Landscape and Urban Planning 203 (2020) 103889

Contents lists available at ScienceDirect

Landscape and Urban Planning

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

Green Apartheid: Urban green infrastructure remains unequally distributed across income and race geographies in South Africa

Zander S. Venter[a,*], Charlie M. Shackleton[b], Francini Van Staden[c], Odirilwe Selomane[d], Vanessa A. Masterson[e]

[a] Terrestrial Ecology Section, Norwegian Institute for Nature Research – NINA, 0349 Oslo, Norway
[b] Department of Environmental Science, Rhodes University, Makhanda 6140, South Africa
[c] Department of Environmental Affairs and Development Planning, Western Cape Government, South Africa
[d] Centre for Complex Systems in Transition, Stellenbosch University, South Africa
[e] Stockholm Resilience Centre, Stockholm University, Stockholm 10691, Sweden

ARTICLE INFO

Keywords:
Access
Green space
Environmental justice
Global South
Inequalities

ABSTRACT

Urban green infrastructure provides ecosystem services that are essential to human wellbeing. A dearth of national-scale assessments in the Global South has precluded the ability to explore how political regimes, such as the forced racial segregation in South Africa during and after Apartheid, have influenced the extent of and access to green infrastructure over time. We investigate whether there are disparities in green infrastructure distributions across race and income geographies in urban South Africa. Using open-source satellite imagery and geographic information, along with national census statistics, we find that public and private green infrastructure is more abundant, accessible, greener and more treed in high-income relative to low-income areas, and in areas where previously advantaged racial groups (i.e. White citizens) reside. Areas with White residents report 6-fold higher income, have 11.7% greater tree cover, 8.9% higher vegetation greenness and live 700 m closer to a public park than areas with predominantly Black African, Indian, and Coloured residents. The inequity in neighborhood greenness levels has been maintained (for Indian and Coloured areas) and further entrenched (for Black African areas) since the end of Apartheid in 1994 across the country. We also find that these spatial inequities are mirrored in both private (gardens) and public (street verges, parks, green belts) spaces, hinting at the failure of governance structures to plan for and implement urban greening initiatives. By leveraging open-access satellite data and methods presented here, there is scope for civil society to monitor urban green infrastructure over time and thereby hold governments accountable to addressing environmental justice imperatives in the future. Interact with the data here: green-apartheid.zsv.co.za.

1. Introduction

Green space and green infrastructure in cities and towns are increasingly recognized as crucial in any urban planning or policy strategy to promote urban sustainability, climate resilience and liveability. Positive relationships between urban greenery (e.g. parks, street trees) and many aspects of human wellbeing have been established. Ecosystem services and benefits derived from green infrastructure include improvement of air quality, amelioration of the urban heat island effect, carbon sequestration, water infiltration for recharging aquifers, and providing food and habitat for other biodiversity in the urban matrix (du Toit et al., 2018; Livesley et al., 2016; Lovell & Taylor, 2013; Venter et al., 2020). These services provide indirect societal benefits through improvement in physical and psychological health, social cohesion, sense of place, safety and livelihood needs (such as firewood, wild foods and traditional medicines in some African countries) to mention just a few (du Toit et al., 2018; Nesbitt et al., 2017; Rojas-Rueda et al., 2019; Twohig-Bennett and Jones, 2018). However urban green spaces and the benefits they provide are disproportionately available to some (Ernstson, 2013; Wolch, Byrne, & Newell, 2014).

As a way to highlight the multiple functions of urban green space, alongside gray infrastructure that denotes the concrete, steel and asphalt structures that dominate urban ecosystems, the term 'urban green infrastructure' is progressively gaining traction in urban planning domains. Although a number of definitions of green infrastructure are in use, most include the same elements highlighted by Kambites and Owen

* Corresponding author at: Norwegian Institute for Nature Research, Gaustadalléen 21, NO-0349 Oslo, Norway.
E-mail address: zander.venter@nina.no (Z.S. Venter).

https://doi.org/10.1016/j.landurbplan.2020.103889
Received 21 March 2020; Received in revised form 23 June 2020; Accepted 23 June 2020
Available online 06 July 2020

(2006, p483). These are that urban green infrastructure is “the connected network of multifunctional, predominantly unbuilt, space that supports both ecological and social activities and processes”, which requires particular planning perspectives to ensure it is available, networked and even multifunctional (Pauleit et al., 2011; Sandström, 2002). For the purposes of this paper, the term green infrastructure can be interpreted as synonymous with the terms ‘green space’ and ‘urban nature’, more often used in sociological literature. A variety of measures have been used in assessing the availability of green infrastructure, the most common ones being (i) absolute area or percentage of a specified area that is under green infrastructure, (ii) the absolute or percentage expressed on a per capita basis, and (iii) the mean or median distance an urban dweller has to travel to get to an urban green space of a specified size (Rigolon, Browning, Li and Shen (2018)). There are fewer measures of green infrastructure quality used mainly due to the complexity of cultural and socioeconomic perceptions of urban nature qualities.

Although the results may vary somewhat in relation to which measures of green infrastructure access or availability are used (Ferguson et al., 2018) and the elements of green infrastructure considered (Shanahan et al., 2014), there is growing concern about the uneven or inequitable patterns of urban greenery within many towns and cities, and the potential predictability of which areas or population groups have least access. Whilst there are exceptions (e.g. Riley & Gardiner, 2020), several reviews (e.g. Gerrish & Watkins, 2018) and empirical studies from different world regions have shown that lower income residential areas within towns and cities are more likely to have the least access to green infrastructure in the form of green spaces or street trees (Astell-Burt & Feng, 2019; McConnachie & Shackleton, 2010; Nero, 2017; Sathyakumar et al., 2019; Shen et al., 2017). In many settings, this also overlaps with areas dominated by racial minorities (Heynen et al., 2006; Landry & Chakraborty, 2009; Nesbitt et al., 2019; Watkins & Gerrish, 2018). For example, Astell-Burt & Feng (2019) reported that public green infrastructure availability in more affluent areas of Adelaide, Australia, was almost double that found in the poorer neighbourhoods, and in South Africa, Kuruneri-Chitepo & Shackleton (2011) reported that the poorest areas had none or few street trees, which was in stark contrast to affluent areas. Such differences translate to reduced benefits from the ecosystem services provided by green infrastructure in poorer neighbourhoods (Escobedo et al., 2011) and hence resonate with debates relating to environmental justice of who receives what benefits or ecosystem disservices from environmental and green infrastructure (Ernstson, 2013; Wolch, Byrne & Newell, 2014). These disparities in access to urban green infrastructure are increasingly recognised as an important environmental justice issue (Wolch, Byrne & Newell, 2014; Kabisch and Haase, 2014). Similar patterns have been reported at larger spatial scales, such as comparisons between towns and cities of differing mean or median affluence (Gwedla & Shackleton (2017); Li et al. (2018); Rigolon, Browning and Jennings (2018)), mostly from Global North countries. However, there are relatively few national scale analyses of green infrastructure and patterns of access, other than for Germany (Wüstemann, Kalisch, & Kolbe, 2017), which revealed a positive relationship between household income (and education) and vegetative cover of public urban green spaces, but not distance to public green spaces. Additionally, most of the work to date has been confined to public green infrastructure with little examination of how access to private green infrastructure, typically urban domestic gardens, alters or echoes that pattern.

South Africa is a compelling country to examine such patterns and relationships because it provides an obverse to the mostly Global North analyses in that the racial minorities (descendants of White European colonists) are generally the wealthiest group in the country (Gradín, 2014). In contrast, Black South Africans, who make up 86% of the population, continue to suffer generally lower levels of education and incomes than their White counterparts. This is a consequence of centuries of institutionalized racial discrimination during the colonial and subsequent Apartheid periods, resulting in spatially segregated neighbourhoods (Posel, 2001). The Apartheid (Afrikaans for ‘apartness’) political system of separate development and inequality was broadly based on a racial hierarchy that systematically disadvantaged those who were classified as ‘Coloured’, ‘Indian/Asian’ or ‘Black’. The archetypal ‘Apartheid city’ was designed around the spatial segregation of these race groups, with people forcibly removed to ‘group areas’ and regulations around social interaction in public space (Davies, 1981, Simon & Christopher, 1984). These laws and government were officially dismantled in 1994, and the establishment of democracy came with defined socio-economic priorities including basic service delivery and rapid human settlement development. However, the legacies of Apartheid urban planning and colonial rule before it, are still deeply felt in everyday life for South Africans (Makakavhule & Landman, 2020). This segregation is also mirrored in the distribution and extent of urban green infrastructure. For example, McConnachie and Shackleton (2010) showed markedly less public urban green infrastructure per capita in the poorer neighbourhoods of mostly Black residents than the more affluent ones of mostly White residents. The same applies with respect to the provision of street trees (Kuruneri-Chitepo & Shackleton, 2011, Gwedla & Shackleton, 2017). Indeed, there are many areas in poorer neighbourhoods that have no street trees at all. Consequently, residents in the poorer areas voice higher levels of dissatisfaction about the poor provision and quality of public green infrastructure than do those in more affluent areas (Shackleton et al., 2018; Shackleton & Blair, 2013). This is especially so in the numerous post-Apartheid, government-built social housing areas where environmental justice, sustainability and quality of life aspects have been neglected, despite some supportive policy prescriptions to the contrary (Chishaleshale et al., 2015). In a relatively new urban planning era that emphasizes spatial equity and justice, South Africa has introduced the National Spatial Planning and Land Use Management Act (SPLUMA, Act 16 of 2013) providing legislative structure for green infrastructure equality, but in the context of these planning priorities there has not yet been a national assessment of access to urban green infrastructure.

South Africa also adds an additional perspective in that the needs and uses of green infrastructure go beyond those commonly covered in the literature from Global North settings. Whilst a lot of emphasis is still put on green infrastructure for regulating and cultural services, the significance of provisioning services to urban dwellers in the South is generally greater than that found in the Global North (Adegun, 2017; Shackleton et al., 2018), driven to varying extents by the high poverty levels, large volumes of new urban migrants from rural areas, and the use of specific biodiversity resources for African identity or spirituality (Cocks et al., 2016). For example, Kaoma & Shackleton (2015) reported that 20% of cash and non-cash income to Black households in the poorer neighbourhoods was obtained from collection of wild biodiversity resources from private and public green infrastructure. There is also extensive use of private and public green infrastructure for urban agriculture, including crop cultivation and livestock grazing (e.g. Khumalo & Sibanda, 2019). South African cities, and African cities in general, are rapidly expanding, often in areas with low economic and human capacity. This threatens the biodiversity and ecosystem services supported by green infrastructure in social settings where it is most needed (Cities and Biodiversity Outlook, 2012).

