Distribution of Urban Forest Benefits from Street Trees in San Francisco, California

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ABSTRACT

Valuation of environmental benefits from street trees allows urban forest managers to improve the immediate environment and maximize economic benefits for residents. However, due to inherent heterogeneity in the geographic distribution of urban trees communities experience varying levels of benefits derived from vegetation, with more affluent neighborhoods characterized by greater canopy cover and environmental benefits. Composed of over 700,000 trees located on private and public land, the distribution of San Francisco's urban forest follows a similar pattern along socioeconomic condition. My research aimed to assess the extent of the spatial relationship between the annual environmental benefits (from energy cost reductions, carbon sequestration, and air quality improvements) and socioeconomic factors including median household income, median residential unit value, and race. To gauge heterogeneity and model the spatially varying relationships among these socioeconomic indicators of community welfare I used geographically weighted regression (GWR) at the neighborhood level. While ordinary least squares (OLS) regression delivered a global relationship, coefficients derived through GWR explain more variance in the relationship, demonstrating the increased modeling accuracy of spatially varying regressions. Furthermore, the significant predicted relationships determined from the regression equations did not support previous findings in the literature. My findings suggested resident affluence to be inversely correlated with street tree benefits, while Black & African American population levels had a positive predicted effect. These unexpected relationships can be further explored with further research to characterize forest structure between metropolitan and suburban areas in the city.

KEYWORDS

urban forestry, ecosystem services, amenity values, street trees, San Francisco

INTRODUCTION

Valuation of benefits from street trees allow urban forest managers to improve local environment conditions and maximize net economic benefits borne by local residents. Amenity values include reducing energy consumption costs, sequestering carbon, and improving atmospheric conditions (Bell et al. 2008, McPherson et al. 2005). Valuation techniques differ between environmental amenities, which utilize various economic and biophysical factors. For example, valuation of sequestered carbon is derived from current in carbon prices (Poudyal et al. 2010) while value of energy cost reductions is derived from estimated impacts of shade tree leaf area on heating and cooling costs for property owners (Leung et al. 2011). Best urban forestry management practices are determined by maximizing total benefits derived for the local environment, government, and communities derived from urban trees (McPherson et al. 2005). Typically, governments and forest managers aggregate benefits across large areas failing to assess differences in tree benefits experienced locally.

As with many resources, urban forest benefits tend to be distributed unequally across socioeconomic groups. Studies have shown strong positive correlations between socioeconomic status and tree canopy cover (Perkins et al. 2004). Similarly, studies have found statistical evidence that areas of higher median income and home value are more likely to have greater canopy cover and tree density (Jensen et al. 2004). Conversely, areas with predominant minority populations and lower socioeconomic status tend to have low tree species diversity, stem density, and overall canopy cover (Conway and Bourne 2013, Zhou and Kim 2013). Understanding the factors that influence the distribution of urban forest amenities can improve planning, allowing residents to experience the same level of benefits from urban trees regardless of socioeconomic status.

Urban forest benefits can be experienced at different scales, such as reaching citywide carbon mitigation goals through sequestration, reducing local energy costs from shade trees, or being exposed to air pollution levels (Poudyal et al. 2010, Leung et al. 2011, Escobedo and Nowak 2009). With studies demonstrating negative correlations between minority groups, as well as low socioeconomic status, and tree canopy cover (Zhou and Kim 2013), the distribution of vegetation can be considered an environmental justice concern. Despite inequitable dispersion of urban vegetation against socioeconomic conditions and racial composition, economic and environmental benefit assessments aggregate value across large spatial regions (Roy et al. 2012). Studies either assess the relationship between the presence of urban vegetation and socioeconomic factors, or estimate amenity value for an entire study area without evaluating differences in localized benefits. Decision makers would therefore need to consider the distribution and spatial relationship between amenity values and socioeconomic factors to ensure benefits are equitably borne by constituents.

My research aimed to assess the spatial relationship between benefits from urban street trees (carbon sequestration, air quality improvements, and energy cost reductions) and socioeconomic factors including household income, home value, and racial composition for San Francisco neighborhoods. I predicted that there would be a positive correlation between urban forest amenity values and median income and household value, indicators of community affluence and wellbeing. I also predicted a negative correlation between benefits and proportion of minority population, indicating environmental justice hotspots. Additionally, I aimed to determine the socioeconomic factor with the strongest correlation with amenity value. I predicted that home value would have the most significant effect due to a greater municipal budget gathered from higher property taxes. Lastly, I intended to assess whether the relationships I found between socioeconomic indicators and street tree benefits were consistent with the literature for urban canopy cover.

METHODS

Study Site

San Francisco's urban forest is composed of approximately 700,000 trees located on private property and public land, along streets and in parks, totaling a tree canopy of only 13.7%--a percentage comparatively less than other major US cities (Urban Forestry Plan). Able to thrive due to the city's moderate microclimate, San Francisco's urban trees offer varying levels of environmental benefits due to physical and biological differences between tree species. The estimated 105,000 street trees constitute a part of the city's green infrastructure and are under the jurisdiction of San Francisco's Department of Public Works (DPW). Due to lack of sufficient government funding, the DPW has transferred responsibility of street tree maintenance to adjacent private property owners and instituted a 12-year pruning cycle instead of the recommended 3 (Tree Maintenance Transfer Plan). Consequently, many urban forestry projects are developed and lead by community organizations, volunteers, and non-profit organizations such as Friends of the Urban Forest.

