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Urban green space exposure is low and unequally distributed in an Amazonian metropolis

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Abstract

Urban green spaces are important for interactions between people and non-human nature, with their associated health and well-being impacts, although their distribution is often unequal. Here, we characterize the distribution of urban green spaces in Belém, the largest city in the Amazon Delta, and relate it to levels of human development and social vulnerability across the city; this is the first such analysis to be conducted for a Brazilian Amazon city. We first conducted a supervised maximum likelihood classification of images at 5–m spatial resolution taken in 2011 by the RapidEye satellites to map the distribution of green space across the urban part of the municipality of Belém. We then calculated two measures of urban green space at the level of human development units: the proportional cover of vegetation (Vegetation Cover Index; VCI) and the area of vegetation per person (Vegetation Cover per Inhabitant; VCPI), and we used hurdle models to relate them to two measures of socioeconomic status: the Social Vulnerability Index and the Human Development Index, as well as to demographic density. We find that VCI and VCPI are higher in more socially vulnerable areas. We explain how this pattern is driven by historical and ongoing processes of urbanization, consider access to urban green space and the benefits to human health and well-being and discuss equitable planning of urban green space management in the Amazon. We conclude that the assumption that urban greening will bring health benefits risks maintaining the status quo in terms of green exclusion and repeating historical injustices via displacement of socially vulnerable residents driven by demand for access to urban green spaces.

Introduction

The global human population is expected to reach 9.4–10 billion by the year 2050, and 68% of these people are expected to live in urban areas by 2050 (United Nations Department of Economic and Social Affairs 2019, 2022). Urban life can bring many benefits, including better access to education, healthcare and social services and cultural and political activities (Dye 2008), but urbanization leads to lower levels of contact with non-human nature (Soga & Gaston 2016), with accompanying impacts on mental and physical health and well-being (Marselle et al. 2021). Urban green spaces such as gardens, parks and forest fragments are important spaces for interactions between people and non-human nature, and these have health and well-being benefits (Tzoulas et al. 2007, Bertram & Rehdanz 2015, Hedblom et al. 2019, Hunter et al. 2019, Rojas-Rueda et al. 2019, Reyes-Riveros et al. 2021). They are also important for regulating ecosystem services such as air purification and carbon sequestration and for the mitigation of the negative impacts of urbanization, such as the heat-island effect (Bowler et al. 2010, McPherson et al. 2013, Aram et al. 2019, Hewitt et al. 2020). The importance of these areas is also reflected in international agreements such as the United Nations' Sustainable Development Goals, where Target 11.7 explicitly calls for the provision by 2030 of 'universal access to safe, inclusive and accessible, green and public spaces, particularly for women and children, older persons and persons with disabilities' (United Nations 2015).

However, globally, the distribution of these beneficial urban green spaces remains unequal, with larger, better and more accessible green spaces often being situated in more affluent areas, whereas the coverage of green space is lower in less affluent areas (Boone et al. 2009, Hoffimann et al. 2017, Rigolon et al. 2018, Mears et al. 2019, Klompmaker et al. 2023). This inequitable distribution of urban green space is a public health problem that is strongly associated with social inequalities (World Health Organisation 2010). The literature on the distribution of and access to urban green spaces in the Global South has grown (Rigolon et al. 2018), but the body of research focused on the Global North is far greater (Van den Berg et al. 2015, Nagendra et al. 2018, Nawrath et al. 2021, Rigolon et al. 2021, Pinto et al. 2022). Importantly, exposure to urban green spaces is lower in cities of the Global South, and the inequality of exposure is almost twice that of cities of the Global North (Chen et al. 2022). Furthermore, the health and well-being benefits of urban green space are context dependent, and patterns found in the Global North may not hold for the Global South (Amano et al. 2018, Nawrath et al. 2021, Nawrath et al. 2022).

Knowledge about urban sustainability in the Global South remains relatively sparse, and key areas such as the Amazon remain greatly under-studied (Nagendra et al. 2018, Rigolon et al. 2018). The Amazon is one of the most biodiverse places on the planet (Antonelli & Sanmartín 2011, Silva et al. 2005), and at the municipal level most of the Brazilian Amazon region has relatively high levels of green infrastructure (Silva & Prasad 2019). However, its population is increasingly urban: some 76% of the population of the Brazilian Amazon lives in urban areas (Fajardo et al. 2023), where vulnerabilities to external stressors such as climate change are increased (Fischer et al. 2012). Very few studies have specifically analysed the availability of urban green space in Amazonian cities or the implications of this for biodiversity and human health and well-being (Santos et al. 2013, Lapola et al. 2019, Espinoza et al. 2023), and ours is the first study to relate the distribution of urban green space to levels of socioeconomic vulnerability within an Amazonian city.

The process of urbanization in the Brazilian Amazon has been quite distinct from that of other regions of Latin America, owing in part to difficulties in access that have led to the establishment of the main urban centres along waterways that have acted as the main routes for transporting people and goods (Corrêa 1987). Belém was the first urban centre established in the Amazon, chosen for its strategic position at the mouth of the Amazon Basin (Corrêa 1987, Cardoso & Neto 2013). It remains the largest city in the Amazon delta and the second largest, after Manaus, in the Amazon. Its growth and expansion have followed cycles driven by different processes, including the establishment of the Companhia Geral de Comércio do Gr*ã*o-Pará e Maranh*ã*o in 1755, with a view to incentivizing the production of commodities such as cotton, rice and cacao for export to Europe, and the Amazon rubber cycle between the mid-nineteenth century and the end of the First World War (Corrêa 1987, Cardoso & Neto 2013, Ponte 2015). The period from the end of the Second World War onwards is marked by significant population growth and urban remodelling, with consolidation of the occupation of the Primeira Legua Patrimonial (essentially the centre of the city) and relocation of the lower-income population to more peripheral parts of the city or into areas of irregular occupation known locally as *baixadas*, which are equivalent to what the international community frequently calls *favelas* or slums (Corrêa 1987, Cardoso & Neto 2013, Ponte 2015).

Here, we aimed to characterize the distribution of urban green spaces in Belém using images from RapidEye satellites with a spatial resolution of 5 m that characterize an area as vegetated based on monitoring of photosynthetic activity. We also aimed to relate this distribution to levels of human development and social vulnerability across the city. Because of there being more vulnerable populations in peripheral areas of the city, where remnant vegetation cover is likely to be higher, we expected to find more cover of green space and more green space per inhabitant where social vulnerability is higher and human development lower. This is the opposite relationship to that often seen in Europe and North America, where larger and higher-quality green spaces are closer to more affluent neighbourhoods (Boone et al. 2009, Hoffimann et al. 2017, Klompmaker et al. 2023). We discuss access to urban green space in Belém and its benefits to human health and well-being, as well as the implications for conservation in and around large urban centres in the Amazon.

Materials and methods

Study area

Belém is the capital of the Amazonian state of Pará, in the northern region of Brazil (latitude 01°27'21" S, longitude 48°30'16" W; Fig. 1a–c). It has 1.3 million inhabitants as of 2022, more than double the population in 1970, and it extends across 1059.45 km^2, giving it an overall demographic density of 1230.23 inhabitants/km^2 (IBGE 2022). However, this density is not uniform. The metropolitan region, which includes the municipality of Belém and six neighbouring municipalities, has a poor to very poor quality of life according to the Urban Well-Being Index (IBEU), with an index of 0.251 on a scale of 0–1 (Ribeiro & Ribeiro 2016). While there are some large green spaces in Belém, only c. 15% of the original vegetation cover of the municipality remains, owing at least in part to a disorganized process of urban expansion (Bordalo 2006, Prefeitura Municipal de Belém 2020). As a unit of analysis, we chose the 159 urban human development units (HDUs; territorial spaces within metropolitan areas that can be part of a neighbourhood, a complete neighbourhood or, in some cases, even a small municipality) that make up the municipality of Belém because they are the smallest sampling unit for which data on multiple socioeconomic and quality-of-life indicators are available. Their limits are defined by socioeconomic homogeneity, and they are formed based on census sectors (Sales Barros et al. 2017). The average density across the 159 HDUs is 12 997.25 inhabitants/km^2, but this varies between 48.63 and 107 496.66 inhabitants/km^2 (Fig. S1 & Supplementary Materials S2).

