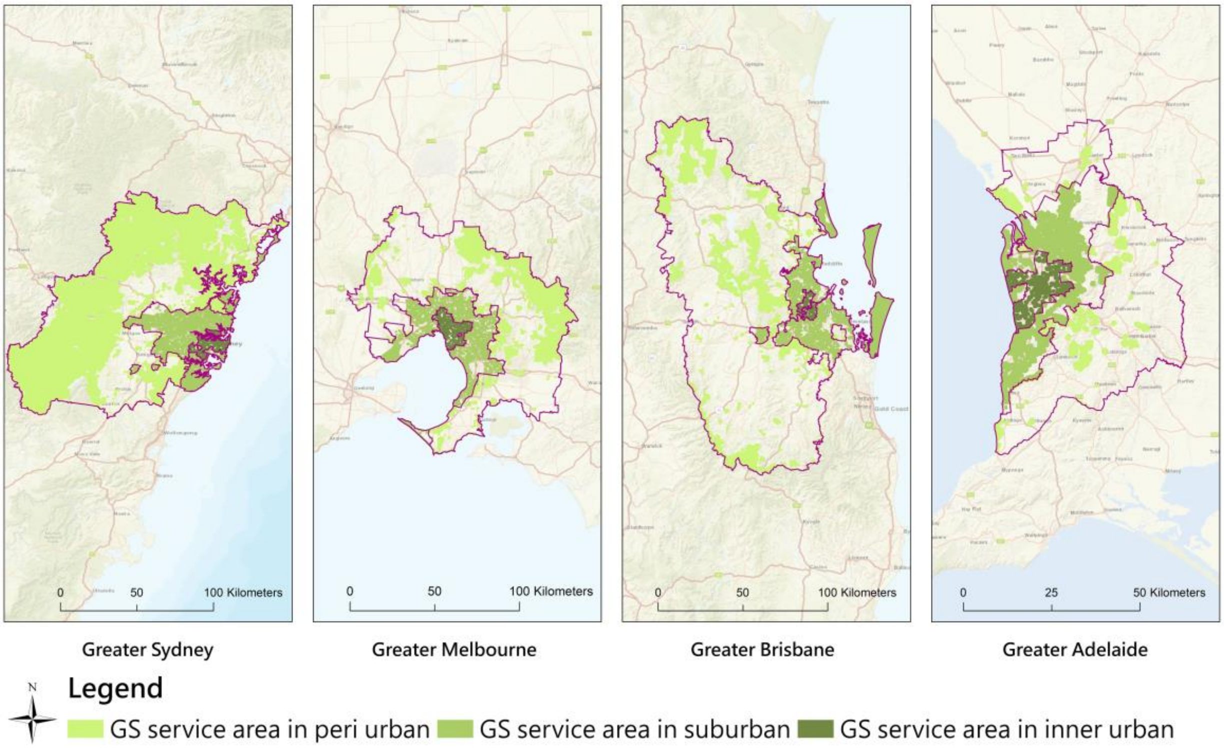

Figure 6. 500 m catchment service area of UGS.

When it comes to the 500 m catchment service zones of metropolitan areas (see Figure 7), inner urban and suburban UGS generally service more than 90% of the local residents. Melbourne is an exception, with its suburban UGS servicing slightly less at around 88% of its local population and Adelaide's inner urban UGS only services 81% of its local population. Peri urban areas present more varied levels of UGS service among the four cities. Sydney reaches almost 80%, while Melbourne meets less than 70%, and both Brisbane and Adelaide's periurban UGS services only 52% of local population.

With regard to the 1000 m service zone (see Figure 8), with the exception of Adelaide's 98%, all inner urban and suburban areas service more than 99% of the settled population. UGS within the peri urban areas of Sydney can service almost 89% of all the population, and

Melbourne can also service around 86% of its population. On the other hand, both Brisbane and Adelaide cannot service around 30% of their periurban residents. As a consequence, UGSA from the role of Green Space itself, Sydney performs the best in all levels and subunits, and Melbourne and Brisbane are present in the middle position. Greater Adelaide seemed to need some improvement. It is also noteworthy that in inner urban areas, 100% of the population can reach UGS within 1000 m.