In this paper we engage with the first of Low (2013s) three dimensions of environmental justice i.e. distributive justice which addresses fairness in provision of public spaces and related resources, but we operationalize this by examining inequalities in access to urban green infrastructure at the national scale. Bringing together the dearth of national level examinations of urban green infrastructure distributions, and the South African context, we aimed to examine how private and public green infrastructure are related to race and relative income geographies across South Africa. To do this we coupled national census tract statistics for urban areas with high resolution satellite remote sensing of urban greenery and tree cover, and open-source geographical data on recreational areas. Given the evidence from local-scale studies (e.g. Gwedla & Shackleton, 2017) and the historical context of Apartheid in South Africa, we firstly hypothesized that green infrastructure is more treed, greener, abundant and accessible in high-income relative to low-income areas, and in areas where White citizens reside. In contrast to previous studies that have focused on public green infrastructure, we were able to leverage satellite imagery to isolate private gardens and test the hypothesis that these socio-economic differences in green infrastructure are equally evident in both public and private areas. With the availability of historical satellite imagery back to the 1980s, we were also able to explore the trajectories of neighborhood greenness. Given that it has been 26 years since the fall of Apartheid in 1994, we tested whether socio-economic and racial differences in neighborhood greenness have changed and been adequately redressed under the new political dispensation.

2. Methods

2.1. Census data

To quantify the spatial distribution of race and income over South Africa, we used the 2011 national census data provided by Statistics South Africa (http://www.statssa.gov.za/) at the smallest geographical unit available ("small area code") after filtering for census tracts designated as "urban" (Fig. 1). Here urban is defined by Statistics South Africa as contiguous administrative units with residential and business land use, identified by interpretation of aerial photographs. Resulting census units had a mean area of 0.49 km^2 and median population size of 615 (interquartile range of 300) people. Dominant race categories reported in the census include "White", "Black African", "Coloured" and "Indian" and are of historical significance given their alignment with the designations enacted during Apartheid. While some audiences may be uncomfortable with the use of the terms 'Coloured', 'White' and 'Black African' as racial categories, we use these terms as they are the categories used by the national census and have contextual relevance to the analysis. The Apartheid regime imposed a classification of people into hierarchical racial categories, and however morally and ontologically objectionable and ambiguous the underpinnings of such a racial classification, the legacy of this is that such categories have become part of the lived experience of South Africans and are therefore important to include in an analysis of the legacy of Apartheid spatial planning (Posel, 2001). We calculated the percentage racial category composition of each census tract and defined White, Black African, Coloured and Indian dominated census tracts as those with > 75% of the total population number. Race categories of 'Asian' and 'Other' were excluded from the analysis as there were not enough urban census tracts available to provide statistical power in the analysis. Annual income is reported at the household level in 11 income brackets spanning a range of 0 to 25 million ZAR (US$1 = approx. R7.50 in 2011). We used the mean interval values for each income bracket to aggregate

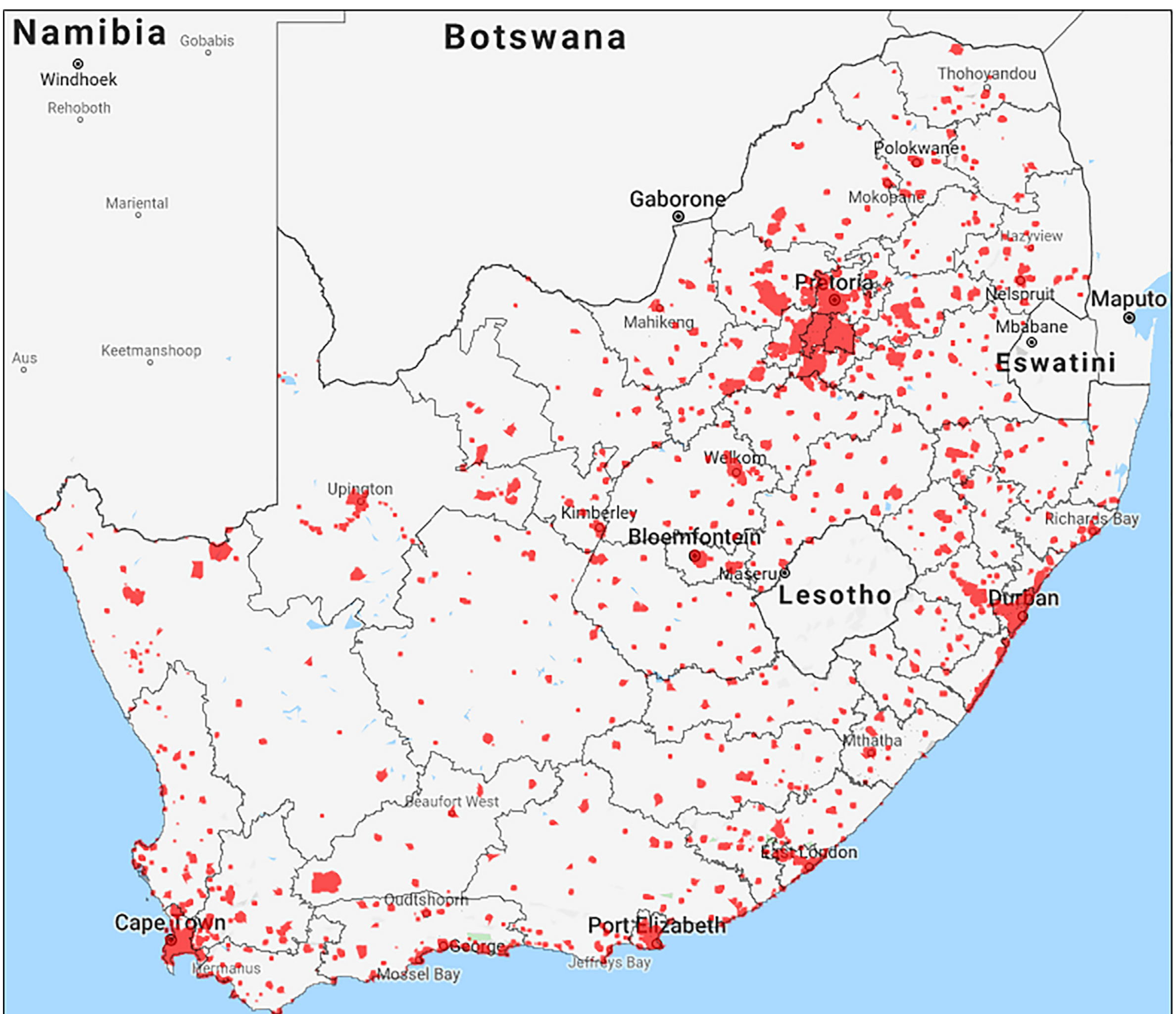

Fig. 1. Distribution of urban census tracts used in our analysis (red). District municipality polygons are outlined in black. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

data up to total income per census tract and then calculated a per capita monthly income by dividing by the number of census tract residents.

2.2. Green infrastructure data

2.2.1. Spatial designations of green infrastructure

We considered urban green infrastructure to include any vegetation elements (grass, shrubs, trees) forming parks, green corridors, gardens, street verges, and green roofs. Green infrastructure was stratified into private and public space, where public space included open public areas and street/road verges, and private space the inhabited matrix in between (Fig. S1). OpenStreetMap (OSM) data (https://www.openstreetmap.org/) were used to define parks using geometries with attribute descriptions including 'park', 'playground' and 'protected area'. Although OSM data are volunteered geographic information, and thus data quality is a concern, they have been widely used as a proxy for recreational area (Haklay, 2010; Sehra et al., 2013). The park polygons we extracted were also visually inspected against Google street maps and the South African protected area database as a reference to ensure data quality over major cities in South Africa. Observed discrepancies resulted in the exclusion of OSM geometries defined as 'dog park', 'pitch', and 'village green'. OSM data may not adequately capture municipal commonages or city green belts at the outskirts of smaller cities, however we were not able to gather alternative higher quality data with national representation. Street verges were defined by buffering line geometries in the South African road network with a 10 m buffer. We chose 10 m because this is the minimum grain size of satellite data spatial resolution and that most street verges will be within this distance of the road. Although creating varying buffer sizes depending on road width is theoretically possible, we were not able to do this because of computational power limitations. Finally, we used a dataset identifying the location of every building in the country (limited to urban areas in our study), provided by the national electricity provider, Eskom, to define private space as any land in between roads and parks that contains more than 5 buildings per 100 m^2 (Fig. S1). Although we understand building locations are not purely representative of private land tenure given that some buildings will be on public or municipal land, and that small green spaces between private houses (e.g. servitudes, alleys) will be under public management, we do not have additional data to exclude these cases. Further, we expect the effect to be very small given that the vast majority of city buildings are residential and therefore privately owned. We also acknowledge that these data do not include buildings in informal settlements which may be areas with some of the largest deficits in green infrastructure. These areas are nevertheless included in our analysis but will be picked up as public space.

2.2.2. Satellite measures of vegetation greenness and tree cover

Once we delineated private from public space, we used satellite remote sensing techniques within the Google Earth Engine platform (Gorelick et al., 2017) to measure vegetation greenness and fractional tree cover. We derived the normalized difference vegetation index (NDVI) from the Sentinel-2 MutiSpectral Instrument which produces imagery at 10 m spatial resolution. NDVI has been widely used as a proxy for vegetation greenness, but also vigor, productivity and cover (Pettorelli et al., 2005; Tucker, 1979). The high spatial resolution of the imagery allowed us to distinguish green infrastructure in the 10 m-buffered street segments from private gardens (Fig. S1). We collected all available Sentinel 2 imagery over South Africa during 2016, masked cloud cover in the images using the 'pixel_qa' band, calculated NDVI and then extracted the median NDVI value for the year. All imagery has been orthorectified and atmospherically corrected by Google Earth Engine and is thus provided as analysis-ready data. Although 2016 data do not match the 2011 census timestamp, we assume that urban green infrastructure has not changed significantly over the interim. Sentinel data is only available post 2016 and it was chosen specifically for its high spatial resolution. Fractional tree cover was also extracted from the Sentinel 2 data for 2016 using a machine learning workflow outlined in detail in Venter et al. (2018). Here fractional tree cover was defined as any woody plant cover distinguished from impervious, bare ground or herbaceous vegetation using visual interpretation of very high resolution satellite imagery. The mean NDVI and fractional tree cover values were extracted for private and public space geometries within each census tract and then aggregated up to census tract-level averages. In addition to extracting NDVI and fractional tree cover for OSM park geometries, we calculated fractional park coverage and Euclidean distance to closest park per census tract as well the average park surface area. We used simple Euclidean distance as opposed to network distance approaches because we did not have access to a routable road network nor did we have the computational capacity to perform this analysis at a national scale.