As a major metropolitan area, San Francisco hosts a diverse population, with residents ranging across a broad socioeconomic and racial spectrum. According to the 2010 census, San Francisco has a higher median value of owner-occupied housing units at $744,600 and median household income at $75,606 compared to California averages, at $366,400 and $61,094 respectively. Racial composition for the city is also different than state averages, with a significantly smaller proportion of White, larger proportion of Asian, yet similar proportion of

Black residents (Census 2010). With distinct socioeconomic variation, San Francisco neighborhoods presented in Figure 1 are not all representative of city-level statistics. Spatial variation in human geography at the neighborhood scale enables the comparative analysis of distribution of city features, including value of urban trees.

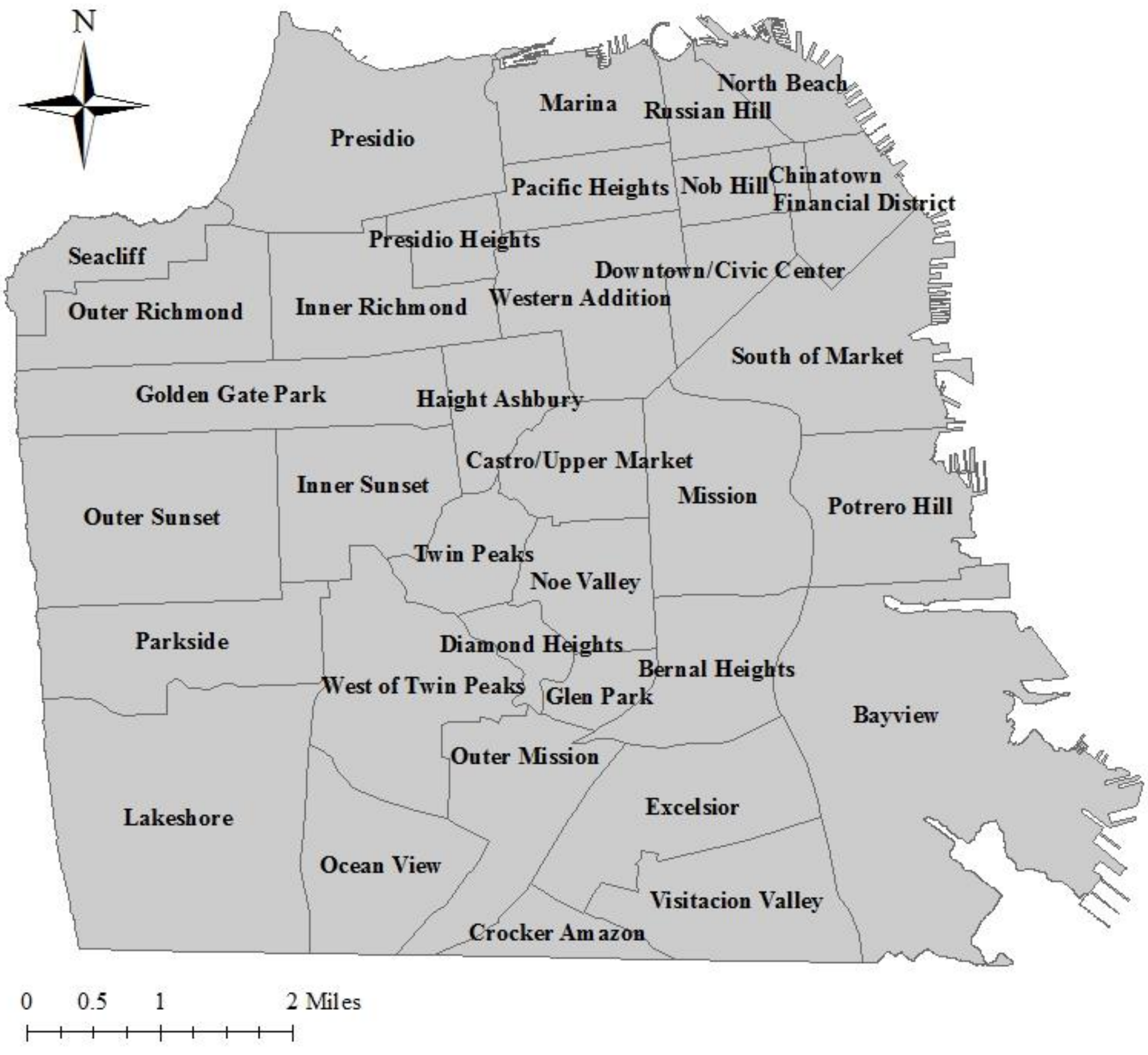

Figure 1. Map of neighborhoods in San Francisco, California. Data was downloaded from the San Francisco Planning Department for each of its 36 planning neighborhoods.