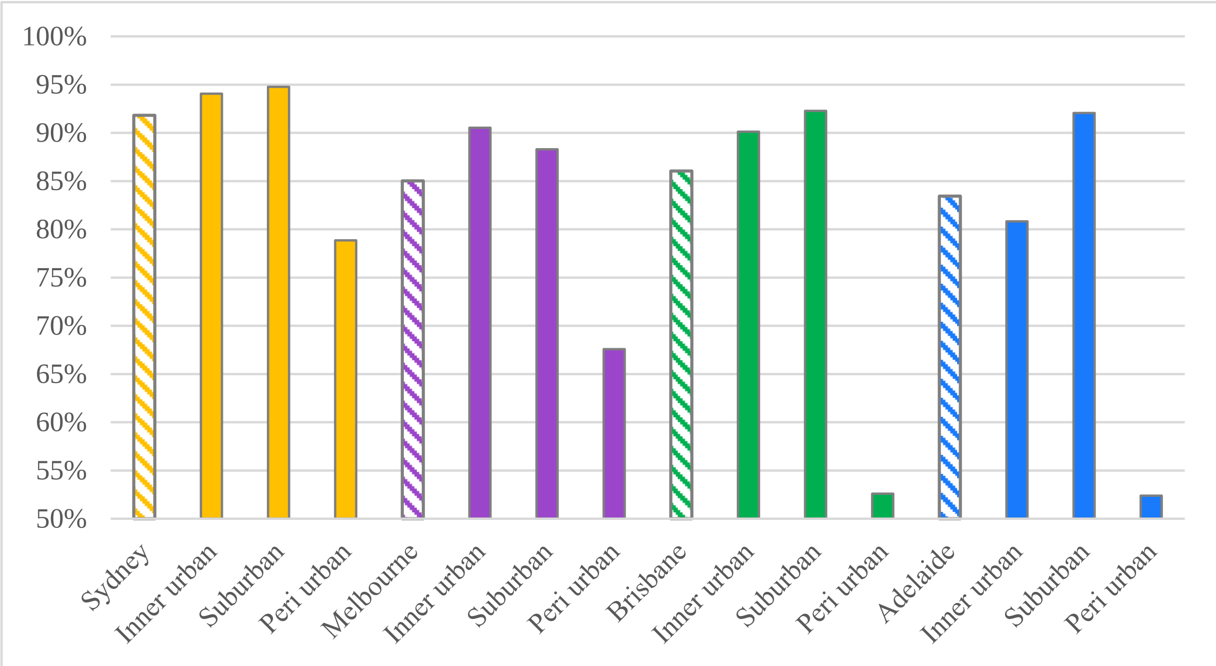

Figure 7. Percentage of local population located within 500 m of green spaces.

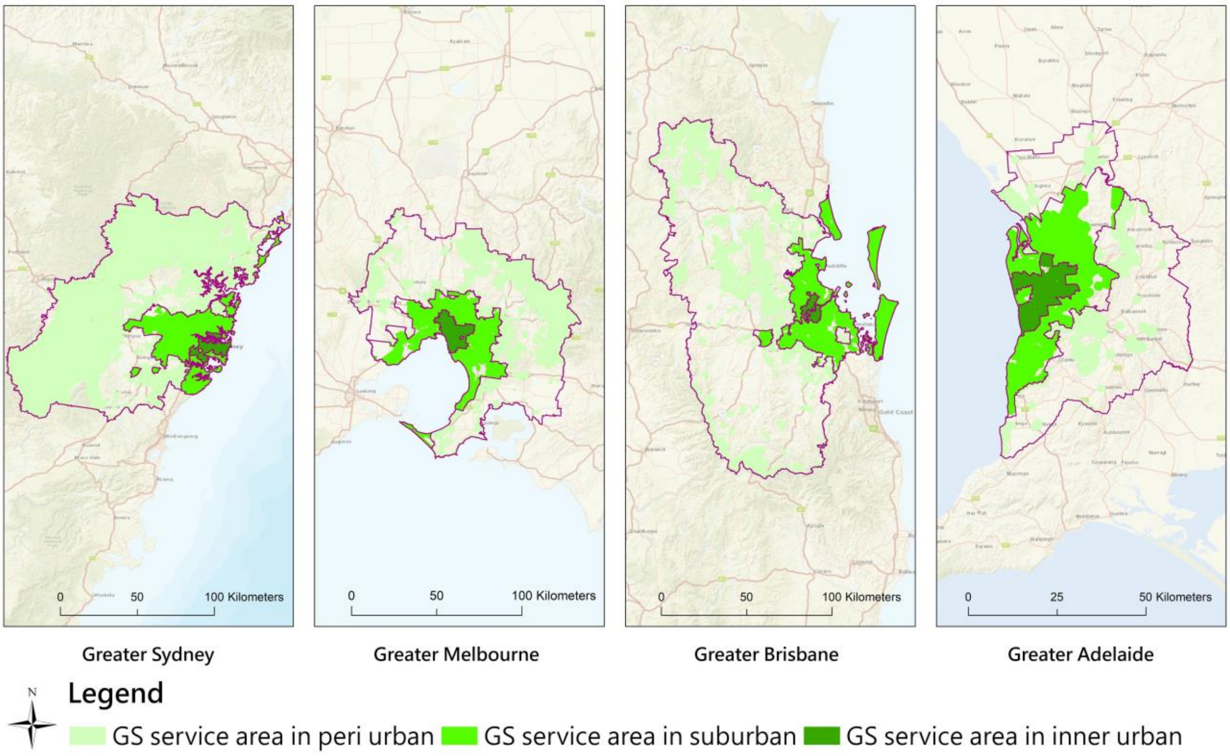

Figure 8. 1000 m catchment service area of UGS.

4.4. Residential Green Space Accessibility in the Four Selected Cities

In contrast with the above assessment approach which is calculated from a relatively broad-scale perspective, there are several indicators for UGSA, which focus on the assessment of local areas. Metrics in this section mostly are of the compound metric type, integrating Proximity [53,70,73,75] and Area [53,73,75].

On average, the distance to the nearest green space in the four metropolitan areas ranges from 200 to 400 m. Of these, Sydney presents a better UGSA at only 242 m; furthermore, all Sydney's zones, including inner urban, suburban, and peri urban perform the best within the cites sample. As for the remaining cities, the mean nearest distance is more than 300 m. For this metric, Melbourne follows Sydney, then Brisbane, and then Adelaide. Residents in inner urban Adelaide must walk an average of 300 m to access green space. In general, suburban localities have better and shorter access to green space whilst peri urban areas must access green space over a longer distance. Suburban Melbourne shows a different pattern, with its suburban access averaging 260 m and being greater than that of the inner city's 246 m. In suburban Sydney, residents on average can access green space within 200 m, while other cities require travelling and walking a distance of more than 200 m. Within peri urban areas, residents generally have to travel further to access green space. For example, in Sydney's peri-urban areas, the distance to green space is on average 432 m, while in Melbourne it is 1.5 times that, and in Adelaide and Brisbane it is 3 times that at a distance of 1208 m on average.