2.2.3. Long-term changes in vegetation greenness

To assess historical changes in neighborhood greenness (NDVI) since Apartheid, we could not use the Sentinel satellites and therefore used the Landsat satellite archive to collect data at 30 m resolution between 1990 and 2018. To estimate per-pixel trajectories in NDVI (greening or browning trends), we calculated the slope of the regression line through annual medoid NDVI composites. See Figs. S2 and S3 for illustration and Venter et al., (2020) for methodological details. Because of the relatively coarse resolution, we were not able to distinguish public from private spaces and we therefore aggregated NDVI means and trajectories over both public and private spaces in each census tract. We were also not able to account for urban expansion or changes in census tract geometries over this time period. Therefore we have to assume that browning (decline in NDVI) from urban expansion is equally likely to have occurred across all income and race categories.

2.3. Statistical analyses

All statistical analyses were conducted in RStudio (RStudio Team 2020). Remote sensing measures and park coverage and accessibility metrics were aggregated to mean values per census tract. There is a strong West-East general vegetation productivity gradient over South Africa which results in eastern cities being greener with more tree cover than those in the west. Therefore, the relation between socio-economic data and urban green infrastructure across the national extent is dependent on this productivity gradient. To deal with this we normalized NDVI and fractional tree cover values to the district municipality (Fig. 1) averages. Using district municipalities as a spatial aggregation unit is meaningful because it is both relevant to policy decision making and its restricted spatial extent reduces the variance in climate-driven greenness.

To explore the relationship between socio-economic and green infrastructure statistics, we used simple linear regression. Population density, per capita income, park distance, size and cover were log transformed in order to meet the parametric assumptions of linear regression. In the case of park cover and size, which had a distribution clumped at zero (many census tracts with no parks), we performed a ln (y + 1) transformation to prevent infinite values (Lachenbruch, 2002). Given that we are reporting results for the entire urban population and not a sample thereof, we reported median values ± interquartile ranges instead of means ± standard deviations. In keeping with the latest best practice in scientific hypothesis testing (Amrhein et al., 2019), we refrain from any form of significance testing, but rather focus on reporting the spread of the data and the magnitude of differences/relationships between/among variables. We do this particularly because our data has very large sample sizes (census tracts over South Africa) and consequently significance tests are likely to be biased toward finding significance.

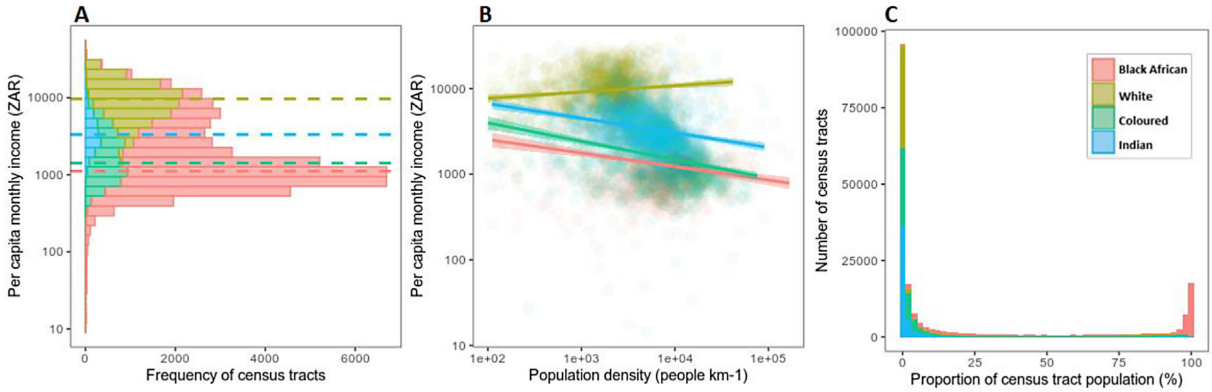

Fig. 2. The frequency distributions of per capita monthly income are plotted, as stacked histograms for each race category (A). Median income values per race are plotted with dashed lines. The relation between monthly income and population density across racial categories is plotted with linear regression lines and 95% confidence interval ribbons (B). Each point is a census district. The frequency distribution of census tracts across proportional racial population composition are plotted in C. Population density and per capita monthly income are plotted on log-transformed scales.

3. Results

3.1. Demographic summary data

Citizens in White dominated census districts earn 9655 ± 7305 ZAR per month (median ± interquartile range), while those in Black African-dominated districts earn 1114 ± 1213 ZAR (Fig. 2A). White dominated census districts report median monthly incomes 8.6, 6.8, and 2.9 times, respectively, greater than those of Black African, Coloured and Indian dominated census districts. Population density is negatively correlated to income for Black African, Coloured and Indian racial groups, whereas this trend is not apparent for White dominated census tracts (Fig. 2B). The racial composition of census districts is strongly polarized (Fig. 2C). There are 58,733 census districts (69% of total) with one race contributing more than 95% to the census tract population. There are thus very few census tracts with a contribution from each racial group that matches the national demographic ratio of 70:13:13:4 for Black-African:White:Coloured:Indian in urban areas. This indicates that the spatial distribution of individual racial groups is strongly clustered.

3.2. Green infrastructure distribution

Census tract income is positively correlated to public and private green infrastructure NDVI and fractional tree cover (Fig. 3). For every 100% increase (doubling) in per capita income, NDVI and tree cover increase by 2.2 and 3.5%, respectively within private gardens (Fig. 3A). These relationships are similar in magnitude to those for public spaces (streets and parks) where NDVI and tree cover increase by a mean of 2.4 and 2.7%, respectively, for a doubling in income (Fig. 3B, C). The positive relationship between income and green infrastructure NDVI and tree cover is ubiquitous across all race categories although strongest for White dominated census tracts. White dominated census tracts contain 15, 12.7, and 7.4% higher tree cover than other census tracts in private gardens, streets and parks, respectively, whereas NDVI values were 10.4, 11.3 and 5% higher (Fig. 3). NDVI and tree cover were consistently below the district municipality average for Black-African, Coloured and Indian dominated census tracts across private and public space.

Census tracts without parks (91%) report monthly incomes that are on average 82% (6825 ZAR) less than those with parks (Fig. 4A). This is consistent across races although there are greater discrepancies in income within Black African and Coloured dominated census tracts. Wealthier census tracts contain residential areas in closer proximity to parks (Fig. 4B). For a doubling of income there is a 23% decrease in distance to closest park; e.g. citizens in census tracts with 500 ZAR per month live on average 3.6 km away from a park, whereas those earning 1000 ZAR per month live 2.6 km away from a park. Citizens in White dominated census tracts live on average 700 m closer to a park than the average distance for Black African, Indian and Coloured census tracts (Fig. 4B). Black African citizens live the furthest (1.7 km) from parks. Fractional park coverage per census tract is positively correlated to income although there is relatively large error around the regression lines (ribbons in Fig. 4C). There is a 9% increase in park coverage with a doubling of income. There is little difference in park coverage between racial groupings (Fig. 4C). The relation between park size and income varied between race categories (Fig. 4D). White dominated census tracts increased in park area with increasing income, whereas the opposite was true for census tracts dominated by other racial groups. Although median park sizes are 0 ha for all race groups due to many census tracts containing no parks, the mean park sizes for Black African, White, Coloured and Indian census tracts are 168, 1196, 264, and 4 ha, respectively.

The regression coefficients for street NDVI, tree cover and distance to parks are remarkably consistent across the various district municipalities and across the vegetation productivity gradient in South Africa (Fig. 5). All but three of the 52 district municipalities display a positive correlation between monthly income and both street greenness and tree cover (Fig. 5A, B). Similarly, all but two of the district municipalities had a negative instead of positive correlation between income and distance to parks (Fig. 5C). The two largest cities in South Africa, Cape Town (Fig. 6) and Johannesburg (Fig. 7) have the strongest regression fits ($R^2 = 0.47$ and $R^2 = 0.47$) for the relation between income and street greenness. The spatial overlap between Black-African, Indian, and Coloured, poor census tracts and those with very low street greenness is striking (Figs. 6 and 7). The district municipalities of Mangaung (containing the provincial capital, Bloemfontein) and Nelson Mandela Bay displayed the highest regression fits ($R^2 = 0.43$ and 0.32, respectively) for the relation between income and distance to parks (Fig. 5C).

3.3. Change since Apartheid

The socio-economic and racial inequalities in neighborhood greenness (private and public space) have been maintained, and in some cases, entrenched over the past 28 years (Fig. 8). After smoothing over the inter-annual climate-driven variations in greenness, we find that White-dominated census tracts have increased in vegetation greenness by 4.3 ± 6.2% (median ± interquartile range) since 1990 (Fig. 8A and B). Black African census tracts have slightly decreased in greenness by 0.5 ± 1.3% over the same period while Coloured and Indian census tracts have shown slight increases of 2.4 ± 6.2% and 0.6 ± 6.6%,