Data Collection

To gauge heterogeneity of socioeconomic characteristics I collected census data for each of the 36 neighborhoods recognized by the San Francisco Planning Department. The explanatory variables I selected for my study included household income, home value, racial composition, and total street length. Houshold income and home value act as typical indicators of community affluence and wellbeing, with racial composition indicating potential environmental justice hotspots. Data from the 2010 Census, provided by the US Census Bureau, aggregates information including residents' median household income (in US$) and population for each racial category ("White," "Black or African American," "American Indian or Alaska Native," "Asian," "Native Hawaiian and Other Pacific Islander," "Some Other Race," or "Two or More Races") into specified geographic areas called census blocks. Data from the 2005-2009 American Community Survey, also provided by the US Census Bureau, reports additional socio-economic attributes including median home value (in US$) at the census tract level, a larger geographic unit than the census block. I opted to collect data at the neighborhood level, consolidated from smaller census units, presented in the Planning Department's Socio-Economic Profiles report, to account for regional street tree management differences. Total street length was calculated in ArcMap 10.2.1 calculating the lengths of street features in each neighborhood. I used percentage of each racial group to control for variation in neighborhood population size. Table 1 summarizes each of the nine explanatory variable used in my study (see Appendix A for values and spatial distributions of each variable).

Table 1. Summary of explanatory variables used in my study. Data was collected from aggregated neighborhood values presented in the San Francisco Neighborhoods: Socio-Economic Profiles report created by the SF Planning Department. Total street length was computed by calculating street feature length in ArcMap 10.2.1 using San

Francisco Planning Department data. Household income and home value are typical indicators of community affluence and wellbeing.

Variable (units)	**Variable Name**	**Mean**	**Std Dev**	**Min**	**First Quartile**	**Median**	**Third Quartile**	**Max**
Median Household Income (US$)	*HHincome*	78847	28372	17630	65513	79477	94390	162903
Median Home Value (US$)	*HomeValue*	948626	450957	497297	696414	836252	942815	2301282
Black/African American (%)	*P_black*	0.052	0.059	0.010	0.020	0.020	0.060	0.320
Asian (%)	*P_asian*	0.317	0.186	0.080	0.140	0.330	0.475	0.840
White (%)	*P_white*	0.525	0.212	0.120	0.370	0.540	0.700	0.840
Native American Indian (%)	*P_natamer*	0.003	0.004	0.000	0.000	0.000	0.005	0.010
Native Hawaiin/Pacific Islander (%)	*P_nathawa*	0.002	0.007	0.000	0.000	0.000	0.000	0.030
Other/Two or More Races (%)	*P_other*	0.099	0.056	0.020	0.060	0.080	0.110	0.250
Total Street Length (US feet)	*streetlength*	178264	113138	26772	96009	158872	223885	583588

To compute annual environmental amenity values using iTree Streets, valuation software developed by the US Forest Service, I gathered street tree inventory data including species and diameter at breast height (dbh). The Urban Forest Map, developed by Friends of the Urban Forest, Cal Fire, the city of San Francisco, and other urban forestry organizations, provides current street tree inventory data in the form of point features in a GIS-compatible shapefile. Of the estimated 105,000 street trees (SF Urban Forest Plan), I used inventory data for 64,583 trees from the Urban Forest Map. While the dataset provided data for 88,407 plots, I eliminated 23,818 points that were classified as non-trees or lacked data for both species and dbh. Points with tree species assignments but without a dbh value were assigned an average value for trees of the same species. Dbh values ranged from seedlings of 0.29 inches to mature trees of 140 inches, with a mean value of 14.0 inches. Using the San Francisco Planning Department's "planning neighborhoods" boundary shapefile, I used the Spatial Join tool in ArcGIS to classify the corresponding neighborhood for each tree. Table 2 summarizes street tree size for the city of San Francisco and each of its 36 neighborhoods.

Table 2: Summary of diameter at street tree size. Measured in diameter at breast height (dbh) in US inches for San Francisco and its 36 neighborhoods. Inventory data was downloaded from the Urban Forest Map. Species average values were assigned to trees without a dbh value.