The current socio-spatial configuration of any city is a product of its history and the processes of urban expansion and consolidation, but in the case of Belém the city's changing relationships with water and *várzea* (floodplain forests) is important. In the city centre, as early as the eighteenth century, some floodplain forests were being drained to make way for urban infrastructure (Cardoso & Neto 2013), including one of Belém's most iconic urban green spaces, the Praça Dom Pedro II in the historic centre, which sits on top of the first flooded area to be drained for urbanization in the city (Cardoso & Neto 2013). However, drainage required a lot of resources, and such floodplain forests were largely avoided for urban development until the mid-twentieth century (Cardoso & Neto 2013). On the other hand, in less politically and economically important regions, traditional populations of *ribeirinhos* occupied the floodplain forest and subsisted via traditional uses of natural resources, including connection to the river as a means of transport and access to resources (Cardoso & Neto 2013). In the twentieth century, population growth accelerated, and economic decline contributed to a strong wave of rural to urban migration that contributed to the occupation of 40% of the city centre's floodplain forests by low-income, socially vulnerable populations in *baixadas* (Cardoso & Neto 2013, Braga & Gouveia 2020). From the 1960s onwards, plans were put in place to help the city centre to 'recuperate', which led to the relocation of low-income populations from the city centre *baixadas* to purpose-built housing estates in more peripheral parts of the city to make way for the lucrative real estate market that financed draining of the floodplain forests in areas such as the Bacia das Armas close to the Port of Belém, between the Reduto, Nazaré and Umarizal neighbourhoods.

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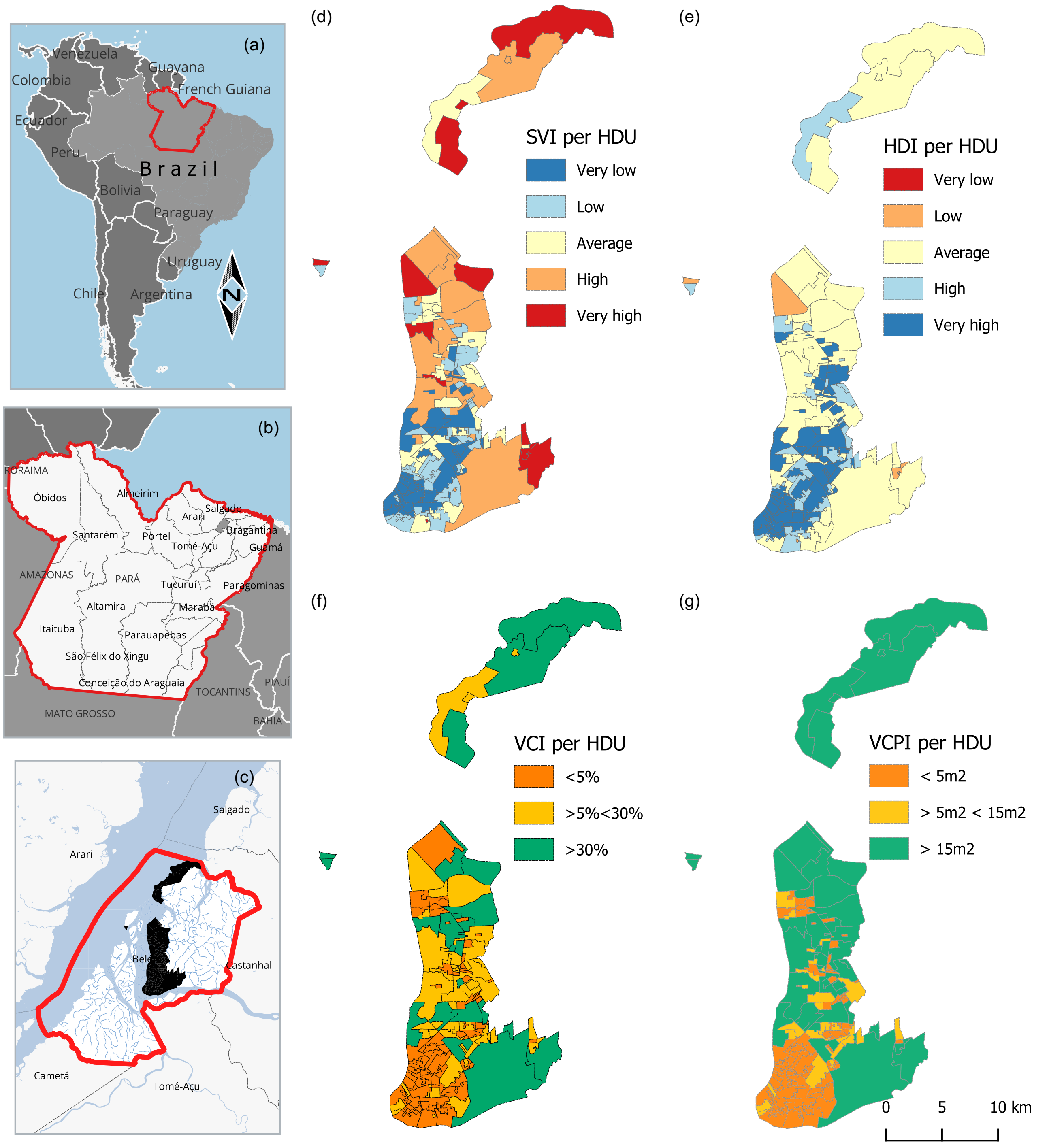

Figure 1. Map of (a–c) the location of the study area within the metropolitan region of Belém, the state of Pará and South America, and maps of human development unit (HDU) levels of (d) the Social Vulnerability Index (SVI), (e) the Human Development Index (HDI), (f) the Vegetation Cover Index (VCI) and (g) the Vegetation Cover per Inhabitant (VCPI).

Calculating urban green space distribution

We here define urban green space as a set of intra-urban areas that have vegetation, tree (native and/or introduced), shrub or herbaceous coverage, including formal parks, greenways, forest reserves and other natural areas, gardens, informal open spaces and privately owned green spaces accessible to fee-paying members of the public that can be used for recreation, socialization or other community activities (Bertini et al. 2016, Taylor & Hochuli 2017). Thus, unlike some authors, we do not include street trees in our analyses because we intended to focus on 'usable' green space that serves recreation, socialization or other community purposes. Some large green spaces were removed from the data as they were football pitches and thus not included in the definition of green space used here.

To map the distribution of urban green space in Belém, we used images of the year 2011 from the RapidEye satellites at 5–m spatial resolution and a scale of 1:10 000 (see Tables S1 & S2 & Supplementary Materials S1) obtained from the Geo-Catálago digital platform hosted by the Ministério do Meio Ambiente

(MMA; Brazilian Ministry for the Environment; http://geocatalogo.mma.gov.br/index.jsp). The 2011 data matched the time period of the most recently available socioeconomic data for Brazil from the 2010 census, which forms the basis of the indices used as explanatory variables here. The RapidEye satellite sensors detect five spectral bands: blue (440–510 nm), green (520–590 nm), red (630–690 nm), red edge (690–730 nm) and near-infrared (760–880 nm).

