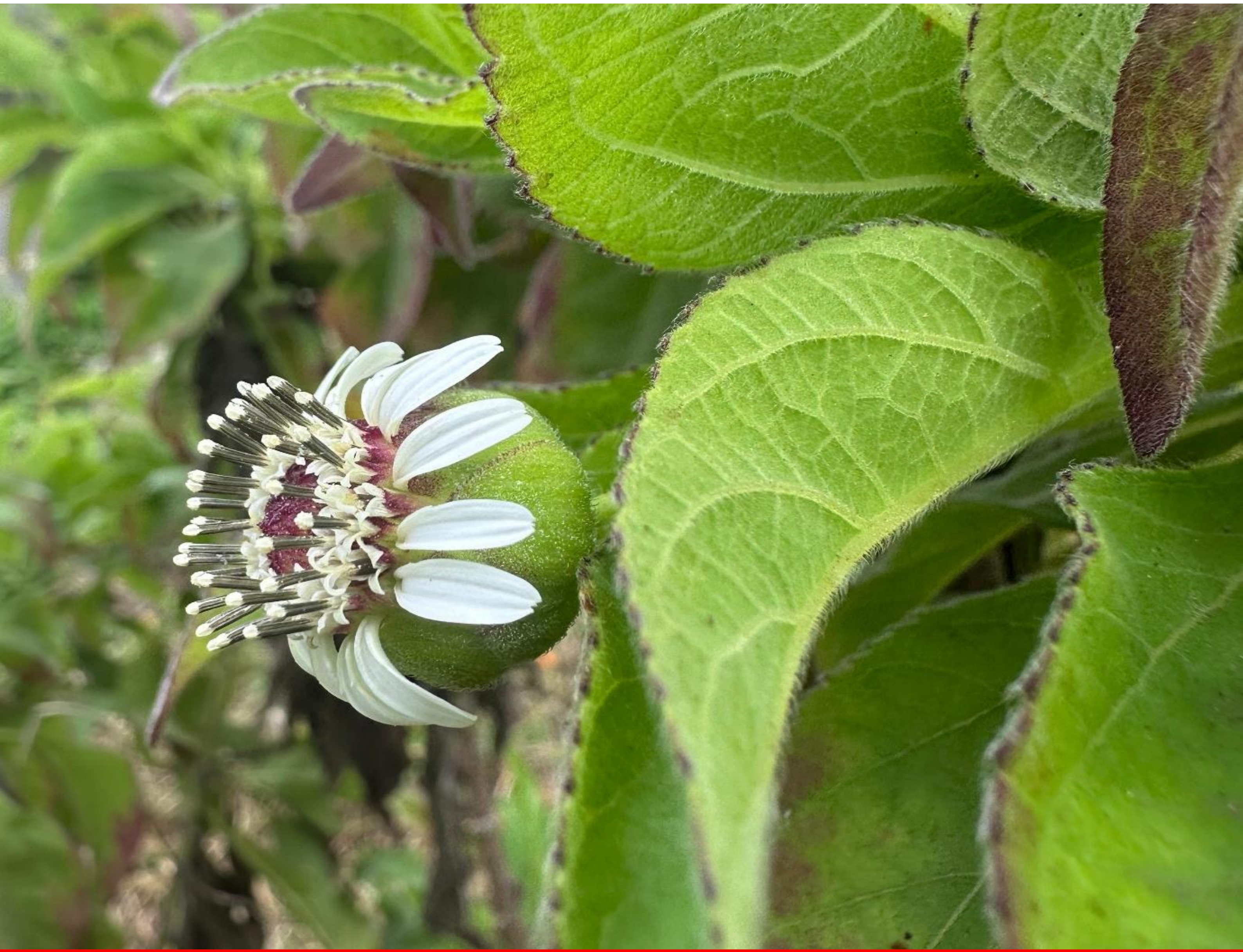
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Restoring native and endemic flora in Puerto Ayora's urban greenspaces

MSc Thesis

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[1] *Scalesia affinis*, photo by Paúl Mayorga

Contents

Abstract

Urban greenspaces (UGs) have the great potential to restore native and endemic species in places such as the Galápagos Islands, where urbanization processes induce significant pressures on its unique biodiversity. Given the worrisome status of the flora in the archipelago, it is imperative to explore how UGs can contribute to the recovery of these plant species through enhancing the ecological quality and accessibility of UGs. Research on this topic specific to the Galápagos Islands is limited. In particular, UG planning in Puerto Ayora —the largest city in the archipelago with the highest urbanization rate—requires further investigation. This study aims to broaden the knowledge on the role of Puerto Ayora's UGs in native and endemic species restoration by: 1. Examining the spatial-temporal distribution of native and endemic and introduced species through linear regression models. 2. Assessing the richness of native and endemic species in UGs related to habitat type, UG size, and population density in the surrounding areas, using linear regression models. 3. Conducting a qualitative assessment of the spatial distribution of UGs to determine their effectiveness in facilitating nature interactions and increasing resident support for native and endemic species restoration. 4. Examining how the results of these analyses can be adopted in urban expansion projects. The main findings of this study suggest that the ecological quality and accessibility of UGs in Puerto Ayora is inadequate and that the current design of UGs may be ineffective in restoring native and endemic species. Given the influence of UG size, habitat type, and population density in the surrounding area on native and endemic species richness, it is of great importance to include these factors in urban expansion projects. In densely built areas where UG expansion is not feasible, the focus should be on converting UGs into greenspace types that feature a high richness of native and endemic species, such as ecological gardens.

Key words: restoration, native and endemic species, urban greenspaces, ecological quality, accessibility of urban greenspaces.

1. Introduction

The Galápagos Islands form a tropical cluster of 128 volcanic islands, islets and rocks (Tye et al., 2002). Positioned squarely on the equator and influenced by various warm and cool-water currents, alongside their considerable separation from the mainland, these islands stand out as an exceptionally dynamic biogeographical environment (Edgar et al., 2010). This unique environment has fostered the development of diverse ecosystems that harbor some of the highest level of endemism (Galápagos Conservancy, 2020). In the archipelago, only four islands are inhabited by humans: Floreana, Santa Cruz, San Cristobal, and Isabela.

Nevertheless, the process of urbanization presents significant environmental obstacles to the archipelago (CDF, 2024). Urban places on the Galápagos Islands are growing in area and population, with an increase in urban impervious surfaces of 170 ha (127%) in the last two decades (Benítez et al., 2018). The number of impervious surfaces is an indicator for environmental quality (El Garouani et al., 2017) and is primarily associated with asphalt and concrete; materials that inhibit water infiltration into the soil (Yang & He, 2017). By developing infrastructure, urbanization processes destroy or modify native habitats and create new ones. This imposes great environmental challenges on the ecosystems of the archipelago, as natural areas are declining and fragmenting, and ecosystem processes are being altered (Müller et al., 2013). Santa Cruz, with 78% of the population of Galápagos living in its capital, Puerto Ayora (CDF, 2023), faces the highest urbanization rate of the archipelago.

Puerto Ayora is divided into 17 neighborhoods; among those, the el Mirador neighborhood, which is an urban expansion project initiated by local authorities to deal with the longstanding demographic pressure. This resulted in an expansion of 40% in Puerto Ayora's urban area (Bonilla, 2020). The project started in 2008, designating el Mirador to accommodate 800 inhabitants in a total area of 171.100 m^2, including 20.800 m^2 of green spaces (Bonilla, 2020). Initially, el Mirador was envisioned as an ecological and sustainable expansion project. However, the observation of uncontrollable and disordered growth, with at least 100 new constructions annually in the neighborhood, raises questions about whether this growth aligns with its sustainable development plan (CDF, 2023).