The distance to the nearest green space is mapped in Figure 9. The maximum distance to green space in inner urban areas is around 1 km, while that of suburban areas ranges from about 2 km to about 5 km; moreover, in the peri urban areas of Melbourne, Brisbane and Adelaide, the distance to green space is around 5 km, and the maximum is around 10 km.

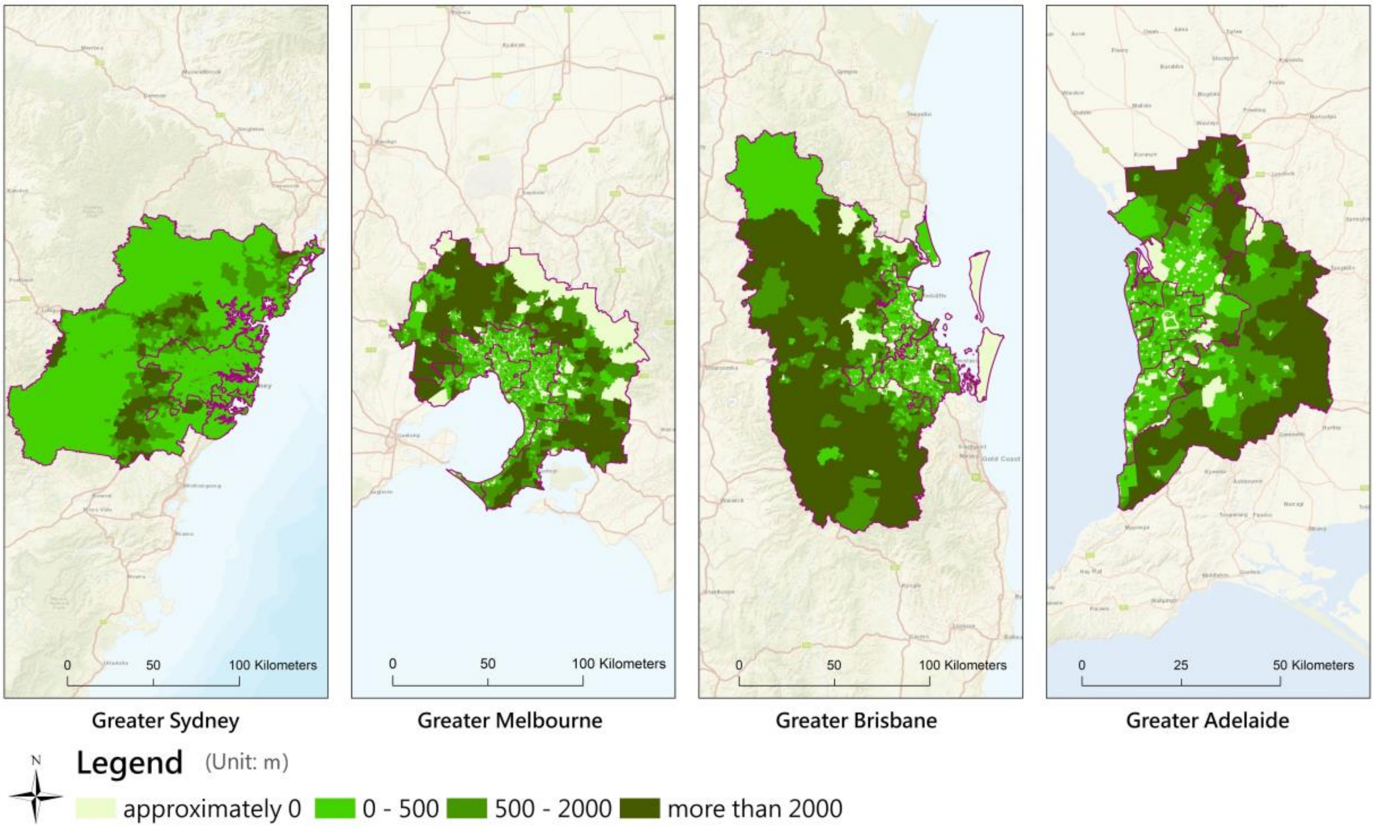

Figure 9. Distance to the Nearest Green Space within each SA1 locality in metres. Note that peri-urban areas have limited recreational green space close by.

Accessible UGS within 500 m radius is calculated based on the equation shown in Table 2. The analysis shows that Sydney provides the most accessability to UGS since 14.48% of green spaces falls within the 500 m radius area measured. However, Brisbane, Adelaide and Melbourne have less UGS within the selected radius with 13.41%, 11.66% and 10.59%, respectively. Generally, suburban areas demonstrate the highest score, followed by peri urban and then inner urban areas. However, Sydney presents a different pattern. The peri urban area of Sydney can access a larger size of UGS than its inner urban or suburban zones. Considering the differences between metropolitan zones, whilst Melbourne's zones are largely consistent, Sydney shows a considerable disparity between the UGS accessibility of its inner urban, suburban, and peri urban zones. Figure 10 shows the spatial distribution of the accessible UGS area around households within the local (SA1) area.