We carried out a supervised maximum likelihood classification (MAXVER) of these images using the OTB BAYES algorithm in the Orfeo ToolBox (https://www.orfeo-toolbox.org/CookBook/recipes/pbclassif.html) in *QGIS* software version 3.22.11 (QGIS Development Team 2022). Firstly, compositions of false-colour bands were generated to highlight vegetation using a combination of bands 5 (near-infrared), 4 (red edge) and 3 (red). These images were then submitted to supervised classification, which aimed to associate each pixel of the image with a spectral pattern, with those associated with the presence of vegetation identified by representative training samples (Moreira 2011). We used the MAXVER parametric classifier, which classifies the pixel clusters considering the weighting of the distances between the averages of the digital levels of the class defined in the selection. Algorithm performance in terms of correct classification of vegetation was evaluated based on estimated precision (1), recall (0.999681), F-score (0.99984) and Kappa index (0.998882). Subsequently, these data were vectorized (see Fig. S2 in Supplementary Materials S2), thus enabling the calculation of the area of vegetation in each HDU. The minimum mapping area for RapidEye satellite imagery is 0.25 ha, and thus we excluded any area of vegetation below 0.25 ha.

Measures of the distribution of green space

We used two distinct measures of the distribution of urban green space at the level of the HDUs in Belém. Firstly, we calculated the Vegetation Cover Index (VCI) as a measure of the provision of green space (Silva 2016, Silva et al. 2018) using Equation 1:

$$VCI_n = \frac{VC_n}{A_n} \times 100 \quad (1)$$

where VC_n is the area covered by vegetation in neighbourhood n and A_n is the total area of neighbourhood n. A VCI value above 30% in urban areas is considered sufficient for a high quality of life, a VCI of 5–30% is sufficient for a reasonable quality of life and a VCI below 5% is insufficient for a reasonable quality of life (Silva 2016, Silva et al. 2018).

We calculated the Vegetation Cover per Inhabitant (VCPI) as a measure of population pressure on green space (Silva 2016, Silva et al. 2018) using Equation 2:

$$VCPI_n = \Sigma VC_n / IH_n \quad (2)$$

where VC_n is the area covered by vegetation in neighbourhood n and IH_n is the total number of inhabitants of neighbourhood n. Thus, higher values of VCPI indicate that population pressure on green space is lower, and vice versa.

Socioeconomic data

To explore the relationship between the distribution of urban green space and socioeconomic conditions we used two indices for the year 2010, representing the most recent available data. The first is the Índice de Vulnerabilidade Social (Social Vulnerability Index; SVI) obtained from the Social Vulnerability Atlas developed by the Instituto de Pesquisas (IPEA; Institute for Economic and Applied Research; IPEA 2021). The second is the Índice de Desenvolvimento Humano (Human Development Index; HDI) obtained from the Brazilian Human Development Atlas developed by the IPEA in partnership with the United Nations Development Program and the Fundaçāo Joao Pinheiro (IPEA et al. 2021).

The SVI is calculated as the arithmetic mean of three sub-indices – urban infrastructure, human capital and income and work – on a scale from 0 to 1, where 0 corresponds to the ideal or desirable situation and 1 corresponds to the worst situation (IPEA 2021). The HDI also consists of three dimensions – longevity, education and income – and varies between 0 and 1, where values closer to 1 represent higher levels of human development and thus the ideal or desirable situation (IPEA et al. 2021). For both SVI and HDI, each sub-index is itself made up of a series of socioeconomic variables (see Table S3 & Supplementary Materials S3).

We also included the demographic density in each HDU as an explanatory variable and tested for an interaction between demographic density and the above socioeconomic indices.

Data analysis

As both the VCI data and VCPI are zero-inflated (27% of HDUs have zero vegetation cover), we used hurdle models to model the relationships between VCI and VCPI and between SVI and HDI. We first fitted logistic regressions to predict the probability of non-zero values of VCI and VCPI as a function of the SVI and the HDI. In both cases we included an additive term for demographic density, as the interaction was non-significant. We then fitted generalized linear models (GLMs) using a gamma distribution and log link to model the relationship between the non-zero values of VCI and the interaction between the SVI and demographic density and that between the HDI and demographic density, as well as a Gaussian distribution and log link to model the relationship between the non-zero values of VCPI and the SVI and the HDI. In both of the latter cases we included an additive term for demographic density, as the interaction was non-significant. Model residuals were plotted to check for normality, homoscedasticity of variance and highly influential data points. All analyses and model checks were implemented in the language *R* (R Core Team 2022), and the code used is provided in Supplementary Materials S4.

Results

Distribution of urban green spaces and social inequality in Belém

The VCI varied between 0% and 80.53% of each HDU (mean of 12.1%). Eighty-six of the 159 HDUs (54.08%) had levels of urban green space lower than that considered necessary for a reasonable quality of life, and more than half of these (46 HDUs) are in the city centre (Fig. 1f).

The spatial distribution of levels of development and levels of social vulnerability reveal patterns of spatial social inequality in urban areas of the municipality of Belém. Specifically, the HDUs with very high levels of development (HDI > 0.8) and very low levels of social vulnerability (SVI < 0.2) were mostly concentrated in the city centre and along the central-eastern area (Fig 1d,e), and these in large part coincided with the areas of highest demographic density (Fig. S2). Indeed, four of the five HDUs with the highest values of development (HDI > 0.94) and five of the six HDUs with

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the lowest levels of social vulnerability (SVI < 0.1) were concentrated in four neighbourhoods of the city centre: Reduto, Nazaré, Batista Campos and Marco. The other HDU with a very high HDI and very low SVI was far from the city centre but is a closed condominium in the Parque Verde neighbourhood. On the other hand, three of the four HDUs with lowest levels of development (HDI < 0.6) and highest levels of social vulnerability (SVI > 0.58) were very far from the city centre, in the Brasília, Águas Lindas and Cotijuba neighbourhoods. The fourth HDU with very low levels of development and very high SVI is a *baixada* in the Condor neighbourhood of the city centre.

Distribution of urban green space in relation to socioeconomic conditions

The probability of non-zero levels of VCI in Belém increased significantly with levels of social vulnerability (GLM, $\beta = 8.461$, SE = 2.202, $p < 0.001$; Fig. 2a) and decreased with levels of human development (GLM, $\beta = -12.08$, SE = 2.773, $p < 0.001$; Fig. 2b), indicating that a total lack of urban green space was more likely where social vulnerability was lower. However, the probability of non-zero levels of VCI also decreased significantly with increasing demographic density (GLM, $\beta_{SVI} = -0.00024$, SE = 0.000019, $p < 0.001$; GLM, $\beta_{HDI} = -0.000252$, SE = 0.000019, $p < 0.001$; Fig. 2c), indicating that a total lack of urban green space was more likely where demographic density was higher.

For HDUs with non-zero levels of vegetation cover we found a significant interaction between increasing levels of social vulnerability and demographic density in relation to the increase in the VCI (GLM, $p < 0.05$; Fig. 3a). The relationship between the VCI and SVI was always positive, but the overall levels of vegetation cover were lower where demographic density was higher (Fig. 3a). We also found a significant interaction between greater levels of the HDI and demographic density at lower levels of the VCI (GLM, $p < 0.05$; Fig. 3b). The relationship between VCI and HDI was always negative, but the VCI values were lower where demographic density was higher, and at low levels of demographic density the relationship was less apparent (Fig. 3b). Thus, there was more urban green space in more socially vulnerable areas, particularly where population density was also low.

This result is exemplified by the contrast between neighbourhoods in the city centre such as Reduto, Nazaré and Batista Campos, all of which are made up of HDUs with high HDI values, very low SVI and VCI and values and high demographic density, and neighbourhoods that are far from the city centre such as Aurá, Paracuri and Itaiteua, which are made up of HDUs with very high social vulnerability, very low levels of both development and urban green space and relatively low demographic density.