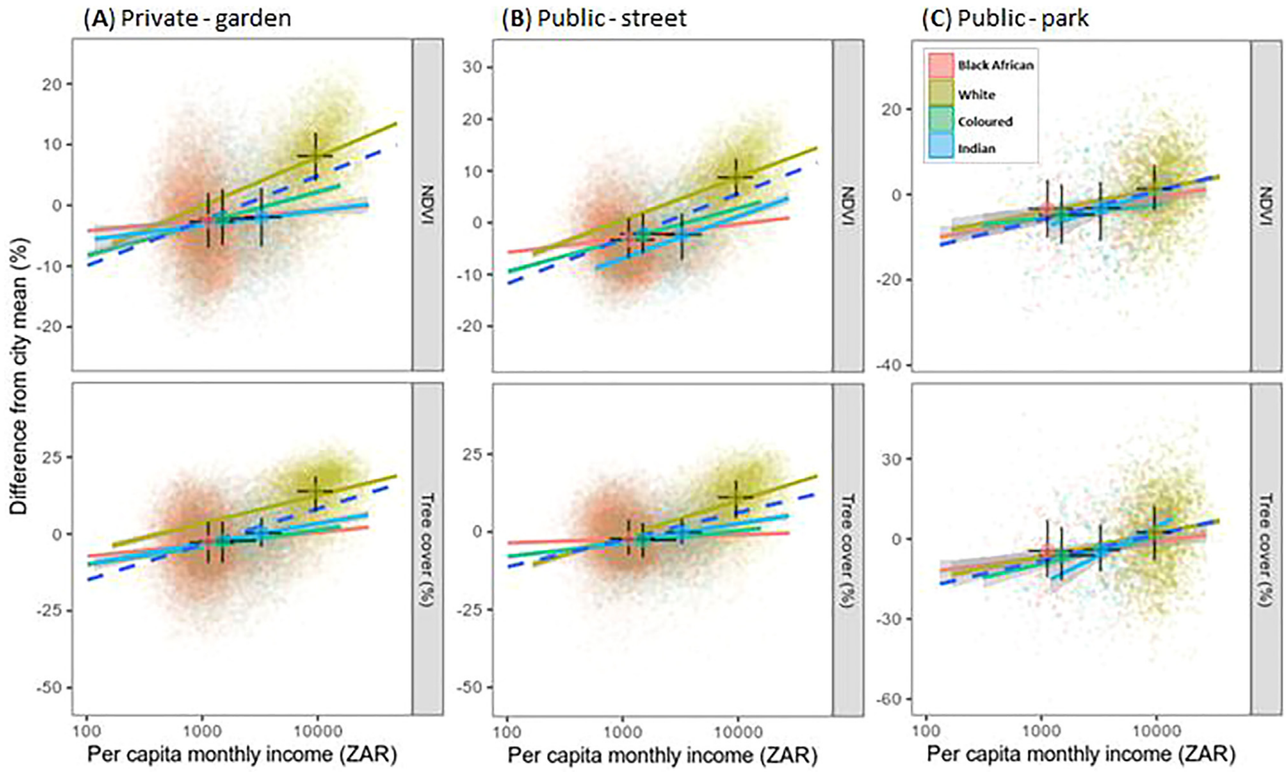

Fig. 3. Relation between per capita income and measures of private (A, B) and public (C) green infrastructure, including the normalized difference vegetation index (NDVI) and fractional tree cover. NDVI and tree cover values are expressed as percentage relative differences to respective district municipality means. Data points represent census tracts and are faded to highlight densities. Solid-fill points with black vertical and horizontal bars indicate data medians and quantile ranges, respectively. A dashed linear trend line is fitted through all points along with coloured linear trend lines for each race category. Per capita monthly income has been log transformed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

respectively. Neighborhood greenness trajectories are positively related to income across all census tracts except for those dominated by Indian citizens (Fig. 8c).

4. Discussion

We find support for our hypothesis that urban green infrastructure is disproportionately more abundant in high-income relative to low-income and in White relative to Black-African, Coloured and Indian' census tracts, within the South African context where there is a strong historical overlap between wealth and race. The census tracts with parks have on average 82% higher income than those without and White citizens live, on average, 700 m from a park whereas Black African citizens live 2.6 km away. This finding aligns with studies conducted at smaller spatial scales in other countries and in South Africa. At the intra-city scale, there are increasing numbers of studies showing stark differences in various measures of urban green infrastructure between neighbourhoods. These are often, albeit not always, correlated with average income for the neighbourhoods and race (e.g. Li & Liu, 2016; Nesbitt et al., 2019; Ogneva-Himmelberger et al., 2009). However, Ferguson et al. (2018) caution that such relationships may vary depending on what measures of green infrastructure are included. They found that the distribution of urban parks in Bradford (UK) were positively correlated with wealth and the proportion of White households, but the abundance of street trees was higher in lower income neighbourhoods dominated by citizens of Asian descent. In contrast we found that almost all measures of green infrastructure, including park area and tree cover, were unequally distributed across race and income in a similar manner.

Our national-scale analysis also supports the argument that neighborhood level disparities in access to green infrastructure are mirrored at inter-city or regional scales (Rigolon, Browning, & Jennings, 2018), where there may be competition for national funding associated with urban greening and environmental improvement. Rigolon, Browning, and Jennings (2018) perform a multivariate analysis of 99 of the largest cities in the USA to show that those with higher median incomes and low proportions of ethnic minorities (Latinxs and Blacks) had the highest green scores. Cities with a majority Latinx population not only had low green scores, but also fewer park amenities and lower spending per person on parks. In China, Li et al. (2018) examined patterns across 289 cities and found a positive association between availability of public green infrastructure and per capita GDP. In a comparison of ten towns in South Africa, Gwedla and Shackleton (2017) reported differences in the abundance of street trees between and within towns, explained by resident wealth and development history. However, there are relatively few national scale analyses of urban green infrastructure and the bulk of the work to date has been conducted in Global North countries, with relatively few contributions from Global South countries, other than South Africa (e.g. Gwedla & Shackleton, 2019; Kuruneri-Chitepo & Shackleton, 2011; McConnachie & Shackleton, 2010) and China (e.g. Li et al., 2018; Li & Liu, 2016; Wang & Lan, 2019). Our study provides scope for similar assessments of distributional aspects of environmental justice (sensu Low, 2013) at the national level in other countries in the Global South given the advent of open-source satellite data with global coverage.

While the migration of people within the country has increased rapidly since the fall of Apartheid in 1994, the urban areas still reflect the legacy imprinted by separation of races (see Figs. 6 C & E; 7 C & E). The factors behind these are multiple. First, movement of people from predominantly rural areas to the cities is dominated by relocation to informal settlements, which are often on the margin of the city and are usually not planned development and therefore do not receive all the basic services provided by cities (Balbi et al., 2019), let alone green spaces. Secondly, income plays a major role in who can move to which

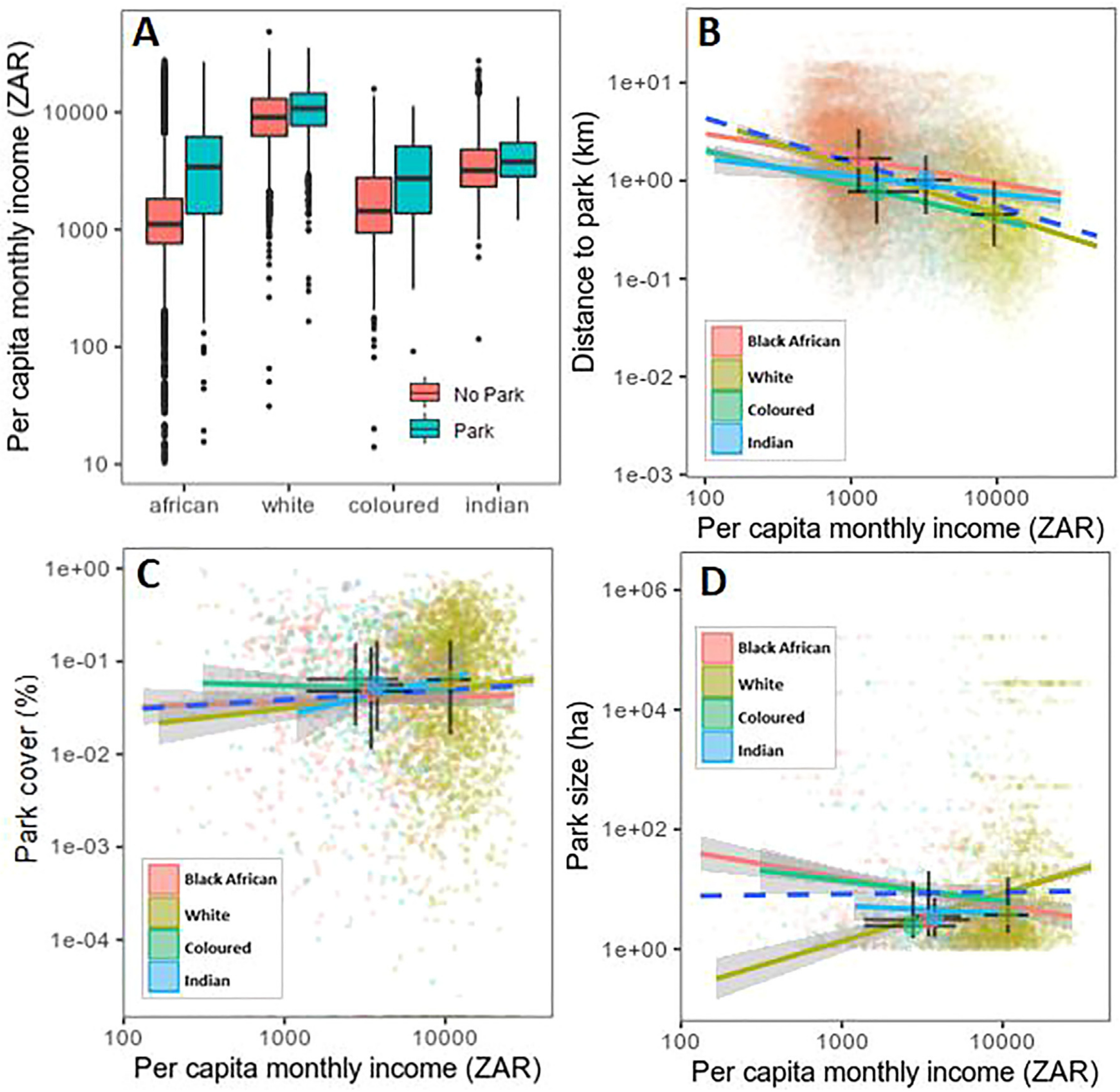

Fig. 4. Box-and-whisker plots of log-transformed monthly income for census districts with and without parks, for each race category (A). Three park attributes including distance from residence (B), the percentage of census tract covered by park (C) and park size (D) are plotted against log-transformed monthly income. Please refer to the caption in Fig. 3 for description of data points and trend lines. Park distance, size and cover are also log-transformed.