By creating new habitats, urbanization facilitates the proliferation of generalist, invasive species, leading to the displacement of native and endemic plant species (Müller et al., 2013; CDF, 2024). Moreover, as urban settlements feature gardens and parks where numerous introduced species are cultivated and often escape, there is understandable concern that urban centers may serve as focal points for the spread of introduced species into the broader environment (Chytry et al., 2008; Štajerová et al., 2017), where they could induce considerable harm on native and endemic plant communities (Pyšek et al., 2017). Trophic effects on animal communities also need to be considered, as it is thought that invasive plants can induce massive ecosystem level changes (Szabo et al., 2012; Tallamy et al., 2021). To illustrate this, a study by Hood-Nowotny et al. (2023) found that the introduced *Rubus niveus* (blackberry) causes food web disturbances in Galápagos, contributing to the rapid decline of the green warbler finch.

Introduced plant species are generally over-represented in urban centers compared to the rest of the city and the surrounding rural areas (Chocholoušková & Pyšek, 2003; Štajerová et al., 2017). Although only 3% of the Galápagos Islands are populated by humans, our presence in this small fraction is deteriorating native and endemic plant populations (CDF, 2024). Currently, there are approximately 810 introduced plant species, with at least 270 naturalized and 113 actively invading the natural areas of the islands (Buddenhagen et al., 2004; Guézou & Trueman, 2009; Toral-Granda et al., 2017; Causton et al., 2018; Jaramillo et al., 2018). With more than half of the endemic plant species classified as threatened, and increasing pressures from human activities and introduction pathways, the status of the archipelago's flora is worrisome (Toral-Granda et al., 2017; CDF, 2024).

To counteract the detrimental effects of urbanization, the urban ecological restoration project of the Galápagos Verde 2050 program was launched in 2014 by the Charles Darwin Foundation (CDF), to restore degraded urban environments on the Galápagos Islands through the propagation of native and endemic plant species in urban greenspaces (UGs) (CDF, 2024). UGs are essential components of any urban area, crucial for maintaining environmental quality and sustainability (Gupta et al., 2012). Besides, UGs are thought to play an important role in biodiversity conservation (Aronson et al., 2017). Within these spaces a great variation exists, with habitats ranging from intact patches of native vegetation to gardens, parks, and modified areas that may be highly different from native ecosystems (Cilliers et al., 2013; Aronson et al., 2017). Considering the vulnerable status of Galápagos' flora, it is of great importance to focus on the inclusion of native and endemic species to improve the ecological quality of UGs. Native and endemic species are more likely to increase biodiversity, provide resources for specialized urban animals, and are adapted to local conditions (Anderson & Minor, 2021; Berthon et al., 2021; Klaus & Kiehl, 2021). Additionally, when UGs are used for education and to increase residents' connectedness to nature by observing plants and animals, the use of native and endemic plant species can increase residents' identification with "their" city (Standish et al., 2013; Klaus & Kiehl, 2021).

Conservation biologists have long argued that interaction with the natural world increases understanding and knowledge of biodiversity, thereby enhancing the willingness to protect it (Kareiva, 2008; Coldwell & Evans, 2017; Colléony et al., 2020). However, it is thought that urbanization will result in conservation support that relies on resident's connection with only a small number of common urban species, which are not on the priority list for conservation (Dunn et al., 2006). When featuring native and endemic species, UGs could play an important role in enhancing the support for the restoration of these vulnerable plant species (Kareiva, 2008; Coldwell & Evans, 2017; Colléony et al., 2020).

Access to the National Park surrounding Puerto Ayora is highly restricted, with residents only permitted to enter when accompanied by a certified guide, a requirement that incurs significant costs. This makes the park largely inaccessible for regular visits. As a result, enhancing the accessibility of UGs is essential for providing residents with opportunities to engage with nature. While there are a few open-access beaches near Puerto Ayora, these areas primarily feature aquatic ecosystems, offering limited interaction with the native and endemic terrestrial flora of Santa Cruz. Therefore, urban UGs play a critical role in fostering nature connections and ensuring residents have access to the island's unique plant species.

The World Health Organization (WHO) has provided several guidelines to ensure the provisioning of adequate UGs for urban residents. Among these guidelines, they recommend that a UG of a minimum size of 0.5 ha should be accessible within a linear distance of 300 meters for each resident (WHO, 2016). However, due to Puerto Ayora's small size and the impracticality of providing sufficient UGs of this scale, it is important to incorporate alternative recommendations, such as the Instituto Nacional de Estadísticas (INE) (2018) guideline, which suggests providing 10 m^2 of UG per inhabitant, alongside the WHO's approach. In 2012, the National Institute of Statistics and Censuses (INEC) provided the first report of the urban green index, which serves as an environmental indicator of the amount of UG area per inhabitant of provincial capitals in Ecuador. They calculated an UG index of 5.58 m^2 of UG per inhabitant of Puerto Ayora (INEC, 2012), which is considerably lower than the 10 m^2 of UG per inhabitant that the INE recommends. Within Puerto Ayora, the number of inhabitants per hectare can vary from 5 to 500 between blocks (Delgado & Bryon, 2018), suggesting great differences in UG indexes on the neighborhood level.

Given the concerning status of the flora on the Galápagos Islands and the rapid urbanization rate, it is imperative to evaluate the success of UGs in restoration efforts for native and endemic species. Exploring the potential scenarios of UG planning in the neighborhood el Mirador, which is currently still under construction, may provide valuable information for future urban ecological restoration projects. This study aims to assist the Galapagos Verde 2050 program by investigating the following main research question: *how can the ecological quality and the accessibility of urban greenspaces be improved in Puerto Ayora, with a specific case study of the el Mirador neighborhood?* To provide some background information on the effect of urbanization on the distribution of plant species in Puerto Ayora, the first part of this study will focus on assessing the sub-question: *how has the spread of introduced and native and endemic plant species in urban settings of Puerto Ayora changed on a spatial-temporal scale?* Thereafter, the following sub-question will be investigated: *to what extent does the native and endemic plant species richness differ across urban greenspaces in Puerto Ayora?* Since the designs of UGs vary substantially (Cilliers et al., 2013; Aronson et al., 2017), it is of great importance to investigate the species richness of different UGs, to identify which UG types feature the greatest success of native and endemic plant species restoration. Additionally, considering the potential of nature interactions by residents to increase support for native and endemic plant species restoration, it is of great importance to evaluate the accessibility of UGs on the neighborhood level. This will be analyzed with the following research question: *how are urban greenspaces in Puerto Ayora spatially distributed, in terms of size and proximity, on the neighborhood level?* Consequently, a last sub-question will investigate the outcomes of these analyzes to formulate recommendations for improving future planning of UGs: *how can the newly developed el Mirador neighborhood serve as a case study for urban greenspace planning recommendations in Puerto Ayora?*

As the ecological quality and the accessibility of UGs in Puerto Ayora are rather unexplored, this study will produce information that explores the contribution that urban areas can have on the recovery of native and endemic plant species. Besides, although focusing on the specific context of urban settings on the Galápagos Islands, the findings of this study may produce valuable insights into the implementation of restoration efforts in other urban areas, as ecological degradation due to urbanization is a significant issue observed in many vulnerable ecosystems throughout the world (Zipperer et al., 2020).

2. Concepts

2.1. Native and endemic species richness across various types of UGs

Considering the ability of native and endemic species to enhance biodiversity and provide resources for specialized urban animals (Anderson & Minor, 2021; Berthon et al., 2021; Klaus & Kiehl, 2021), their richness will be used as a measure of ecological quality in UGs. In this study, native and endemic species richness in UGs will be investigated through three variables: habitat type, UG size, and population density.

In Puerto Ayora, UGs can be categorized into four habitat types: parks, aesthetic gardens, semi-natural areas, and ecological gardens. Fig.1 represents the expected pattern of native and endemic species richness across the habitat types. This pattern is explained by degree of human interference, where highly modified areas are thought to have a lower native and endemic species richness (Cilliers et al., 2013; Aronson et al., 2017; Klaus & Kiehl, 2021). Among the habitat types, parks, aesthetic gardens, and ecological gardens are all highly modified UGs. However, since restoration of native and endemic species is the main focus in ecological gardens in Puerto Ayora, these gardens are expected to feature the highest native and endemic species richness.