	# Trees	Mean	Std Dev	Min	First Quartile	Median	Third Quartile	Max
Planning Neighborhoods								
Bayview	5251	11.0	10.5	1.0	5.2	10.0	12.0	135.0
Bernal Heights	3233	12.8	13.8	1.0	5.6	9.1	13.5	100.0
Castro/Upper Market	2809	16.1	16.9	0.5	7.2	12.0	17.1	100.0
Chinatown	82	14.0	13.5	3.7	6.8	10.0	12.0	70.0
Crocker Amazon	374	11.6	6.6	3.0	6.9	10.3	14.8	42.0
Diamond Heights	326	25.9	20.1	3.0	12.0	20.0	35.0	100.0
Downtown/Civic Center	1991	13.4	10.6	1.3	6.8	10.3	14.8	100.0
Excelsior	1855	12.0	10.6	2.0	5.6	9.1	13.5	80.0
Financial District	1198	17.2	12.6	1.6	6.7	12.0	25.0	90.0
Glen Park	763	15.8	17.0	1.0	7.2	11.9	18.0	135.0
Golden Gate Park	40	18.1	13.4	3.0	10.3	14.8	22.9	48.0
Haight Ashbury	1942	16.4	17.2	0.6	7.2	11.9	18.0	100.0
Inner Richmond	2686	18.6	24.1	1.0	5.0	10.3	17.1	140.0
Inner Sunset	1420	10.3	6.7	0.6	5.6	9.1	13.5	62.0
Lakeshore	994	13.0	15.1	3.0	3.0	6.0	18.0	90.0
Marina	926	16.6	16.1	2.5	7.2	12.0	18.0	125.0
Mission	5306	14.5	15.3	0.2	6.0	10.0	15.4	106.0
Nob Hill	586	21.0	20.1	3.0	7.2	12.0	27.5	90.0
Noe Valley	2146	16.2	19.0	0.8	6.1	10.3	15.0	100.0
North Beach	1036	21.6	25.6	3.0	6.9	12.0	24.0	125.0
Ocean View	1812	11.2	8.6	1.5	4.7	9.1	14.8	90.0
Outer Mission	2358	12.4	9.2	2.0	6.0	10.4	14.2	70.0
Outer Richmond	2508	10.4	12.3	2.0	3.0	6.0	12.0	125.0
Outer Sunset	2626	13.5	12.5	1.3	4.7	10.2	14.8	83.3
Pacific Heights	1114	15.8	14.3	3.0	9.9	12.0	18.0	126.0
Parkside	1698	12.6	12.9	2.9	3.7	9.1	13.9	83.3
Potrero Hill	1752	10.5	7.0	1.6	6.2	9.9	12.0	79.4
Presidio	44	12.5	6.6	3.0	9.8	10.3	15.5	30.0
Presidio Heights	827	24.6	26.0	3.0	9.9	14.8	30.0	135.0
Russian Hill	869	23.2	20.0	3.0	10.3	14.8	29.4	100.0
Seacliff	179	17.5	18.2	3.0	6.0	12.0	20.7	90.0
South of Market	3788	11.2	9.5	0.5	4.7	9.5	12.0	125.0
Twin Peaks	128	8.1	6.6	1.3	3.0	6.9	10.4	35.7
Visitacion Valley	925	10.4	7.9	0.3	4.7	9.1	12.0	70.4
West of Twin Peaks	1776	11.5	9.5	1.3	4.8	9.1	14.0	100.0
Western Addition	7215	14.8	13.6	1.0	6.0	12.0	18.0	135.0
City of San Francisco								
Total	64583	14.0	14.6	0.2	6.0	10.3	15.0	140.0

With the neighborhood classified inventory data, I calculated the annual benefit value for energy cost reductions, carbon sequestration, and air quality improvements from street trees within each locale using iTree Streets. The program utilizes accepted biophysical algorithms to estimate urban forest structure, growth rates, and environmental interactions unique to each tree species or genus in order to quantify benefit value (McPherson 2010). I found a substantial range in total annual street tree amenity value among neighborhoods from $146,394 to $727, with a mean value of $32,271 and standard deviation of $30,009. Table 3 summarizes total annual benefit as well as the three component amenity values for SF neighborhoods. Neighborhoods with the highest total annual benefits included the Western Addition, Mission, Bayview, South of Market, and Outer Sunset with $146,394, $105,342, $88,051, $58,012, and $53,065 respectively. Neighborhoods with the lowest total annual benefits included the Presidio, Golden Gate Park, Chinatown, Twin Peaks, and Seacliff with $727, $1,161, $1,406, $1,431, and $3,147 respectively. Annual benefit values and spatial distributions of street tree amenities can be found in Appendix B.

Table 3. Summary of street tree benefit values. Values were calculated using iTree Streets benefit assessment tools with street tree inventory data collected from the Urban Forest Map. Total Annual Benefit was calculated by summing three component benefit values.

Variable (unit)	Mean	Std Dev	Min	First Quartile	Median	Third Quartile	Max
Annual Energy Benefits (US$)	27700	26288	663	12857	22295	36082	132450
Annual CO2 Benefits ($)	2835	2760	64	1559	2073	3779	13944
Annual Air Quality Benefits ($)	-2127	10921	-54626	-4234	-199	1989	16272
Total Annual Benefits ($)	32271	30009	727	14522	25965	39595	146394

Analysis

Using a multivariate regression model (Figure 2), I used Ordinary Least Squares (OLS) and Geographically Weighted Regression (GWR) in ArcMap 10.2.1 to assess the relationship between the economic value of urban forest benefits and socioeconomic indicators at the city and neighborhood level. Total street length was included as a variable to account for differences in neighborhood size and capacity for street trees. In order to model the association between variables at the citywide level with a single equation I used OLS. This global regression technique may not represent the true relationship because it does not account for spatial heterogeneity. In order to account for local conditions and management differences between neighborhoods I used GWR. As opposed to OLS, this technique produces localized regression equations for each feature based on size and distance to nearby features. GWR's ability to captures spatial variation by estimating local effects for each neighborhood allowed me to determine areas where a socioeconomic factor had a relatively larger impact on amenity value. I calculated standardized coefficients (Figure 3) and P-values for estimated parameter effects to assess relative magnitude, direction, and strength of relationships. To determine model completeness I used the Spatial Autocorrelation (Global Moran's I) tool to measure regression residuals dispersion, which measures the difference between predicted and observed values. Clustered error terms, as opposed to random or dispersed residuals, would indicate model misspecification due to an omitted variable.

