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Woody species composition, diversity, and ecosystem services of yards along an urban socioeconomic gradient

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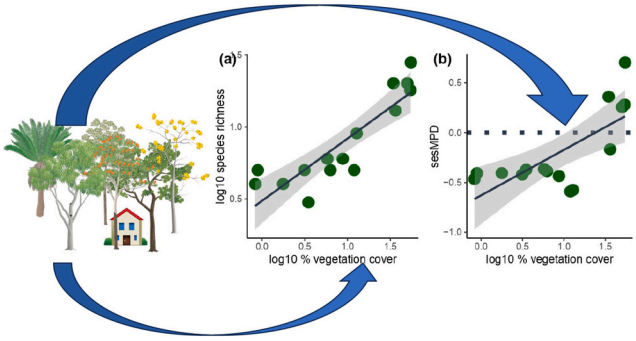
HIGHLIGHTS

- Trees were mostly grown for ornamental and utilitarian purposes in the rich and poorer suburbs, respectively.
- Growing trees for shade was universal across the socioeconomic gradient.
- Exotic species had a higher species richness compared with indigenous species.
- Species richness had a positive relationship with socioeconomic and legacy factors.
- Exotic species contributed more to phylogenetic diversity compared with indigenous species.

GRAPHICAL ABSTRACT



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ABSTRACT

Woody plants offer a wide range of valuable ecosystem services, but their distribution across socioeconomic gradients in urban landscapes remains poorly understood. Thus, we explored the effect of socioeconomic and legacy factors on plant species richness and phylogenetic diversity, and the motivations for growing and keeping certain species. We sampled a total of 300 households across a socioeconomic gradient in the city of Harare, Zimbabwe, in high-, medium- and low-density areas, representing low to high wealth strata. Trees were mostly grown for ornamental purpose in the rich (low-density) suburbs and utilitarian purposes in the poorer medium to high-density areas. However, trees were also grown with similar proportion for shade across the socioeconomic gradient. Proportion of medicinal and fruit trees increased with household density, while wind break trees were more common in low-density suburbs. Exotic species exhibited greater species richness compared with indigenous species, with both combined and separate assessments of indigenous and exotic species richness revealing a significant positive association with socioeconomic and legacy factors. The composition of species displayed considerable variation along the socioeconomic gradient. Notably, in low-density environments, exotic species maintained elevated phylogenetic diversity in comparison to indigenous species. This distinction was particularly pronounced when analysed independently, revealing a significant positive correlation between exotic species richness and both property value and education level. Our study shows that residents filter specific plant species based on their socioeconomic status and that, relative to low-income households, the rich homeowners have unintentionally incorporated enough exotic species to produce novel phylogenetic diversity of woody plants in

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their yards. Thus, we confirm the existence of a socioeconomic gradient in terms of species richness, composition, and phylogenetic diversity. However, the imbalance in species richness and phylogenetic diversity across the socioeconomic gradient can be reduced by increased tree planting in open areas, including along streets in medium to high-density areas to improve ecosystem services.

1. Introduction

The urbanized environment covers approximately 3 % of the Earth's surface (UNDP, 2020). With more than half of the global population (55 %) now residing in cities (Ritchie and Roser, 2018), urban areas have become influential drivers of economic growth, income generation, and efforts to address social issues (Gao and O'Neill, 2020; Jiang and O'Neill, 2017). However, the Anthropocene era has brought about a surge in negative impacts within urban landscapes, including flooding, invasive alien plant species, urban heat island effects, as well as air and water pollution (Grimm et al., 2008; Ruas et al., 2022). Among these challenges, biodiversity loss due to urbanization accompanied by the introduction of exotic species stands out as significant problems (Kondratyeva et al., 2020). This loss of biodiversity varies across urban landscapes, demonstrating pronounced socioeconomic differences often termed as "the luxury effect" (Chamberlain et al., 2019; Hope et al., 2003; Leong et al., 2018).

Indeed, residential landscapes are shaped by homeowners, but the consequences on biodiversity are poorly understood, especially in developing countries (Cavender-Bares et al., 2020). Studies have shown that patterns of plant diversity in urban landscapes are highly correlated with socioeconomic status variables such as level of income, yard area, and human population density (Hope et al., 2003; Leong et al., 2018). Other mechanisms that influence the luxury effect are lifestyle choices (Grove et al., 2006), maintaining social status (Cook et al., 2012) and level of education, which is deemed to be associated with the desire to obtain certain ecosystem services from the environment (Kendal et al., 2012; Kirkpatrick et al., 2011). Furthermore, according to a recent meta-analysis, climate has the potential to amplify the impact of socioeconomic status on biodiversity, with a more pronounced effect observed in urban areas situated in drier regions (Chamberlain et al., 2019). However, most studies that confirm the influence of these socioeconomic variables are primarily derived from the global north, leaving a dearth of information from the global south, where cities exhibit greater heterogeneity (Brelsford et al., 2017; Chamberlain et al., 2019).

Many studies examining the effect of socioeconomic status on plant species diversity primarily rely on remote sensing of vegetation canopy and ground cover, assuming these variables serve as good proxies for actual biodiversity patterns (Chamberlain et al., 2019; Gong et al., 2013; Grove et al., 2006). Consequently, limited efforts have been made to directly measure diversity on the ground (Leong et al., 2018; Padullés Cubino and Retana, 2023). Certainly, assessing diversity at ground level facilitates the differentiation of species origins, such as distinguishing between indigenous and exotic species—an uncommon methodology in numerous urban studies (Chamberlain et al., 2019). While species richness is a basic measure of diversity, it may not be directly correlated with canopy and ground cover. Although it provides information on the number of species in a given area, species richness alone does not reveal variations in species composition or evolutionary relationships (Cadotte et al., 2011). Exploring both biodiversity measures, species richness, and phylogenetic diversity (PD) becomes increasingly crucial for gaining insights into ecosystem function as well as understanding the behaviour of homeowners' species selection (Cadotte et al., 2011; Cadotte et al., 2012).

Currently, there is limited understanding of how other biodiversity metrics, such as phylogenetic diversity (mean pairwise distance: MPD), vary across socioeconomic gradients. While the impact of urbanization on the phylogenetic diversity of birds is relatively well-documented (Ibáñez-Álamo et al., 2017; La Sorte et al., 2018; Muvengwi et al., 2022), its effect on trees remains unclear. Phylogenetic diversity (MPD), which focuses on the distance between species within a community or site, is gaining importance in ecology and conservation (Prescott et al., 2016; Webb et al., 2002). Indeed, the choice of species by homeowners is highly important in determining the phylogenetic diversity of urban landscapes.

Phylogenetic diversity is increasingly used to understand and protect ecosystems by estimating community trait space and ecosystem functioning (Prescott et al., 2016; Srivastava et al., 2012). Further research is needed to confirm the relationship between urban diversity and socioeconomic gradients (Padullés Cubino and Retana, 2023), emphasizing both evolutionary and traditional diversity indices. Limited studies on phylogenetic diversity in urban yards exist, primarily in North America (Knapp et al., 2012; Padullés Cubino et al., 2019). Indeed, more studies are needed before global generalizations can be made. Given homeowners' influence on urban yards, here we seek to address the following objectives: (i) to determine the ecosystem services that motivated homeowners to grow and keep certain species in their yards, and (ii) to determine the effect of socioeconomic variables on plant species richness and phylogenetic diversity.