VCPI varied between 0 and 15 962.36 m^2 per inhabitant, with 115 of the 159 HDUs (72%) falling below the minimum ideal of 15 m^2, of which most (89 HDUs) had very low amounts of urban green space per inhabitant (<5 m^2/inhabitant). These included all of the neighbourhoods in the city centre, but also many other areas far from the city centre (Fig. 1g).

For HDUs with non-zero levels of vegetation cover, the VCPI increased significantly with increasing SVI (GLM, $\beta = 4.079$, SE = 1.103, $p < 0.001$; Fig. 4a) and decreased significantly with increasing HDI (GLM, $\beta = -5.359$, SE = 1.397, $p < 0.001$; Fig. 4b). Although we found no significant interaction with SVI or HDI, the VCPI decreased significantly with increasing demographic density (GLM, $\beta_{SVI} = -0.00024$, SE = 0.000019, $p < 0.001$; GLM, $\beta_{HDI} = -0.000252$, SE = 0.000019, $p < 0.001$; Fig. 2c).

This result is exemplified by the contrast between peripheral neighbourhoods such as Brasília and Cotijuba, both of which have very high levels of social vulnerability and low demographic density, as well as more than 47 m^2 of green space per inhabitant, with city centre neighbourhoods such as Reduto, Nazaré and Batista Campos, which all have HDUs with very high levels of development, very low levels of social vulnerability, high demographic density and also less than 5 m^2 of green space per inhabitant.

Discussion

Despite its location in one of the world's most biodiverse regions, more than half of the urban HDUs in Belém have levels of green space lower than that deemed necessary by the United Nations for a reasonable quality of life, and almost three-quarters have less than the 15 m^2 of green space per inhabitant considered ideal by the Sociedade Brasileira de Arborização Urbana, of which the vast majority have less than 1 m^2 per inhabitant. The distribution of green spaces is not even across the urban area and is higher where levels of social vulnerability are higher, which is in contrast to the often-reported pattern of green space exposure in both the Global North and Global South, wherein larger and higher-quality green spaces are closer to more affluent neighbourhoods (Boone et al. 2009, Hoffimann et al. 2017, Rigolon et al. 2018, Mears et al. 2019, Klompmaker et al. 2023). However, our results add weight to increasing evidence that these patterns may not always hold in the Global South (Amano et al. 2018, Nawrath et al. 2021, Nawrath et al. 2022). In the case of Belém this is at least in part due to more socially vulnerable areas being located in peripheral parts of the city, in the urban–rural transition, where population density is lower. We used the most recently available census data, which means that our results reflect the distribution of urban green space and socioeconomic conditions from more than 10 years ago. However, the proportion of the population in urban versus rural areas of the metropolitan region, which includes the municipality of Belém and six neighbouring municipalities, has remained relatively constant over that time period (c. 96%), as has the proportional coverage of urban area (c. 11.5%) and vegetation (c. 55%; Gutierrez 2022), such that we do not expect that significant changes in urban green space distribution have occurred over that time that would be sufficient to qualitatively change our results.

The evidence for trends such as increased public health outcomes where there is more urban green space may not hold for poorer cities in the Global South where there are larger proportions of poor-quality green space, poor accessibility and different attitudes towards green spaces and their use (Amano et al. 2018). In line with this, we show that the quantity of green space is greater in more socially vulnerable areas of Belém, but these are also often areas in the urban–rural transition with low population densities and probably have remnant native vegetation with little infrastructure to facilitate their access or use. Indeed, while overall greenspace cover is lower, more affluent neighbourhoods in the centre of the city benefit from some of the most structured green spaces, such as the 15-ha Bosque Rodrigues Alves Botanic Gardens in the Marco neighbourhood, which is partly made up of an area of preserved native *terra firme* forest and represents one of the city's main spaces for leisure activities (Secretaria Municipal de Meio Ambiente de Belém 2020). Between the São Braz and Nazaré neighbourhoods, another 5.2 ha of urban green space is contained in Emilio Goeldi Zoo–Botanic Gardens. Utinga Camillo Vianna State Park is a protected area with well-structured walking trails and tourist infrastructure, including 4 km of tracks for walking or

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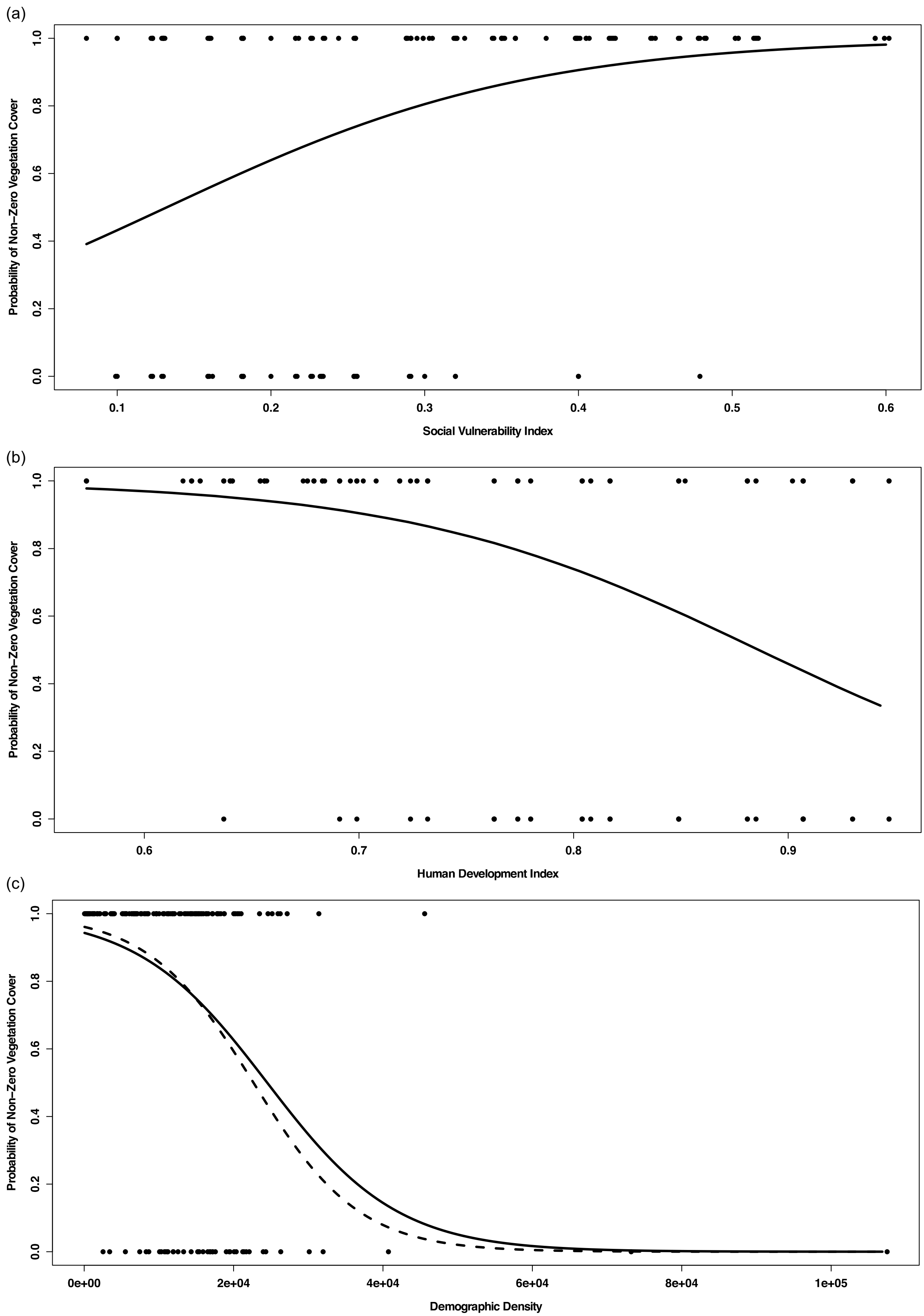

Figure 2. Probability of non-zero levels of vegetation cover in the Belém human development unit as a function of the (a) Social Vulnerability Index, where higher values represent more vulnerable people, (b) Human Development Index, where lower values represent more vulnerable people, and (c) demographic density (solid fitted lines modelled with Social Vulnerability Index, dashed fitted lines modelled with Human Development Index).

