Urban Forestry: Biodiversity of San Francisco's Street Trees

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ABSTRACT

Urban forestry is growing increasingly important due to the rise of urbanization and the aesthetic, economic, and ecosystem benefits that urban trees provide to cities and residents. Potential future environmental shifts also emphasize the growing importance of resilience through planning and management of the urban forest so that it can maintain these benefits. The city of San Francisco acknowledges its low tree abundance and canopy cover compared to other major cities in the US and has made strides towards improving the urban forest. To ensure that this effort leads to an urban forest that serves all residents and is more resilient to increasing hazards, the current urban forest needs to be analyzed to identify areas that could benefit from an increase in tree planting and tree biodiversity which is a predictor of an urban forest ecosystem's resilience. In this study, I analyzed the biodiversity and distribution of San Francisco's street trees, by determining (i) how diverse and distributed the tree species are demographically and, (ii) if there are different levels of biodiversity and street tree distribution between different neighborhoods throughout the city. I performed a secondary data analysis using data from the urban tree database San Francisco Street Tree Map. My study found a very high level of biodiversity amongst the street trees overall and identified neighborhoods that would most benefit from an increase in street tree planting so as to make the distribution of the many benefits that street trees provide more equitable.

KEYWORDS

diversity index, equitability, environmental justice, ecosystem services, neighborhood

INTRODUCTION

Urban forestry is the sustained planning, planting, and protection of trees, residential tree lines, and forests in urban areas (Jensen et al. 2004). Valued for aesthetic reasons, trees provide a pleasant landscape, screening and privacy, and recreation opportunities, all which improve the quality of life for residents (Martin et al. 2016). An economic benefit of the urban forest is increased property values and reduction of the urban heat island effect (Jensen et al. 2004). Furthermore, ecological benefits include ecosystem services such as the removal of pollutants and particulate matter in the air, reduction of local air temperature in the summertime, and support of urban wildlife (Conway and Bourne 2013). These ecosystem services of urban forests will also become more important with increased urbanization and the progression of climate change (Ordóñez et al. 2020). Potential future environmental shifts emphasize the growing importance of a healthy and resilient urban forest and the requirement of planning and management.

To have a healthy and resilient urban forest, biodiversity of the urban trees must be high and the different species must be evenly distributed throughout the city (Sjöman et al. 2012). Ecological systems with greater species richness are more resilient to changes (Anderson 2020). In the case of urban forests, biodiversity is important for resilience against pests and disease (Sjöman et al. 2012). Recurring outbreaks from invasive pests and disease will increase with the effects of climate change, as will average temperature, the frequency of heat waves, and periods of drought, all of which threaten the resilience of the urban forest (Ordóñez et al. 2020). Trees that are genetically similar also have similar susceptibility to injury from both biotic and abiotic stressors, so it is generally recommended that urban forests don't exceed 10% of any one species, 20% of any genus, and 30% of any family (Kendal et al. 2014). This benchmark was first proposed by Santamour in 1990 and has been widely used in urban forests around the world to analyze tree homogeneity (Kenal et al. 2014).

Reflecting the history of the urban forests' planting and care, biodiversity may be different across the city. San Francisco's original landscape had very few trees, the urban forest that exists today is the result of major tree planting efforts throughout the years, primarily during the late 1800s with the creation of Golden Gate Park and the Presidio and the early 1900s with the implementation of street trees, and then later through smaller efforts (*San Francisco Urban Forest Plan (Phase 1: Street Trees)* 2014). When funding for planting of the urban forest was cut by the city in 1981, a nonprofit organization called the Friends of the Urban Forest was created and the organization have since planted over 60k trees, which is about half of the street trees in San Francisco ("Friends of the Urban Forest" n.d.). As of November 2016, San Francisco's street trees are now maintained by San Francisco Public Works due to Proposition E passed by voters with 79% support to transfer the responsibility to the city. Prior to that street tree maintenance was required by property owners ("Street Trees and Plants | Public Works" n.d.). SF Public Works also regulates the removal and planting of trees through the processing and approving of permits ("Street Trees and Plants | Public Works" n.d.). As a result of this, San Francisco is currently in the process of planting 50k trees from 2014 to 2034, with about 2.5k per year, to help the decline of the urban forest and bring ecosystem services to more neighborhoods (*San Francisco Urban Forest Plan (Phase 1: Street Trees)* 2014). To ensure that this effort leads to an urban forest that serves all residents and is more resilient to increasing hazards, the current urban forest needs to be analyzed to identify areas that could benefit from an increase in street trees and street tree biodiversity.

In this study, I examine the biodiversity and distribution of the street trees in the urban forest in San Francisco. Specifically, I determine (i) how diverse and distributed the tree species are demographically and, (ii) if there are different levels of biodiversity and street tree distribution between different neighborhoods throughout the city. I will be doing secondary data analysis using data from the urban tree database San Francisco Street Tree Map, which is a census of almost all of the street trees in the city.

METHODS

Study site and dataset

The data set for this study is a street tree census from the San Francisco Street Tree Map from the San Francisco Department of Public Works (SFPW). Within SFPW is the Bureau of Urban Forestry that maintains and cares for all the city's street trees through a program called StreetTreeSF(https://data.sfgov.org/City-Infrastructure/Street-Tree-List/tkzw-k3nq). The Bureau of Urban Forestry maintains the database. Whenever a public tree is planted, pruned, removed, or replaced, the tree is surveyed and the information is updated in the database and Street Tree Map.

The data set has 196K observations and includes almost every street tree in San Francisco with information about species, location, year planted, and other characteristics. The data set was created in 2012 and is updated on a daily basis. After cleaning the data, I was left with 180,042 individual trees made up of 568 species. The other data set I used was Analysis Neighborhoods, which grouped census tracts into neighborhoods based on common real estate and resident definitions (see Figure 2). Both data sets were downloaded from DataSF.

City diversity and distribution demographics

To calculate biodiversity of the street trees, I summed the number of individuals for each of the tree species represented in the city by sorting and organizing the demographic data provided by the tree census. Then I calculated both a Simpson and Shannon diversity index to describe the overall richness and evenness of the tree species using the BiodiversityR package (Roeland 2021). The diversity indices are calculated using the following equations:

<u>Simpson's Diversity Index</u>

Simpson's index, $D = \frac{1}{\sum_{i=1}^{S} (Pi)^2}$ and

<u>Shannon's Diversity Index</u>

Shannon's index, $H = -\sum_{i=1}^{S} Pi \ ln(Pi)$ and

Where Pi is the proportion of individuals that contribute to the total in the sample, e.g. the proportion is Pi for the ith species, and S is the richness calculated as the total number of species in the community.

To visualize how overall abundance was distributed by species, I created rank abundance and graphed it by species. Abundance, calculated as the number of tree individuals for each species, is on the Y-axis and name of species is along the X-axis.

To determine the resilience of the urban forest, I used Microsoft Excel to categorize the trees by species, genus and family. I used abundance to see whether the street trees comprised more than 10% of any one species, 20% of any genus, and 30% of any family to determine whether the urban forest is well distributed in terms of species demographics and therefore resilient to potential risks such as disease and pests (Kendal et al. 2014). This 10/20/30 benchmark recommended first by Santamour in 1990 has been widely used to improve resilience through biodiversity in many urban forests around the world (Kendal et al. 2014).

Neighborhood comparisons

I visualized the distribution of street tree diversity using GIS. This analysis allowed me to compare neighborhoods that have more or less biodiversity and to identify areas that potentially need an increase in species richness. From my clean data set, I divided street tree populations by neighborhood geospatially in ArcMap and created new attribute tables for each. I converted those attribute tables into Excel files and then inputted them into RStudio to calculate Simpson and Shannon diversity indices for each neighborhood. Once I had those values, I inputted them into ArcMap again as a new field in the neighborhood shapefile to create diversity index color ramps.

Due to time constraints, I selected fifteen out of the forty-one neighborhoods to study if there were differences in street tree abundance and species richness. In each of the fifteen neighborhoods I took a random sample of ten blocks using a random point generator in ArcMap. From those blocks, I gathered the total abundance of street trees and species richness and put the data into an Excel file. I imported this data into RStudio for statistical analysis. The data was originally heavily skewed, so I performed a square root data transformation that made it more normal. Then I created boxplots for each neighborhood and calculated a one way analysis of variance with neighborhood as the predictor and total abundance and species richness as the response variable. I also calculated Tukey's test to find which neighborhoods were significantly different from each other. I added compact letter display outcomes to my boxplots to better visualize significant differences between neighborhoods.

RESULTS

City diversity and distribution

Diversity indices

For all the street trees in the study, I calculated a value of 0.98 for Simpson's Diversity Index. I also calculated a value of 4.43 for Shannon's Diversity Index.