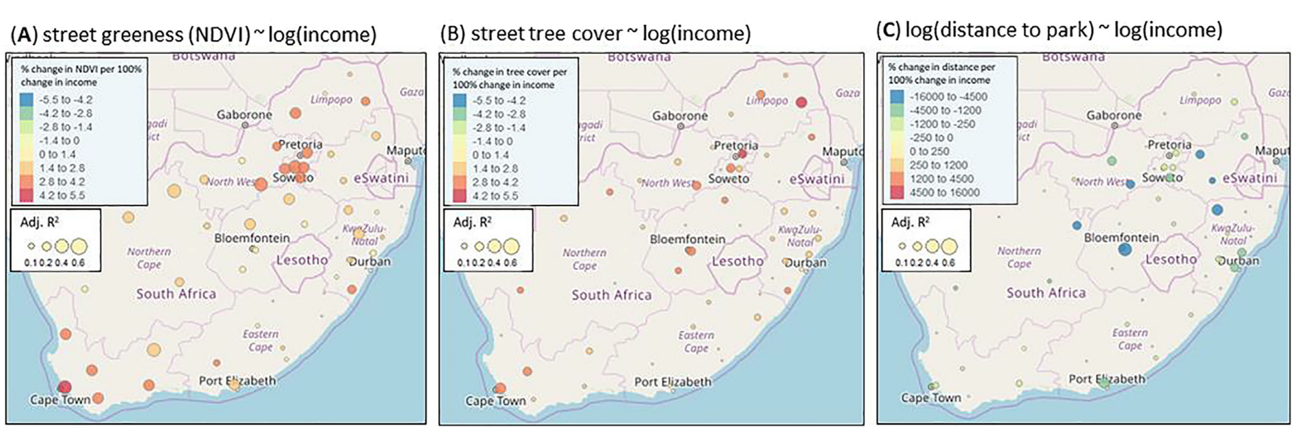

Fig. 5. Map displaying the slope (colour scale) and adjusted R^2 (size scale) for the linear regression of green infrastructure variables on per capita income. A separate linear model was performed for each municipal district (see Fig. 1), and points reflect the municipality centroids. The reader can interpret these values as the slope and fit of the linear trend lines plotted in Fig. 3 except here they are stratified by district municipality and not race. The slopes of trends are displayed as percentage changes in dependent variables per 100% change in per capita income. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

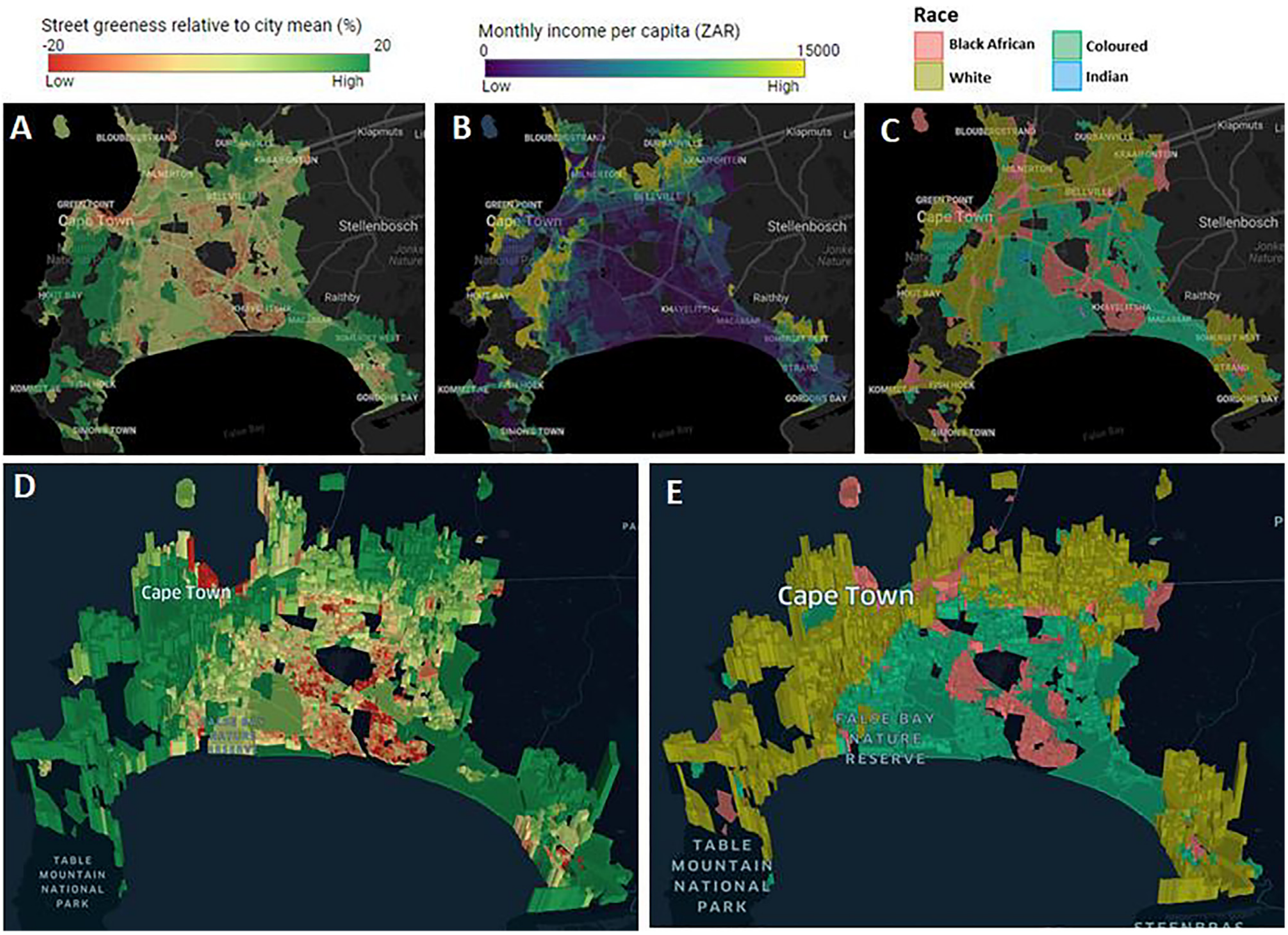

Fig. 6. Maps of census tracts in the City of Cape Town district municipality. Census tracts are coloured by relative street greenness (A, D), income (B) and race (C, E). The height of census tracts in D and E represents income. Empty space within the city represents non-residential areas that were not accounted for in the 2011 census.

part of the city – this is tightly coupled to race in South Africa, and the path dependency of the previous conditions (e.g. wealth inequality) means that it is harder to break away from these low levels of income. Despite substantial increases in income gains among all race groups, the majority of the Black population still falls far below the median income (Gradín, 2014). Third, the government development of low-cost housing in South Africa often includes little provision for green spaces and green infrastructure (McConnachie & Shackleton, 2010). Given the race and income dynamics in South Africa (Fig. 5), and income/race and green infrastructure outcomes (Figs. 7 and 8), it is not difficult to imagine how unequal distribution of green infrastructure has been unchanged in the last 25 years.

The inequalities in access to green infrastructure are mirrored in both private and public urban areas. For a doubling of income, tree cover increased by 3.5% in private gardens and 2.7% in public street verges and parks. This relationship holds across race categories, although is strongest for census tracts with predominantly White residents. The discrepancies in tree cover are notable because urban trees offer some distinct ecosystem services over general and open green spaces that include shading and thermal stress mitigation, air quality improvement and aesthetic value (Roy et al., 2012; Säumel et al., 2016). Others have also found a similar socio-economic bias occurring where tree-cover is lower on both public parkland and in private residential yards in socio-economically disadvantaged neighbourhoods in Brisbane (Shanahan et al., 2014) and in Montreal but here disparities were more substantial in public street vegetation than private land (Pham et al., 2012). In Sheffield in the UK, parks were accessible to disadvantaged groups, but these disadvantaged neighbourhoods had lower access to private garden space (Barbosa et al., 2007).

It is important to note that there are many census tracts without any parks at all (91%), and these census tracts report monthly incomes that are on average 82% less than those with parks. This illustrates that living in close proximity to public parks is a luxury afforded to wealthier citizens. This is also a double blow to poor urban households who are both less likely to have access to private green areas or yard space, and live further from public green areas, and by implication, have even fewer opportunities to experience nature. This mirrors public green infrastructure access in many other cities around the world (Heynen et al., 2006; Rigolon, Browning, Li, et al., Rigolon, Browning, & Jennings (2018), 2018), where disadvantaged and lower income groups are deprived benefit from the suite of ecosystem services provided from both private and public green infrastructure (Escobedo et al., 2011), illustrating the multiple ways in which access is stratified by income and race (Wolch et al., 2014, Kabisch and Haas, 2014). Access to public green infrastructure and nature experiences has been linked to social and psychological wellbeing (Larson et al., 2016), community cohesion (Weinstein et al., 2015) and resilience (Wolch et al., 2014), and greener residential areas have also been linked to enhanced social cohesion, physical activity and stress reduction (Groenewegen et al., 2012). As lower access to green infrastructure disproportionately affecting Black-African, Coloured and Indian census tracts, the distributional aspects of environmental justice are highlighted here (Low, 2013; Kabisch & Haase, 2014). In fact, socio-economic inequalities in access to green infrastructure can be both a symptom of, and also exacerbate disadvantages of marginalized residents (Heynen et al., 2006). In South Africa, the historical and contemporary neglect of providing adequate public spaces in Black-African, Coloured and Indian urban areas, coupled with chronic levels of poverty in urban areas may reinforce these