$$StreetTreeBenefits_i = \beta_0 + \beta_1 HHincome_i + \beta_2 HomeVal_i + \beta_3 P\_black_i + \beta_4 P\_asian_i + \beta_5 P\_white_i + \beta_6 P\_natamer_i + \beta_7 P\_nathawa_i + \beta_8 P\_other_i + \beta_9 streetlength_i + u_i$$

Figure 2. Multivariate regression model for OLS and GWR. Beta coefficients used to measure magnitude and direction of relationship between explanatory variable and street tree benefits.

$$Std\_B_k = B_k (SD_{x_k} / SD_y)$$

Figure 3. Formula for standardized coefficients. Due to mean zero and variance of one, standardized coefficients can be used to compare the relative magnitude of effect between regression parameters (k) from a one deviation change in an explanatory variable (x).

RESULTS

Model Summary

The OLS model explained 48.2% of the variation in total annual benefits according to the adjusted-R^2 value, which accounts for the number of predictors, while local values in GWR range from 0.354 to 0.646. Of the 36 neighborhoods, nine had local measures of fit below global OLS estimates (see Appendix C for adjusted-R^2 values) and were clustered in the city's Southwest as seen in Figure 4, explaining less of the variation in the amenities locally than the global model. Figure 5 shows the distribution of these measures of fit for San Francisco under the OLS model and neighborhoods under the GWR model. Additionally, the results of the Spatial Autocorrelation (Global Moran's I) analysis reported random residual dispersion indicating independence and homoskedastic variance in model errors.

Relative Effects

I found positive predicted effects of median home value and total street length, as well as proportion of Black & African American, Asian, White, and Other & Two or More Races, on street tree amenity value. Conversely, I found negative predicted relationships for median household income as well as the proportion of Native American Indian and Native Hawaiian & Pacific Islander. I used standardized coefficients to compare the relative magnitude and direction of effect for each explanatory variable. Accounting for differences in indicator distributions, one standard deviation increase in an explanatory variable would result in a predicted deviation shift in the dependent variable equal to the standardized coefficient. The distribution and relative magnitude of effects are presented in Figure 6 for OLS and GWR models (see Appendix C for standardized coefficient values).

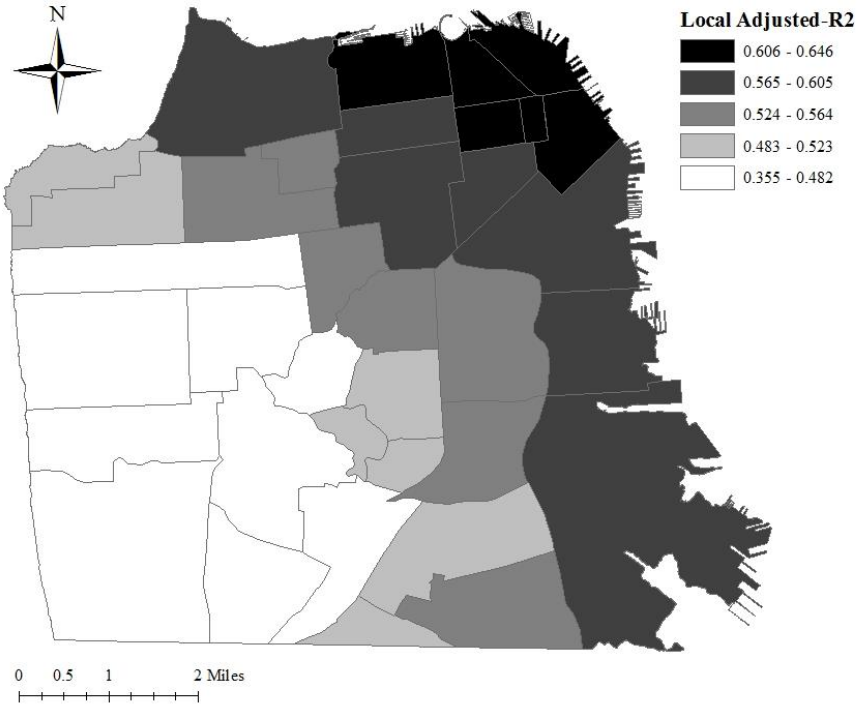

Figure 4. Spatial distribution of local regression equation measures of fit. Neighborhoods in white have adjusted R^2 values less than the OLS global estimate. These neighborhoods include: Golden Gate Park, Inner Sunset, Lakeshore, Ocean View, Outer Mission, Outer Sunset, Parkside, and West of Twin Peaks.