Rank abundance diagram & 10/20/30 Benchmark

There were 568 species in my study, but I show only the forty most abundant species in my rank abundance diagram (Figure 1). Table 1 gives the species names to the ranks, as well as their total abundance in the street tree population. A rank abundance diagram showing a curve with all 568 species can be found in Appendix A. There is a relatively steady decline from the most abundant species such as the Sycamore London Plane with 11626 individuals, New Zealand Christmas Tree with 8740 individuals, the Brisbane Box with 8709 individuals, and the Swamp Myrtle with 7375 individuals, to the fortieth most abundant species, the Little Gem Magnolia with 1003 individuals. The rank abundance diagrams in Figure 1 and in Appendix A show no large jumps between species in terms of number of individuals, however there is a noticeable drop between the 9th and 10th ranked species with the Green Gem with 5579 individuals and the Kwanzan Flowering Cherry with 4003 individuals.

The most abundant species was the Sycamore London Plane (Platanus x hispanica) with 11,626 individuals and making up 6.46 % of the total population. The most abundant genus was Prunus with 15,080 individuals and making up 8.38% of the total population. The most abundant family was Myrtaceae with 44,690 individuals and making up for 24.82% of the total population. Species, genus, and family did not exceed 10%, 20%, and 30% respectively, therefore San Francisco's street tree population satisfied the 10/20/30 benchmark.

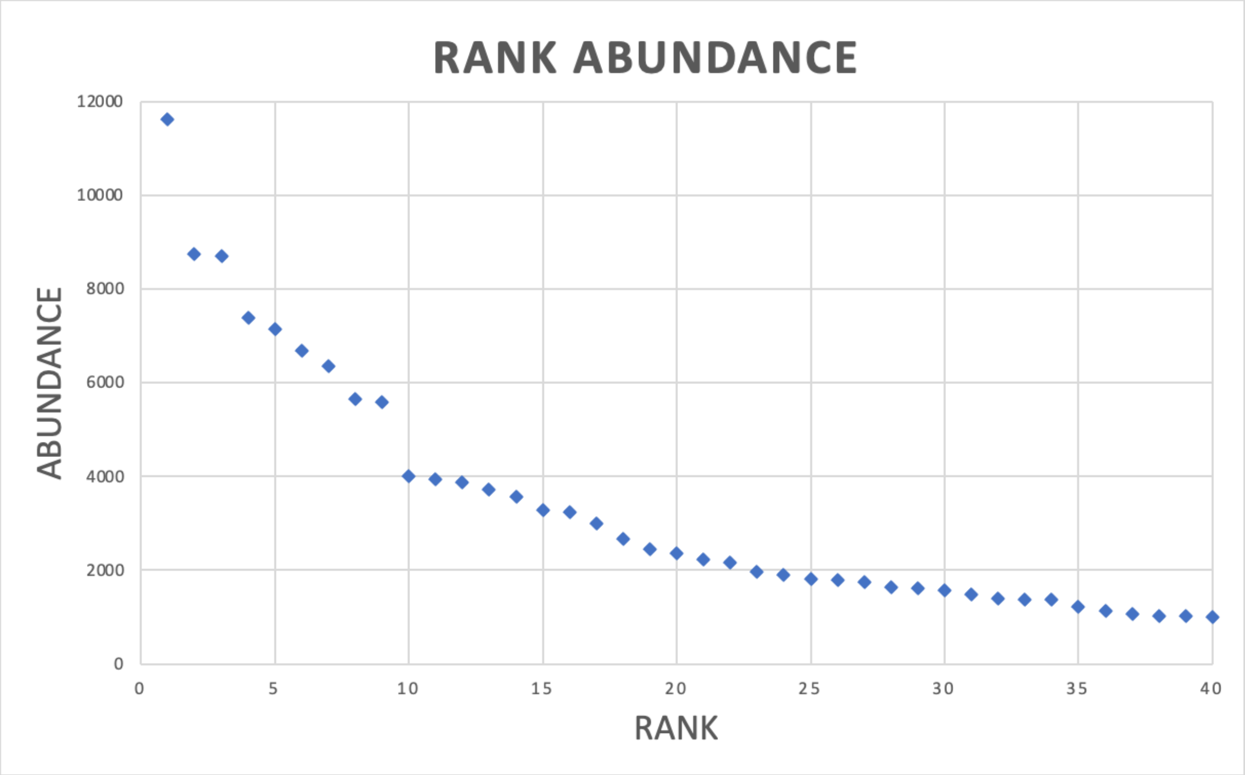

Figure 1: Rank abundance diagram of the forty most popular street tree species. See Table 1 for species name.

Table 1: The forty most popular street tree species in San Francisco and their total abundance.

Species Name	Rank	Abundance
Platanus x hispanica :: Sycamore: London Plane	1	11626
Metrosideros excelsa :: New Zealand Xmas Tree	2	8740
Lophostemon confertus :: Brisbane Box	3	8709
Tristaniopsis laurina :: Swamp Myrtle	4	7375
Pittosporum undulatum :: Victorian Box	5	7145
Prunus cerasifera :: Cherry Plum	6	6691
Magnolia grandiflora :: Southern Magnolia	7	6347
Arbutus 'Marina' :: Hybrid Strawberry Tree	8	5646
Ficus microcarpa nitida 'Green Gem' :: Indian Laurel Fig Tree 'Green Gem'	9	5579

Prunus serrulata 'Kwanzan' :: Kwanzan Flowering Cherry	10	4003
Acacia melanoxylon :: Blackwood Acacia	11	3948
Maytenus boaria :: Mayten	12	3880
Olea europaea :: Olive Tree	13	3718
Corymbia ficifolia :: Red Flowering Gum	14	3558
Callistemon citrinus :: Lemon Bottlebrush	15	3273
Ginkgo biloba :: Maidenhair Tree	16	3249
Pyrus calleryana :: Ornamental Pear	17	2989
Prunus serrulata :: Ornamental Cherry	18	2677
Eriobotrya deflexa :: Bronze Loquat	19	2454
Ulmus parvifolia :: Chinese Elm	20	2366
Pinus radiata :: Monterey Pine	21	2240
Ligustrum lucidum :: Glossy Privet	22	2174
Pyrus kawakamii :: Evergreen Pear	23	1976
Cupressus macrocarpa :: Monterey Cypress	24	1891
Tristaniopsis laurina 'Elegant' :: Small-leaf Tristania 'Elegant'	25	1816
Pittosporum crassifolium :: Karo Tree	26	1791
Melaleuca quinquenervia :: Cajeput	27	1738
Cordyline australis :: Dracena Palm	28	1648
Ficus nitida :: Laurel Fig	29	1622
Myoporum laetum :: Myoporum	30	1561
Liquidambar styraciflua :: American Sweet Gum	31	1489
Juniperus chinensis :: Juniper	32	1401

Ficus retusa nitida :: Banyan Fig	33	1370
Tristania conferta ::	34	1369
Jacaranda mimosifolia :: Jacaranda	35	1214
Lagunaria patersonii :: Primrose Tree	36	1132
Schinus terebinthifolius :: Brazilian Pepper	37	1061
Washingtonia robusta :: Mexican Fan Palm	38	1030
Eucalyptus polyanthemos :: Silver Dollar Eucalyptus	39	1014
Magnolia grandiflora 'Little Gem' :: Little Gem Magnolia	40	1003

Neighborhood comparisons

Diversity index maps

There were 41 neighborhoods established by the city (Figure 2). Figures 3 and 4 show diversity index color ramps by neighborhood for both the Simpson and Shannon diversity indices respectively. All Simpson and Shannon values by neighborhood are also listed (Table 2).

Simpson's diversity index ranged from the highest calculated value of 0.98 in Bernal Heights, Potrero Hill, Glen Park, Noe Valley, and in the Mission to the lowest value of 0.86 in the Tenderloin. Shannon's diversity index ranged from the highest calculated values of 4.52 in Potrero Hill, 4.46 in Bernal Heights, and 4.33 in Bayview to the lowest value of to 2.76 in the Tenderloin.