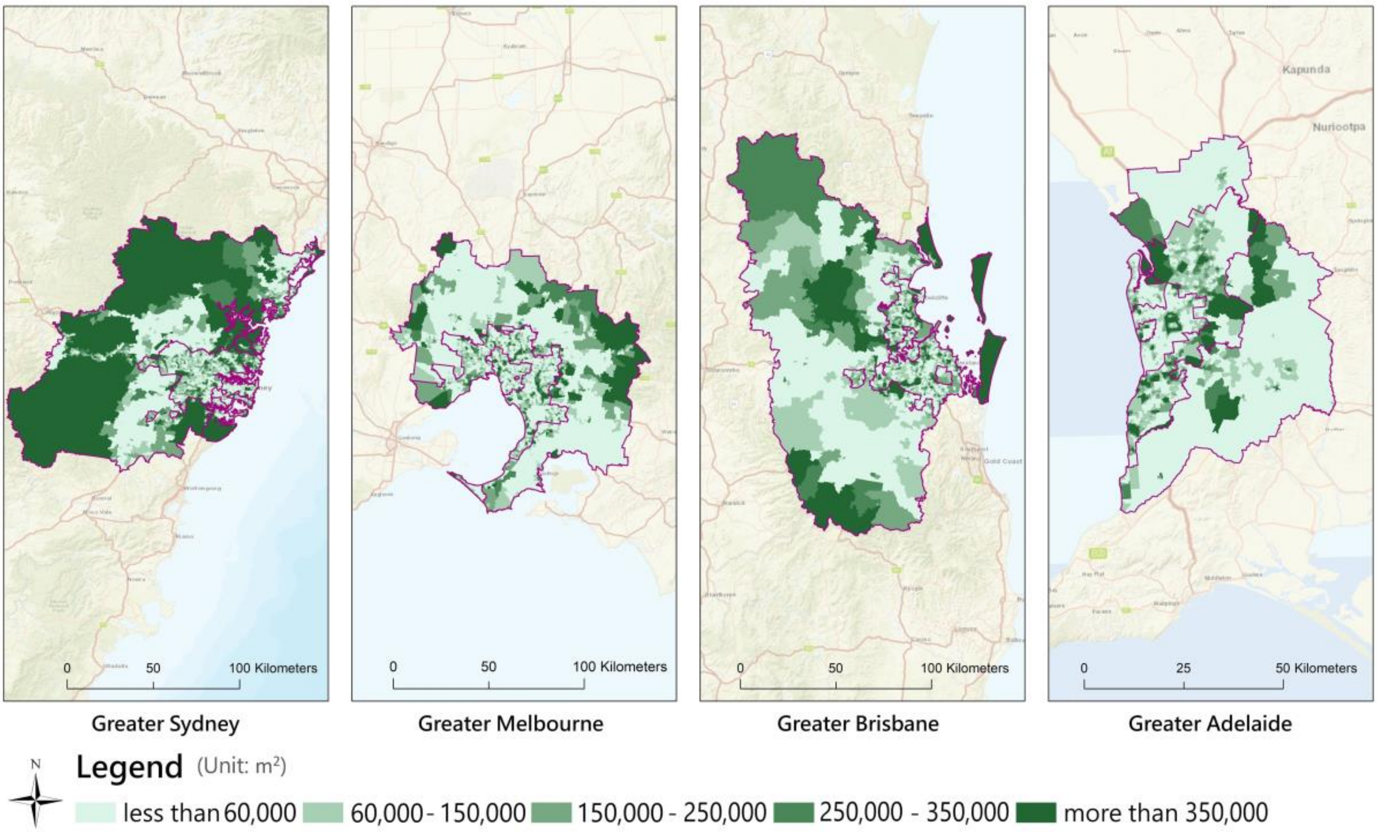

Figure 10. Average accessible UGS within 500 m radius by SA1.

Although Sydney generally received the top score in terms of the area of accessible UGS within a 500 m radius, its inner city performs poorly. In Sydney's inner city, green space that locals can access make up a only 9.37% of the area within 500 m. This puts it in third place behind Adelaide and Brisbane. Melbourne received the lowest overall score in accessing UGS; however, its inner urban areas perform the best overall, with accessible green space making up 10.02% of the land area within a 500 m radius around the dwelling. On the other hand, Brisbane's green space accessibility metric puts it in second place; however, within suburban areas, 14.64% of the 500 m buffer zone are green spaces. Within metropolitan Adelaide, green space areas that residents in suburban areas are able to access occupy 13.99% of the accessible area within a 500 m radius, placing it third ahead of Melbourne; however, both Adelaide's inner urban and peri-urban areas have relatively poor accessible urban green space area with only 8.65% and 9.58% of green space area within 500 m (Figure 11).