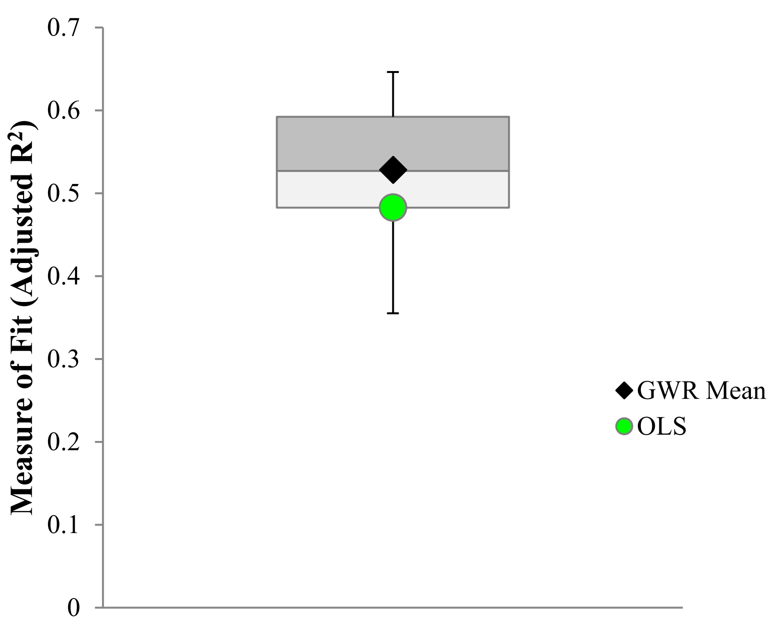

Figure 5. Distribution of measures of fit. The boxplot shows the distribution of adjusted R^2 for local GWR regression equations. OLS measure of fit was also plotted for comparison. Adjusted R^2 was used to compare differences in ability to explain variation in street tree amenity value.

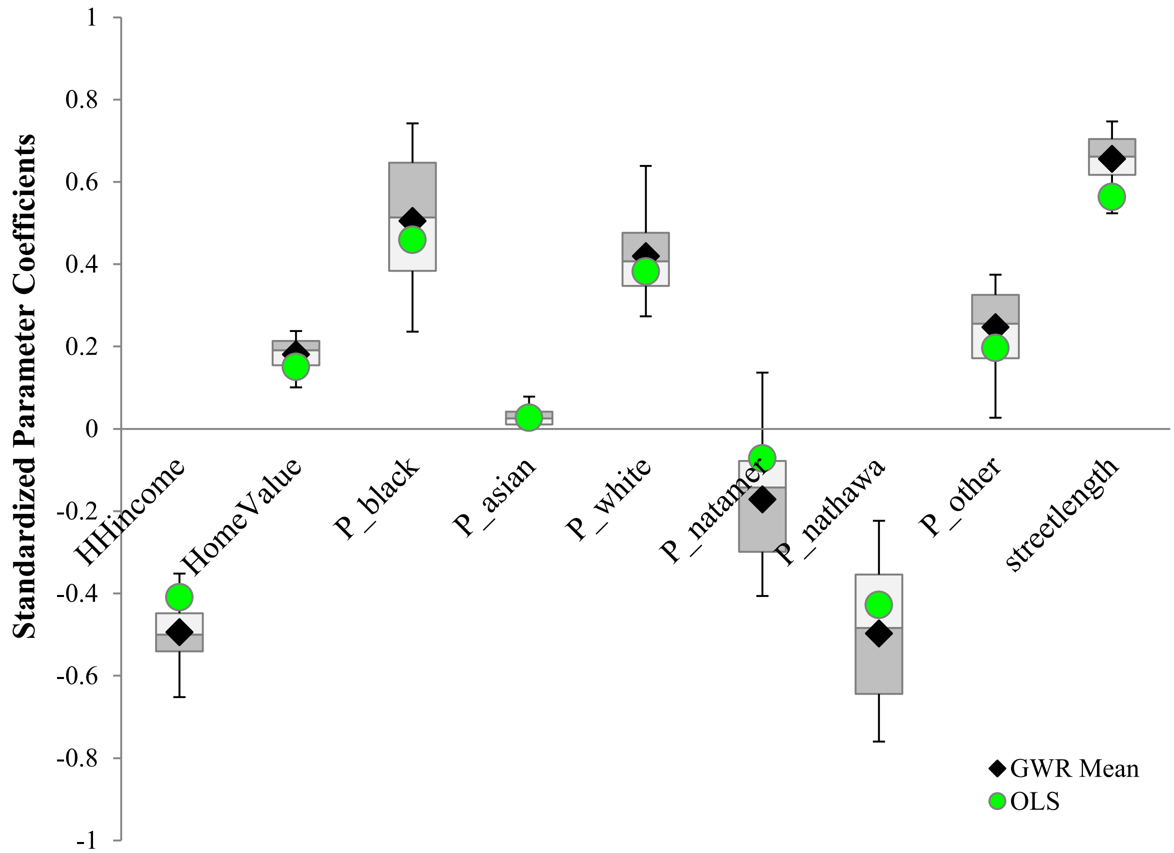

Figure 6. Distribution of standardized parameter coefficients. The boxplots shows the distribution of standardized coefficients for local GWR regression equations for each explanatory variable in my study. The OLS standardized coefficients are also plotted in comparison. Standardized coefficients were used to compare the relative effect on street tree amenity value from a standard deviation change in the explanatory variable.