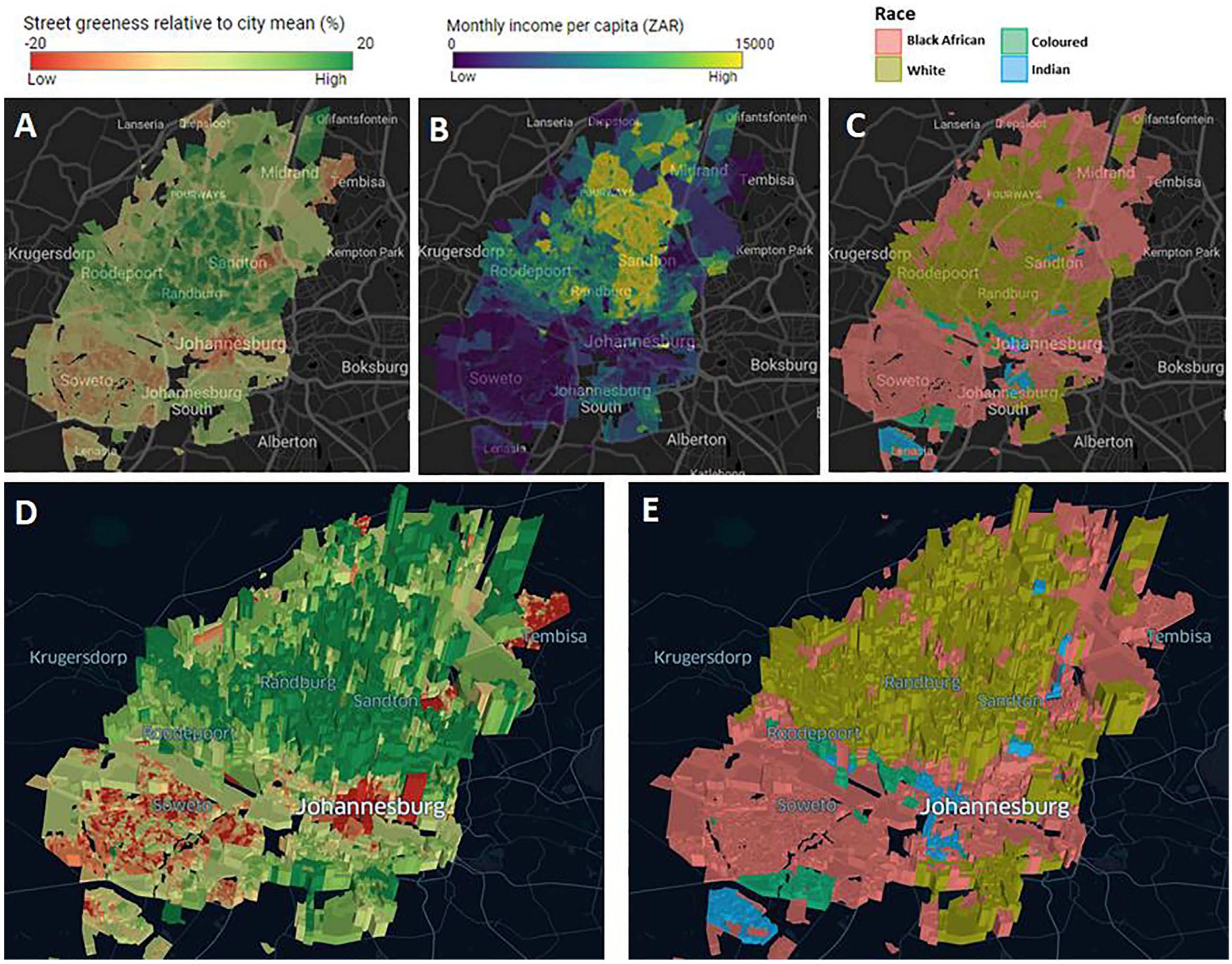

Fig. 7. Maps of census tracts in the City of Johannesburg district municipality. Census tracts are colored by relative street greenness (A, D), income (B) and race (C, E). The height of census tracts in D and E represents income. Empty space within the city represents non-residential areas that were not accounted for in the 2011 census.

inequities further (Harrison, 2008; McConnachie & Shackleton, 2010).

The governance context since the change in political order provides cues for interpreting these results. Apartheid spatial geography has remained largely unchanged (Western Cape Government, 2016), and green infrastructure inequality has worsened with the influx of poor rural migrants to towns and cities (Harrison, 2008). There has also been long-standing misalignment between the pre-1994 spatial planning and land use management and the Constitution of the Republic of South Africa (1996). This has been corrected by the national Spatial Planning and Land Use Management Act (SPLUMA, Act 16 of 2013) which provides legislative priority to equitable access to green infrastructure which has been a national priority from early post-Apartheid (NDPC, 1999; New Urban Development Framework of 2009). The policy context is now also aligned to the United Nation's Sustainable Development Goals (SDGs), with equal access to public green infrastructure to redress spatial inequalities – and emphasizing vulnerable groups and efforts to increase public green spaces as spaces of social inclusion and cohesion. Our analysis cannot account for any changes that might take place due to the SPLUMA due to its recent implementation. However, our results clearly indicate that settlements throughout South Africa targeted for subsidized housing development have a backlog of green infrastructure inequality, thus highlighting the need for effective implementation of SPUMLA going forward.

Indeed, the deepening entrenchment of inequality in access to urban green infrastructure may also be attributed to inadequate implementation of urban greening initiatives. Most smaller municipalities have low financial, staff and skill capacities to support urban green infrastructure development and maintenance. The cooperation between government departments and other entities that could aid greening programs is largely lacking (Chishaleshale et al., 2015; Gwedla & Shackleton, 2015), and is likely worsened by perceived perspectives that public green infrastructure is an optional luxury (Southworth, 2003). At the neighborhood level, challenges include vandalism, free-ranging livestock damaging green spaces and trees, and how community members relate to urban green programs and how benefits are perceived (Shackleton et al., 2018). Given the complexity of barriers to green infrastructure development, some have noted that the implementation of legislation should focus on creating partnerships across levels of government and on the synergies between sustainability outcomes and socio-economic development (Heynen et al., 2006).

The use of satellite remote sensing with open-access data to measure green infrastructure distributions in urban areas provides scope for ongoing monitoring and accountability of government greening policies. We were able to detect decadal changes in neighborhood greenery using the Landsat data archive and relate this to changes in national policy agendas. An improvement on our work could be to distinguish urban expansion within census tracts and thus disentangle development from 'browning' trends. It would also be more precise to account for changes in census tract geometries and population demographics over time so as to avoid attributing greening and browning

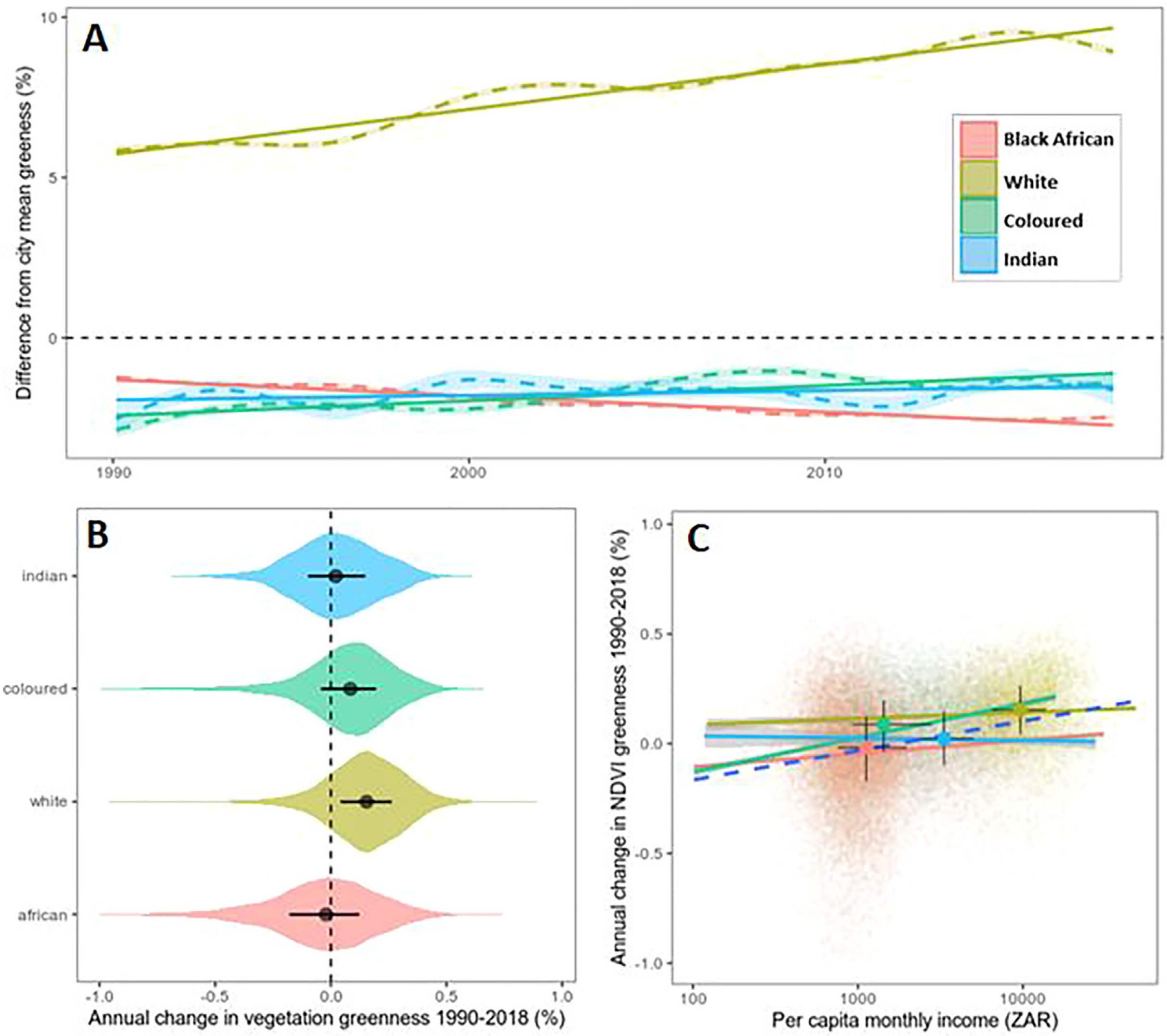

Fig. 8. Trajectories in neighborhood greenness (relative to city means) are fitted with linear trend line (solid lines) and generalized additive model lines (dashed) for each race category (A). The distribution of regression line slopes (i.e. slope of linear trend line in A) per census tract are displayed using a violin plot with data medians and interquartile ranges plotted with dots and horizontal bars (B). The regression line slopes are plotted against log-transformed per capita monthly income (C). Data points represent census tracts and are faded to highlight densities. Solid-fill points with black vertical and horizontal bars indicate data medians and quantile ranges, respectively. A dashed linear trend line is fitted through all points along with coloured linear trend lines for each race category. The reader is encouraged to consult Figs. S2 and S3 for a visual illustration of these trajectories.

trends to the wrong socioeconomic categories. With higher resolution satellites such as Sentinel 2, we have the ability to map green infrastructure with more accuracy and detail. This may open up potential to provide national accounts of more nuanced aspects of urban green infrastructure such as shape, structure and function. This data can also act as an important supplement to crowdsourced geographic information on urban green spaces (OpenStreetMap; OSM) which has known quality issues that may lead to biased maps of green infrastructure distribution (Haklay, 2010; Sehra et al., 2013). Indeed, less affluent areas often contain less formal, small green spaces which may not be mapped by OSM and which may have exacerbated the inequities recorded in our analysis. In this way, our satellite-based analysis played an important role in corroborating trends evident in OSM park distributions. We also acknowledge that the fine grain spatial scale (census tract with mean size 0.49 km^2) of our analysis may have inflated the number of data points with no parks and tree cover, and future studies should consider using a range of spatial scales in their analysis of green infrastructure inequity (Mears & Brindley, 2019).