Additionally, several studies have indicated that a greater patch size results in an increasing number of plant species (Angold et al., 2006; Li et al., 2006). Since variation in size exists among UGs in Puerto Ayora, it is key to investigate the influence of this factor on native and endemic species richness.

Also, according to Aronson et al. (2017), human population density of the surrounding urban matrix is an important factor that may negatively influence native species richness. Another study by Spears et al. (2013) found that population density is an important predictor for alien species richness. As invasive species are a great threat to native and endemic plant communities (Müller et al., 2013; CDF, 2024), UGs in densely populated neighborhoods in Puerto Ayora may feature a lower native and endemic species richness.

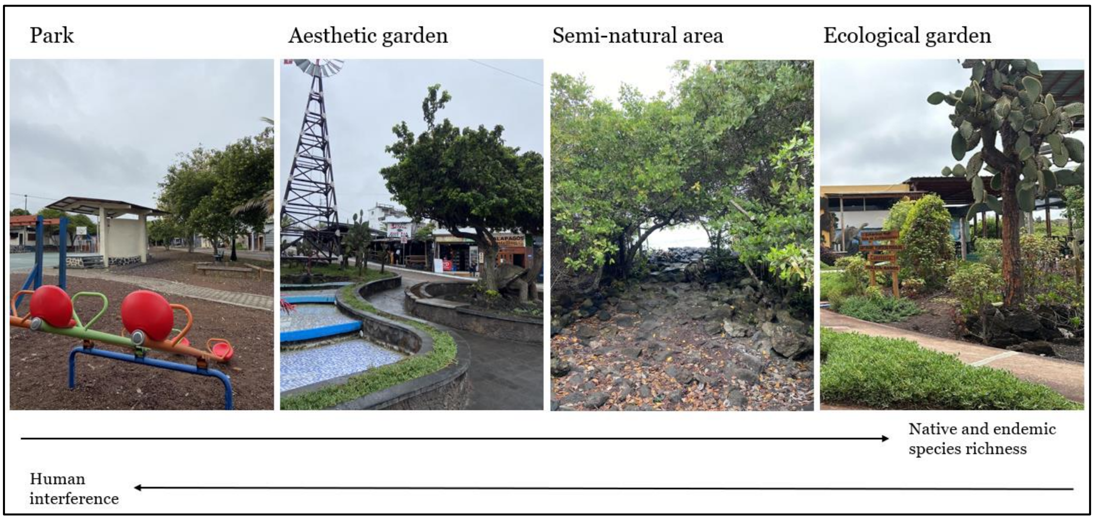

Figure 1: The various habitat types of UGs in Puerto Ayora along the expected gradient of native and endemic species richness and level of human interference. Parks in Puerto Ayora are highly modified areas featuring playgrounds surrounded by vegetation. Human interference is thought to be high since these places serve as spots for social gatherings and recreational activities. Aesthetic gardens are also highly modified areas, located in the touristic center of Puerto Ayora, where, in most cases, they aim to showcase the native and endemic vegetation of Santa Cruz. Semi-natural areas are predominantly composed of mangrove species. These areas are accessible only via walking paths that surround or cut through them, resulting in minimal human interference in these UGs. Ecological gardens have been established by the CDF to restore the native and endemic flora of Santa Cruz. Thus, these UGs are managed to enhance the survival of native and endemic species and reduce the growth of invasive species.

2.2. Accessibility of urban greenspaces and restoration support of residents

The frequency of nature interactions in Puerto Ayora is likely decreasing due to high urbanization rates, which may undermine support for nature conservation (Kareiva, 2008; Coldwell & Evans, 2017). Although Puerto Ayora is a small, isolated city situated within a protected nature reserve, access to these protected areas is highly restricted, as entry is only permitted with a certified naturalist guide. This creates significant barriers for residents seeking to visit these natural spaces. Consequently, UGs are vital for providing daily nature interactions to the residents of Puerto Ayora. Assessing the accessibility of UGs is therefore crucial in understanding how easily residents can reach these areas and connect with nature in their everyday lives.

Accessibility can be evaluated using place-based and person-based approaches (Miller, 2007). Place-based approaches assess the accessibility of a specific location or spatial unit by measuring physical distance or travel time between desired activity locations and key daily locations, such as a residence or workplace. This includes methods like calculating travel time or distance to the nearest opportunity and the number of opportunities within a specific area (Delafontaine et al., 2012). Person-based accessibility, on the other hand, considers the spatiotemporal constraints individuals face, allowing for variability in accessibility throughout the day and across different people (Delafontaine et al., 2012).

Due to the difficulty of obtaining detailed and representative information about individuals' activities in Puerto Ayora, this study will use a place-based approach to assess accessibility. Two measurements will be used: distance to the nearest UG and UG area. To account for population differences between neighborhoods, the mean distance to the nearest UG per household in each neighborhood will be calculated. Additionally, UG area will be measured by calculating the UG index for each neighborhood, which estimates the amount of UG area per inhabitant.

3. Methods

3.1. Study area

Since the last decades, the tourism industry on the Galápagos islands has expanded substantially. In 1980, less than 20,000 tourists visited the islands. Four decades later, in the year 2019, the number of tourists had increased to 271,000 (Galapagos Tourism Observatory, 2021). As an increase in tourism often leads to population growth, this is closely related to urbanization processes (Burbano et al., 2022). The city of Puerto Ayora, which is the main center of tourism in the archipelago, is selected as the study area for this research. Between 1990 and 2015, Puerto Ayora had a growth in population size of 175% (Bonilla et al., 2020). In 2018, the number of inhabitants in el Mirador and Puerto Ayora were 310 and 11,822, respectively (Delgado & Bryon, 2018). For this study, a total of 41 UGs were surveyed, categorized into aesthetic gardens, ecological gardens, parks, semi-natural areas, and potential gardens (Fig.2). As of 2024, UGs in this city cover an area of 23,782 square meters, this excludes the potential gardens located in El Mirador.

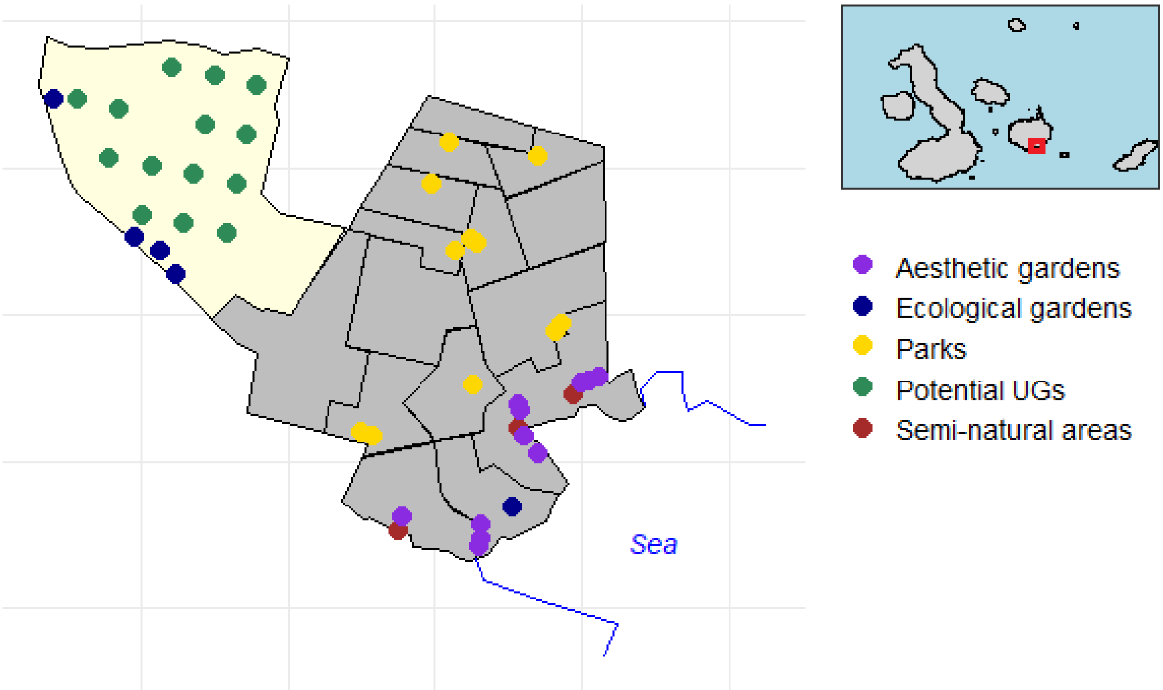

Figure 2: This map shows Puerto Ayora (grey) and el Mirador (yellow), and their UGs. The overview map shows the location of the city on the Galápagos Islands.