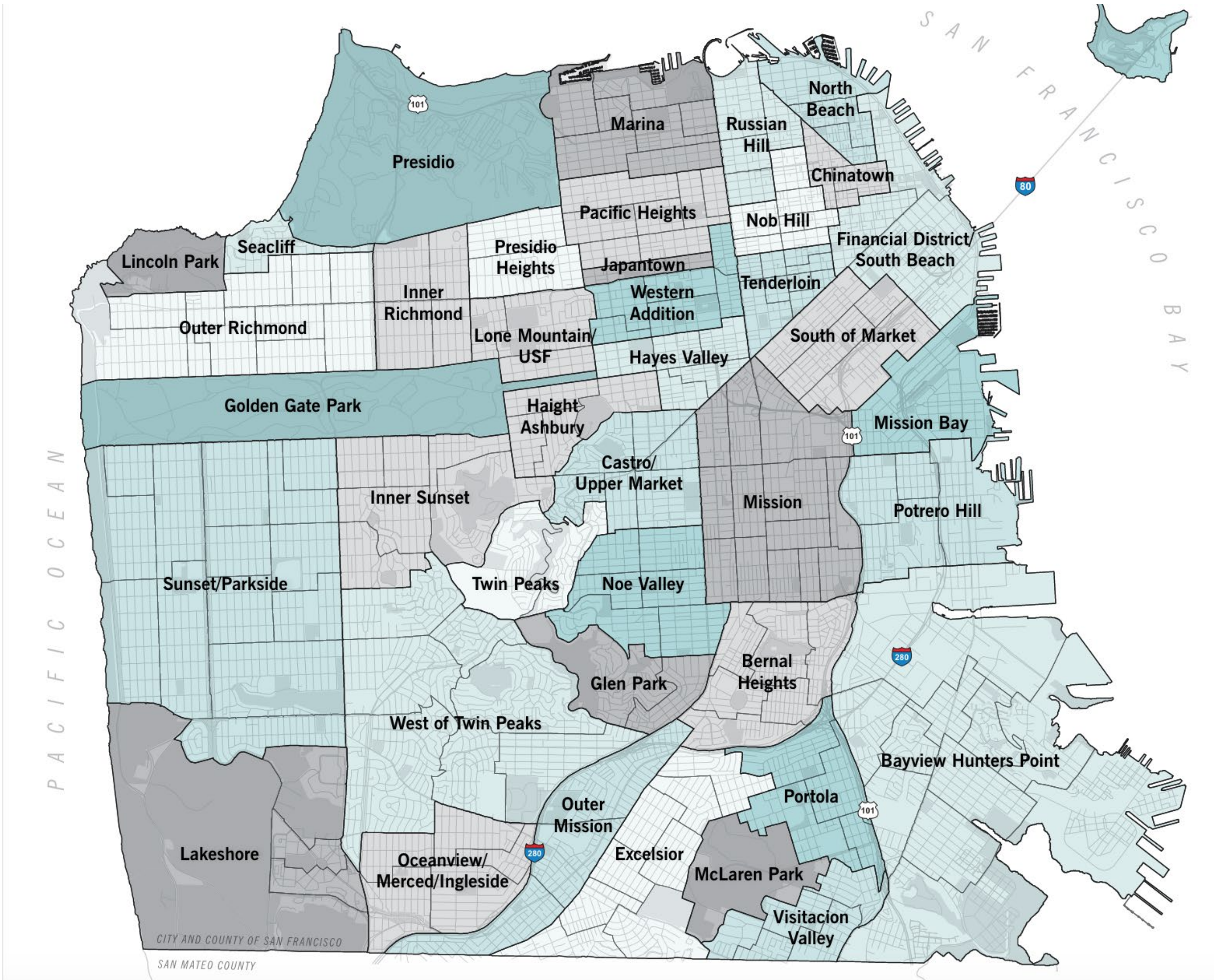

Figure 2: Map of San Francisco neighborhoods taken from the San Francisco Planning Department's socioeconomic profiles survey.

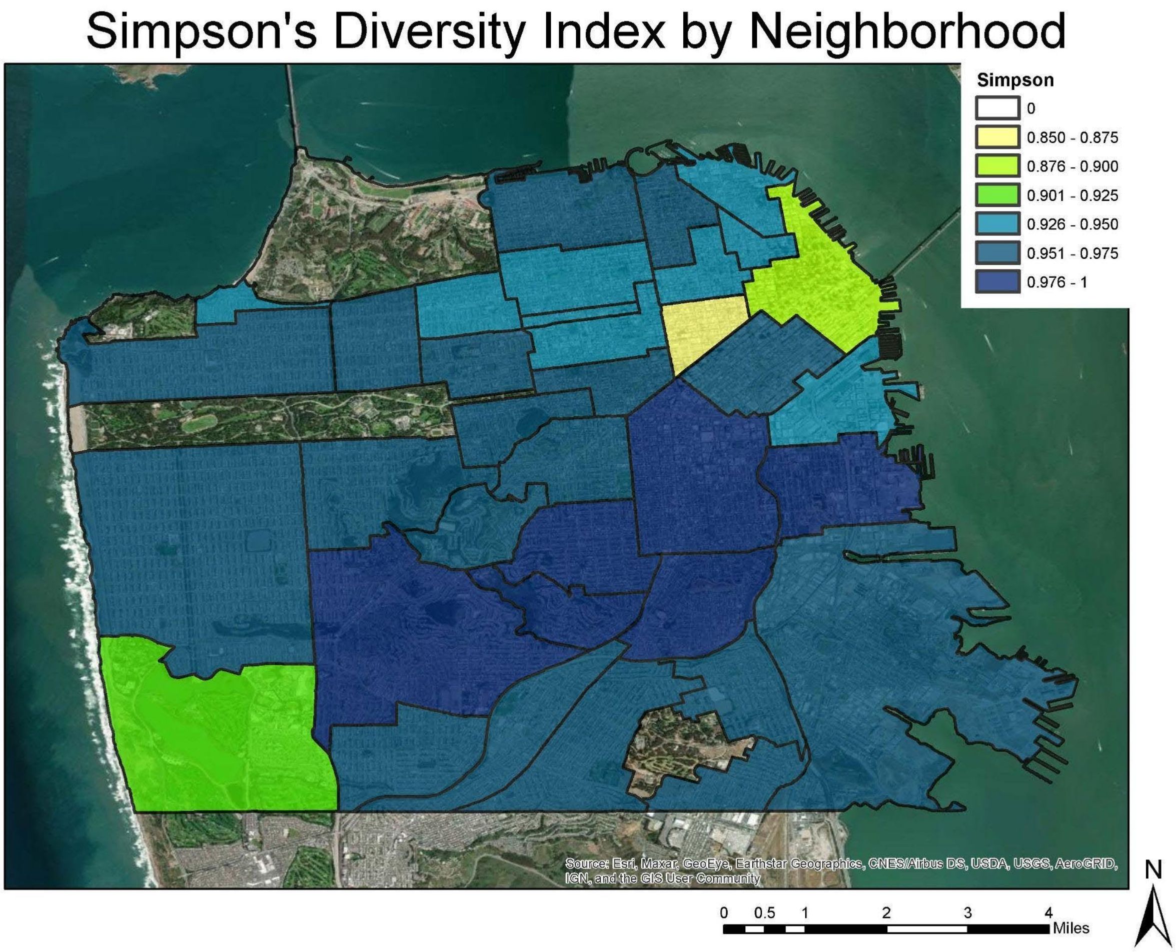

Figure 3: Simpson diversity index values by all street trees in each neighborhood. Areas with no color are parks and were not included.