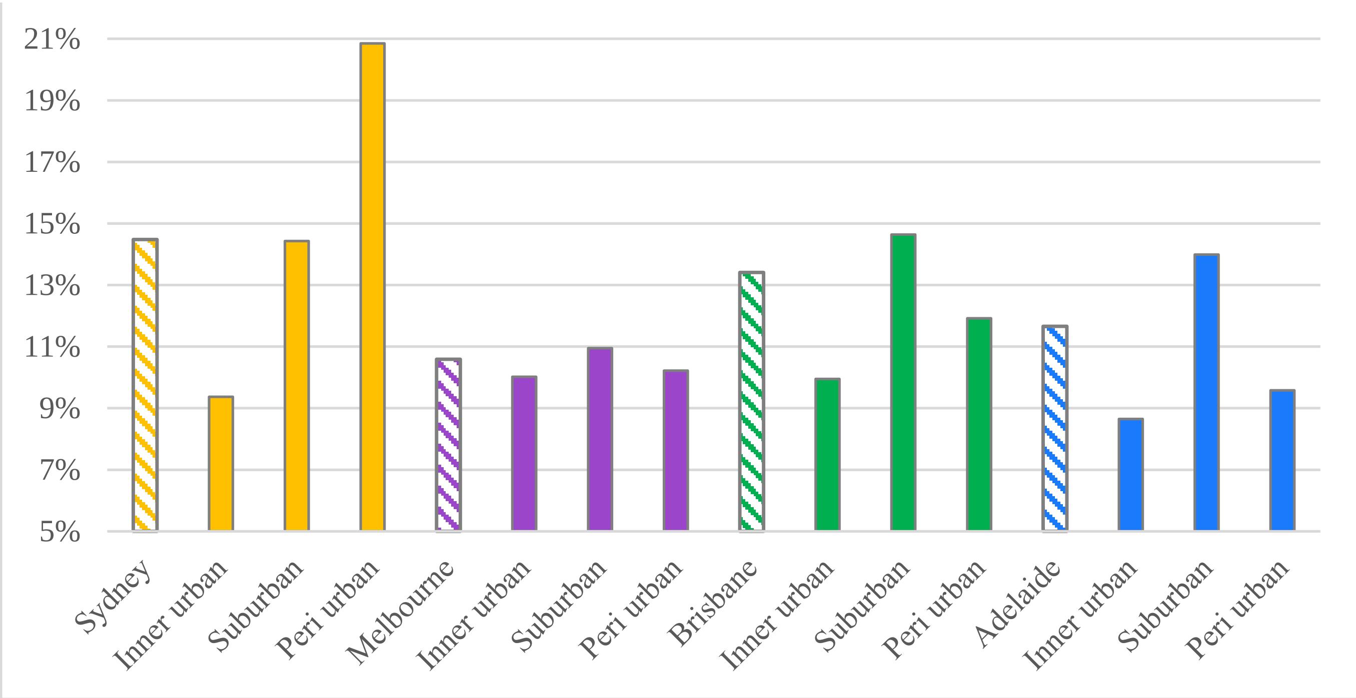

Figure 11. Comparing four capital cities (hatched bars) including three Metropolitian Zone (fully colored bars) for each based on the percentage of mean green spaces within 500 m radius.

There are two more assessment approaches that applied compound type of metrics which, respectively, focus on Area Based Provision and Population Share Area. For the Area-Based Provision, we have the indicators of Accessible UGS within 500 m of the SA1 area. As for Population Share area, we analyze the Accessible UGS per capita within 500 m of SA1 area.

Figure 12 illustrates the application of metric 10 (see Table 2) which cacluates the access to UGS within a 500 m radius of SA1 areas. In general, people who live in the suburbs can access more UGS than those in inner urban areas, while people living in peri urban areas can access significantly more UGS than those in suburban areas. Sydney can access 1.033 km^2 UGS on average, while Brisbane can access 0.917 km^2; on the other hand, individuals who live in Melbourne can access only 0.484 km^2, and Adelaide can access 0.383 km^2. Adelaide presents the least amount of accessible UGS according to this measure. It is noteworthy that there is considerable inequality within Sydney. Although Sydney performs well at the city level and within peri urban areas, its inner urban area has the least amount of accessible UGS in the study sample with an average of only 0.155 km^2 of accessible UGS.

Figure 13 illustrates the application of metric 11 (see Table 2) which calculates UGS accessible within 500 m from the perimeter of each SA1 area per capita. Overall, people in suburban areas can access a greater share of UGS than those within inner urban areas. Equally, people in peri urban areas can access a greater share of UGS than those in suburban areas. Adelaide is an exception in that people living in its peri urban areas can access a lesser share of UGS than those in suburban areas.

For inner urban zones, Melbourne residents can access a share of over 2000 m^2 UGS while residents in other cities can typically can access a share of around 1000 m^2. For suburban areas, Brisbane's inhabitants can access 10 times more UGS than those in its inner urban areas. Adelaide and Sydney and finally Melbourne follow Brisbane when it comes to this metric.