3.2. *Assessing spatial-temporal patterns of plant species in Puerto Ayora*

Species distribution data were analyzed using herbaria collections from the CDF, which include plant species observations from Puerto Ayora and El Mirador with geographic coordinates. Observations were made by scientists during field excursions without a systematic or predefined sampling design. This dataset spans collections from 1963 to 2024 and is supplemented by plant observations from the iNaturalist platform. The combined dataset was filtered to focus on species categorized as either native and endemic or introduced, resulting in 645 records of native and endemic species and 1298 records of introduced species. All statistical analyses were performed using R (version 4.4.1), with results visualized using the *ggplot2* package.

To investigate whether introduced plant species are over-represented near the city center, the mean distances to the center for native and endemic versus introduced species were compared. Geographic distances from each observation point to the city center were computed using the distHaversine function from the *geosphere* package. Normality of distance distributions for both species categories was assessed using the Shapiro-Wilk test. Since the results indicated significant deviations from normality in both groups, the Mann-Whitney U test was used to compare the distributions.

To examine trends in the distance to the center over time for both species categories, linear regression models were conducted, regressing distance to the center of plant observations against observation dates. The decades of the 1960s and 1970s were excluded from this analysis due to insufficient observations (fewer than 10 records for both categories combined). The models provided estimates for the slopes, with standard errors and p-values used to determine the statistical significance of the coefficients. Residual plots were analyzed to check for normality and homoscedasticity.

3.3. Investigating the native and endemic species richness in UGs

Data on the richness of native and endemic species were collected through standardized ten-minute surveys conducted across all UGs in Puerto Ayora and el Mirador, excluding the potential UGs. To compare UG species richness with natural areas, a dataset from the GNPD (2019) was utilized, which details the most common native and endemic species in the natural regions surrounding Puerto Ayora. The size of each UG was measured using QGIS 3.28, while population density in the surrounding areas was estimated based on data from the open GeoData source of the CDF. All statistical analyses were performed using R (version 4.4.1) and visualized with the *ggplot2* package.

To analyze native and endemic species richness across different habitat types, UGs were classified according to the scheme presented in Fig. 1. Differences in species richness among habitat types were evaluated with Analysis of Variance (ANOVA), and post-hoc comparisons were made using Tukey's Honest Significant Difference (HSD) test to identify specific group differences. The normality of species richness within each habitat type was assessed using the Shapiro-Wilk test.

To investigate the relationship between UG size and native and endemic species richness, a linear regression model was performed, regressing species richness against UG size. The normality of residuals from this model was tested with the Shapiro-Wilk test. For analyzing the effect of population density on species richness, a linear regression model was used, with population density as predictor and species richness as dependent variable. Due to non-normality in the residuals, both species richness and population density were log-transformed. Both linear regression models estimated the slope, with statistical significance of the coefficients assessed through standard errors and p-values.

The relative importance of predictors—habitat type, UG size, and log-transformed population density—on species richness was examined using the likelihood ratio test. The full linear regression model, including all predictors, was compared against reduced linear regression models, which excluded one of the predictors. Multicollinearity among predictors was evaluated by calculating variance inflation factors (VIF) with the *car* package. The Shapiro-Wilk test was used to check for normality, and residual plots were reviewed for any patterns.

Similarity between UGs based on their species richness was explored by hierarchical clustering analysis using Euclidean distance as the similarity coefficient. The clustering results were visualized in a dendrogram to illustrate the hierarchical relationships and distances between UGs. Additionally, Permutational Analysis of Variance (PERMANOVA) was conducted to test the significance of the differences in species richness across habitat types.

Finally, the frequency of the five most common species in natural areas around Puerto Ayora for each UG habitat type was analyzed to estimate the similarity between UGs and the surrounding natural environments.

3.4. Calculating the UG index and the average distance to the nearest UG

For this analysis, several datasets and sources were utilized. Geographic data for neighborhood blocks, including the number of inhabitants per neighborhood in 2015, were obtained from the open GeoData source of the CDF. Information about the locations of public spaces and property types was provided by the municipality of Santa Cruz. The projected UG index and mean distance to the nearest UG for El Mirador were calculated using the project plan of El Mirador (Bonilla, 2020), which provided estimates of the residential population and UG area.

In QGIS 3.28, the green areas of the public spaces in Puerto Ayora were exported to a shape file containing polygons delineating UG areas. Polygons representing public gardens managed by the CDF were also added to this file. Inaccessible UGs, due to improper maintenance, were excluded from this analysis. Unlike the INEC report (INEC, 2012), which includes facilities such as sports fields and stadiums in UG calculations, this study excluded these areas since they feature artificial surfaces without natural vegetation in Puerto Ayora and el Mirador. To assess differences in UG size between neighborhoods, the UG index was calculated by dividing the UG area (m^2) in each neighborhood by its number of inhabitants. The proximity of UGs was estimated by calculating the distance to the nearest UG for each residential property. The Distance to Nearest Hub (Points) tool in the QGIS Processing Toolbox was used to compute these distances, and the Group Stats plugin in QGIS was used to determine the average distance to UGs for each neighborhood. UG index and distance to the nearest UG were not calculated for the neighborhoods of Consejo de Gobierno and Punta Estrada due to their very low or nonexistent populations. However, UGs located in Consejo de Gobierno were considered in the calculations for other neighborhoods, as they are available to residents in the surrounding areas.

The results of this analysis are divided into two sections: one focusing on the neighborhoods of Puerto Ayora, and the other on the case study of El Mirador. Since the potential UGs in El Mirador are still under construction, only currently existing UGs in the area were used to calculate the current values of the UG index and mean distance to the nearest UG.

4. Results

4.1. Spatial-temporal distribution of introduced and native and endemic plant species

With 66.8%, the proportion of introduced species observations in the study sample was substantially higher than the proportion of native and endemic species observations (Fig. 3). The mean distance to the city center for introduced species was 0.54 km. For native and endemic species this was 0.62 km, which is significantly higher than the mean distance of introduced species to the center ($P < 0.001$).

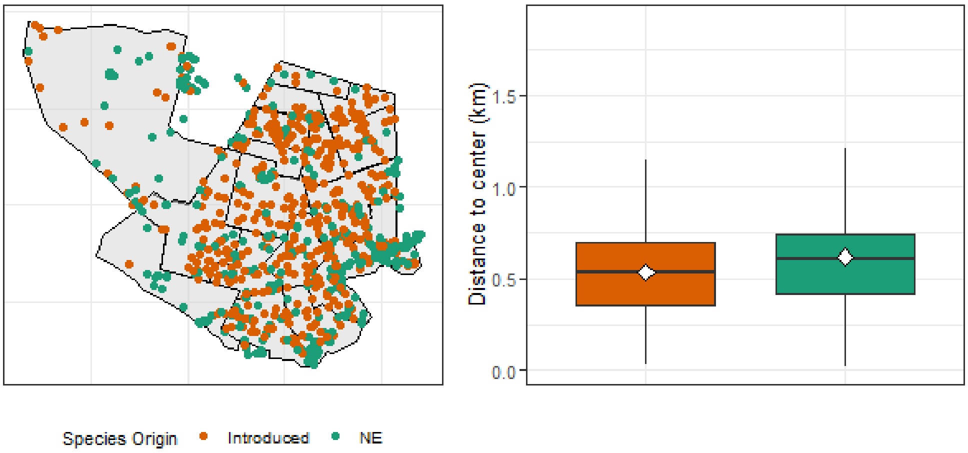

Figure 3: The map (left) shows the spatial distribution of introduced and native and endemic (NE) species collections from 1963 to 2024 in Puerto Ayora. On the right, the mean distances for both categories to the city center are visualized.