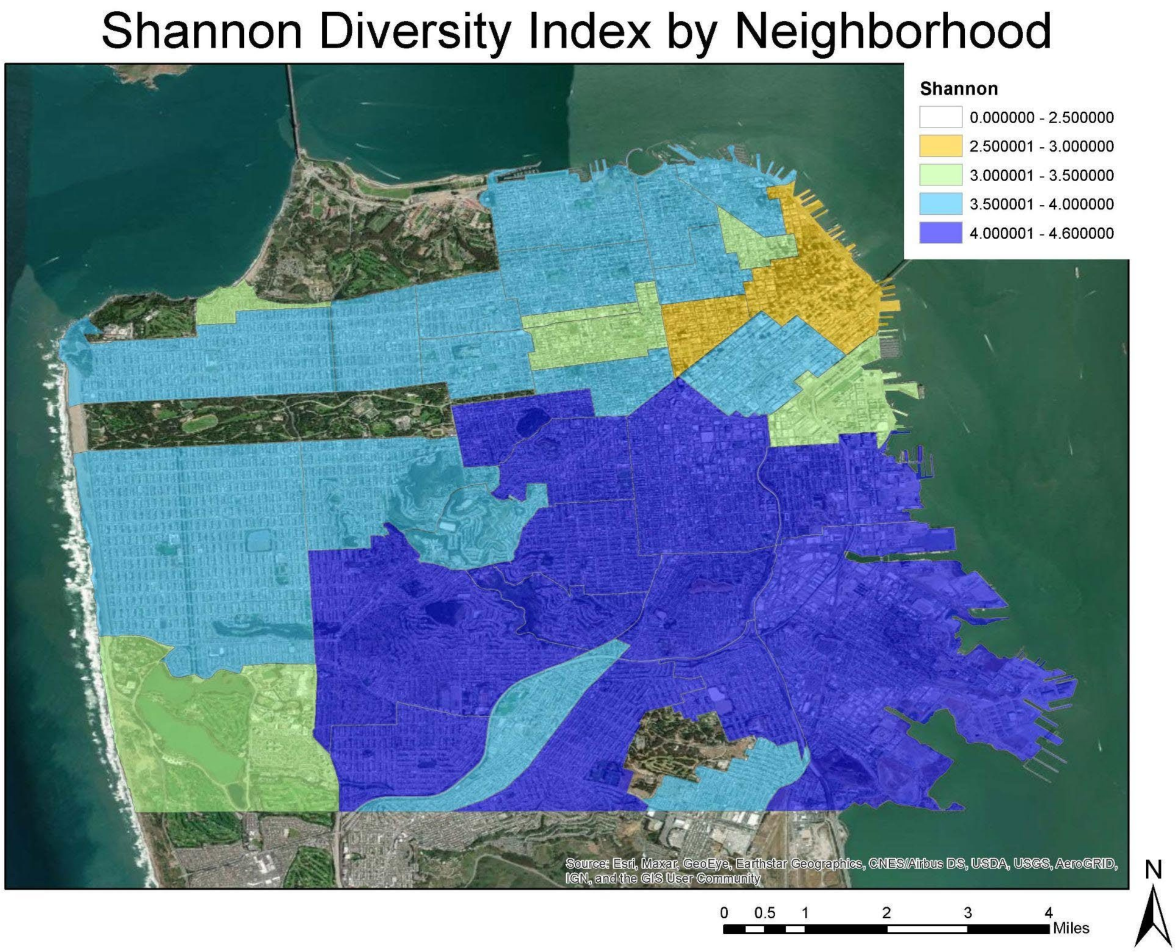

Figure 4: Shannon diversity index values by all street trees in each neighborhood. Areas with no color are parks and were not included.

Table 2: Neighborhood Shannon and Simpson diversity values. San Francisco's overall values are listed again at the bottom.

Neighborhood	Shannon	Simpson
Bayview	4.3341	0.97477
Bernal Heights	4.4634	0.98048
Castro Upper Market	4.1189	0.97117
Chinatown	3.3064	0.94703
Excelsior	4.1645	0.97321

Financial District/South Beach	2.9287	0.87855
Glen Park	4.2548	0.97728
Haight Ashbury	4.1071	0.97448
Hayes Valley	3.8698	0.96301
Inner Richmond	3.8807	0.96615
Inner Sunset	3.9973	0.96302
Japantown	3.2711	0.93367
Lakeshore	3.1515	0.91886
Lone Mountain/USF	3.9058	0.96742
Marina	3.7663	0.95249
Mission	4.317	0.97662
Mission Bay	3.4978	0.94815
Nob Hill	3.6655	0.94628
Noe Valley	4.3261	0.97704
North Beach	3.6633	0.94143
Oceanview/Merced/Ingleside	4.1746	0.96916
Outer Mission	3.8768	0.95066
Outer Richmond	3.8669	0.95744
Pacific Heights	3.5536	0.93898
Portola	4.1556	0.9737
Potrero Hill	4.5215	0.97979
Presidio Heights	3.6291	0.94815
Russian Hill	3.9706	0.96189

Sea Cliff	3.3674	0.9266
South of Market	3.6778	0.95352
Sunset/Parkside	3.7269	0.95707
Tenderloin	2.7603	0.86197
Twin Peaks	3.9209	0.96805
Visitacion Valley	3.9222	0.97007
West of Twin Peaks	4.2675	0.97363
Western Addition	3.4226	0.93075
San Francisco	**4.4315**	**0.97744**

Box Plots & ANOVA

Difference between neighborhood tree abundance was significantly different, $F(14, 135) = 7.61$, $p < 0.0001$ (Figure 5). Difference between neighborhood species richness was significantly different, $F(14, 135) = 6.56$, $p < 0.0001$ (Figure 6). Post hoc analyses using a compact letter display from Tukey's test show where the differences occurred (Appendix B). The letters hovering over the upper right corner of each boxplot are a compact letter display from Tukey's test. Different letters designate significantly different groups. Groups with the same letter are not significantly different from each other.

For tree abundance, neighborhoods Western Addition, the Financial District, the Mission, and Pacific Heights were significantly higher than the Sunset, Chinatown, and Visitacion Valley. Pacific Heights, Hayes Valley, the Mission, and West of Twin Peaks had significantly higher average species richness per block from neighborhoods Chinatown and North Beach.

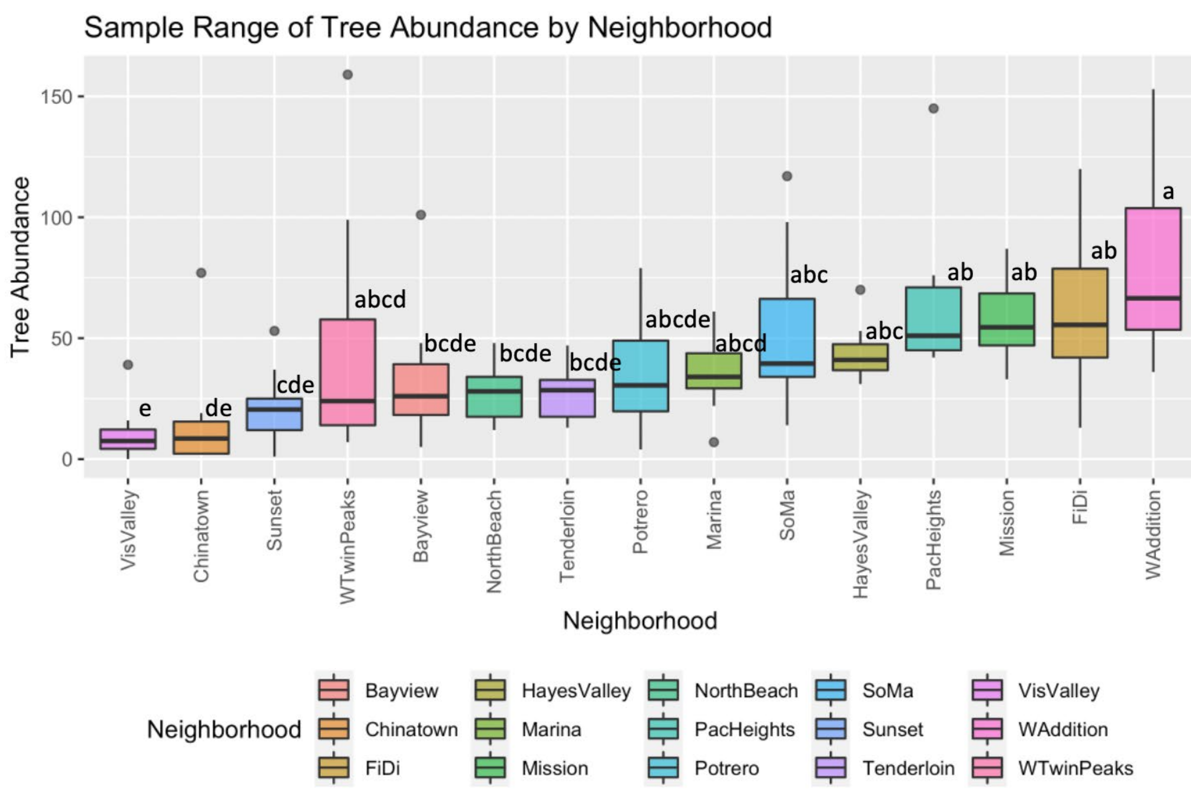

Figure 5: Tree abundance boxplots for select neighborhoods.