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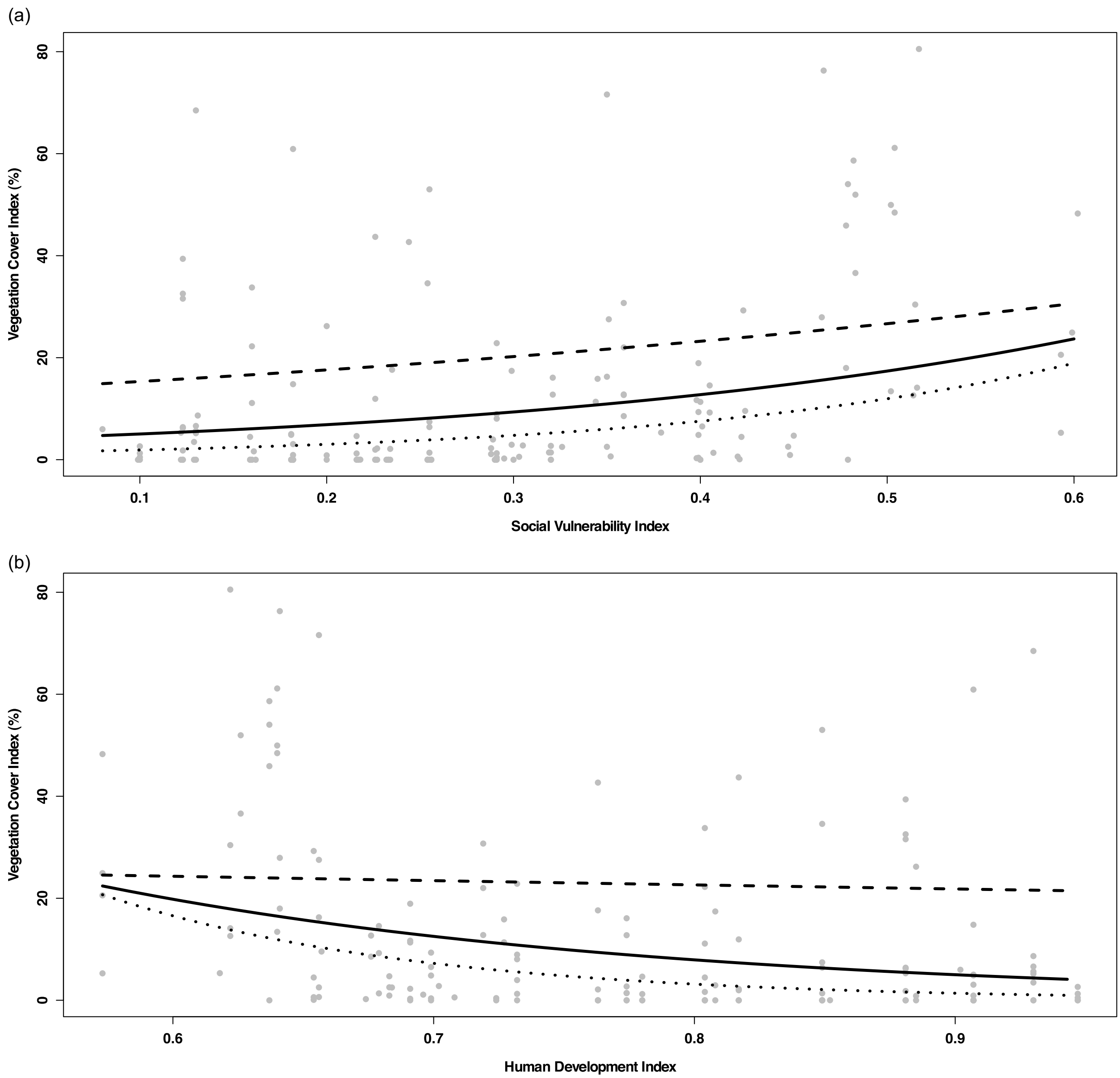

Figure 3. Proportional vegetation cover (Vegetation Cover Index) in the Belém human development units as a function of the interaction between (a) the Social Vulnerability Index and demographic density and (b) the Human Development Index and demographic density. The solid lines represent average demographic density (12 997.24 people/km^2), the short-dash lines represent high demographic density (20 000 people/km^2) and the long-dash lines represent low demographic density (5000 people/km^2).

cycling. It is located in a single, very large HDU that has high levels of social vulnerability. However, many local residents have never visited the Park and claim that it is structured to benefit the urban elite (Santos et al. 2020). The Park also harbours reservoirs of water that are important for the whole metropolitan region of Belém, whereas the neighbouring communities suffer from frequent cuts to their water supply, and the water is of low quality when it is available (Santos et al. 2020). This speaks to the importance of taking into account not only the amount of green space but also its quality and accessibility when considering the benefits of such spaces to human health and well-being (Amano et al. 2018, Mears et al. 2019).

Across Belém, the green spaces measured via satellite imagery include a wide array of types of space, including public parks, private gardens, protected areas and other informal green spaces such as fragments of remnant vegetation. Because we specifically targeted spaces that could potentially be used for recreation, socialization or other community activities, we excluded street trees, which, in any case, were not captured by the present methodology. Street trees nevertheless offer a number of benefits in urban landscapes, including improved aesthetics, ecosystem services, increased human health and well-being and habitat for animals (Locke et al. 2015, Salmond et al. 2016, Wood & Esaian 2020). A key issue that is relevant to climate change will be the benefits of street trees in moderating micro-climates; data from Belém show significantly lower temperatures in areas with more tree cover (Costa et al. 2013). Belém is amongst the Brazilian cities with the lowest levels of street trees, and this has substantial