Nevertheless, mapping fine-scale nuances in green space composition (trees vs open space), shape and size becomes important when linking green infrastructure accounts to ecosystem services provision and demand. For example, park shape and structural composition are important factors determining the aesthetic value attributed to them (Grahn & Stigsdotter, 2010). The demand for ecosystem services derived from green infrastructure depends largely on the cultural and socio-economic context of the urban area. Further understanding is required to assess perceptions of access to public urban green infrastructure and how Eurocentric public space designs may exclude already disadvantaged groups and their particular cultural ontologies of nature (Cocks & Shackleton, in press). Another aspect that warrants further attention is how the quality of green space shapes landscapes of fear and safety in urban areas and consequently access, as authors have documented concerns that woody vegetation provides cover for criminal activity (e.g. Perry et al., 2018; Adegun, 2018). We also require research toward understanding the structural processes that shape and maintain inequity in access to both private and public urban green infrastructure (Ernstson, 2013; Heynen et al., 2006). Therefore, integrating remote sensing data with context specific understandings of how local residents experience and value green infrastructure may be an important addition to urban planning workflows.

5. Conclusion

The clear links between urban green infrastructure and human wellbeing implies that equitable access and distribution of quality urban nature is a matter of human rights. We find that the legacy of Apartheid and socio-economic segregation has entrenched and reinforced inequalities in access to green infrastructure over urban South Africa. The burden of responsibility lies in the hands of both government and individuals given that this inequity is mirrored in both private and public space across virtually all South African municipalities and that it has not changed, but worsened since the end of Apartheid. It is often a challenge for the government to allocate budget to urban greening initiatives in light of larger socio-economic development concerns. However, there is sufficient evidence, alluded to in the Sustainable Development Goals, to show that the ecosystem services derived from green infrastructure are fundamental for socio-economic development and general human wellbeing. Therefore any instruments of economic development as well as redistributive justice would do well to include urban greening agendas to dismantle the racial, economic and green Apartheid in South African cities. Finally, the use of satellite remote sensing for monitoring urban greening initiatives and spatial inequalities provides scope for social justice advocates and civil society to hold governments accountable. Future applications should consider how inequalities vary with coarser spatial scales and attempt to consider how perceptions and valuation of green infrastructure quality can be incorporated in a spatially-explicit manner. The detailed geographical data presented in this manuscript is publicly available for those wishing to identify areas in greatest need of greening or to conduct further research.

Declaration of Competing Interest

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

Acknowledgements

VAM's time was supported by a grant from the Swedish Research Council (VR 2017-06337). CMS contribution was sponsored by the South African Research Chairs Initiative of the Dept of Science and Innovation and the National Research Foundation of South Africa (Grant No. 84379). Any opinion, finding, conclusion or recommendation expressed in this material is that of the author and the NRF does not accept any liability in this regard.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2020.103889.

References

Adegun, O. B. (2017). Green infrastructure in relation to informal urban settlements. *Journal of Architecture and Urbanism, 41*(1), 22–33. https://doi.org/10.3846/20297955.2017.1296791.

Adegun, O. B. (2018): When green is grievous: downsides in human-nature interactions in informal urban settlements. Journal of Urbanism: International Research on Placemaking and Urban Sustainability. doi: 10.1080/17549175.2018.1470102.

Amrhein, V., Greenland, S., & McShane, B. (2019). Scientists rise up against statistical significance.

Astell-Burt, T., & Feng, X. (2019). Does sleep grow on trees? A longitudinal study to investigate potential prevention of insufficient sleep with different types of urban green space. 100497–100497 *SSM - Population Health*. https://doi.org/10.1016/j.ssmph.2019.100497.

Balbi, S., Selomane, O., Sitas, N., Blanchard, R., Kotzee, I., O'Farrell, P., & Villa, F. (2019). Human dependence on natural resources in rapidly urbanising South African regions. *Environmental Research Letters, 14*(4), Article 044008. https://doi.org/10.1088/1748-9326/aafe43.

Barbosa, O., Tratalos, J. A., Armsworth, P. R., Davies, R. G., Fuller, R. A., Johnson, P., & Gaston, K. J. (2007). Who benefits from access to green space? A case study from Sheffield, UK. *Landscape and Urban Planning, 83*(2–3), 187–195.

Chishaleshale, M., Shackleton, C. M., Gambiza, J., & Gumbo, D. (2015). The prevalence of planning and management frameworks for trees and green spaces in urban areas of South Africa. *Urban Forestry & Urban Greening, 14*(4), 817–825. https://doi.org/10.1016/j.ufug.2015.09.012.

Cities and Biodiversity Outlook (2012). Secretariat of the Convention on Biological Diversity, Montreal, 64 pages.

Cocks, M., Alexander, J., Mogano, L., & Vetter, S. (2016). Ways of belonging: meanings of "nature" AMong Xhosa-speaking township residents In South Africa. *Journal of Ethnobiology, 36*(4), 820–841. https://doi.org/10.2993/0278-0771-36.4.820.

Cocks, M. L. & Shackleton, C. M. (Eds) (in press). Diversities of nature in cities: enriching belonging, wellbeing and bioculture. Earthscan/Routledge, London.

Davies, R. J. (1981). The spatial formation of the South African city. *GeoJournal, 2*, 59–72.

du Toit, M. J., Cilliers, S. S., Dallimer, M., Goddard, M., Guenat, S., & Cornelius, S. F. (2018). Urban green infrastructure and ecosystem services in sub-Saharan Africa. *Landscape and Urban Planning, 180*, 249–261. https://doi.org/10.1016/j.landurbplan.2018.06.001.

Ernstson, H. (2013). The social production of ecosystem services: A framework for studying environmental justice and ecological complexity in urbanized landscapes. *Landscape and Urban Planning, 109*, 7–17.

Escobedo, F. J., Kroeger, T., & Wagner, J. E. (2011). Urban forests and pollution mitigation: Analyzing ecosystem services and disservices. *Environmental Pollution, 159*(8), 2078–2087. https://doi.org/10.1016/j.envpol.2011.01.010.

Ferguson, M., Roberts, H. E., McEachan, R. R. C., & Dallimer, M. (2018). Contrasting distributions of urban green infrastructure across social and ethno-racial groups. *Landscape and Urban Planning, 175*, 136–148. https://doi.org/10.1016/j.landurbplan.2018.03.020.

Gerrish, E., & Watkins, S. L. (2018). The relationship between urban forests and income: A meta-analysis. *Landscape and Urban Planning, 170*, 293–308. https://doi.org/10.1016/j.landurbplan.2017.09.005.

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment, 202*, 18–27. https://doi.org/10.1016/j.rse.2017.06.031.

Gradín, C. (2014). Race and income distribution: Evidence from the USA, Brazil and South Africa. *Review of Development Economics, 18*(1), 73–92. https://doi.org/10.1111/rode.12070.

Groenewegen, P. P., van den Berg, A. E., Maas, J., Verheij, R. A., & de Vries, S. (2012). Is a green residential environment better for health? If so, why? Annals of the Association of American Geographers 102(5), 996–1003. JSTOR.

Grahn, P., & Stigsdotter, U., K (2010). The relation between perceived sensory dimensions of urban green space and stress restoration. *Landscape and urban planning, 94*, 264–275.

Gwedla, N., & Shackleton, C. M. (2015). The development visions and attitudes towards urban forestry of officials responsible for greening in South African towns. *Land Use Policy, 42*, 17–26. https://doi.org/10.1016/j.landusepol.2014.07.004.

Gwedla, N., & Shackleton, C. M. (2017). Population size and development history determine street tree distribution and composition within and between Eastern Cape towns, South Africa. *Urban Forestry & Urban Greening, 25*, 11–18. https://doi.org/10.1016/j.ufug.2017.04.014.

Gwedla, N., & Shackleton, C. M. (2019). Perceptions and preferences for urban trees across multiple socio-economic contexts in the Eastern Cape, South Africa. *Landscape and Urban Planning, 189*, 225–234. https://doi.org/10.1016/j.landurbplan.2019.05.001.

Haklay, M. (2010). How good is volunteered geographical information? A comparative study of OpenStreetMap and ordnance survey datasets. *Environment and Planning B: Planning and Design, 37*(4), 682–703. https://doi.org/10.1068/b35097.

Harrison, P. (2008). The origins and outcomes of South Africa's Integrated Development Plans. In S. Parnell, E. Pieterse, D. Wooldridge, D. Swilling, & M. van Donk (Eds.), Consolidating developmental local government: Lessons from the South African experience. UCT Press.

Heynen, N., Perkins, H. A., & Roy, P. (2006). The political ecology of uneven urban green space: The impact of political economy on race and ethnicity in producing environmental inequality in Milwaukee. *Urban Affairs Review*. https://doi.org/10.1177/1078087406290729.

Kabisch, N., & Haase, D. (2014). Green justice or just green? Provision of urban green spaces in Berlin, Germany. *Landscape and urban planning, 122*, 129–139.

Kambites, C., & Owen, S. (2006). Renewed prospects for green infrastructure planning in the UK. *Planning Practice & Research, 21*(4), 483–496. https://doi.org/10.1080/02697450601173413.

Kaoma, H., & Shackleton, C. M. (2015). The direct-use value of urban tree non-timber forest products to household income in poorer suburbs in South African towns. *Forest Policy and Economics, 61*, 104–112. https://doi.org/10.1016/j.forpol.2015.08.005.

Khumalo, N. Z., & Sibanda, M. (2019). Does urban and peri-urban agriculture contribute to household food security? An assessment of the food security status of households in Tongaat, eThekwini Municipality. *Sustainability, 11*(4), 1082. https://doi.org/10.3390/su11041082.

Kuruneri-Chitepo, C., & Shackleton, C. M. (2011). The distribution, abundance and composition of street trees in selected towns of the Eastern Cape, South Africa. *Urban Forestry & Urban Greening, 10*(3), 247–254.

Lachenbruch, P. A. (2002). Analysis of data with excess zeros. *Statistical Methods in Medical Research, 11*(4), 297–302.

Landry, S. M., & Chakraborty, J. (2009). Street trees and equity: evaluating the spatial distribution of an urban amenity. *Environment and Planning A*. https://doi.org/10.1068/a41236.

Larson, L. R., Jennings, V., & Cloutier, S. A. (2016). Public parks and wellbeing in urban areas of the United States. *PLOS ONE, 11*(4), Article e0153211. https://doi.org/10.1371/journal.pone.0153211.

Li, H., & Liu, Y. (2016). Neighborhood socioeconomic disadvantage and urban public green spaces availability: A localized modeling approach to inform land use policy. *Land Use Policy, 57*, 470–478. https://doi.org/10.1016/j.landusepol.2016.06.015.