2. Methods

2.1. Study area

This study was conducted in urban yards located in the low-, medium-, and high-density suburbs of Harare, Zimbabwe, within the coordinates of 17°40′ to 18°00′ S latitude and 30°55′ to 31°15′ E longitude (Fig. 1). Harare receives an annual rainfall of 650–850 mm, mainly from November to March (Mbiba et al., 2021; Muvengwi et al., 2019). The average temperature ranges between 16 and 22 °C. The soil is mostly sandy loam. Harare has various types of green spaces that include vleis (marshes or wetlands), grasslands, and miombo woodland patches dominated by *Brachystegia spiciformis* (Muvengwi et al., 2020). Harare is a relatively flat city (hence homogenous).

2.2. Data collection

In this study, we established a socioeconomic gradient by dividing suburbs into three strata: low-, medium-, and high-density areas (Fig. 1). The division was based on three apparent proxies of wealth i.e., yard area, human population density (Wania et al., 2014), and general property value (socioeconomic status) in the neighbourhood. We could not use average income per household (Clarke et al., 2013) because of lack of proper currency in Zimbabwe. Based on our selection of properties from each category (low-, medium-, and high-density), we took the median cost (US$) of eight properties that were listed in each sampled suburb, as advertised by PropertyBook (source: https://www.propertybook.co.zw/ accessed on the 26th of October 2023). To achieve a comprehensive sample, we employed a three-tier random selection process. First, we selected five suburbs to sample in each urban stratum. Then, within each suburb, ten streets were randomly chosen for sampling. Finally, two yards were sampled along each street, resulting in a total of 100 yards sampled in each stratum and a grand total of 300 households across the socioeconomic gradient. Total yard area for households that were sampled along the urban density gradient from high-, medium-, and low-density were 25,700 m^2, 76,500 m^2 and 304,500 m^2, respectively. Our sampling strategy was skewed towards the enumeration of households rather than focusing on spatial coverage.

This approach was adopted to facilitate the equitable representation of homeowners, as they exert a considerable influence on the vegetation within their yards. The emphasis on household numbers allowed for a more targeted and balanced sampling, enabling a comprehensive assessment of the impact of homeowners on the local vegetation. During the survey, we documented all woody plants (trees and shrubs) present in the sampled yards to species level. Additionally, we administered a structured questionnaire (Appendix A) to homeowners, gathering information on their level of education, watering frequency, and ecosystem services that motivated them to keep and plant specific woody plants in their yards. The level of education of homeowners was scored as follows: primary = 1, Zimbabwe Junior Certificate = 2, Ordinary level = 3, Advanced level = 4, and Tertiary = 5. Suburb age data were sourced from records provided by the Harare City Council. General neighbourhood human population density was obtained from the 2022 census report (ZIMSTAT, 2022).

To determine vegetation cover for each sampled suburb (Fig. 1), a Landsat 9 (L9) image was downloaded from the United States Geological Survey (USGS) database (https://earthexplorer.usgs.gov/). The L9 image was processed in ArcGIS Pro 3 utilizing the Normalized Difference Vegetation Index (NDVI) to classify vegetation cover. NDVI, a standardized index, calculates vegetation greenness by exploiting the contrast between the near-infrared (NIR) and red bands of multispectral raster datasets. The NDVI equation, given by:

$$NDVI = \frac{(IR - R)}{(IR + R)}$$

where IR represents pixel values from the infrared band and R represents pixel values from the red band, was employed for this classification. In ArcGIS Pro 3, a composite operation was performed on single-band datasets, resulting in the creation of a merged single raster. The bands were subsequently combined to display the data as a colour composite. The colour composite raster was converted to NDVI using the NDVI tool. NDVI values close to 1 were regarded as vegetation, and the vegetation class was specifically delineated using NDVI values > 0.5.

Following the classification, the extent of vegetation cover within each suburb was determined by overlaying the suburbs layer onto the classified image. The Zonal Geometry tool in ArcGIS was used to calculate the vegetation area within each suburb. The vegetation cover percentage for each suburb was then computed and displayed using the formula.

$$Vegetation\ cover\ (\%) = \frac{\text{Vegetation Cover Area}}{\text{Suburb Area}}\ x\ 100$$

2.3. Phylogenetic diversity measures

We examined the variation in phylogenetic diversity along an urban socioeconomic gradient by computing mean pairwise distance (MPD) and its corresponding standardized effect size (Faith, 1992; Webb et al., 2002). We calculated mean pairwise distance (MPD: the average distance between all species in a phylogenetic tree). Because the phylogenetic index MPD is influenced by species richness, we corrected for this by permutational calculation of the standardized effect sizes (ses) (Kembel et al., 2010).

Standardized effect sizes for MPD (sesMPD) for each yard was calculated by shuffling taxa labels 999 times whilst maintaining species richness and occurrence constant using the following equation:

$$ses = \frac{Observed - Mean\ (null)}{SD\ (null)}$$

when the ses is >0 for MPD it means that species in the community are phylogenetically more distant than expected by chance (i.e. phylogenetic dispersion); < 0 values point to phylogenetic clustering.