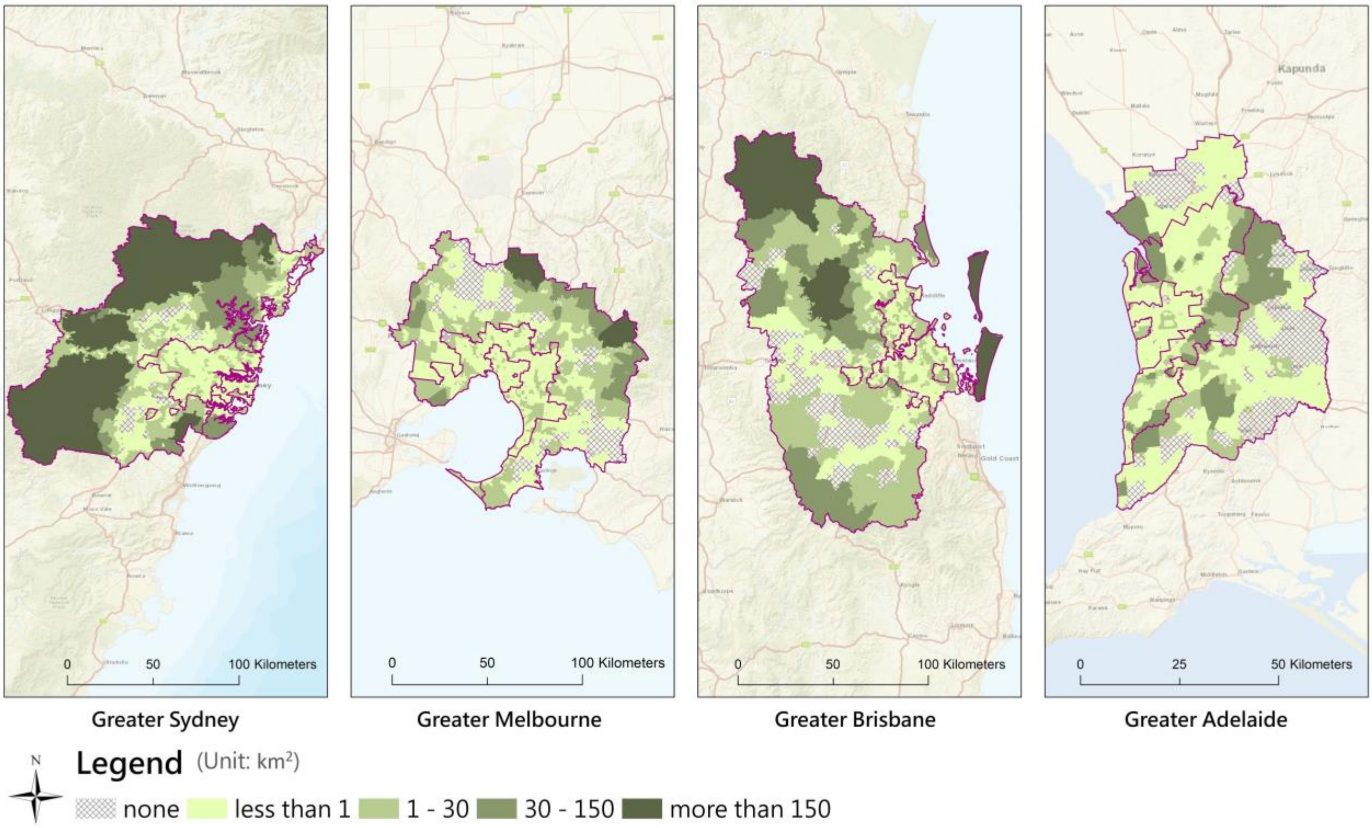

Figure 12. Accessible UGS within 500 m of SA1 area (km^2).

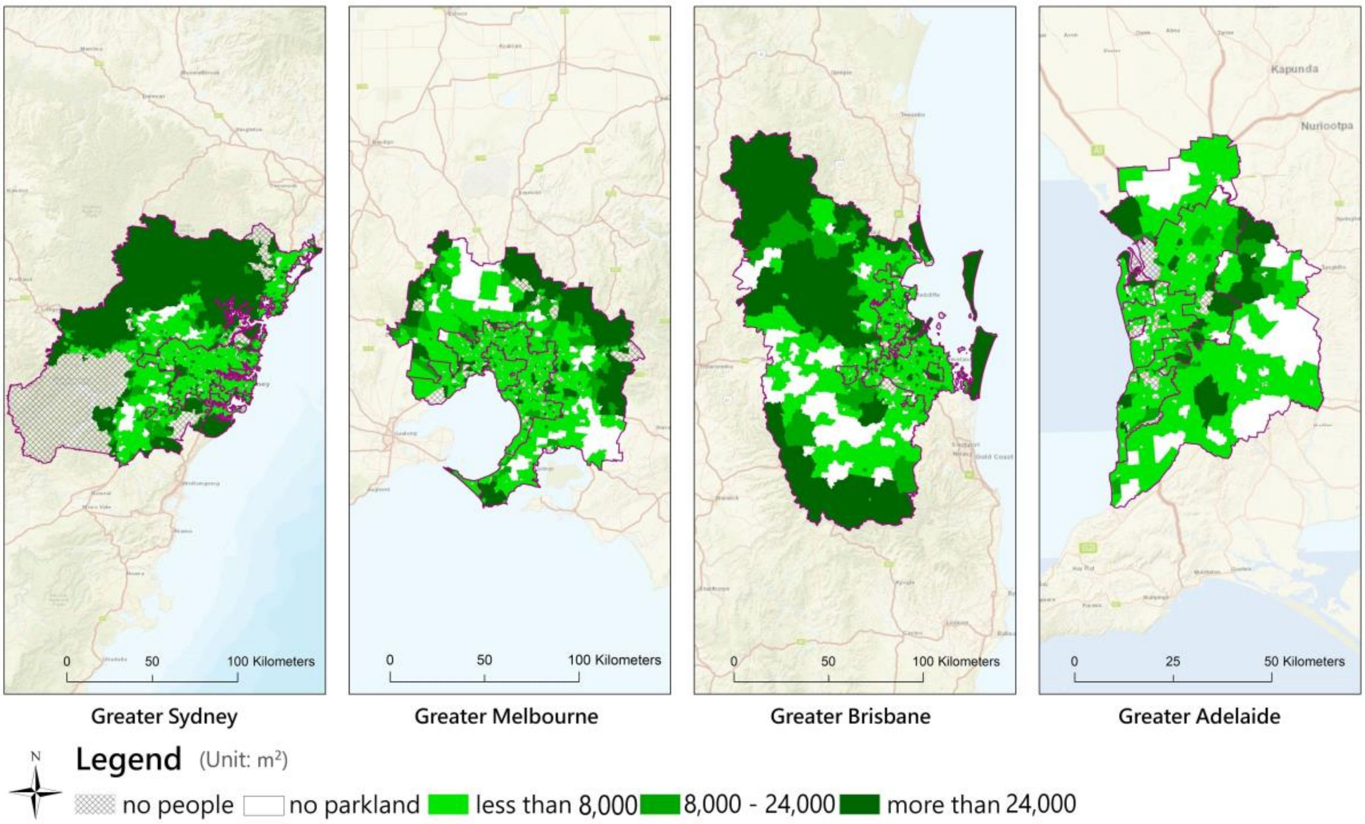

Figure 13. Accessible UGS per capita within 500 m of SA1 area.