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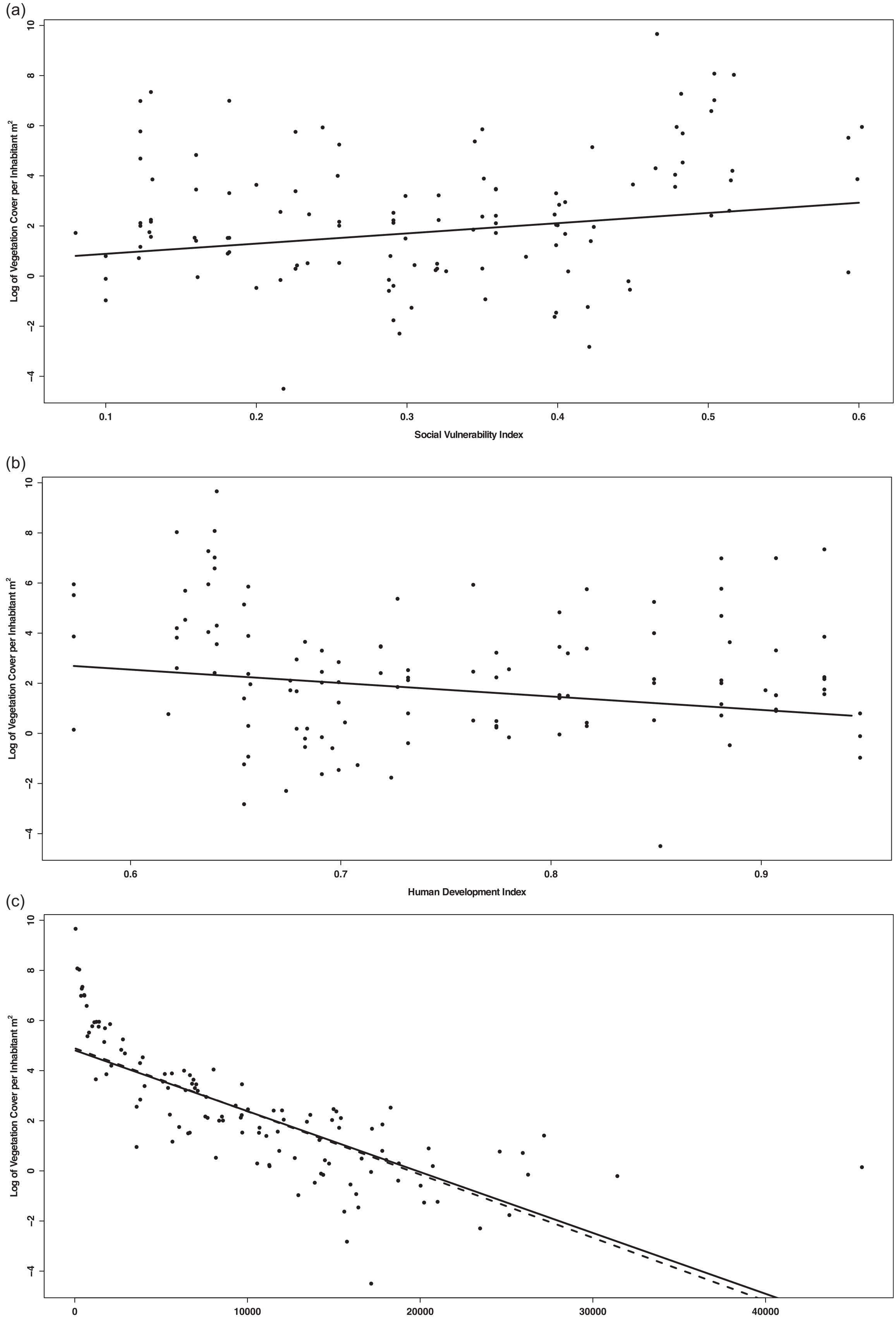

Figure 4. Natural logarithm of vegetation cover per inhabitant in the Belém human development units as a function of (a) the Social Vulnerability Index, (b) the Human Development Index and (c) demographic density (solid lines modelled with Social Vulnerability Index, dashed lines modelled with Human Development Index).

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implications for well-being, particularly in the most densely populated areas of the city centre where there is no or very little urban green space available.

Inequity of urban green spaces also extends to questions of procedural equity and equity as recognition (Anguelovski et al. 2020, Korpilo et al. 2022). For example, there is evidence that people who perceive lower levels of participation in and recognition by local green space planning and management in Denmark differ from those who perceive higher levels of participation and recognition in terms of both the value they assign to different types of urban green space and their preferences for greening actions (Korpilo et al. 2022). Specifically, people who felt unrecognized and tended not to participate in community and environmental decision-making valued urban green spaces for sport rather than for nature or environmental activities, and they tended to prefer beaches over large natural areas (Korpilo et al. 2022). Urban green space planning has been characterized as deeply political and underpinned by an unquestioned assumption that the creation of green and sustainable cities is a moral imperative, with a naivety existing regarding the economic, ecological, social and health benefits of urban greening (Anguelovski et al. 2020). An overly simplistic view of the benefits of urban greening is linked to perverse outcomes, including green exclusion and privilege (Anguelovski et al. 2019) and green gentrification and displacement (Pearsall 2012, Anguelovski et al. 2018, Rigolon & Németh 2019).

In Belém, plans put in place from the 1960s onwards made three key contributions to gentrification of the city centre: an intense increase in the value of real estate in the region; the freeing-up of land for development; and the relocation of low-income, socially vulnerable residents (Cardoso & Neto 2013, Braga & Gouveia 2020). The processes of declining urban green space in the centre of the city and decreasing social vulnerability of the population in some neighbourhoods are intimately linked and help to explain the results found here, including that both Reduto and Nazaré have very high levels of human development, very low levels of social vulnerability and also very low levels of urban green space and green space per inhabitant. On the other hand, in more peripheral areas of the city, exceptions to the trend include neighbourhoods such as Cabanagem and Una, where low-income populations were relocated from the city centre in the 1970s and 1980s into planned social housing estates, where informal occupation followed (Prefeitura Municipal de Belém 2010). One HDU encompasses the entirety of these two neighbourhoods and has high levels of social vulnerability (SVI = 0.424) but relatively low proportional vegetation cover (VCI = 9.57%) and very low levels of vegetation cover per person (VCPI = 7.12 m^2), with green spaces mostly representing small gardens and isolated fragments on urban lots. This is in contrast to peri-urban closed condominiums such as the Cristal Ville and Vila Naval do Marex complexes, which make up one of only four HDUs with more than 68% vegetation cover, extremely high levels of green space per inhabitant (VCPI = 1547.32 m^2) and one of the lowest levels of social vulnerability (SVI = 0.13) and the highest level of human development (HDI = 0.93) in Belém. Urban greening actions in the areas with lowest levels of VCI and VCPI need to be carefully planned to avoid reinforcing existing inequalities. Urban greening as an urban renewal strategy has in fact been criticized as market-driven and thus targeted to middle- and upper-income residents (Haase et al. 2017).

Our results support the idea that, in Belém, the assumption that urban greening will bring health and well-being benefits risks, at best, maintaining the status quo in terms of green exclusion and privilege, as evidenced by spaces such as Utinga Camillo Vianna State Park, Bosque Rodrigues Alves Botanic Gardens and Emilio Goeldi Zoo–Botanic Gardens. At worst, it risks repeating historical injustices via displacement of more socially vulnerable residents in a new wave of gentrification, this time driven by demand for access to urban green space. Avoiding this requires recognition of the relational values of urban green space to residents in different socioeconomic and sociocultural groups, which has been given too little attention (Botzat et al. 2016, Wessels et al. 2021). In Belém, this should include, amongst other factors, a recognition of the *ribeirinho* origins of low-income populations living in *baixadas* and the ways in which this represents a potential model of sustainable urban living. It would require public policies to resolve the lack of basic sanitation, address public health issues and utilize solutions for water treatment that are ecologically compatible with the floodplain forest ecosystem (Cardoso & Neto 2013).

Conclusions

The majority of urban HDUs in Belém have far lower than ideal levels of green space, both overall and per inhabitant. This is likely to have health and well-being impacts in neighbourhoods across the socioeconomic spectrum, and these impacts will probably worsen under predicted climate change. The generally higher levels of urban green space in more socially vulnerable areas are largely driven by a strong pattern of spatial social inequality, with high levels of social vulnerability at the periphery of the city where there are larger tracts of remnant vegetation. These are generally less accessible than the more highly structured urban green spaces in more affluent areas of the city centre, such that trends for increased health and well-being where green space availability is higher may not hold in this case. This highlights the need to consider relational values of urban green space in Amazonian cities, where many low-income residents living in precarious unofficial *baixadas* originating from *ribeirinho* traditions are likely to value different types and aspects of urban green space compared to more affluent city-centre dwellers. We conclude that, in Belém, an oversimplified view of the distribution of urban green space in relation to socioeconomic factors risks maintaining the inequitable distribution of green space access.