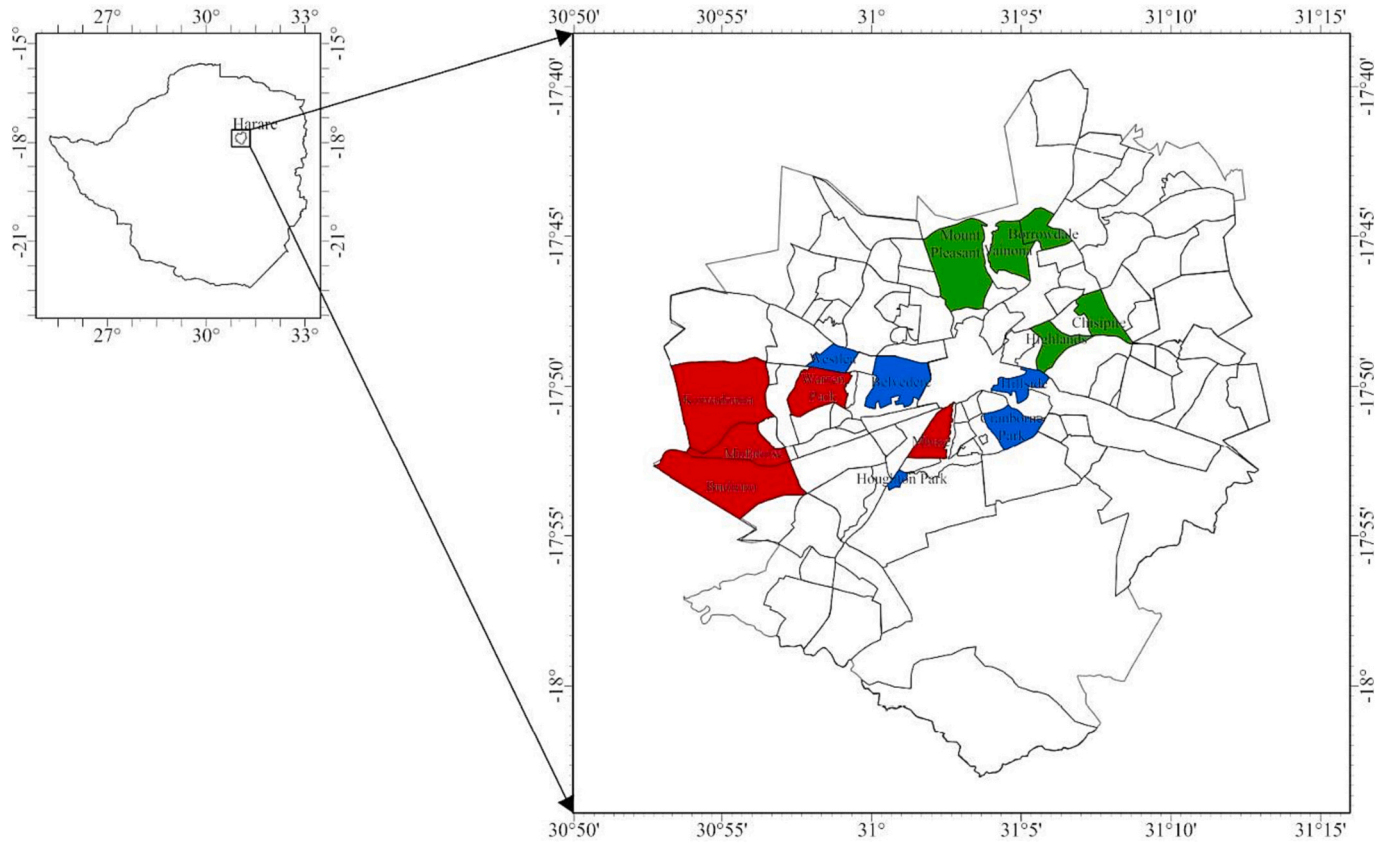

Fig. 1. Study site location (Harare, Zimbabwe) and the sampled suburbs in high- (red), medium- (blue) and low-density (green) suburbs.

2.4. Data analysis

Ecosystem services that motivated homeowners to grow certain species across the socioeconomic gradient were analysed using chi-squared tests. Sampling completeness was assessed using species accumulation curves. To test for significant differences in assemblage composition, Analysis of Similarity (ANOSIM) was applied (Clarke and Warwick, 2001). The output was interpreted based on the *R*-statistic since *p*-values become more unreliable with increase in sample size (Clarke and Warwick, 2001). *R*-statistic measures the dissimilarity between assemblages from different sites, with values close to 1 indicating high dissimilarity. *R*-statistic values ≥0.3 were considered important. Non-metric Multidimensional Scaling (nMDS) ordination diagram was produced to visually display patterns in woody species composition across the socioeconomic gradient based on Jaccard distance (low-, medium- and high-density).

Initially, we conducted a comprehensive analysis of pairwise Spearman correlations among our selected variables, as shown in Appendix B: Fig. S1 using the '*corrplot*' package in R (Wei and Simko, 2017). We modelled the impact of socioeconomic status (measured by property value, level of education, and watering frequency) and city legacy (suburb age) on diversity indices, including species richness, sesMPD, and percent vegetation cover, using generalized linear models (GLMs). We performed model selection using the second-order sample-size corrected Akaike information criterion (AICc) within the R package MuMIn, allowing us to identify the most parsimonious models for further analysis. Subsequently, we conducted linear regression analyses to assess the relationship between each covariate and the diversity response variables. To ensure the validity of our models, we examined their normality and goodness of fit through diagnostic plots, using the *performance* package (Lüdecke et al., 2021). We compared species richness between indigenous and exotic species using independent *t*-test.

3. Results

3.1. Sampling completeness

Our results showed that sampling completeness was achieved after sampling about 30 households, all the curves became asymptotic (Fig. 2a). There was a large difference in the cumulative area as well as the number of species that were sampled across the urban gradient (Fig. 2b). We recorded a total of 107 woody plant species, 71 exotic, and 36 indigenous to Zimbabwe in all households (Table S1). Exotic species had a significantly higher species richness ($t = 3.084$, df = 20.74, *p*-value = 0.006) than indigenous species (Appendix B: Fig. S2).

3.2. Assemblage composition

There was high overall dissimilarity in species composition across the urban landscape for all the woody species (Global $R = 0.504$, Table 1), exotic (Global $R = 0.446$, Table 1) and indigenous species (Global $R = 0.365$, Table 1). Our pairwise tests and the nMDS diagrams showed that there was more dissimilarity for high- *vs*. low- compared

Table 1
Analysis of similarity (ANOSIM) of woody assemblages that were recorded in urban yards across a socioeconomic gradient (low-, medium-, and high-density yards). For all comparisons, the *p*-values were significant at <0.05, but our interpretation was based on the *R*-statistic (Clarke and Warwick, 2001). Values highlighted in bold are ≥0.3 and regarded as markedly dissimilar.

Vegetation category	*R* value
Combined indigenous and exotic woody plants	
Global R value	**0.504**
High vs Medium	0.200
High vs Low	**0.818**
Medium vs Low	**0.529**
Exotic woody plants	
Global R value	**0.446**
High vs Medium	0.164
High vs Low	**0.760**
Medium vs Low	**0.467**
Indigenous woody plants	
Global R value	**0.365**
High vs Medium	0.197
High vs Low	**0.625**
Medium vs Low	0.274