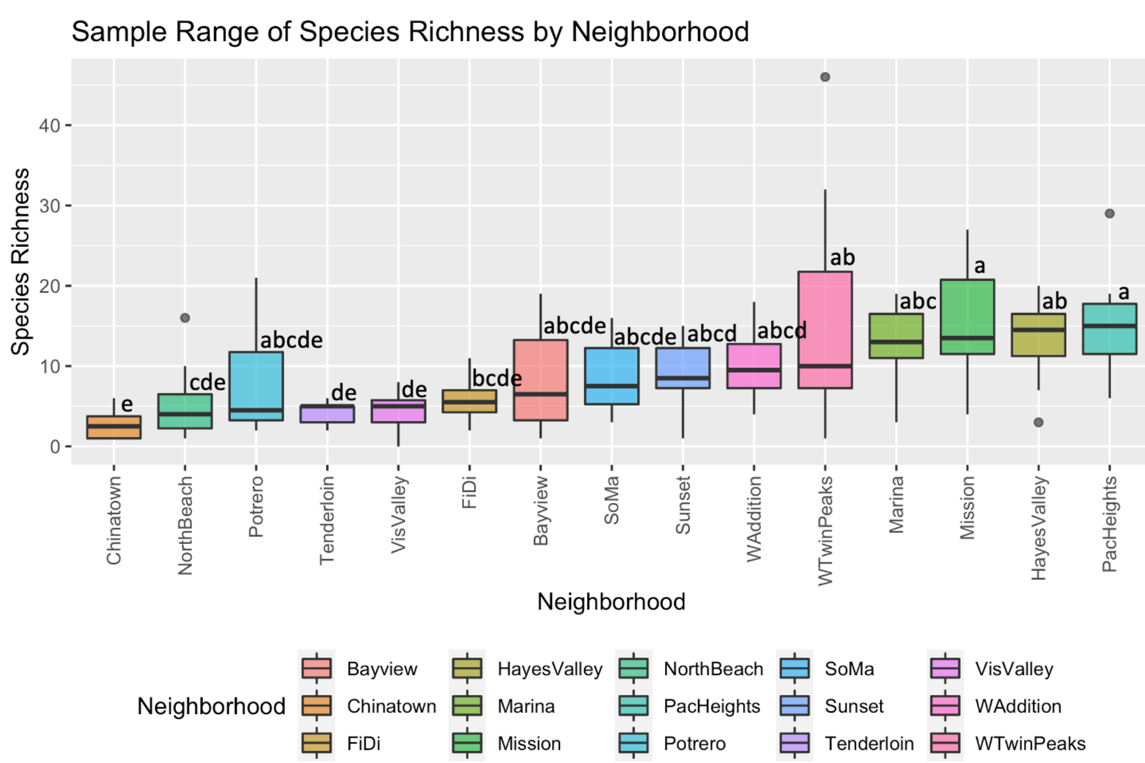

Figure 6: Species richness boxplots for select neighborhoods.

DISCUSSION

My study found an overwhelmingly high level of biodiversity across San Francisco's street trees, likely due to the history of the city's urban forest. In addition, I found a statistically significant difference in street tree abundance and species richness per block in select neighborhoods. Although species richness is also important, since San Francisco already has such a high level of biodiversity, efforts should be more so focused on increasing tree abundance in neighborhoods that have a significantly lower number of trees so as to bring more equitability toward the distribution of ecosystem services more efficiently.

Diversity and distribution demographically

Diversity Indexes

The biodiversity values I calculated were exceedingly high. Simpson and Shannon's diversity indexes are similar because they both measure species richness and evenness, also known as relative abundance. Simpson's index is "less sensitive to species richness and heavily weighted towards the most abundant species. It gives the probability that any two individuals drawn at random from an infinitely large community belong to different species (Galle et al. 2021)." This index ranges from 0 to 1 and for my study I calculated a value 0.97744. "The Shannon Index increases as the community's richness and evenness increase. Values range from 0 to 5, but in most ecological studies, typically fall between 1.5 and 3.5, and rarely exceed 4 (Galle et al. 2021)," but for my study I calculated a value of 4.4315.

The diversity values I calculated were so high likely because San Francisco's urban forest is almost entirely planted by people. Blood et al. (2016) states that in many places in North America, an estimated ⅓ of trees in the urban forest are planted with the rest originating from remnant or regenerated forest. This is not the case for San Francisco. Prior to European arrival, the city's environment was made up of sand dunes, grasslands, wetlands, riparian, and coastal scrub vegetation, meaning that the original landscape had very few trees ("San Francisco Urban Forest Plan" 2014). Blood et al. (2016) also mentions that additional species richness in an urban area compared to the surrounding area is due to human planting and maintenance. This statement aligns with what we see in San Francisco.

Other cities in the US may prefer the planting of native tree species. In Doroski et al.'s (2020) study that looked at urban tree planting programs in the Northeastern US, municipal land managers voiced a preference for native species and species that would increase diversity. There was a preference for native tree species due to the area's originally forested landscape. San Francisco doesn't share that ecological history. There are 32 tree species listed on the SF Public Works' Recommended Tree List Suited for Most Areas in San Francisco, and out of those 32, only one is native to California. Native species are not a priority in this city's urban forest because there weren't many trees here to begin with. However, the list does note non-native invasive species that are not allowed to be planted.

This lack of emphasis on the purposeful planting of native species may be a factor into the incredibly high level of species richness because residents are more free to choose what kind of tree they want planted. The Shannon index rarely exceeds 3.5 in most ecological cases, but because San Francisco's urban forest is almost entirely man made, the higher value of 4.43 that I calculated in my analysis is reasonable and not unexpected.

10/20/30 Benchmark

San Francisco's street tree population passed the 10/20/30 benchmark. The abundance percentages were 6.46%, 8.38%, and 24.42% for species, genus, and family respectively. Most of the urban forests in previous studies had problems with homogeneity and did not pass the benchmark. In Sjöman et al. 's (2012) study on the urban forests of ten major Nordic cities, only one city passed the rule that no one species should exceed 10% of the total tree population. Contrasting that, the city that had the greatest problem was Helsinki, with one tree representing 44.3% of the total tree population therefore making the urban forest vulnerable if pests or diseases targeted that one species. Similarly in Kendal et al. 's (2014) paper that looked at over 100 cities around the world, only 11% of the study met the species benchmark. A more recent paper by Doroski et al. (2020) found 52 cities in the Northeastern US to pass the benchmark well, however this study collated the over the 52 cities and only looked at recently planted trees.

There were 568 tree species in San Francisco's street tree population. The rank abundance diagram shows the 40 most popular. The first most common tree species is the London Plane with over 11,000 individuals. This tree is favorable in the city due to its resistance to fungus and tolerance of smog, soot, dust, and reflected heat which are all characteristic of an urban sidewalk environment ("Street Trees and Plants | Public Works" n.d.).

Neighborhood comparisons

Although San Francisco's street tree population has a great level of biodiversity overall, I also wanted to compare the street tree populations between different neighborhoods to see if there were noticeable differences. Through analysis of variance, I found significant differences in the total abundance and species richness of street trees per block between different neighborhoods. The Western Addition, Financial District, the Mission, and Pacific Heights had significantly higher average tree abundance per block from neighborhoods the Sunset, Chinatown, and Visitacion Valley. Pacific Heights, Hayes Valley, the Mission, and West of Twin Peaks had significantly higher average species richness per block from neighborhoods Chinatown and North Beach.

Although there were significant differences between neighborhoods for both tree abundance and species diversity, lower tree abundance is a more pressing issue. A difference in tree abundance suggests an unequal distribution of ecosystem services.

It may be that historically, municipal tree planting activities were more likely in areas with higher income that already had higher canopy cover, but in their study, Watkins et al. (2017) found that with nonprofit plantings, the probability that a neighborhood was the location of tree planting decreased as neighborhood canopy cover and household income increased. This means that nonprofit urban tree planting organizations target neighborhoods in need for more socially just distribution of ecosystem services. However, another study found a lack of physical availability of tree planting space in environmental justice communities (Danford et al. 2014). Danford et al. (2014) found that in Boston, low income neighborhoods were associated with disproportionately low levels of canopy cover, however the study maintains that predictors of canopy distribution vary between cities depending on historical and cultural context. The study also found that the communities in most need of an increase in street tree abundance may not have the pervious surface necessary, whereas areas that already have high canopy cover may also have more space available for more tree planting. Danford et al. (2014) also referenced research by Pincetl et al. (2012) that studied the MillionTreesLA initiative in Los Angeles that found although the goal of the organization was to redress the issue of poorer neighborhoods of color having fewer trees, in reality trees were planted where partnerships could be forged. This means that the poorer neighborhoods that were originally the target of this initiative were underserved because residents and community groups were responsible for requesting planting and many of these groups did not request trees.

In addition to potential differences in planting locations due to socioeconomic conditions, San Francisco has three main microclimates that vary considerably from the coast to the bay, the coastal zone/fog belt, the transition zone, and the bay zone/sun belt (Martin et al. 2016). Martin et al.'s 2016 study on the effects of the microclimate on growth and health of urban tree species in the city found that different species are better adapted to different microclimate conditions, likely due to variations in drought tolerance and the degree of tree care and maintenance also impacts the growth and health of street trees and can be highly variable. Martin et al. (2016) found no consistent patterns across microclimates in height or crown size implying that pruning, aka maintenance, isn't necessarily more prevalent in certain neighborhoods and that regardless of potential differences in social and community involvement with street trees, microclimate significantly impacts the growth and health of different species.

In line with what previous studies have found, I speculate that the Sunset has low tree canopy due to its geographical history. The Sunset is overlaid on sand dunes and is an area of San Francisco that did not originally have trees.