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References

Amano T, Butt I, Peh KS-H (2018) The importance of green spaces to public health: a multi-continental analysis. *Ecological Applications* 28: 1473–1480.

Amaral RDdAM, Morato RG, Mariano RS, Ferreira JMR (2021) Ferramentas para gestão da floresta urbana. *Revista de Gestão Ambiental e Sustentabilidade* 10: 1–10.

Anguelovski I, Brand AL, Connolly JJT, Corbera E, Kotsila P, Steil J, et al. (2020) Expanding the boundaries of justice in urban greening scholarship: toward an emancipatory, antisubordination, intersectional, and relational approach. *Annals of the American Association of Geographers* 110: 1743–1769.

Anguelovski I, Connolly J, Brand AL (2018) From landscapes of utopia to the margins of the green urban life. *City* 22: 417–436.

Anguelovski I, Connolly JJ, Garcia-Lamarca M, Cole H, Pearsall H (2019) New scholarly pathways on green gentrification: what does the urban 'green turn' mean and where is it going? *Progress in Human Geography* 43: 1064–1086.

Antonelli A, Sanmartín I (2011) Why are there so many plant species in the Neotropics? *Taxon* 60: 403–414.

Aram F, Higueras García E, Solgi E, Mansournia S (2019) Urban green space cooling effect in cities. *Heliyon* 5: e01339.

Bertini MA, Rufino RR, Fushita AT, Lima MIS (2016) Public green areas and urban environmental quality of the city of São Carlos, São Paulo, Brazil. *Brazilian Journal of Biology* 76: 700–707.

Bertram C, Rehdanz K (2015) The role of urban green space for human well-being. *Ecological Economics* 120: 139–152.

Boone CG, Buckley GL, Grove JM, Sister C (2009) Parks and people: an environmental justice inquiry in Baltimore, Maryland. *Annals of the Association of American Geographers* 99: 767–787.

Bordalo CAL (2006) O desafio das águas numa metrópole Amazônida: uma reflexão das políticas de proteção dos mananciais da região metropolitana de Belém-PA (1984–2004). Núcleo de Altos Estudos Amazônicos. Programa de Pós-Graduação em Desenvolvimento Sustentável do Tropico Úmido [www document]. URL https://repositorio.ufpa.br/jspui/bitstream/2011/3718/1/Tese_DesafioAguasMetropole.pdf

Botzat A, Fischer LK, Kowarik I (2016) Unexploited opportunities in understanding liveable and biodiverse cities. A review on urban biodiversity perception and valuation. *Global Environmental Change* 39: 220–233.

Bowler DE, Buyung-Ali L, Knight TM, Pullin AS (2010) Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landscape and Urban Planning* 97: 147–155.

Braga NTdS, Gouveia MdS (2020) Dialética da ocupação de áreas de várzea em Belém e propostas de drenagem compreensiva. *Novos Cadernos NAEA* 23: 10.5801/ncn.v23i1.6724.

Cardoso ACD, Neto RdSV (2013) A evolução urbana de Belém: trajetória de ambiguidades e conflitos socioambientais. *Cadernos Metrópole* 15: 55–75.

Chen B, Wu S, Song Y, Webster C, Xu B, Gong P (2022) Contrasting inequality in human exposure to greenspace between cities of Global North and Global South. *Nature Communications* 13: 4636.

Corrêa RL (1987) A periodização da rede urbana da Amazônia. *Revista Brasileira de Geografia* 4: 39–68.

Costa ACL, Silva Junior JA, Cunha AC, Galbraith D, Feitosa JRP, Mattos A (2013) Distribuiçao geoespacial e horária da temperatura do ar na cidade de Belém, estado do Pará, Brasil. *Brazilian Geographical Journal: Geosciences and Humanities Research Medium* 4: 150–168.

Dye C (2008) Health and urban living. *Science* 319: 766–769.

Espinoza NS, Santos CAC, Oliveira MBL, Silva MT, Santos CAG, Silva RM, et al. (2023) Assessment of urban heat islands and thermal discomfort in the Amazonia biome in Brazil: a case study of Manaus city. *Building and Environment* 227: 109772.

Fajardo W, Pinto AL, Lins TM, Barone V (2023) Cidades Amazônicas: um Chamado à Ação [www document]. URL https://amazonia2030.org.br/wp-content/uploads/2023/07/Cidades-Amazonicas-um-chamado-a-acao.pdf

Fischer EM, Oleson KW, Lawrence DM (2012) Contrasting urban and rural heat stress responses to climate change. *Geophysical Research Letters* 39: L03705.

Gutierrez CBB (2022) *Dinâmica da urbanização na região metropolitan de Belém e mudanças nos regimes sazonais durante o clima atual e futuro num cenário amazônico*. PhD thesis. Federal University of Pará, Brazil [www document]. URL https://repositorio.ufpa.br/handle/2011/15857

Haase D, Kabisch S, Haase A, Andersson E, Banzhaf E, Baró F, et al. (2017) Greening cities – to be socially inclusive? About the alleged paradox of society and ecology in cities. *Habitat International* 64: 41–48.

Hedblom M, Gunnarsson B, Iravani B, Knez I, Schaefer M, Thorsson P, Lundström JN (2019) Reduction of physiological stress by urban green space in a multisensory virtual experiment. *Scientific Reports* 9: 10113.

Hewitt CN, Ashworth K, MacKenzie AR (2020) Using green infrastructure to improve urban air quality. *Ambio* 49: 62–73.

Hoffimann E, Barros H, Ribeiro AI (2017) Socioeconomic inequalities in green space quality and accessibility-evidence from a southern European city. *International Journal of Environmental Research and Public Health* 14: 916.

Hunter RF, Cleland C, Cleary A, Droomers M, Wheeler BW, Sinnett D, et al. (2019) Environmental, health, wellbeing, social and equity effects of urban green space interventions: a meta-narrative evidence synthesis. *Environment International* 130: 104923.

IBGE (2022) Panorama IBGE Belém, Pará, Brasil. [www document]. URL https://cidades.ibge.gov.br/brasil/pa/belem/panorama

IPEA (2021) IVS: Atlas da Vulnerabilidade Social [www document]. URL http://ivs.ipea.gov.br/index.php/pt/

IPEA, FJP, PNUD (2021) Atlas do Desenvolvimento Humano no Brasil [www document]. URL http://www.atlasbrasil.org.br/

Klompmaker JO, Hart JE, Bailey CR, Browning MHEM, Casey JA, Hanley JR, et al. (2023) Racial, ethnic, and socioeconomic disparities in multiple measures of blue and green spaces in the United States. *Environmental Health Perspectives* 131: 017007.

Korpilo S, Kaaronen RO, Olafsson AS, Raymond CM (2022) Public participation GIS can help assess multiple dimensions of environmental justice in urban green and blue space planning. *Applied Geography* 148: 102794.

Lapola, DM, Braga, DR, Di Giulio, GM, Torres, RR, Vasconcellos, MP (2019) Heat stress vulnerability and risk at the (super) local scale in six Brazilian capitals. *Climatic Change* 154: 477–492.

Locke DH, Roman LA, Murphy-Dunning C (2015) Why opt-in to a planting program? Long-term residents value street tree aesthetics. *Arboriculture and Urban Forestry* 41: 324–333.

Marselle MR, Lindley SJ, Cook PA, Bonn A (2021) Biodiversity and health in the urban environment. *Current Environmental Health Reports* 8: 146–156.

McPherson EG, Xiao Q, Aguaron E (2013) A new approach to quantify and map carbon stored, sequestered and emissions avoided by urban forests. *Landscape and Urban Planning* 120: 70–84.