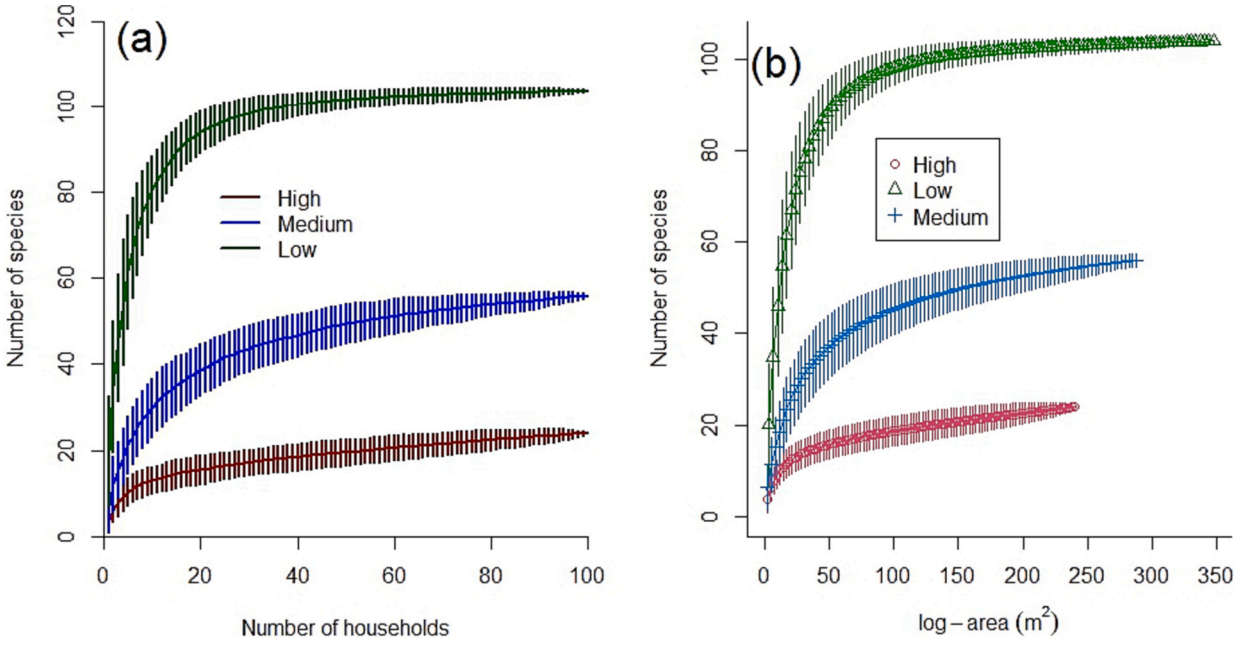

Fig. 2. Species accumulation curves showing changes in number of species with an increase in number of households sampled (a) and changes in number of species with area sampled (b) across the urban strata. Bars represent 95 % confidence limits.

with medium- *vs.* low-density yards (Fig. 3, Table 1).

3.3. Ecosystem services highlighted by homeowners

The main motivations for household owners to plant trees were, provision of shade and fruits across the luxury gradient (Fig. 4a). There was significant association ($\chi^2 = 82.28, p < 0.0001$) between motivation and strata (Fig. 4a). The proportion of medicinal and fruit trees increased with household density (Fig. 4a). Trees for wind break are absent in high-, a few in medium- and relatively high in low-density yards (Fig. 4a). There were few ornamental trees in high-, but similar relatively high proportions for medium- and high-density suburbs. The proportions of exotic trees are virtually the same across the strata ($\chi^2 = 0.471$, df = 2, $p = 0.790$), and dominate over indigenous trees at 70 % of total trees (Fig. 4b).

3.4. Species richness, vegetation cover and phylogenetic diversity measures

3.4.1. Combined indigenous and exotic woody species

The analysis revealed several noteworthy relationships. First, species richness displayed significant positive relationships with key socioeconomic factors, namely property value, watering frequency, and level of education ($R^2 = 0.70$, F = 34.14, $p < 0.001$; $R^2 = 0.30$, F = 7.091, $p = 0.020$; $R^2 = 0.43$, F = 21.23, $p < 0.001$, respectively, Fig. 5, Table 2). Additionally, there was a significant positive association between species richness and the legacy effect of suburb age ($R^2 = 0.43$, F = 11.64, $p = 0.046$, Fig. 5, Table 2). However, human population density, a legacy of 'colonization' had a significant negative relationship ($R^2 = 0.54$, F = 17.6, $p = 0.001$, Fig. 5, Table 2) with species richness. Furthermore, the standardized mean pairwise distance (sesMPD) exhibited positive relationships with property value, watering frequency, and level of education ($R^2 = 0.54$, F = 17.63, $p = 0.001$; $R^2 = 0.29$, F = 6.642, $p = 0.023$; $R^2 = 0.58$, F = 20.51, $p = 0.001$, respectively), with a positive and negative correlation observed with suburb age and human population density, respectively ($R^2 = 0.38$, F = 9.482, $p = 0.009$; R^2, =0.41, F = 10.57, $p = 0.006$, Fig. 5, Table 2). Percent vegetation cover displayed significant positive relationships with property value, watering frequency, and level of education ($R^2 = 0.73$, F = 39.67, $p < 0.001$; $R^2 = 0.51$, F = 15.5, $p = 0.002$; $R^2 = 0.59$, F = 20.83, $p < 0.001$, respectively), while suburb age and human population density had a positive and negative relationship with percent vegetation cover, respectively ($R^2 = 0.46$, F = 12.8, $p = 0.003$; $R^2 = 0.61$, F = 22.54, $p < 0.001$, Fig. 5, Table 2). Vegetation cover had a significant positive relationship with species richness and sesMPD ($R^2 = 0.75$, F = 43.36, $p < 0.001$; $R^2 = 0.48$, F = 14.09, $p = 0.002$, respectively, Appendix B: Fig. S3).

3.4.2. Indigenous woody species

The results indicate positive relationships between species richness for indigenous species and three socioeconomic factors: property value ($R^2 = 0.62$, F = 24.01, $p < 0.001$), watering frequency ($R^2 = 0.32$, F = 7.44, $p = 0.017$), and level of education ($R^2 = 0.60$, F = 21.8, $p < 0.001$), (Fig. 6, Table 3). Notably, suburb age exhibited a lasting impact, showing a significant positive relationship with species richness ($R^2 = 0.33$, F = 7.91, $p = 0.015$, Fig. 6, Table 3). Indeed, human population density had a significant negative relationship with species richness ($R^2 = 0.51$, F = 15.78, $p = 0.002$). Conversely, socioeconomic and legacy factors had no significant relationships with sesMPD (Table 3).

3.4.3. Exotic species

Species richness displayed significant positive relationships with property value ($R^2 = 0.73$, F = 39.03, $p < 0.001$, Fig. 7, Table 3), watering frequency ($R^2 = 0.26$, F = 5.814, $p = 0.031$, Fig. 7), and level of education ($R^2 = 0.57$, F = 19.46, $p < 0.001$, Fig. 7). Furthermore, it exhibited a significant positive relationship with the city's legacy, suburb age ($R^2 = 0.45$, F = 12.30, $p = 0.004$, Fig. 7, Table 3). Human population density had a significant negative relationship with species richness ($R^2 = 0.57$, F = 19.62, $p < 0.001$). In contrast, while indigenous phylogenetic diversity showed no significant relationships with both socioeconomic and legacy effects, exotic species phylogenetic diversity demonstrated a significant positive relationship with property value ($R^2 = 0.27$, F = 6.23, $p = 0.027$, Fig. 7, Table 3) and level of education ($R^2 = 0.23$, F = 5.08, $p = 0.042$). A significant negative relationship between phylogenetic diversity and human population density was recorded ($R^2 = 0.38$, F = 9.56, $p = 0.009$). However, sesMPD did not show a significant relationship with watering frequency and suburb age (Fig. 7 and Table 3).