5. Discussion

This research has examined the spatial variation of green space accessibility within and between four metropolitan areas. It has done this using a spatial classification of population density dividing each city into inner urban, suburban and peri-urban areas. Such a comparative approach is currently lacking, as identified by Žlender & Ward Thompson [95] and Rigolon [52]. The complexity of green space accessibility is demonstrated through the evaluation and application of various metrics compiled from literature. Such an approach can enhance future planning of urban green space accessibility. In the following discussion we first discuss the significance of the results of green space accessibility in the Australian context. We then discuss the broader global significance of the results. Finally, we contextualise and discuss the usefulness of the various metrics and suggest how they may contribute to the future evaluation of urban green space accessibility and its implications for just urban environments in Australia and other urban contexts.

5.1. Green Space Accessibility within Australian Metropolitan Areas

Urban green spaces can provide social, cultural, and economic resources to assist the daily life of individuals and communities in urban areas. Green space accessibility is related to health and wellbeing [96–98] and therefore has implications for the achievement of just urban environments. Such targets form part of the Sustainable Development Goals and are key to making cities inclusive, healthy, and resilient [99]. There are different dimensions of environmental justice, as discussed by Schlosberg [47] and Jennings et al. [100]. This research focused on the distributive dimension, which mainly addresses uneven opportunities to access green spaces. The diverse approach applied to analyze the different urban structures of the four selected Australian metropolitan cities allows various insights into these cities' social, environmental, and economic performance and, notably, the environmental inequality between them. We first used the metrics to compare the cities and understand the inequality within each city.

In Sydney, analysis of peri urban areas shows a rather positive outcome due to the great amount of green space in the periphery of the city. However, in its inner urban areas individuals cannot access as much due to a lack of UGS and denser populations. The peri urban area has over 60% of the land count as green spaces, and dwellers share over 8000 m^2 of UGS per capita, which is two to four times than the peri-urban areas of Melbourne and Brisbane. Peri-urban areas of Sydney provide good accessibility according to the Population Share Area and Area-Based Provision metrics, however, perform relatively weakly in terms of Proximity metrics. In contrast, the inner urban areas of these cities perform strongly on Proximity, with almost 95% of the dwellers living within 500 m from green spaces; moreover, 220 m is the distance to the nearest green spaces on average.

As for Melbourne, its inner urban area provides sufficient UGS for its population. However, its suburban areas are deficient in UGS whilst its inner urban areas perform relatively strongly in terms of in the Population Share Area metric and the Area-Based Provision metric. Accessible UGS per capita within 500 m of the SA1 area of Melbourne is 2088 m^2, which places it first among the selected inner urban areas. Melbourne's Accessible UGS area within 500 m radius from the SA1 centroid places it first among all the studied inner urban areas. However, Melbourne's suburbs perform relatively poorly according to the various accessibility metrics. Hence, there is room for improvement in the suburbs of Melbourne.

In contrast, suburban Brisbane includes a great deal of UGS in and around its suburban areas, which perform better than its inner urban areas. The green spaces coverage rate of its suburban area is as much as 40%, placing it first inamongst the study cities according to this measure. The inner urban area of Brisbane also scores well according to the Area-Based Provision metrics but less well on the Proximity-related metrics. Accordingly, Brisbane's future parks and green spaces need to be placed carefully to improve certain dimensions of accessibility such as proximity.

In the case of Adelaide, its suburban areas contribute the most to the UGS accessibility for the entire city, due to the amount of UGS in and around suburban residential areas. Yet, its peri urban areas have much less UGS, with residents in these areas disadvantaged when it comes to recreational green space. The UGS coverage rate of its peri-urban areas is only 6%. In general, compared with other metropolitan areas, people in Adelaide suffer the most from UGS inequality and spatial inequality accross the different metropolitan zones.

5.2. Comparison with Global Standards and the SDGs

A variety of global standards have been applied to assess the four study cities in this paper (see Table 4 for detailed figures). English Nature has recommended [73], a"Population Share" of at least 20 m^2 of accessible greenspace per person. According to the indicators of UGS per person in a SA1, used in this research, more than 50% of the SA1 do not yet meet the standard. Suburban Adelaide performs the best with 55.45% meeting the standard, and inner urban areas of Sydney perform the worst with 85.40% of the SA1 providing less than 20 m^2 per person. Green space area accessibility within 500 m of SA1 per person varies greatly with from as little as 3% to as much as 25% of the SA1 not meeting the standard. For example, in suburban Brisbane only 1.20% of the SA1 did not meet the standard, while 23.89% of the SA1 in peri urban areas of Adelaide access less than 20 m^2 per capita.