Mears M, Brindley P, Maheswaran R, Jorgensen A (2019) Understanding the socioeconomic equity of publicly accessible greenspace distribution: the example of Sheffield, UK. *Geoforum* 103: 126–137.

Moreira MA (2011) *Fundamentos do sensoriamento remoto e metodologias de aplicação*, 4th edition. Viçosa, Brazil: Universidade Federal de Viçosa (UFV).

Nagendra H, Bai X, Brondizio ES, Lwasa S (2018) The urban south and the predicament of global sustainability. *Nature Sustainability* 1: 341–349.

Nawrath M, Elsey H, Rijal ML, Dallimer M (2022) Greenspaces and human well-being: perspectives from a rapidly urbanising low-income country. *Environments* 9: 148.

Nawrath M, Guenat S, Elsey H, Dallimer M (2021) Exploring uncharted territory: do urban greenspaces support mental health in low- and middle-income countries? *Environmental Research* 194: 110625.

Pearsall H (2012) Moving out or moving in? Resilience to environmental gentrification in New York City. *Local Environment* 17: 1013–1026.

Pinto LV, Inácio M, Ferreira CSS, Ferreira AD, Pereira P (2022) Ecosystem services and well-being dimensions related to urban green spaces – a systematic review. *Sustainable Cities and Society* 85: 104072.

Ponte JPX (2015) Belém do Pará: cidade e água. *Cadernos Metrópole* 17: 41–60.

Prefeitura Municipal de Belém (2010) Anuário estatístico de Belém [www document]. URL http://www.belem.pa.gov.br/app/c2ms/v/?id=1&conteudo=2995

Prefeitura Municipal de Belém (2020) Caracterização Geral do Município de Belém. Relatório 3.1 [www document]. https://arbel.belem.pa.gov.br/wp-

content/uploads/2022/05/VOLUME-I-CARACTERIZACAO-GERAL-DE-BELEM.pdf
QGIS Development Team (2022) QGIS Geographic Information System Version 3.22.11. Open Source Geospatial Foundation Project [www document]. URL http://qgis.osgeo.org
R Core Team (2022) R: \ language and environment for statistical computing [www document]. URL https://www.R-project.org/
Reyes-Riveros R, Altamirano A, De La Barrera F, Rozas-Vásquez D, Vieli L, Meli P (2021) Linking public urban green spaces and human well-being: a systematic review. *Urban Forestry & Urban Greening* 61: 127105.
Ribeiro LCQ, Ribeiro MG (2016) Índice de Bem-Estar Urbano (IBEU) dos Municípios brasileiros. Rio de Janeiro, RJ [www document]. URL https://ibeu.observatoriodasmetropoles.net.br/wp-content/uploads/2021/03/IBEU-MUNICIPAL_FINAL.pdf
Rigolon A, Németh J (2019) Green gentrification or 'just green enough': do park location, size and function affect whether a place gentrifies or not? *Urban Studies* 57: 402–420.
Rigolon A, Browning MHEM, Lee K, Shin S (2018) Access to urban green space in cities of the Global South: a systematic literature review. *Urban Science* 2: 67.
Rigolon A, Browning MHEM, McAnirlin O, Yoon H (2021) Green space and health equity: a systematic review on the potential of green space to reduce health disparities. *International Journal of Environmental Research and Public Health* 18: 2563.
Rojas-Rueda D, Nieuwenhuijsen MJ, Gascon M, Perez-Leon D, Mudu P (2019) Green spaces and mortality: a systematic review and meta-analysis of cohort studies. *Lancet Planet Health* 3: e469–e477.
Sales Barros N, Pamplona Ximenes Ponte J, Bentes Machado Sardo Leão M, de Cássia Lopes Pinheiro A, Durans Pessoa de Souza R, Guedes Sabino TA (2017) As unidades de desenvolvimento humano na região metropolitana de Belém. In B Oliveira Marguti, MA Costa and CB Favarão (eds), *Territórios em números : insumos para políticas públicas a partir da análise do IDHM e do IVS de UDHs e regiões metropolitanas brasileiras, livro 2* (pp. 227–260). Brasília, Brazi: IPEA, INCT.
Salmond JA, Tadaki M, Vardoulakis S, Arbuthnott K, Coutts A, Demuzere M, et al. (2016) Health and climate related ecosystem services provided by street trees in the urban environment. *Environmental Health* 15: S36.
Santos CAC, Lima JRA (2013) Análise dos Efeitos da Expansão Urbana de Manaus-AM Sobre Parâmetros Ambientais Através de Imagens de Satélite (Analysis of the urban expansion effects of Manaus-AM on environmental parameters through satellite images). *Revista Brasileira de Geografia Física* 6: 1–14.
Santos JS, Costa AD, de Oliveira RD (2020) Parque Estadual do Utinga: pertencimento, pressões antropogênicas e mudanças socioespaciais em Belém-Pará. *Periódico Técnico e Científico. Cidades Verdes* 8: 27–43.
Secretaria Municipal de Meio Ambiente de Belém (2020) Bosque Rodrigues Alves [www document]. URL https://semma.belem.pa.gov.br/areas-especiais-e-protegidas/bosque-rodrigues-alves/
Silva DCC (2016) *Proposta metodológica para elaboração de um índice espacial de sustentabilidade ambiental aplicado a bacias hidrográficas.* São Paulo, Brazil: Programa de Pós-Graduaçao em Ciências Ambientais, UNESP.
Silva DMd, Grandine G, Simonetti VC, Silva DCdCe (2018) Análise espacial da cobertura vegetal no centro urbano do município de Salto de Pirapora (SP). *Caminhos de Geografia* 19: 361–371.
Silva JMC, Prasad S (2019) Green and socioeconomic infrastructures in the Brazilian Amazon: implications for a changing climate. *Climate and Development* 11: 153–166.
Silva JMC, Rylands AB, Fonseca GAB (2005) The fate of the Amazonian areas of endemism. *Conservation Biology* 19: 689–694.
Soga M, Gaston KJ (2016) Extinction of experience: evidence, consequences and challenges of loss of human–nature interactions. *Frontiers in Ecology and the Environment* 14: 94–101.
Taylor L, Hochuli DF (2017) Defining greenspace: multiple uses across multiple disciplines. *Landscape and Urban Planning* 158: 25–38.
Tzoulas K, Korpela K, Venn S, Yli-Pelkonen V, Kaźmierczak A, Niemela J, James P (2007) Promoting ecosystem and human health in urban areas using green infrastructure: a literature review. *Landscape and Urban Planning* 81: 167–178.
United Nations (2015) Transforming our World: The 2030 Agenda for Sustainable Development [www document]. URL https://sdgs.un.org/publications/transforming-our-world-2030-agenda-sustainable-development-17981
United Nations Department of Economic and Social Affairs (2019) World Urbanization Prospects: The 2018 Revision [www document]. URL https://population.un.org/wup/Publications/
United Nations Department of Economic and Social Affairs (2022) World Population Prospects 2022: Summary of Results [www document]. URL https://population.un.org/wpp/Publications/
Van den Berg M, Wendel-Vos W, van Poppel M, Kemper H, van Mechelen W, Maas J (2015) Health benefits of green spaces in the living environment: a systematic review of epidemiological studies. *Urban Forestry & Urban Greening* 14: 806–816.
Wessels N, Sitas N, Esler KJ, O'Farrell P (2021) Understanding community perceptions of a natural open space system for urban conservation and stewardship in a metropolitan city in Africa. *Environmental Conservation* 48: 244–254.
Wood EM, Esaian S (2020) The importance of street trees to urban avifauna. *Ecological Applications* 30: e02149.
World Health Organisation (2010) *Urban HEART: Urban Health Equity Assessment and Response Tool.* Geneva, Switzerland: World Health Organization.