4. Discussion

Our findings emphasize the existence of a socioeconomic gradient in Harare, which is characterized by high species richness, vegetation cover, and phylogenetic diversity moving from poorer to richer suburbs. Assemblage composition was highly different between low- and high-density yards. Across the urban strata, trees were mainly grown for ecosystem services such as shade, fruit, ornamental, and wind break. Interestingly, the proportion of medicinal and fruit trees increased with household density, i.e., from wealthy to poorer suburbs. The proportions

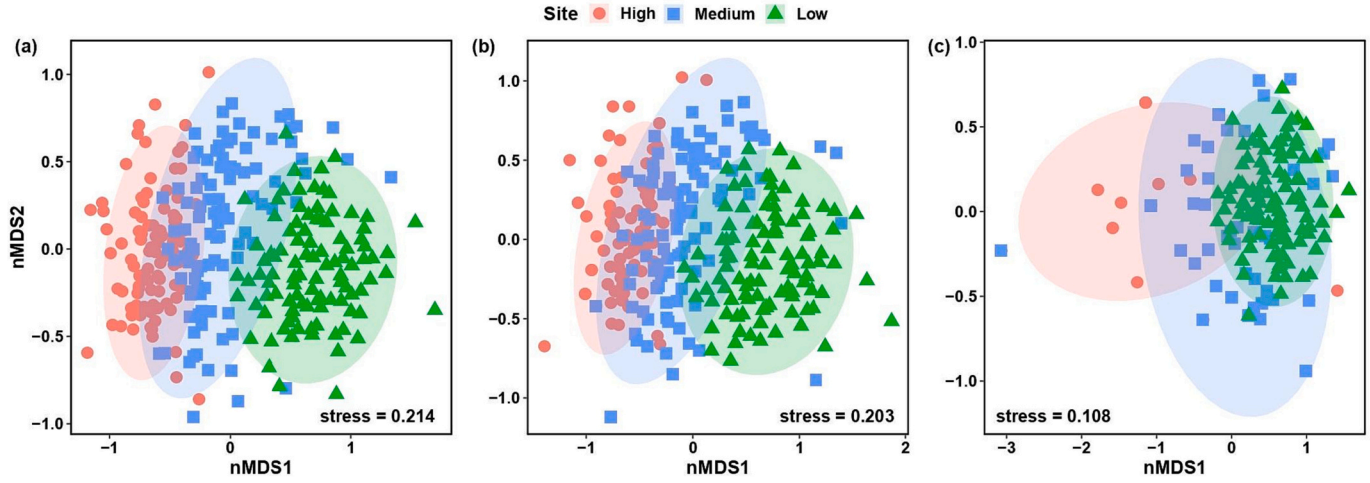

Fig. 3. Non-metric multi-dimensional scaling (nMDS) ordination of presence of woody species in sampled yards across the urban luxury gradient (high-, medium-, and low- density), (a) combined indigenous and exotic woody plants, (b) exotic woody plants and (c) indigenous woody plants.

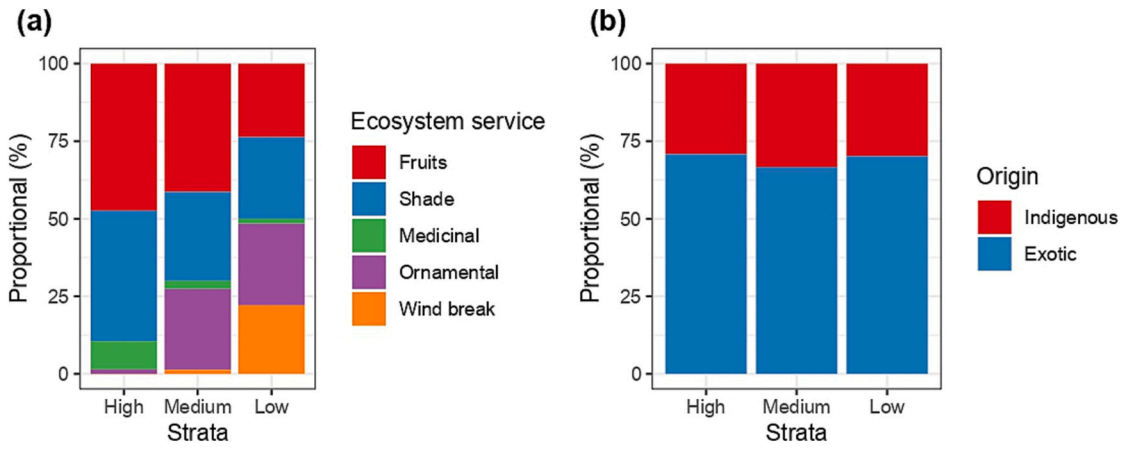

Fig. 4. Variation in ecosystem services for planting and keeping woody plants in households: (a) the proportions of all five ecosystem services in household yards across the urban socioeconomic gradient, and (b) proportion of indigenous and exotic trees in household yards.