In the UK standards specify that people should have access to 20 ha of urban green space within a 300 m distance from the place of residency [73]. We have applied a similar version of this standard integrating both "Area-Based Provision" and "Proximity" measures (see metric 10). Our results show a wide disparity among the areas studied with as little as 20% or as much as 75% of the SA1 not meeting the standard. Peri-urban areas of Sydney perform the best in this regard with only 28.28% not meeting the standard, while the inner urban of Sydney performed the most poorly with 73.63% not meeting the standard.

In Germany, there is a standard that specifies that every house should have access to urban green space within walking distance [70]. This is interpreted in our "Green Space Catchment" metric. The European Environment Agency also suggests that households should have access to UGS within 15 min walking distance, which is around 900 to 1000 m [77]. The STAR Community Rating System of U.S. Green Building Council also sets the threshold that a certain percentage of populations be within a 1/2 mile or 10-min walk of public parkland. In low density regions the population threshold is 70% and in high density region the population threshold is 85%. Accordingly, the percentage of "people living within 1000 m of UGS" indicates that inner urban of Sydney performs the best with 100% of residents achieving this metric.

In the Netherlands, compound metrics are used to calculate standards, including "Population share" and "Proximity" metrics and the resulting standard states that there should be a minimum of 60 m^2 UGS within a 500 m radius around households [75]. Amongst the studied Australian metropolitan zones, most have up to 10% of SA1 units that cannot meet this standard. Suburban Sydney has only 2.15% while peri-urban areas shows a maximum of 35.90%. In terms of proximity, there is also a target from the UK that people should be able to access UGS within 300 m of their neighbourhood [73]. Accordingly, we have used the standard distance to the nearest UGS of less than 300 m. Among the four metropolitan areas, around 30% to 80% of the SA1 has a figure less than 300 m. The suburban area of Sydney performs the best with 78.02% of its SA1 areas meeting the standard.

There are diverse ways to assess citizens' accessibility to urban green spaces. Metrics reveal different relationships and interactions between people and green spaces and demonstrate distinct insights into the study sites. There is no single approach to monitor UGSA accessibility and related spatial inequality. Here we have evaluated various metrics in a comparative way. Future studies can further examine possible combinations of such metrics in indexes to reveal and synthesise the data and therefore provide new insights. Part of the challenge of making UGSA "accessible" is to communicate results quickly and clearly. For this reason, digital planning support systems with intuitive interfaces can assit communities to evaluate the limitations and strengths or their own districts and localities. Such approaches are helpful in both lobbying governments for funding and for commitment to new urban green infrastructure [101,102].

As noted in the background section we have focused on distributive justice in this study. Future studies can consider metrics that describe procedural, and recognition-based accessibility justice [47]. Gaining insight across these three types of accessibility measures is particularly important when engaging communities with different political, cultural and health dimensions. Standards vary from country to country but provide an indication of possible global targets. A more global approach to integrating initiatives such as the SDGs is needed to help improve and shape environmental justice within cities. Further, for studies to contribute to global agendas such as the NUA and the SDGs, Schlosberg's [47] three types of measures need a great deal more consideration and integration. Accessibility is not just a physical challenge but also a legal and cultural challenge.

Some studies have tried to define sustainability standards for SDGs to evaluate the performance of global cities [103,104]. Green space standards are one way of measuring environmental justice issues [105,106]. Globally, there is a lack of such comparative measures and these could help cities both assess their own performance and to generate political momentum and investment in this area. Open data is a key aspect of this challenge [101,102] and whilst nations such as Australia have excellent publicly available census and spatial data, this is not analyzed and presented in ways that make it accessible to the population to support debate and decision making. There is, therefore, a procedural dimension of justice that is lacking here. The different types of standards presented here illustrate the complexity of achieving comprehensive environmental equity within cities. Standards also can help guide future planning of green cities globally [107].

6. Conclusions

Urban green spaces provide a range of critical services to cities in Australia and around the world. The value of such spaces has become especially evident during the COVID pandemic when urban green space has been used as healthy, spacious areas for relaxation and exercise. Various approaches and indicators for analyzing UGS accessibility have been used in previous research. There is a need to assemble such approaches and to facilitate an understanding of the comparitive achievements of cities globally. In this paper, we have adopted a multi-dimensional approach to UGS accessibility and have applied them to understand the contextual and local characteristics of UGS in each Australian metropolitan area in a way that is also applicable to metropolitan areas around the world.

Following a review of approaches for measuring global urban green space accessibility, we constituted three types of metrics based on 15 global thresholds or standards. Using this multi-dimensional approach has demonstrated the diverse utility of the different metrics. From the three types, green space coverage, green space catchment and green space accessibility we have drawn significant conclusions about the methods and also what they reveal.

We conclude with three main findings. The first of these is that despite ranking highly in liveability indexes, Australian cities are not always just or fair when it comes to the provision of green space that is so important for health and well being. The second is that a range of measures can be used to better understand green space accessibility but that these need to be consistent across cities within Australia and globally to understand the limitations of urban structures at multiple scales. Finally, although there is a range of initiatives to address urban greening within Australian cities, this is not always linked to environmental or green space justice issues and there is no national approach to address green space equity.

As Australia continues to urbanize, the methods and findings presented here will prove critical to ensure green space can become standardized and a basic human right for all urban residents wherever they live, be it in one of the metropolitan centres or in regional cities. Likewise, within metropolitan areas, there is disparity and especially of the margins of metropolitan areas, there needs to be a concerted focus to design new green spaces and to ensure the standards there match or surpass the older, more established urban centres.

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