The coefficients of the linear regression models, with observation year as predictor and distance to the center as dependent variable, indicate a slope for introduced species and native and endemic species of 1.663e-10 and -7.677e-11, respectively (Fig.4). This indicates that for introduced species, there is a positive relationship between the distance to the center and time. For native and endemic species, this relationship is negative. The model for introduced species indicates that the distance to the center is significantly increasing over time ($P < 0.001$). The model for native and endemic species indicates that the distance to the center is significantly decreasing over time ($P < 0.05$).

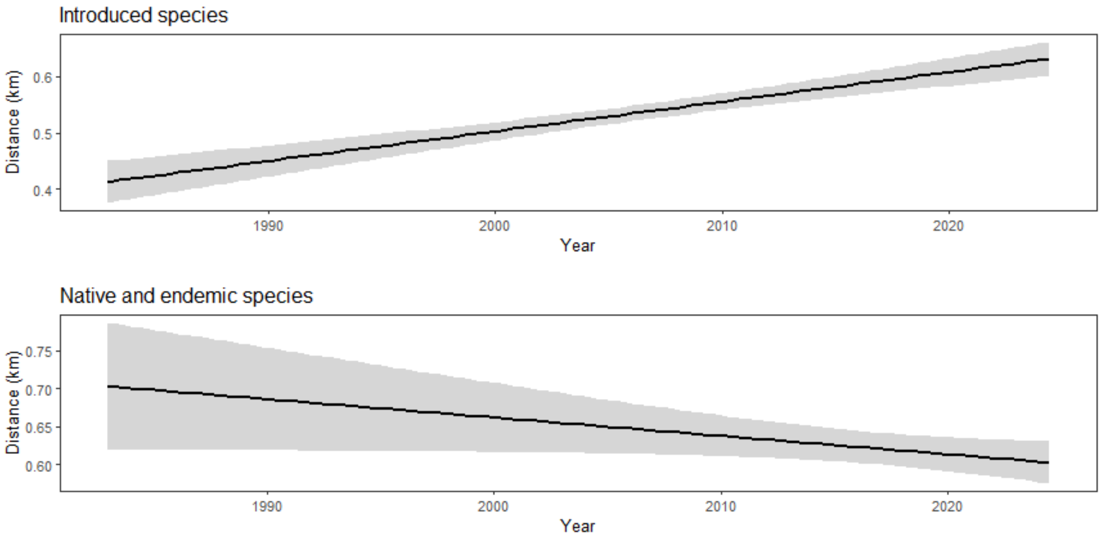

Figure 4: The linear regression of distance to the center of Puerto Ayora from 1980 to 2024 for introduced and native and endemic species observations.

4.2. Native and endemic species richness in UGs

4.2.1. Species richness versus habitat type, UG size, and population density

The analysis of native and endemic species richness across different UG habitat types reveals significant variations. As shown in Figure 5, ecological gardens have a notably higher mean richness of native and endemic species compared to aesthetic gardens and semi-natural areas, with significant differences observed ($P = 0.028$ and $P = 0.019$, respectively). Although not statistically significant ($P = 0.08$), ecological gardens also tend to exhibit higher species richness compared to parks.

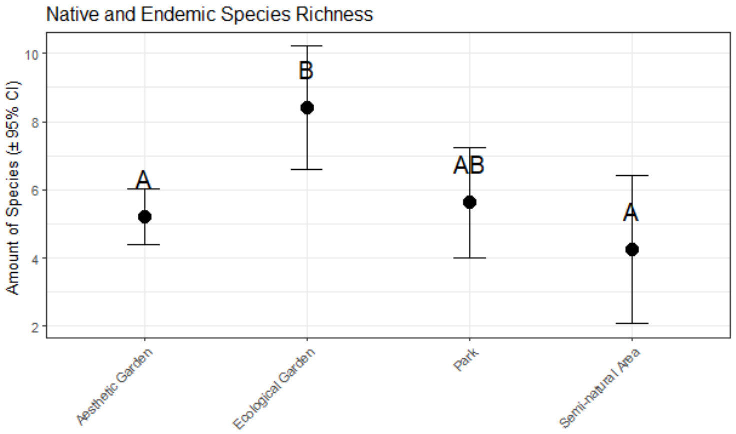

Figure 5: The mean richness of native and endemic species for the different UG habitats.

Regarding UG size, the linear regression model indicates a significant positive relationship between UG size and species richness (P < 0.05), suggesting that larger UGs support greater species richness (Fig. 8). Conversely, the analysis of species richness in relation to population density, using a log-transformed linear regression model, reveals a significant negative relationship (P < 0.01), indicating that species richness decreases as population density increases (Fig. 8).

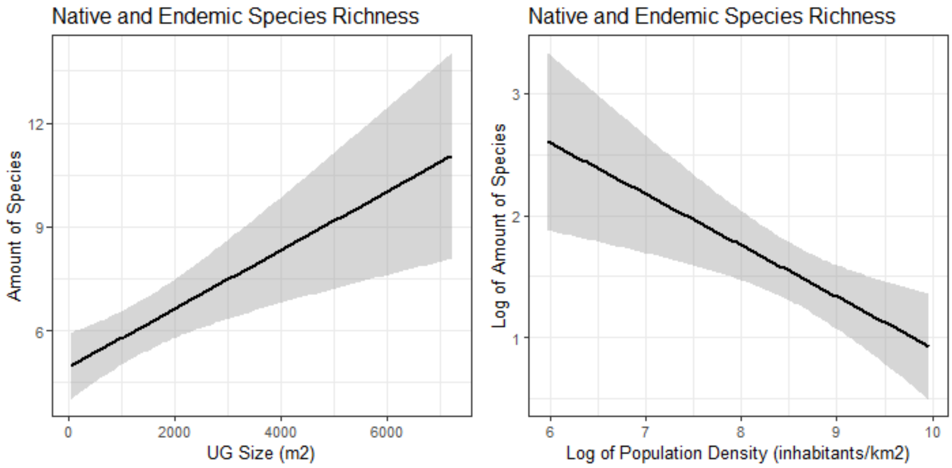

Figure 6: Native and endemic species richness related to UG size and population density.

By comparing the full linear regression model—including habitat type, UG size, and log-transformed population density as predictors—with the reduced models, the likelihood ratio tests revealed that only UG size significantly improved the model's ability to explain native and endemic species richness (P < 0.001).

4.2.2. Hierarchical clustering analysis

Hierarchical clustering analysis, based on Euclidean distances, further illustrates the differences in species composition among habitat types. Parks are clustered together with lower Euclidean distances, indicating that species richness within parks is more similar across different locations (Fig. 6). In contrast, ecological gardens exhibit larger Euclidean distances, highlighting their distinct species composition relative to other UG habitats. This clustering pattern is supported by the PERMANOVA results, which reveal a significant effect of UG habitat type on species composition (P < 0.001).

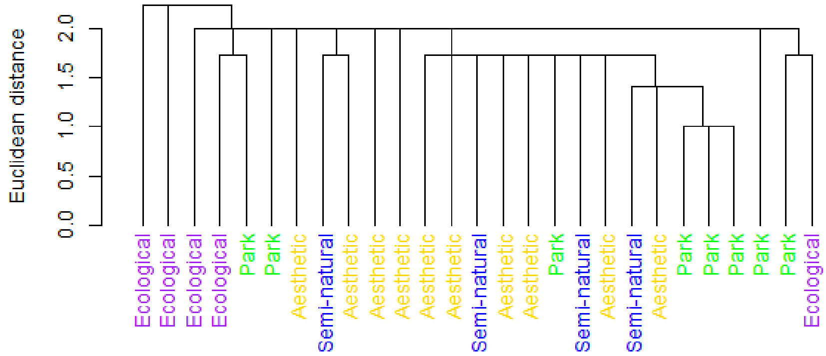

Figure 7: The Euclidean distance dendogram of the hierarchical clustering analysis, indicating how different UG habitats are grouped based on their similarity in native and endemic species richness.