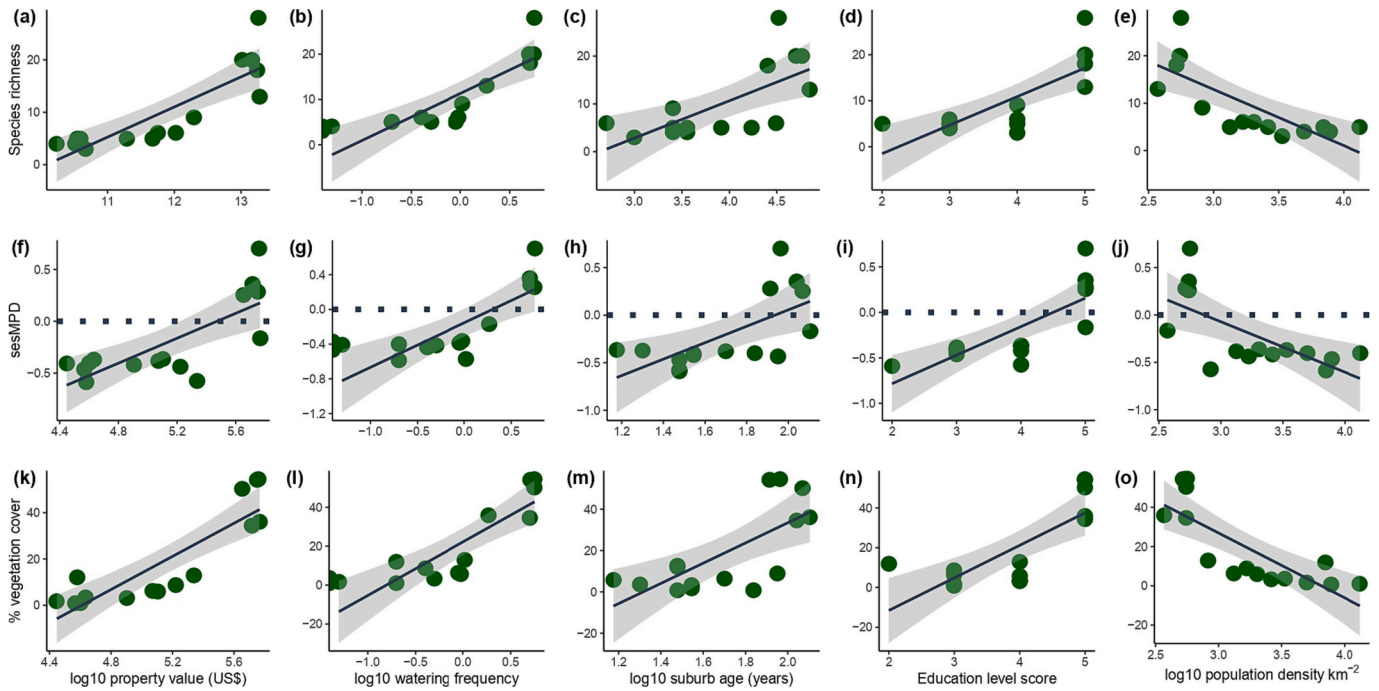

Fig. 5. Linear models Illustrating the impact of socioeconomic (property value, level of education, and watering frequency) and legacy (suburb age, population density) factors on species richness (a-e), sesMPD (f-j), and % vegetation cover (k-o) for all species (combined indigenous and exotic) in the urban landscape of Harare, Zimbabwe. Model specifications are provided in Table 2. The grey shaded envelopes represent the 95 % confidence intervals. The dotted horizontal line for sesMPD represents the null expectation, with values above the line representing phylogenetic dispersion and values below the line representing phylogenetic clustering.

of exotic trees were virtually the same across the strata.

4.1. Ecosystem services, assemblage composition and species richness

Household yards were dominated by exotic species across the urban socioeconomic gradient. Woody plant assemblages displayed variations along the socioeconomic gradient, which we attribute to an increase in choice with wealth. People in the richer suburbs can select different species from urban nurseries, which has a bearing on species composition. Within strata, low-density yards exhibited higher similarity, as evidenced by their clustering patterns for all-, indigenous-, and exotic species, compared to medium- and high-density areas (*see* Fig. 3). Dissimilarity in assemblage composition was more pronounced between low-and high-density yards, similar to a contemporary study in Salt Lake Valley, USA where income was positively related to the variety of plant species grown (Blanchette et al., 2021). Interestingly, invasive species were predominantly prevalent in low-density yards, suggesting that the global distribution of invasive species has been primarily influenced by affluent residents. Of particular interest is the observation that the two invasive species (*Psidium guajava* and *Annona squamosa*) recorded in high-density yards were fruit trees, whereas in low-density yards, they were mainly comprised of ornamental plant species. This distinction in the types of invasive/alien species in different socioeconomic areas adds further nuance to the understanding of urban ecology dynamics in Harare.

We found greater woody species richness in the wealthy households than poorer ones similar to findings elsewhere (Hope et al., 2003; Martin et al., 2004). The low species richness recorded in the high-density yards

Table 2
Linear models analysing the associations between socioeconomic and legacy factors and vegetation diversity measures for combined indigenous and exotic woody species across the socioeconomic gradient in Harare, Zimbabwe.

Model	Adj. R^2	F-value	P-value	Std. Error
Richness = −58 + 5.75*property value	0.703	34.14	< 0.001	4.25
Richness = 7.2 + 1.87*watering frequency	0.303	7.09	0.0195	6.51
Richness = −20.6 + 18*suburb age	0.432	11.64	0.0464	5.88
Richness = −13.9 + 6.2*education level	0.591	21.23	<0.001	4.99
Richness = 48.4–11.8*population density	0.406	10.57	0.006	0.306
sesMPD = −3.29 + 0.6*property value	0.543	17.63	0.001	0.27
sesMPD = −0.342 + 0.0932*watering frequency	0.287	6.64	0.023	0.33
sesMPD = −1.67 + 0.865*suburb age	0.377	9.48	0.009	0.31
sesMPD = −1.41 + 0.313*education level	0.582	20.51	0.001	0.26
sesMPD = 1.52–0.532*population density	0.406	10.57	0.006	0.31
%Vegetation cover = −165 + 35.8*property value	0.734	39.67	< 0.001	10.66
%Vegetation cover = 22.2 + 27.6*watering frequency	0.509	15.50	0.002	14.49
%Vegetation cover = −64.3 + 48.9*suburb age	0.457	12.80	0.003	15.23
%Vegetation cover = −44.3 + 16.4*education level	0.586	20.83	0.001	13.30
%Vegetation cover = 126–33*population density	0.606	22.54	<0.001	12.97

results from complete land clearing at construction (Mbiba et al., 2021) and that the houses are so closely packed that not many trees can be grown per household (Muvengwi et al., in review). This probably also indicates why there are so few indigenous trees because these were cleared prior to building. Similarly, low-income homeowners could not afford yard care services leading to a lower diversity (Blanchette et al., 2021). After separating the woody species into indigenous and exotic, the richness of exotic trees was higher than that of indigenous trees across the urban strata, similar to other studies (Aronson et al., 2014).

4.1.1. Ecosystem services

Popularity of exotic species across the urban gradient, is mainly supported by two common motivations, fruit, and shade (Fig. 4). Trees were also fairly commonly grown for ornamental purposes in the medium- and low-density yards (26 % of households in both strata), which could be a reflection of mechanisms such as lifestyle choices (Grove et al., 2006), and keeping up social status (Cook et al., 2012). Indeed, trees were largely planted as windbreak in the low-density households, while medicinal trees ranked high in high-density yards which indicates the importance of socioeconomic factors in tree selection across this urban gradient.

The fact that medicinal purpose was largely common (9 %) in the high-density yards suggests limited use or access to expensive modern health care in these areas. Shade was one of the most popular reasons for growing trees, and most likely influenced the dominance of exotic trees, for example, Shortleaf fig (*Ficus citrifolia*), Jacaranda (*Jacaranda mimosifolia*), Blackwood (*Acacia melanoxylon*), and Indian lilac (*Azadirachta indica*). Although we did not investigate the functional traits of sampled trees, the popularity of exotic trees could be mainly based on their traits such as increased naturalization potential, easy to propagate, fast growth, high adaptability, resistance to pests, and tolerance to a large range of environmental conditions and diseases (Prinzing et al., 2002). Elsewhere, the socio-economic level of the neighbourhood was correlated to the main floristic gradients in the garden (yard) vegetation (Bigirimana et al., 2012; Lubbe et al., 2010). Garden plants in wealthy neighbourhoods had mainly an ornamental function, while in poor neighbourhoods they had more utilitarian functions (Marquardt et al., 2021), which is highly similar when motivations such as fruit and medicine are considered for this study.