Li, F., Wang, X., Liu, H., Li, X., Zhang, X., Sun, Y., & Wang, Y. (2018). Does economic development improve urban greening? Evidence from 289 cities in China using spatial regression models. *Environmental Monitoring and Assessment, 190*(9), 541. https://doi.org/10.1007/s10661-018-6871-4.

Livesley, S. J., McPherson, G. M., & Calfapietra, C. (2016). The urban forest and ecosystem services: Impacts on urban water, heat, and pollution cycles at the tree, street, and city scale. *Journal of Environmental Quality, 45*(1), 119–124. https://doi.org/10.2134/jeq2015.11.0567.

Lovell, S. T., & Taylor, J. R. (2013). Supplying urban ecosystem services through multifunctional green infrastructure in the United States. *Landscape Ecology, 28*(8), 1447–1463. https://doi.org/10.1007/s10980-013-9912-y.

Low, S. (2013). Public space and diversity: Distributive. In G. Young, & D. Stevenson (Eds.). *procedural and interactional justice for parks* (pp. 295–310). Surrey: The Ashgate research companion to planning and culture, Ashgate Publishing.

Makakavhule, K. & Landman, K. (2020). Towards deliberative democracy through democractic governance and design of public spaces in the South African capital city, Tshwane. Urban Design International, https://doi.org/10.1057/s41289-020-00131-9.

McConnachie, M., & Shackleton, C. M. (2010). Public green space inequality in small towns in South Africa. *Habitat International, 34*(2), 244–248. https://doi.org/10.1016/j.habitatint.2009.09.009.

Mears, M., & Brindley, P. (2019). Measuring urban greenspace distribution equity: The importance of appropriate methodological approaches. *ISPRS International Journal of Geo-Information, 8*(6), 286.

Nero, B. F. (2017). Urban green space dynamics and socio-environmental inequity: Multiresolution and spatiotemporal data analysis of Kumasi, Ghana. *International Journal of Remote Sensing, 38*(23), 6993–7020. https://doi.org/10.1080/01431161.2017.1370152.

Nesbitt, L., Hotte, N., Barron, S., Cowan, J., & Sheppard, S. R. J. (2017). The social and economic value of cultural ecosystem services provided by urban forests in North America: A review and suggestions for future research. *Urban Forestry & Urban Greening, 25*, 103–111. https://doi.org/10.1016/j.ufug.2017.05.005.

Nesbitt, L., Meitner, M. J., Girling, C., Sheppard, S. R. J., & Lu, Y. (2019). Who has access to urban vegetation? A spatial analysis of distributional green equity in 10 US cities. *Landscape and Urban Planning, 181*, 51–79. https://doi.org/10.1016/j.landurbplan.2018.08.007.

Ogneva-Himmelberger, Y., Pearsall, H., & Rakshit, R. (2009). Concrete evidence & geographically weighted regression: A regional analysis of wealth and the land cover in Massachusetts. *Applied Geography, 29*(4), 478–487. https://doi.org/10.1016/j.apgeog.2009.03.001.

S Pauleit, S., Liu, L., Ahern, J., & Kaźmierczak, A. (2011). Multifunctional green infrastructure planning to promote ecological services in the city. https://doi.org/10.1093/acprof:oso/9780199563562.003.0033.

Perry, E. C., Moodley, V., & Bob, U. (2018). Open spaces, nature and perceptions of safety in South Africa: A case study of Reservoir Hills, Durban. *Alternation, 15*(1), 240–267.

Pettorelli, N., Vik, J. O., Mysterud, A., Gaillard, J.-M., Tucker, C. J., & Stenseth, N. Chr (2005). Using the satellite-derived NDVI to assess ecological responses to environmental change. *Trends in Ecology & Evolution, 20*(9), 503–510. https://doi.org/10.1016/j.tree.2005.05.011.

Pham, T.-T.-H., Apparicio, P., Séguin, A.-M., Landry, S., & Gagnon, M. (2012). Spatial distribution of vegetation in Montreal: An uneven distribution or environmental inequity? *Landscape and Urban Planning, 107*(3), 214–224. https://doi.org/10.1016/j.landurbplan.2012.06.002.

Posel, D. (2001). Race as common sense: racial classification in twentieth-century South Africa. African Studies Review 44(2), 87–113. JSTOR. https://doi.org/10.2307/525576.

Rigolon, A., Browning, H. E. M. M., Lee, K., & Shin, S. (2018). Access to urban green space in cities of the global south: a systematic literature review. *UrbanScience, 2*(3), https://doi.org/10.3390/urbansci2030067.

Rigolon, A., Browning, M., & Jennings, V. (2018). Inequities in the quality of urban park systems: An environmental justice investigation of cities in the United States. *Landscape and Urban Planning, 178*, 156–169. https://doi.org/10.1016/j.landurbplan.2018.05.026.

Riley, C. B., & Gardiner, M. M. (2020). Examining the distributional equity of urban tree canopy cover and ecosystem services across United States cities. *PLOS ONE, 15*(2), Article e0228499. https://doi.org/10.1371/journal.pone.0228499.

Rojas-Rueda, D., Nieuwenhuijsen, M. J., Gascon, M., Perez-Leon, D., & Mudu, P. (2019). Green spaces and mortality: A systematic review and meta-analysis of cohort studies. *The Lancet Planetary Health, 3*(11), e469–e477.

Roy, S., Byrne, J., & Pickering, C. (2012). A systematic quantitative review of urban tree benefits, costs, and assessment methods across cities in different climatic zones. *Urban Forestry & Urban Greening, 11*(4), 351–363.

RStudio Team (2020). RStudio: Integrated Development for R. RStudio, PBC, Boston, MA URL http://www.rstudio.com/.

Sandstro¨m, U. G. (2002). Green infrastructure planning in urban Sweden. *Planning Practice & Research, 17*(4), 373–385. https://doi.org/10.1080/02697450216356.

Sathyakumar, V., Ramsankaran, R., & Bardhan, R. (2019). Linking remotely sensed Urban Green Space (UGS) distribution patterns and Socio-Economic Status (SES) – A multiscale probabilistic analysis based in Mumbai, India. *GIScience & Remote Sensing, 56*(5), 645–669. https://doi.org/10.1080/15481603.2018.1549819.

Säumel, I., Weber, F., & Kowarik, I. (2016). Toward livable and healthy urban streets: Roadside vegetation provides ecosystem services where people live and move. *Environmental Science & Policy, 62*, 24–33.

Sehra, S. S., Singh, J., & Rai, H. S. (2013). Assessment of OpenStreetMap Data – A review. *International Journal of Computer Applications, 76*(16), 17–20. https://doi.org/10.5120/13331-0888.

Shackleton, C. M., & Blair, A. (2013). Perceptions and use of public green space is influenced by its relative abundance in two small towns in South Africa. *Landscape and Urban Planning, 113*, 104–112. https://doi.org/10.1016/j.landurbplan.2013.01.011.

Shackleton, C. M., Blair, A., De Lacy, P., Kaoma, H., Mugwagwa, N., Dalu, M. T., & Walton, W. (2018). How important is green infrastructure in small and medium-sized towns? Lessons from South Africa. *Landscape and Urban Planning, 180*, 273–281. https://doi.org/10.1016/j.landurbplan.2016.12.007.

Shanahan, D. F., Lin, B. B., Gaston, K. J., Bush, R., & Fuller, R. A. (2014). Socio-economic inequalities in access to nature on public and private lands: A case study from Brisbane, Australia. *Landscape and Urban Planning, 130*, 14–23. https://doi.org/10.1016/j.landurbplan.2014.06.005.

Shen, Y., Sun, F., & Che, Y. (2017). Public green spaces and human wellbeing: Mapping the spatial inequity and mismatching status of public green space in the Central City of Shanghai. *Urban Forestry & Urban Greening, 27*, 59–68. https://doi.org/10.1016/j.ufug.2017.06.018.

Simon, D., & Christopher, A. J. (1984). The apartheid city. *Area, 16*(1), 60–62.

Southworth, B. (2003). Urban design in action: The City of Cape Town's Dignified Places Programme – implementation of new public spaces towards integration and urban regeneration in South Africa. *Urban Design International, 8*(3), 119–133. https://doi.org/10.1057/palgrave.udi.9000097.

Tucker, C. J. (1979). Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment, 8*(2), 127–150. https://doi.org/10.1016/0034-4257(79)90013-0.

Twohig-Bennett, C., & Jones, A. (2018). The health benefits of the great outdoors: A systematic review and meta-analysis of greenspace exposure and health outcomes. *Environmental research, 166*, 628–637.

Venter, Z. S., Cramer, M. D., & Hawkins, H.-J. (2018). Drivers of woody plant encroachment over Africa. *Nature Communications, 9*(1), https://doi.org/10.1038/s41467-018-04616-8.

Venter, Zander S, Scott, S. L., Desmet, P. G., & Hoffman, M. T. (2020). Application of Landsat-derived vegetation trends over South Africa: Potential for monitoring land degradation and restoration. *Ecological Indicators, 113*, Article 106206. https://doi.org/10.1016/j.ecolind.2020.106206.

Wang, Q., & Lan, Z. (2019). Park green spaces, public health and social inequalities: Understanding the interrelationships for policy implications. *Land Use Policy, 83*, 66–74. https://doi.org/10.1016/j.landusepol.2019.01.026.

Watkins, S. L., & Gerrish, E. (2018). The relationship between urban forests and race: A meta-analysis. *Journal of Environmental Management, 209*, 152–168. https://doi.org/10.1016/j.jenvman.2017.12.021.

Weinstein, N., Balmford, A., DeHaan, C. R., Gladwell, V., Bradbury, R. B., & Amano, T. (2015). Seeing community for the trees: The links among contact with natural environments, community cohesion, and crime. *BioScience, 65*(12), 1141–1153. https://doi.org/10.1093/biosci/biv151.

Western Cape Government. (2016). Department of Environmental Affairs and Development Planning. Land use planning law reform in the Western Cape. The road to transformation.

Wolch, J. R., Byrne, J., & Newell, J. P. (2014). Urban green space, public health, and environmental justice: The challenge of making cities 'just green enough'. *Landscape and Urban Planning, 125*, 234–244. https://doi.org/10.1016/j.landurbplan.2014.01.017.

Wüstemann, H., Kalisch, D., & Kolbe, J. (2017). Access to urban green space and environmental inequalities in Germany. *Landscape and Urban Planning, 164*, 124–131.