4.2.3. Presence of the most common species in the National Park among UGs

The presence of the five most frequently observed native and endemic species in the natural areas around Puerto Ayora—*Bursera graveolens, Piscidia carthagenensis, Scalesia affinis, Opuntia echios,* and *Croton scouleri* (GNPD, 2019)—varies considerably among UG habitats (Fig. 7). None of the UGs contained *Bursera graveolens*, and *Scalesia affinis* was exclusively found in ecological gardens. Semi-natural areas did not feature any of these five species.

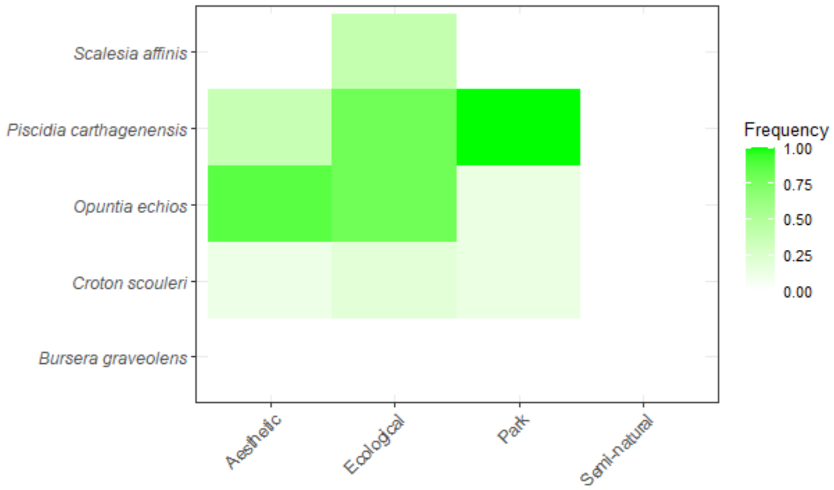

Figure 8: The five most frequently observed native and endemic species in the National Park surrounding Puerto Ayora, along with their frequencies across the various UG habitats. The frequency represents the proportion of locations within each UG habitat type where these species are present. Additional information on the species richness across the different UG habitats can be found in Supplementary Table 1 & 2.

4.3. UG Index and distance to nearest UG

UG indexes and mean distances to the nearest UG vary between neighborhoods (Fig. 9). The exact values are represented in Table 1. The calculated UG index for the total area of Puerto Ayora, el Mirador excluded, is 2.1 m^2 of UG per inhabitant. On the neighborhood level, UG indexes range from 0 to 15.7 m^2 of UG per inhabitant. Only the UG indexes of the neighborhoods Pelikan Bay and Los Cactus, with 15.7 m^2 and 11.8 m^2 of UG per inhabitant respectively, meet the INE recommendation of a minimum of 10 m^2 of UG per inhabitant (INE, 2018). The neighborhoods Pampas Coloradas, los Arrayanes, and la Cascada do not have any UGs, and therefore, have an UG index of 0. Moreover, it seems that generally, neighborhoods with a low UG index also have a greater mean distance to the nearest UG. With a mean distance of 346 meters to the nearest UG for the households in Pampas Coloradas, this neighborhood does not meet the WHO recommendation of the provisioning of an UG within a distance of 300 meters for each resident (WHO, 2016). For all other neighborhoods, the mean distance to the nearest UG complies with the WHO recommendation. However, between and within the neighborhoods variation in distance to the nearest UG exists, with the lowest value of 18 meters measured in Escalesia and the highest value of 505 meters measured in Pampas Coloradas. For 23% of the residential buildings in Puerto Ayora, the distance to the nearest UG is greater than 300 meters. The households with the greatest distance to the nearest UG are mainly located in the neighborhoods Pampas Coloradas, Miraflores, los Cactus, and los Arrayanes. The three neighborhoods that have the lowest UG index combined with the greatest distance to the nearest UG are Pampas Coloradas, los Arrayanes, and La Cascada, in descending order.

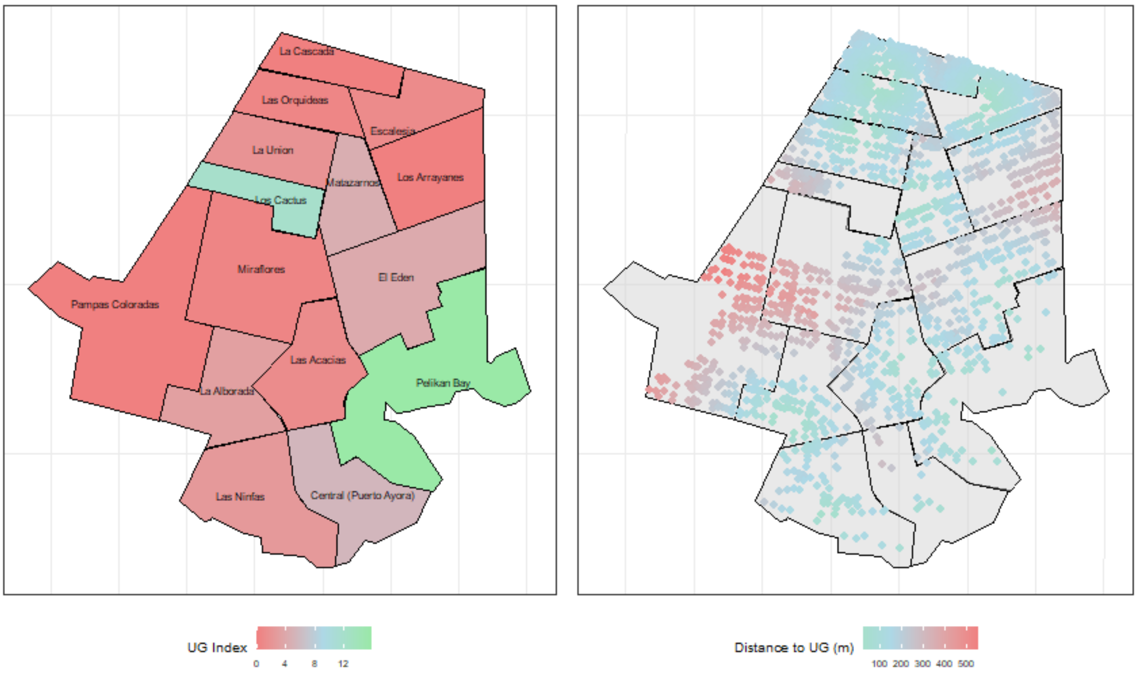

Figure 9: The map on the left shows the UG index for each neighborhood in Puerto Ayora. On the right, the distance to the nearest UG for the households within the neighborhoods are visualized.

Table 1: Demographic information for the neighborhoods in Puerto Ayora in the year 2015. Additionally, UG indexes and the distances to the nearest UG are represented for each neighborhood.