4.2. Species richness and phylogenetic diversity measures

The species richness, as well as the variation in the standardized effect size of the mean pairwise distance (sesMPD), were found to be influenced by various socio-economic factors, including property value, level of education, and watering frequency, as well as the legacy effect of suburb age. Notably, the relationship between level of education and urban biodiversity, a relatively unexplored topic in African cities, aligns with previous research from the Global North, where a strong correlation between education and urban biodiversity has been observed (Kirkpatrick et al., 2011; Schell et al., 2020). This suggests that the level of education may be associated with the desire to derive specific ecosystem services from the environment (Kendal et al., 2012; Kirkpatrick et al., 2011), which could have played a significant role in shaping biodiversity patterns across the urban landscape. Furthermore, education is recognized as a source of empowerment, conferring the ability to make informed decisions, advocate for resource conservation, and participate actively in the formulation of policies that govern natural resource utilization (Grove and Burch, 1997; Machlis et al., 1997). Property value, our proxy for income, also showed a positive

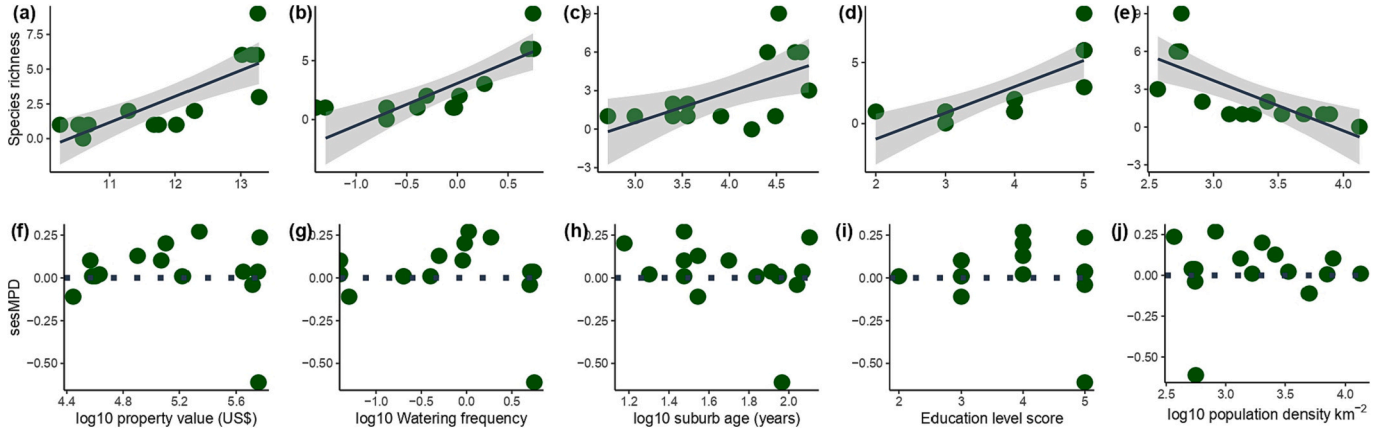

Fig. 6. Linear models Illustrating the impact of socioeconomic (property value, level of education, and watering frequency) and legacy (suburb age) factors on species richness (a-e), and sesMPD (f-j) for indigenous species in the urban landscape of Harare, Zimbabwe. Model specifications are provided in Table 3. The grey shaded envelopes represent the 95 % confidence intervals. The dotted horizontal line for sesMPD represents the null expectation, with values above the line representing phylogenetic dispersion and values below the line representing phylogenetic clustering.

Table 3
Linear models analysing the associations between socioeconomic and legacy factors and vegetation diversity measures for indigenous and exotic woody species across a socioeconomic gradient in Harare, Zimbabwe.

Origin	Model	Adj. R^2	F-value	P-value	Std. Error
Indigenous	Richness = −19.5 + 4.32*property value	0.622	24.01	<0.001	1.65
	Richness = 1.69 + 5.46*watering frequency	0.315	7.44	0.017	2.22
	Richness = −6.71 + 5.54*suburb age	0.330	7.91	0.015	2.20
	Richness = −5.56 + 2.15*education level	0.598	21.80	<0.001	1.70
	Richness = 15.6–3.98*population density	0.514	15.78	0.002	1.87
	sesMPD = 0.39–0.0589*property value	−0.055	0.27	0.609	0.21
	sesMPD = 0.154–0.154*watering frequency	−0.069	0.10	0.756	0.21
	sesMPD = 0.382–0.208*suburb age	0.021	1.31	0.274	0.20
	sesMPD = 0.144–0.0304*education level	−0.054	0.29	0.602	0.21
	sesMPD = −0.065 + 0.028*population density	−0.072	0.06	0.808	0.21
Exotic	Richness = −39.7 + 9.17*property value	0.731	39.03	<0.001	2.75
	Richness = 8.38 + 7.03*watering frequency	0.257	5.84	0.031	4.57
	Richness = −13.7 + 12.4*suburb age	0.447	12.30	0.004	3.95
	Richness = −8.56 + 4.15*education level	0.569	19.46	<0.001	3.48
	Richness = 34.1–8.23*population density	0.571	19.62	<0.001	3.47
	sesMPD = −1.27 + 0.247*property value	0.272	6.23	0.027	0.19
	sesMPD = 0.014 + 0.175*watering frequency	−0.071	0.07	0.798	0.22
	sesMPD = −0.080 + 0.047*suburb age	−0.073	0.05	0.821	0.22
	sesMPD = 0.916–0.283*population density	0.380	9.56	0.009	0.17

relationship with species richness. High income results in a greater number of species through complex social interactions, termed the "ecology of prestige" (Grove et al., 2014), whereby homeowners desire to create an aesthetic that is associated with wealth (Bernholt et al., 2009; Smith et al., 2006).

In contrast to a recent study that reported a negative relationship between neighbourhood age index and species richness (Aznarez et al., 2023), our findings reveal a positive relationship between suburb age and species richness. It is worth noting that the decrease in species richness observed in the previous study could be attributed to the challenge of integrating green infrastructure in those neighbourhoods. Another plausible explanation is that homeowners prioritized ecosystem services over ornamental services, which often requires higher species diversity. In the case of Harare, we hypothesize that the pronounced wealth gap between residents of older, more affluent suburbs and younger, less affluent suburbs may contribute to the substantial difference in species richness. This wealth disparity underscores the need to address environmental injustice concerns in the city of Harare, particularly given the significant variation in vegetation cover between neighbourhoods in affluent and impoverished areas. Certainly, the high-density suburbs stand as a historical legacy of colonization, initially established to facilitate inexpensive labour. Regrettably, since gaining independence, there has been a notable absence of initiatives to rectify these historical injustices and improve the conditions in these areas. The inverse correlation observed between human population density and species richness poses a challenge when attempting to establish green spaces in high-density suburbs. In other words, the more densely populated an area is with humans, the more difficult it becomes to promote and maintain a rich variety of species within green spaces.

This raises an important question about whether high-density suburbs will ever bridge this gap. We contend that this gap could potentially be narrowed through strategic interventions by the Harare City Council, such as the creation of green spaces in gardens and the planting of street trees in poor areas. Considering the differences in yard size across the socioeconomic spectrum, it becomes evident that wealthier individuals have a greater opportunity to cultivate diverse plant species within their yards, further exacerbating the gap between the affluent and the less privileged. Over time, this may result in disparities in the urban climate, with residents in higher-income areas better positioned to adapt to climate change (Aznarez et al., 2023; Chamberlain et al., 2019). It is imperative that those who are both affluent and highly educated, often holding influential positions, make decisions that promote equity and do not exacerbate the socioeconomic divide.