Predictor Significance

Under OLS, only total street length as well as the proportion of Black & African American and Native Hawaiian & Pacific Islander residents had significant relationships. However, median household income and proportion of White residents were significant for some neighborhoods under the GWR model. I used P-values to determine the statistical significance of each predictor coefficient. Relationships are considered significant at the 5% significance level when P-values are less than 0.05, and extremely significant when P-values were less than 0.01. The distribution and relative significance of explanatory variables are presented in Figure 7 for OLS and GWR models (see Appendix C for P-values).

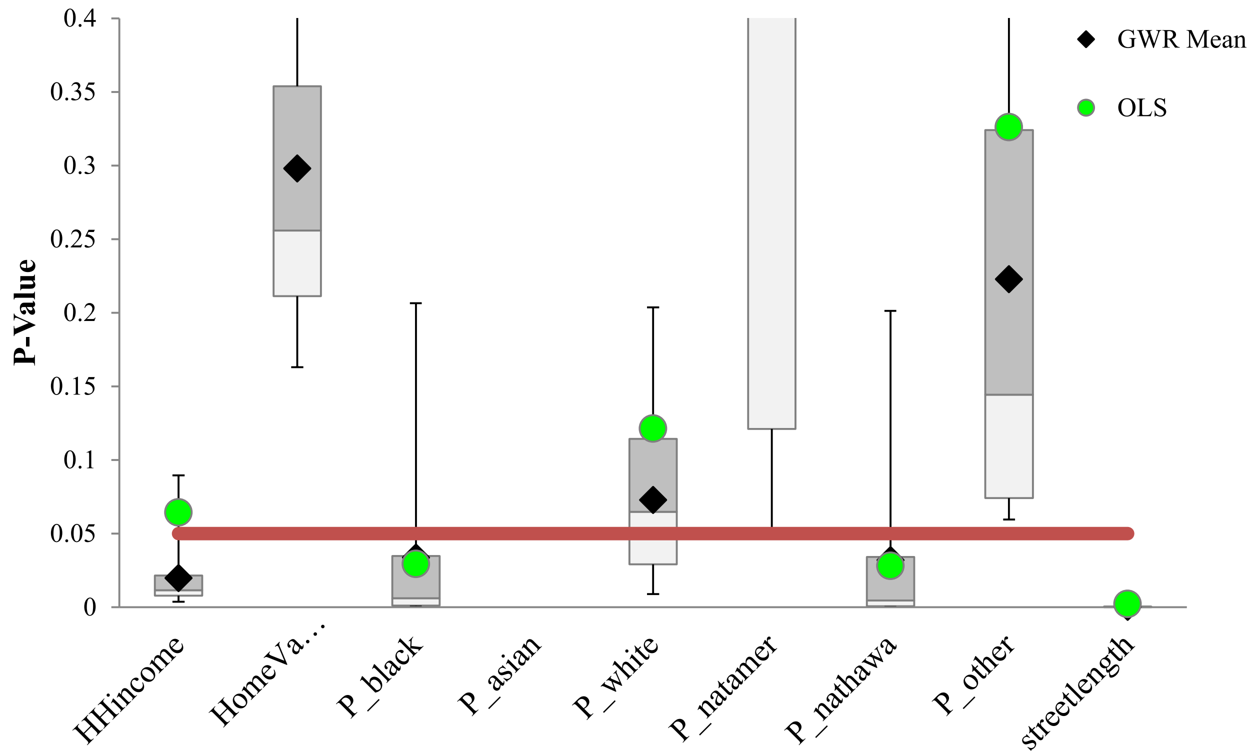

Figure 7. Distribution of parameter P-values. The boxplots shows the distribution of P-values for local GWR regression equations for each explanatory variable in my study. The OLS P-values are also plotted in comparison. P-values were used to assess significance of relationship between street tree amenities and an explanatory variable. Values below the 5% significance line are considered statistically significant effects.

DISCUSSION

Effective management of natural resources in urban settings aims to maximize environmental and economic benefits for residents. According to my results, street tree benefits in San Francisco are not equitably distributed between neighborhoods. The two most surprising significant relationships supported by the data included a positive correlation between Black &

African American populations and amenity value, with household income inversely correlated with benefits. These findings may be due to differences in forest structure between metropolitan and suburban areas. Further research should be conducted to understand these relationships at smaller scales and with component amenities to further improve management decisions.

Interpretations

The model's greater average measure of fit when accounting for spatial heterogeneity with GWR, compared to the global OLS estimate, indicates differences in the influence of local conditions between San Francisco neighborhoods on street tree benefit dispersion. Additionally, the increased predictive power from local GWR regression equations (Ogneva et al. 2009) captured unaccounted, neighborhood-specific variables. These local elements range from physical characteristics of urban landscapes to management procedures (Schneider and Logan 1981). However, despite randomly dispersed residuals indicating the lack of a key omitted variable, the local effects for nine neighborhoods explained less benefit variation than effects for the entire city.