Neighborhood	**Area (ha)**	**Inhabitants**	**UG area (m2)**	**UG Index**	**Distance to UG (m)**
Central (Puerto Ayora)	10.3	249	1,335	5.36	169
Pelikan Bay	19.6	329	5,170	15.71	100
Las Ninfas	12.6	374	889	2.38	116
La Alborada	9.4	970	2,914	3.00	142
Las Acacias	9.3	611	690	1.13	141
El Eden	15.1	744	3,012	4.05	185
Los Arrayanes	9.9	507	0	0	230
Escalesia	6.5	779	779	1.00	108
La Cascada	5.3	1045	0	0	126
Las Orquideas	5.7	1205	511	0.42	106
La Union	7.3	921	1,560	1.69	121
Matazarnos	6.5	579	2,009	3.47	125
El Mirador	74.5	294	11,156	37.95	84
Los Cactus	4.9	335	3,971	11.85	255
Miraflores	15.7	1570	721	0.46	293
Pampas Coloradas	22.9	1248	0	0	346
Consejo De Gobierno	21.8	-	221	-	-

4.4. *El Mirador as a case-study*

According to the project plan of El Mirador (Bonilla, 2020), the amount of UG area will increase with 186% and the number of inhabitants will increase with 172%. The current UG index is 37.9 m^2 of UG per inhabitant and is expected to increase to 39.9 m^2 of UG per inhabitant. Both values are substantially higher than the recommended index of the INE (INE, 2018). Currently, the mean distance to the nearest UG is 329 meters, which is higher than the recommended value by the WHO of 300 meters (WHO, 2016). Variation within the neighborhood is great, with values ranging from 30 meters for households on the west side to 838 meters for houses on the east side (Fig. 10). The projected mean distance to nearest UG is projected to be 86 meters for el Mirador. Between the households, the projected distances vary from 26 meters to 277 meters (Fig. 10), thus not exceeding the recommended value by the WHO.

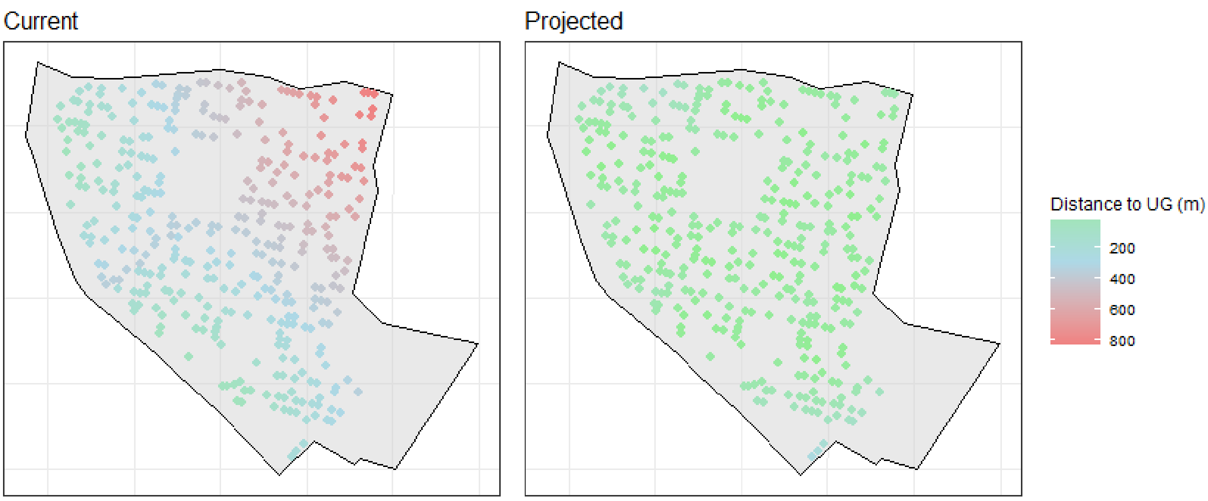

Figure 10: These maps show the current and projected distances for each household to the nearest UG for el Mirador.

5. Discussion

Several studies have suggested that urban settlements may serve as focal points for the spread of introduced species to the surrounding area (Chytry et al., 2008; Štajerová et al., 2017). As 66% of the plant collections between 1963 and 2024 are of introduced origin, it can be suggested that, also in Puerto Ayora, urban areas proliferate the spread of introduced species. Moreover, the distance to the center of introduced species is slightly increasing over time, suggesting that introduced species may have spread from the center to the edges of the city. This is highly detrimental, since their escape to the natural areas of Santa Cruz can induce considerable harm on the already vulnerable native and endemic plant communities (Toral-

Granda et al., 2017; CDF, 2024). Observations of native and endemic plant species closer to the city have slightly increased over time, indicating a trend where UGs may accommodate more native and endemic species. This trend offers a hopeful perspective for native and endemic species restoration in UGs. Although significant, the slopes of these trends are quite small, indicating that the effects may be minimal.

Among the predictors investigated in this study, UG size seems to have the greatest influence on the richness of native and endemic species, with species richness significantly increasing with a greater UG size. The separate significant effects of habitat type and population density on native and endemic species richness suggest that both factors contribute meaningfully to the ecological patterns observed in UGs. However, when UG size is considered in combination with these predictors, the effects of habitat type and population density are diminished. This suggests that UG size may be a more dominant predictor of species richness, potentially overshadowing the contributions of population density and habitat type in the combined model. These findings highlight the complex interplay between UG size, habitat type, and population density. While UG size appears to be the most significant predictor when all factors are considered together, habitat type, and population density should not be overlooked as important factors in UG planning.

Since increasing the UG size and decreasing the population density is often not feasible in densely built-up neighborhoods, it might be more efficient to enhance the habitat quality of UGs in those areas. Ecological gardens in particular seem to have great success in native and endemic species restoration. Compared to parks, semi-natural areas, and aesthetic gardens, these UGs seem to have a higher native and endemic species richness. Furthermore, ecological gardens appear to host native and endemic vegetation that, compared to other UG habitats, resembles the flora found in the natural areas surrounding Puerto Ayora the most, suggesting that these gardens have the potential to replicate habitats similar to those in the surrounding natural environments. Currently, ecological gardens constitute less than 10% of the UGs in Puerto Ayora, underscoring the need to convert existing UGs, or portions of them, into these types of gardens. Contrary to expectations, semi-natural areas appear to host a relatively small number of native and endemic species. These observations may be attributed to the fact that the surveyed semi-natural areas primarily consist of mangrove ecosystems, which are dominated by a limited number of mangrove species. Future research that assesses both species abundance and richness may provide further insight into these findings.

Furthermore, the species observed in semi-natural areas appear to differ substantially from those most commonly found in the natural areas surrounding Puerto Ayora. This discrepancy may arise because the surrounding natural areas are primarily terrestrial ecosystems, as opposed to coastal ecosystems. A more comprehensive analysis should compare these UGs with coastal ecosystems to better understand these differences.

With only 2 out of 15 neighborhoods aligning with the recommended minimum UG index value of 10 m^2 of UG per inhabitant by the INE (INE, 2018), it can be suggested that the amount of UG area in Puerto Ayora is highly inadequate and inequitable. Critical neighborhoods are Pampas Coloradas, los Arrayanes, and la Cascada, having an UG index value of 0. Pampas Coloradas is the only neighborhood that has a mean distance to the nearest UG lower than the recommended value of 300 meters by the WHO (WHO, 2016). However, variation within neighborhoods is great, with 23% of the households across Puerto Ayora experiencing a distance to the nearest UG greater than recommended by the WHO. Thus, considering the poor accessibility of UGs, in terms of size and proximity, it can be suggested that the current UGs in Puerto Ayora may be ineffective in exposing residents to sufficient nature interactions. Given that these interactions are crucial in enhancing the willingness of residents to support restoration efforts (Kareiva, 2008; Coldwell & Evans, 2017), there is an immediate need to increase the accessibility of UGs in Puerto Ayora. The most critical neighborhoods, in descending order, are Pampas Coloradas, los Arrayanes, and la Cascada, scoring the lowest on both UG index and distance to the nearest UG.