There was a positive correlation between watering frequency and species richness. In arid cities such as Harare, the frequency of watering

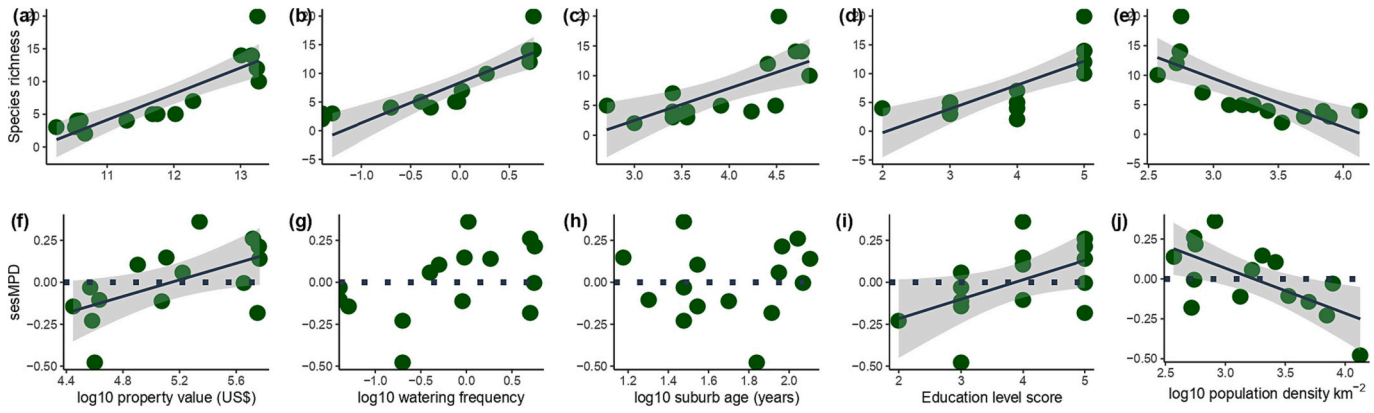

Fig. 7. Linear models illustrating the relationships of socioeconomic (property value, level of education, and watering frequency) and legacy (suburb age) factors with species richness (a-e), and sesMPD (f-j) for exotic species in the urban landscape of Harare, Zimbabwe. Model specifications are provided in Table 3. The grey shaded envelopes represent the 95 % confidence intervals. The dotted horizontal line for sesMPD represents the null expectation, with values above the line representing phylogenetic dispersion and values below the line representing phylogenetic clustering.

demonstrates a strong connection with economic prosperity. Affluent individuals in these drier cities can financially support practices like drilling boreholes, enabling them to augment their watering frequency. This has significant positive influence on factors such as plant diversity, vegetation coverage, and overall ecological diversity (Chamberlain et al., 2019; Jenerette et al., 2013; Leong et al., 2018).

We observed an increase in phylogenetic diversity (sesMPD) associated with wealth, a trend consistent with findings in other studies (Avolio et al., 2015; Knapp et al., 2012; Pearse et al., 2018). Notably, in more affluent suburbs, trees exhibited greater phylogenetic distance, indicating that homeowners could not only afford to acquire plants from urban nurseries but also had the ability to select from a wide range of evolutionary lineages (Kirkpatrick et al., 2011; Kuras et al., 2020). This rise in phylogenetic diversity with affluence suggests a concurrent increase in functional diversity, given the strong correlation between the two (Cadotte et al., 2012; Craven et al., 2018). The positive association between socioeconomic factors and phylogenetic diversity underscores the transformation of urban landscapes into novel ecosystems, with the potential to significantly influence ecosystem functioning (Cadotte et al., 2011). The negative relationship of phylogenetic diversity with human population density, further emphasize the effect affluence can have on woody diversity.

When examining indigenous species, we observed a positive relationship between species richness and both socioeconomic and legacy factors, except for human population density. However, it is noteworthy that phylogenetic diversity, as measured by sesMPD, did not exhibit a significant relationship with these investigated factors. This observation is similar to a study that looked at changes in phylogenetic diversity along an urbanization gradient in the Minneapolis-Saint Paul metropolis, Minnesota, United States of America (Knapp et al., 2012). This intriguing finding suggests that, in the case of indigenous species, their ability to respond to socioeconomic factors in terms of species richness may be primarily influenced by yard area, as opposed to phylogenetic diversity. Furthermore, this observation implies that phylogenetic diversity (sesMPD) of indigenous species may require more time to respond to the socioeconomic and legacy effects. It also underscores the notion that indigenous species within the urban environment may perform similar ecological functions, despite variations in species richness. This nuanced insight highlights the need for a more comprehensive understanding of the dynamics governing the response of native species to urbanization, shedding light on the underlying mechanisms that govern their persistence and adaptation within urban ecosystems. Also, the need to maintain indigenous vegetation patches during development (McKinney, 2006).

Similar to indigenous species, the richness of exotic species demonstrated significant associations with socioeconomic and legacy factors yet displayed a negative relationship with human population density. However, in contrast to sesMPD for indigenous species, which exhibited no notable relationship with socioeconomic factors, sesMPD for exotic species displayed positive significance in correlation with two socioeconomic factors, level of education and property value, while negatively related to human population density. This implies that the overall phylogenetic diversity was notably influenced by the presence of exotic species. This finding underscores the broad spectrum of choices available to individuals with higher socioeconomic status when selecting plants for their yards.

Furthermore, studies in the United States, such as Padullés Cubino et al. (2019), have observed that non-native plant species in some cities were distantly related, which is similar to our findings. It is important to note that their focus encompassed all plants, unlike our study, which specifically concentrates on woody plants. Additionally, previous research has highlighted variations in the response of indigenous and exotic species to socioeconomic gradients. Some instances reveal the socioeconomic gradient manifesting in indigenous species (Lerman and Warren, 2011), while in other cases, it is more apparent in exotic species (Figueroa et al., 2018; Loss et al., 2009). These nuanced observations further contribute to our understanding of the complex interplay between socioeconomics and plant diversity in urban environments.

Our study showed that there was variation in species composition between strata. However, within strata, yards were much more similar in the low-density strata an indication that residents in the same neighbourhood were filtering similar species. Choice of plants to grow was highly influenced by socioeconomic status such as level of education and property value. Disparity in plant woody diversity in yards across socioeconomic gradients in cities of developing countries is expected to be exacerbated by climate change, through increased inaccessibility to water. Unfortunately, the UN goal 6 on access to water focuses on access to safe and affordable drinking water and is silent about access to water to support biodiversity, although emphasis on access to biodiversity is stated in goal 15 (UN, 2023). Woody plants were mostly grown for ornamental purpose in the wealthy suburbs and utilitarian in the poorer suburbs. Lack of equity in the level of woody plant diversity can be reduced by planting street trees in the medium-, and high-density suburbs and investment in water harvesting infrastructure.

CRediT authorship contribution statement

Justice Muvengwi: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft. **Hilton G.T. Ndagurwa:** Conceptualization, Writing – review & editing. **Ed T.F. Witkowski:** Conceptualization, Methodology, Writing – review & editing. **Monicah Mbiba:** Conceptualization, Investigation, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.168976.

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