Chinatown is such a historic and cultural neighborhood in San Francisco. In 2015 the city looked into widening of the sidewalks in Chinatown due to heavy foot traffic with the director of SF Public works saying that "Chinatown was just built for a different era" (Wildermuth 2015). I believe this neighborhood has such low street tree abundance because of its narrow sidewalks and high population density. Having trees in the streets would make navigating the neighborhood on foot even more difficult for residents and tourists. In this case, it would make sense to hold off additional street tree planting if/until the sidewalks are widened.

I was surprised that the Western Addition had a significantly higher tree abundance than Visitacion Valley considering that residents have similar financial backgrounds ("© 2018 San Francisco Planning Department" n.d.) and are in the same general microclimate. I speculate that the Western Addition may have more trees due to its closer proximity to the city center, higher population of white residents who may have more access to tree planting resources, and lack of proximity to a city park. Visitacion Valley may not have as many street trees due to its close proximity to McLaren Park, the third largest public park in the city.

Limitations

My study population was the street trees in San Francisco. I can't apply my conclusions to the entire urban forest in the city because I did not account for the public trees in the city's many public parks. Some neighborhoods may have been focused on less for tree planting due to their proximity to trees in public parks. I don't think I asked the right question in the first place for my second sub question. I wanted to see if there was a difference in diversity and distribution of street trees between neighborhoods, but later realized that the methods I was using weren't going to give me the results I had thought. I was going to take the diversity index of each block in a neighborhood and then perform an ANOVA. Instead I ended up taking a random sample of ten blocks in each neighborhood, gathering tree abundance and species richness, and then calculating ANOVA. However, I did not account for variability in block size between and within neighborhoods. I also did not base my neighborhood selection on any socioeconomic factor unlike other studies such as Danford et al. (2014). Due to time constraints I did not look at every neighborhood, so there may be neighborhoods that would benefit from an increase in tree planting that I did not mention.

Future Directions

Future studies should look at the distribution of ecosystem services provided by street trees in San Francisco by neighborhood. If there are significant differences, it will be clear which neighborhoods should be prioritized in future planning and maintenance. Future studies should also look to see if there is change over time of ecosystem services. For example, if there is a decrease in canopy cover over time, that would mean that street trees are dying and being removed and there would need to be further insight to discover the reasons behind street tree failure. Maybe the tree species being planted are not suitable for that environment or trees are not being properly taken care of.

Management Implications

In conclusion, San Francisco needs more street tree planting, particularly in neighborhoods that have low street tree abundance, but also just overall. Of the many ecosystem services that street trees provide, canopy cover is likely the most important due to its ability to cool the city and the increase in warmer weather with the progression of climate change. San Francisco has the lowest canopy cover of any major city in the US, at 13.7% compared to 21% in Los Angeles and 24% in New York City (*San Francisco Urban Forest Plan (Phase 1: Street Trees)* 2014). However the solution isn't as simple as planting more trees. Young trees need to be planted now so that they will grow into trees that contribute increasing ecosystem services to the community over the course of their growth. Trees also need to be planted with microclimate and equitability of ecosystem services in mind. For that there needs to be an increase in budget. In the 2019-2020 Street Tree SF Annual Report, it is stated that under the current program, dedicated funds don't cover new or replacement tree planting or the maintenance required during the three year establishment period of newly planted trees. Instead, funding is going towards maintenance projects that include sidewalk repair, pruning, and tree replacements. Tree establishment requires weekly watering and more frequent pruning and is the most expensive part of tree planting. The Bureau of Urban Forestry receives some funding for planting establishments, but all of it goes to areas that are experiencing a large number of removals, therefore the planting that is taking place in the city is replacing trees that are being removed and are not adding to the tree population.

Knowledge of resources available to residents needs to be spread. The organization Friends of the Urban Forest plants trees for free to residents by request and cares for them for the first three years before maintenance is taken over by Street Tree SF ("Tree Planting and Care" n.d.). As stated in the Street Tree SF Annual Report, new tree establishment is the hardest and most expensive part of growing the urban forest. Here, a non-profit organization takes care of that, but these services may not be well known in all communities across San Francisco.

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APPENDIX A: Rank Abundance

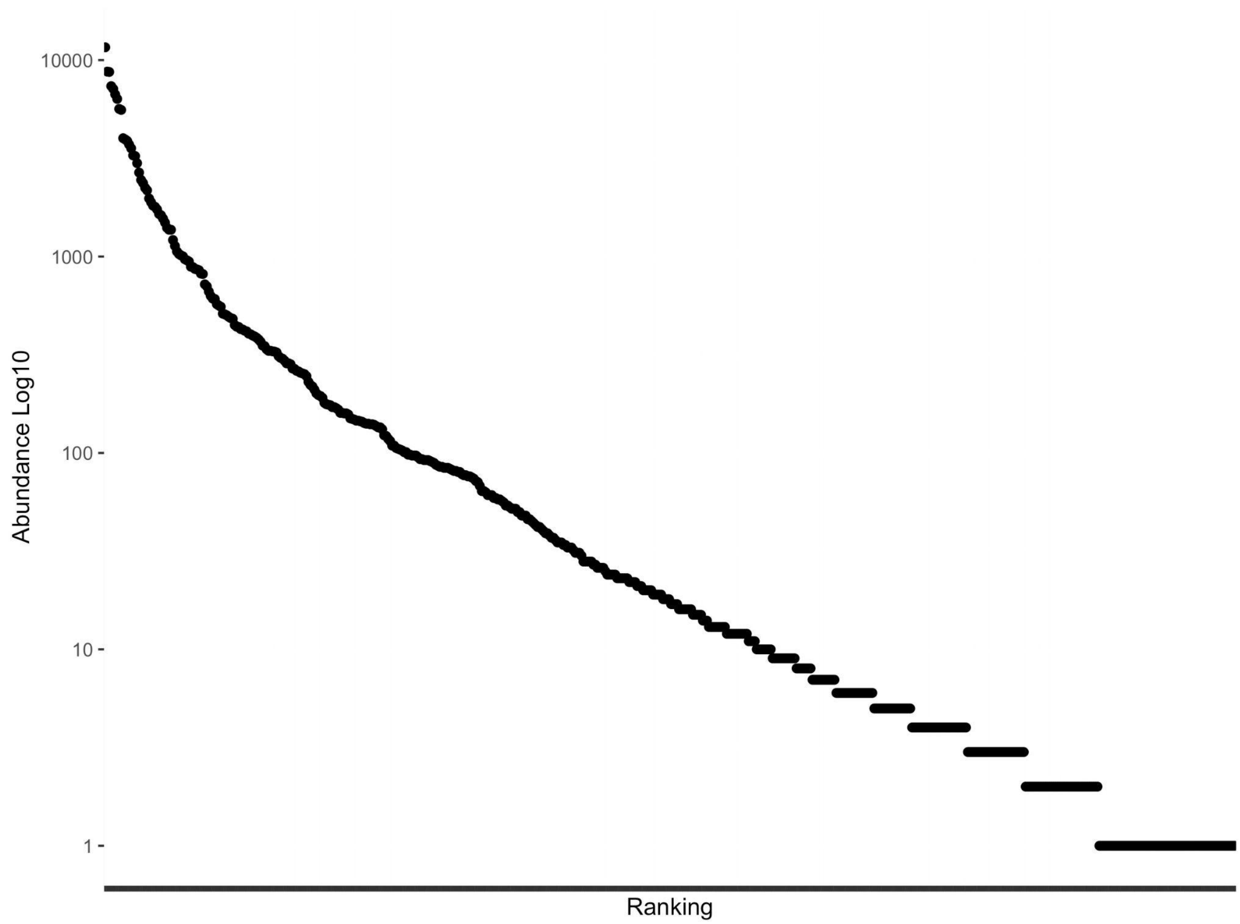

Figure 7: Rank abundance curve including all 568 tree species in San Francisco. Ranking on x-axis and log base 10 of the abundance on the y-axis

APPENDIX B: Tukey's Test

Table 3: Tukey's test for tree abundance. Rightmost column is p-value.