However, as mentioned before, it may be difficult to implement more green in densely populated neighborhoods. Some blocks in Puerto Ayora reach a population density of 542 inhabitants per hectare (Delgado & Bryon, 2018), suggesting that space for urban green may not be available. Therefore, alternative paths should be explored to ensure the provisioning of sufficient nature interactions for residents in these neighborhoods. A simple solution would be to create accessible walking paths through the National Park, allowing residents of Puerto Ayora to engage with nature right near their homes. Providing clear guidelines on how to use these paths would help minimize environmental impact. Although many household border with the National Park, the current lack of access restricts opportunities for nature interaction. However, it should be noted that—next to easily accessible UGs—close proximity to the National Park may also foster conservation support. Further research is needed to examine if proximity without interaction can encourage such support, or if actual engagement with the park is essential. Another promising initiative is the ecological gardens campaign by the CDF, which aims to implement native and endemic gardens in schools, with the help of students and teachers. Since it is thought that children today have a low connection to nature (Hughes et al., 2018), increasing the amount of nature experiences for this group in particular is critical for the restoration of native and endemic plant species. Another measure that could be effective in enhancing nature interactions for residents in dense urban neighborhoods is the implementation of vertical gardens. Vertical gardens can expand UGs by covering façade walls using various plant species through different systems (Ekren, 2017). In the case of Puerto Ayora, the focus should be on native and endemic plant species. These gardens are also thought to be suitable in arid areas, such as the Galápagos Islands, since circulating water is less likely to evaporate on vertical walls than in horizontal gardens (Jain & Janakiram, 2016). Implementing greenspaces in schools and on walls will not only promote nature-interactions and thereby increase support for nature conservation, it will also contribute directly to the restoration of native and endemic species in urban areas. However, more research is needed to evaluate the feasibility, in terms of maintenance and costs, to implement these measures in the specific context of Puerto Ayora.

Given the inevitability of urban expansion projects, like el Mirador, due to the population growth of Puerto Ayora, it is crucial to explore opportunities for implementing UGs that can serve as refuges for native and endemic species and as places where residents can interact with nature. Urban planning projects should prioritize the development of adequately sized UGs that are evenly distributed in relation to population density. This approach will potentially enhance the richness of native and endemic species, as well as the accessibility for residents to these greenspaces. Additionally, as ecological gardens in Puerto Ayora seem to feature a higher species richness than other UG habitats, the implementation of these UGs may be an effective measure in urban expansion projects, such as el Mirador, to restore native and endemic flora. If the UGs in the el Mirador neighborhood will be realized according to its project plan, they have the great potential promote native and endemic species restoration, while simultaneously providing adequate nature interactions to its residents. Nonetheless, it is of great importance to ensure that this sustainable development plan is implemented effectively, especially since uncontrollable and disordered growth has already been observed in el Mirador (CDF, 2023). While top-down control by government institutions, guided by scientific advice, is essential for the plan's success, residents can also play a significant role in contributing to its sustainable realization. According to Kleyn et al. (2020), the extent and quality of UGs, and their accessibility, reflect and shape the responses of residents to those spaces. Thus, capturing resident's perceptions on UGs is crucial for ensuring their sustainability, as incorporation of their feedback may enhance support for urban planning projects. Currently, there is a notable knowledge gap regarding resident participation in UG planning projects in Puerto Ayora. Future research aimed at capturing these perceptions may produce valuable insights that could complement the findings of this study in a more interdisciplinary manner.

6. Conclusion

The findings of this study underscore the urgent need to improve both the ecological quality and accessibility of UGs in Puerto Ayora. The measures required, however, depend on the specific characteristics of the urban environment. Densely built-up neighborhoods demand different solutions compared to newly developed urban areas. In answering the main research question—*how can the ecological quality and the accessibility of urban greenspaces be improved in Puerto Ayora, with a specific case study of the El Mirador neighborhood?*—this study suggests that urban expansion projects should focus on implementing UGs with high ecological quality that are adequately sized and evenly distributed, while densely populated areas may benefit from enhancing the ecological quality of already existing UGs and providing alternative nature-interaction initiatives.

Investigating how the spread of introduced and native and endemic plant species in Puerto Ayora has changed over time reveals that plant communities are currently dominated by introduced species. This highlights the pressing need to reintroduce native and endemic species in urban areas. Further analysis indicates that UG size plays the most significant role in explaining native and endemic species richness, but that habitat type and population density also need to be considered.

In terms of spatial distribution, UGs in Puerto Ayora are unevenly distributed across neighborhoods, with many not meeting WHO and INE standards for size and proximity. However, the case study of the El Mirador neighborhood demonstrates that when planned correctly, urban expansion projects can deliver UGs with sufficient accessibility for all households. These projects should prioritize high ecological quality, especially through the establishment of ecological gardens.

In summary, addressing the challenges of UG management in Puerto Ayora requires a multifaceted approach. This includes balancing the restoration of native and endemic species with practical urban planning solutions that prioritize both the ecological quality and accessibility of UGs. Through these efforts, Puerto Ayora can create a more sustainable urban environment that fosters native and endemic species richness and strengthens residents' connection to nature, preserving the unique flora of Santa Cruz for future generations.

7. Acknowledgement

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8. Supplementary information

Supplementary Table 1: The complete list of frequencies of native or endemic species for each UG habitat type. The frequencies represent the number of different spaces within each UG habitat type where each species was observed.

Frequency of native and endemic species				
Species name	**Aesthetic Garden**	**Ecological Garden**	**Park**	**Semi-natural**
Adiantum henslovianum	1	0	0	0
Ageratum conyzoides	1	1	0	0
Alternanthera filifolia	1	1	0	0
Boerhavia coccinea	8	5	8	2
Conocarpus erectus	7	1	7	2
Cordia lutea	4	3	3	0
Croton scouleri	1	1	1	0
Darwiniothamnus lancifolius	1	0	1	0
Gossypium darwinii	1	1	0	0
Heliotropium curassavicum	2	0	0	0
Maytenus octogona	5	3	3	1
Opuntia echios	7	4	1	0
Passiflora vesicaria	2	4	2	1
Piscidia carthagenensis	3	4	7	0
Scalesia helleri	1	0	1	0
Scutia spicata	2	0	0	0

Sesuvium edmonstonei	4	0	1	3
Volkameria mollis	1	2	2	0
Desmanthus virgatus	0	3	0	0
Ipomoea pes-caprae	0	1	0	0
Plumbago zeylanica	0	2	0	0
Scalesia affinis	0	2	0	0
Vallesia glabra	0	1	0	0
Waltheria ovata	0	3	1	0
Castela galapageia	0	0	2	0
Cryptocarpus pyriformis	0	0	1	0
Ipomoea triloba	0	0	1	0
Scalecia hybrida	0	0	1	0
Senna occidentalis	0	0	1	0
Vachellia macracantha	0	0	1	0
Avicennia germinans	0	0	0	1
Cryptocarpus pyriformis	0	0	0	1
Laguncularia racemosa	0	0	0	2
Rhizophora mangle	0	0	0	3
Tournefortia psilostachya	0	0	0	1

Supplementary Table 2: The complete list of frequencies of introduced species for each UG habitat type. The frequencies represent the number of different spaces within each UG habitat type where each species was observed.

Frequency of introduced species				
Species	**Aesthetic Garden**	**Ecological Garden**	**Park**	**Semi-natural**
Aloe vera	2	0	6	0
Bougainvillea spectabilis	1	0	0	0
Capsicum annuum	1	0	0	1
Catharanthus roseus	5	0	3	0
Cereus hexagonus	2	0	1	0
Cocos nucifera	1	0	2	0
Delonix regia	2	0	5	1
Leucaena leucocephala	1	1	0	1
Oxalis debilis	2	0	0	0
Plantago major	2	0	0	0
Turnera ulmifolia	1	0	2	0
Bauhinia variegata	0	1	2	0
Cenchrus purpureus	0	1	0	0
Cleome viscosa	0	1	0	0
Euphorbia hirta	0	2	0	0
Lantana camara	0	2	0	0
Macroptilium lathyroides	0	4	0	0
Momordica charantia	0	2	1	0
Ricinus communis	0	1	1	0
Tridax procumbens	0	2	0	0
Amaranthus viridis	0	0	1	0

Bambusa vulgaris	0	0	1	0
Breynia disticha	0	0	3	0
Euphorbia tirucalli	0	0	1	0
Ficus benjamina	0	0	1	0
Melissa officinalis	0	0	1	0
Morinda citrifolia	0	0	2	0
Nicandra physalodes	0	0	1	0
Phyllanthus acidus	0	0	1	0
Punica granatum	0	0	1	0

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