$Neighborhood

	diff	lwr	upr	p adj
Chinatown-VisValley	0.38592756	-2.541110843	3.312966	1.0000000
Sunset-VisValley	1.52072879	-1.406309612	4.447767	0.8960370
Tenderloin-VisValley	2.22509183	-0.701946576	5.152130	0.3621522
NorthBeach-VisValley	2.25303175	-0.674006657	5.180070	0.3412297
Bayview-VisValley	2.51649587	-0.410542535	5.443534	0.1790942
Potrero-VisValley	2.84600274	-0.081035668	5.773041	0.0658653
Marina-VisValley	2.97931309	0.052274686	5.906351	0.0416175

WTwinPeaks-VisValley	3.17249043	0.245452022	6.099529	0.0203591
HayesValley-VisValley	3.71980348	0.792765075	6.646842	0.0020347
SoMa-VisValley	4.02594177	1.098903369	6.952980	0.0004819
FiDi-VisValley	4.66067056	1.733632154	7.587709	0.0000184
Mission-VisValley	4.71594429	1.788905880	7.642983	0.0000136
PacHeights-VisValley	4.96472873	2.037690320	7.891767	0.0000034
WAddition-VisValley	5.76980086	2.842762456	8.696839	0.0000000
Sunset-Chinatown	1.13480123	-1.792237174	4.061840	0.9907683
Tenderloin-Chinatown	1.83916427	-1.087874138	4.766203	0.6844955
NorthBeach-Chinatown	1.86710419	-1.059934219	4.794143	0.6613982
Bayview-Chinatown	2.13056831	-0.796470097	5.057607	0.4371209
Potrero-Chinatown	2.46007517	-0.466963230	5.387114	0.2081513
Marina-Chinatown	2.59338553	-0.333652876	5.520424	0.1444242
WTwinPeaks-Chinatown	2.78656286	-0.140475540	5.713601	0.0800515
HayesValley-Chinatown	3.33387592	0.406837513	6.260914	0.0107468
SoMa-Chinatown	3.64001421	0.712975807	6.567053	0.0029127
FiDi-Chinatown	4.27474300	1.347704592	7.201781	0.0001396
Mission-Chinatown	4.33001672	1.402978318	7.257055	0.0001052
PacHeights-Chinatown	4.57880116	1.651762758	7.505840	0.0000285
WAddition-Chinatown	5.38387330	2.456834894	8.310912	0.0000003
Tenderloin-Sunset	0.70436304	-2.222675370	3.631401	0.9999508
NorthBeach-Sunset	0.73230295	-2.194735450	3.659341	0.9999214
Bayview-Sunset	0.99576708	-1.931271329	3.922805	0.9974993
Potrero-Sunset	1.32527394	-1.601764462	4.252312	0.9632834
Marina-Sunset	1.45858430	-1.468454107	4.385623	0.9226598
WTwinPeaks-Sunset	1.65176163	-1.275276772	4.578800	0.8230643
HayesValley-Sunset	2.19907469	-0.727963719	5.126113	0.3821796
SoMa-Sunset	2.50521298	-0.421825424	5.432251	0.1846562
FiDi-Sunset	3.13994177	0.212903361	6.066980	0.0230559
Mission-Sunset	3.19521549	0.268177086	6.122254	0.0186486
PacHeights-Sunset	3.44399993	0.516961527	6.371038	0.0068107
WAddition-Sunset	4.24907207	1.322033663	7.176110	0.0001591
NorthBeach-Tenderloin	0.02793992	-2.899098485	2.954978	1.0000000
Bayview-Tenderloin	0.29140404	-2.635634364	3.218442	1.0000000
Potrero-Tenderloin	0.62091091	-2.306127497	3.547949	0.9999896
Marina-Tenderloin	0.75422126	-2.172817143	3.681260	0.9998884
WTwinPeaks-Tenderloin	0.94739860	-1.979639807	3.874437	0.9985237
HayesValley-Tenderloin	1.49471165	-1.432326754	4.421750	0.9078094
SoMa-Tenderloin	1.80084995	-1.126188460	4.727888	0.7153742
FiDi-Tenderloin	2.43557873	-0.491459674	5.362617	0.2217415
Mission-Tenderloin	2.49085246	-0.436185949	5.417891	0.1919146
PacHeights-Tenderloin	2.73963690	-0.187401508	5.666675	0.0929711

WAddition-Tenderloin	3.54470903	0.617670627	6.471747	0.0044277
Bayview-NorthBeach	0.26346412	-2.663574284	3.190503	1.0000000
Potrero-NorthBeach	0.59297099	-2.334067417	3.520009	0.9999942
Marina-NorthBeach	0.72628134	-2.200757062	3.653320	0.9999288
WTwinPeaks-NorthBeach	0.91945868	-2.007579727	3.846497	0.9989321
HayesValley-NorthBeach	1.46677173	-1.460266674	4.393810	0.9194453
SoMa-NorthBeach	1.77291003	-1.154128379	4.699948	0.7371970
FiDi-NorthBeach	2.40763881	-0.519399594	5.334677	0.2379648
Mission-NorthBeach	2.46291254	-0.464125869	5.389951	0.2066154
PacHeights-NorthBeach	2.71169698	-0.215341428	5.638735	0.1014429
WAddition-NorthBeach	3.51676911	0.589730708	6.443808	0.0049958
Potrero-Bayview	0.32950687	-2.597531538	3.256545	1.0000000
Marina-Bayview	0.46281722	-2.464221184	3.389856	0.9999998
WTwinPeaks-Bayview	0.65599456	-2.271043848	3.583033	0.9999794
HayesValley-Bayview	1.20330761	-1.723730795	4.130346	0.9840779
SoMa-Bayview	1.50944590	-1.417592501	4.436484	0.9012539
FiDi-Bayview	2.14417469	-0.782863716	5.071213	0.4259804
Mission-Bayview	2.19944842	-0.727589990	5.126487	0.3818884
PacHeights-Bayview	2.44823286	-0.478805550	5.375271	0.2146472
WAddition-Bayview	3.25330499	0.326266586	6.180343	0.0148516
Marina-Potrero	0.13331035	-2.793728051	3.060349	1.0000000
WTwinPeaks-Potrero	0.32648769	-2.600550715	3.253526	1.0000000
HayesValley-Potrero	0.87380074	-2.053237662	3.800839	0.9993914
SoMa-Potrero	1.17993904	-1.747099368	4.106977	0.9866919
FiDi-Potrero	1.81466782	-1.112370583	4.741706	0.7043559
Mission-Potrero	1.86994155	-1.057096857	4.796980	0.6590294
PacHeights-Potrero	2.11872599	-0.808312416	5.045764	0.4468975
WAddition-Potrero	2.92379812	-0.003240281	5.850837	0.0505646
WTwinPeaks-Marina	0.19317734	-2.733861070	3.120216	1.0000000
HayesValley-Marina	0.74049039	-2.186548016	3.667529	0.9999103
SoMa-Marina	1.04662868	-1.880409722	3.973667	0.9958288
FiDi-Marina	1.68135747	-1.245680937	4.608396	0.8035672
Mission-Marina	1.73663119	-1.190407211	4.663670	0.7645103
PacHeights-Marina	1.98541563	-0.941622771	4.912454	0.5603998
WAddition-Marina	2.79048777	-0.136550635	5.717526	0.0790420
HayesValley-WTwinPeaks	0.54731305	-2.379725352	3.474351	0.9999979
SoMa-WTwinPeaks	0.85345135	-2.073587058	3.780490	0.9995330
FiDi-WTwinPeaks	1.48818013	-1.438858272	4.415219	0.9106224
Mission-WTwinPeaks	1.54345386	-1.383584547	4.470492	0.8850096
PacHeights-WTwinPeaks	1.79223830	-1.134800106	4.719277	0.7221679
WAddition-WTwinPeaks	2.59731043	-0.329727971	5.524349	0.1428024
SoMa-HayesValley	0.30613829	-2.620900111	3.233177	1.0000000

FiDi-HayesValley	0.94086708	-1.986171326	3.867905	0.9986295
Mission-HayesValley	0.99614081	-1.930897600	3.923179	0.9974895
PacHeights-HayesValley	1.24492525	-1.682113160	4.171964	0.9784336
WAddition-HayesValley	2.04999738	-0.877041024	4.977036	0.5048362
FiDi-SoMa	0.63472879	-2.292309620	3.561767	0.9999863
Mission-SoMa	0.69000251	-2.237035894	3.617041	0.9999617
PacHeights-SoMa	0.93878695	-1.988251454	3.865825	0.9986618
WAddition-SoMa	1.74385909	-1.183179318	4.670897	0.7591678
Mission-FiDi	0.05527373	-2.871764679	2.982312	1.0000000
PacHeights-FiDi	0.30405817	-2.622980239	3.231097	1.0000000
WAddition-FiDi	1.10913030	-1.817908103	4.036169	0.9925910
PacHeights-Mission	0.24878444	-2.678253965	3.175823	1.0000000
WAddition-Mission	1.05385658	-1.873181829	3.980895	0.9955291
WAddition-PacHeights	0.80507214	-2.121966269	3.732111	0.9997604

Table 4: Tukey's test for species richness. Rightmost column shows p-value

$Neighborhood

	diff	lwr	upr	p adj
VisValley-Chinatown	0.45002196	-0.953418554	1.853462	0.9986651
Tenderloin-Chinatown	0.51258125	-0.890859270	1.916022	0.9948404
NorthBeach-Chinatown	0.58625564	-0.817184876	1.989696	0.9816135
FiDi-Chinatown	0.84445889	-0.558981628	2.247899	0.7461331
Bayview-Chinatown	1.09740099	-0.306039524	2.500842	0.3154242
Potrero-Chinatown	1.10746838	-0.295972138	2.510909	0.3007807
SoMa-Chinatown	1.35678790	-0.046652620	2.760228	0.0695183
Sunset-Chinatown	1.41343476	0.009994242	2.816875	0.0464967
WAddition-Chinatown	1.55814444	0.154703922	2.961585	0.0150656
Marina-Chinatown	1.97213480	0.568694285	3.375575	0.0003143
HayesValley-Chinatown	2.00366949	0.600228973	3.407110	0.0002265
WTwinPeaks-Chinatown	2.10199660	0.698556084	3.505437	0.0000796
PacHeights-Chinatown	2.28823279	0.884792270	3.691673	0.0000100
Mission-Chinatown	2.35090687	0.947466351	3.754347	0.0000048
Tenderloin-VisValley	0.06255928	-1.340881231	1.466000	1.0000000
NorthBeach-VisValley	0.13623368	-1.267206837	1.539674	1.0000000
FiDi-VisValley	0.39443693	-1.009003589	1.797877	0.9996927
Bayview-VisValley	0.64737903	-0.756061485	2.050820	0.9572728
Potrero-VisValley	0.65744642	-0.745994099	2.060887	0.9516720
SoMa-VisValley	0.90676593	-0.496674581	2.310206	0.6411928
Sunset-VisValley	0.96341280	-0.440027719	2.366853	0.5397832
WAddition-VisValley	1.10812248	-0.295318040	2.511563	0.2998431
Marina-VisValley	1.52211284	0.118672324	2.925553	0.0201990
HayesValley-VisValley	1.55364753	0.150207012	2.957088	0.0156339

WTwinPeaks-VisValley	1.65197464	0.248534122	3.055415	0.0067711
PacHeights-VisValley	1.83821082	0.434770308	3.241651	0.0012038
Mission-VisValley	1.90088491	0.497444390	3.304325	0.0006484
NorthBeach-Tenderloin	0.07367439	-1.329766122	1.477115	1.0000000
FiDi-Tenderloin	0.33187764	-1.071562874	1.735318	0.9999602
Bayview-Tenderloin	0.58481975	-0.818620770	1.988260	0.9820124
Potrero-Tenderloin	0.59488713	-0.808553384	1.998328	0.9790680
SoMa-Tenderloin	0.84420665	-0.559233866	2.247647	0.7465323
Sunset-Tenderloin	0.90085351	-0.502587004	2.304294	0.6515799
WAddition-Tenderloin	1.04556319	-0.357877324	2.449004	0.3966637
Marina-Tenderloin	1.45955356	0.056113039	2.862994	0.0329564
HayesValley-Tenderloin	1.49108824	0.087647727	2.894529	0.0258313
WTwinPeaks-Tenderloin	1.58941535	0.185974838	2.992856	0.0116064
PacHeights-Tenderloin	1.77565154	0.372211024	3.179092	0.0021924
Mission-Tenderloin	1.83832562	0.434885105	3.241766	0.0012025
FiDi-NorthBeach	0.25820325	-1.145237268	1.661644	0.9999983
Bayview-NorthBeach	0.51114535	-0.892295164	1.914586	0.9949827
Potrero-NorthBeach	0.52121274	-0.882227778	1.924653	0.9939126
SoMa-NorthBeach	0.77053226	-0.632908260	2.173973	0.8504907
Sunset-NorthBeach	0.82717912	-0.576261398	2.230620	0.7728691
WAddition-NorthBeach	0.97188880	-0.431551718	2.375329	0.5245638
Marina-NorthBeach	1.38587916	-0.017561354	2.789320	0.0567094
HayesValley-NorthBeach	1.41741385	0.013973333	2.820854	0.0451624
WTwinPeaks-NorthBeach	1.51574096	0.112300444	2.919181	0.0212561
PacHeights-NorthBeach	1.70197715	0.298536630	3.105418	0.0043334
Mission-NorthBeach	1.76465123	0.361210712	3.168092	0.0024314
Bayview-FiDi	0.25294210	-1.150498412	1.656383	0.9999987
Potrero-FiDi	0.26300949	-1.140431026	1.666450	0.9999978
SoMa-FiDi	0.51232901	-0.891111508	1.915770	0.9948656
Sunset-FiDi	0.56897587	-0.834464645	1.972416	0.9859774
WAddition-FiDi	0.71368555	-0.689754966	2.117126	0.9104970
Marina-FiDi	1.12767591	-0.275764602	2.531116	0.2726123
HayesValley-FiDi	1.15921060	-0.244229914	2.562651	0.2320525
WTwinPeaks-FiDi	1.25753771	-0.145902804	2.660978	0.1326309
PacHeights-FiDi	1.44377390	0.040333382	2.847214	0.0371362
Mission-FiDi	1.50644798	0.103007464	2.909888	0.0228874
Potrero-Bayview	0.01006739	-1.393373130	1.413508	1.0000000
SoMa-Bayview	0.25938690	-1.144053612	1.662827	0.9999982
Sunset-Bayview	0.31603377	-1.087406750	1.719474	0.9999781
WAddition-Bayview	0.46074345	-0.942697070	1.864184	0.9982819
Marina-Bayview	0.87473381	-0.528706706	2.278174	0.6965465
HayesValley-Bayview	0.90626850	-0.497172019	2.309709	0.6420691

WTwinPeaks-Bayview	1.00459561	-0.398844908	2.408036	0.4665200
PacHeights-Bayview	1.19083179	-0.212608722	2.594272	0.1956474
Mission-Bayview	1.25350588	-0.149934640	2.656946	0.1359300
SoMa-Potrero	0.24931952	-1.154120998	1.652760	0.9999989
Sunset-Potrero	0.30596638	-1.097474135	1.709407	0.9999853
WAddition-Potrero	0.45067606	-0.952764456	1.854117	0.9986441
Marina-Potrero	0.86466642	-0.538774092	2.268107	0.7133814
HayesValley-Potrero	0.89620111	-0.507239404	2.299642	0.6597059
WTwinPeaks-Potrero	0.99452822	-0.408912294	2.397969	0.4842306
PacHeights-Potrero	1.18076441	-0.222676108	2.584205	0.2067726
Mission-Potrero	1.24343849	-0.160002026	2.646879	0.1444450
Sunset-SoMa	0.05664686	-1.346793653	1.460087	1.0000000
WAddition-SoMa	0.20135654	-1.202083974	1.604797	0.9999999
Marina-SoMa	0.61534691	-0.788093610	2.018787	0.9719424
HayesValley-SoMa	0.64688159	-0.756558922	2.050322	0.9575367
WTwinPeaks-SoMa	0.74520870	-0.658231812	2.148649	0.8795433
PacHeights-SoMa	0.93144489	-0.471995626	2.334885	0.5972784
Mission-SoMa	0.99411897	-0.409321544	2.397559	0.4849540
WAddition-Sunset	0.14470968	-1.258730836	1.548150	1.0000000
Marina-Sunset	0.55870004	-0.844740472	1.962141	0.9881530
HayesValley-Sunset	0.59023473	-0.813205785	1.993675	0.9804720
WTwinPeaks-Sunset	0.68856184	-0.714878674	2.092002	0.9310474
PacHeights-Sunset	0.87479803	-0.528642488	2.278239	0.6964381
Mission-Sunset	0.93747211	-0.465968407	2.340913	0.5864603
Marina-WAddition	0.41399036	-0.989450152	1.817431	0.9994677
HayesValley-WAddition	0.44552505	-0.957915464	1.848966	0.9988025
WTwinPeaks-WAddition	0.54385216	-0.859588353	1.947293	0.9908096
PacHeights-WAddition	0.73008835	-0.673352168	2.133529	0.8951155
Mission-WAddition	0.79276243	-0.610678086	2.196203	0.8220135
HayesValley-Marina	0.03153469	-1.371905828	1.434975	1.0000000
WTwinPeaks-Marina	0.12986180	-1.273578717	1.533302	1.0000000
PacHeights-Marina	0.31609798	-1.087342531	1.719538	0.9999781
Mission-Marina	0.37877207	-1.024668450	1.782213	0.9998076
WTwinPeaks-HayesValley	0.09832711	-1.305113405	1.501768	1.0000000
PacHeights-HayesValley	0.28456330	-1.118877219	1.688004	0.9999941
Mission-HayesValley	0.34723738	-1.056203137	1.750678	0.9999312
PacHeights-WTwinPeaks	0.18623619	-1.217204330	1.589677	1.0000000
Mission-WTwinPeaks	0.24891027	-1.154530248	1.652351	0.9999989
Mission-PacHeights	0.06267408	-1.340766434	1.466115	1.0000000