Comparing the relative magnitude and direction of effects between the explanatory variables revealed which socioeconomic factor had the greatest influence on street tree benefit dispersion. Variables with large standardized coefficients had the greatest relative impact. The single physical factor I used, total street length, had the greatest predicted impact on benefit dispersion among explanatory variables. This relationship was expected because using street length controlled for potential planting area for street trees (McPherson 2010). However, my results suggest that among socioeconomic factors areas with more expensive housing, as well as larger Black & African American, Asian, and White groups, there was less value derived from street trees. Conversely, areas with more affluent residents, as well as larger Native American Indian and Native Hawaiian & Pacific Islander groups, tended to experience less benefits.

While the data supported these relationships, only the proportion of Black & African Americans and Native Hawaiian & Pacific Islanders had significant predicted global effects. However, looking at relationships at the neighborhood level a majority predicted significant effects from household income, with some also reporting significance from White populations. This suggests that for the city of San Francisco, minority populations can be used as an indicator of street tree benefits. While conversely, areas with predominant White and affluent populations could be used as indictors of benefits for only some neighborhoods. However, while these variables with significant correlations can inform managers when planning future planning and maintenance activity of street trees, their direction of influence should also be considered.

The direction of effects among significant variables in my study were opposite of what I expected. According to the literature, minority populations are inversely correlated with urban canopy cover (Perkins et al. 2004) and indicators of community affluence and wellbeing were also correlated with canopy cover and urban green space (Zhou and Kim 2013). In comparison, my findings suggest that Black & African American populations in San Francisco actually experience greater benefit from street trees, while areas with more affluent residents receive fewer benefits. Additionally, while home value had a positive correlation, as expected, it did not have a very significant predicted effect on amenities. Therefore, expensive housing is only generally associated with street tree benefits but San Francisco's highest earners are strongly associated with lower amenity values.

These unexpected and inverted relationships seen in San Francisco may be due to differences in metropolitan versus suburban forest structure (Gong et al 2013) or access to urban green spaces (Thompson et al. 2013). In contrast to the Southwest neighborhoods with local adjusted-R^2 lower than the global OLS model, the Northeast region of San Francisco had much higher local measures of fit (Figure 4). This area corresponds with the downtown and marina area of the city. Metropolitan neighborhoods have fewer trees than suburban areas (Schneider and Logan 1981) but may attract higher earning, non-minority residents. Furthermore, this relationship may be magnified in the data due to access to green space, as neighborhoods with more park area will consequently have fewer street trees. For example, neighborhoods around San Francisco's Presidio are characterized by high income households, despite the area having substantially fewer benefits from street trees due large areas of coastal and park land.

Limitations

The amenity values used in this study, acting as a proxy measure of street tree forest structure, were derived from the Urban Forest Map inventory dataset created from existing inventories and crowdsourcing volunteer citizens. Despite potential error in data collected from individuals with a range of experience measuring and identifying vegetation, the Urban Forest Map data is the only publicly available "full" inventory of street trees. Furthermore, bias may have occurred due to regional differences in inventory completion between neighborhoods. If more affluent areas have a greater proportion of their local trees inventoried, there would be a positive bias on the effect of home value and household income on total amenity values. While this has the potential to mischaracterize the disparity of benefits, I assumed that levels of sampling completion were consistent across the city.

Future Directions

Looking at individual amenity benefits from street trees as well as regional differences in average tree size and species distributions, as opposed to aggregated values used in this study, would reveal additional structural and distributional characteristics of the urban forest. For example, assessing the distribution of air quality improvements from trees would indicate areas hurt by air quality degradation from the emission of biogenic volatile compounds (Escobedo and Nowak 2009), a direct human health impact (Yang et al. 2005). Additionally, with the emergence of carbon trading schemes (Poudyal et al. 2010), maximizing annual carbon sequestration rates would become a management imperative. By focusing on the distribution of tree species and size, managers would be able to determine where to focus maintenance activity to promote tree growth, as well as select species for planting better suited for sequestration (Nowak and Crane 2002) and improving ambient air quality (Rowntree and Nowak 1991). The methods in my study could be used to determine distributional impacts for such street tree amenities, allowing decision makers to ensure all constituents experience equitable benefits.

Broader Implications and Conclusions

This research can be used to inform resource managers of the current distribution of benefits from street trees in San Francisco. In the wake of the San Francisco Urban Forest Plan, which lists street tree population growth as the first step in enhancing the city's urban forest, decision makers should target areas receiving less amenity benefits for future planting and maintenance. According to my study results, managers should focus on neighborhoods with more Native Hawaiian & Pacific Islander populations as well as areas with higher earning individuals, as these two are associated with lower amenity values. However, further research and assessments should be conducted within neighborhoods to determine optimal planting locations. By targeting areas typically associated with lower amenity values for future street tree population growth and enhancement, city managers can rectify current inequalities in environmental benefits.

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APPENDIX A: Neighborhood Predictor Values

Table A1. Explanatory variables for each San Francisco neighborhood. Values for socioeconomic indicators were collected from the Planning Department's Socio-Economic Profiles report. Total street length was calculated for each neighborhood in ArcMap 10.2.1 from a San Francisco street shapefile form the Planning Department.

Planning Neighborhoods	Median Household Income (US$) *HHincome*	Median Home Value (US$) *HomeValue*	Black & African American (%) *P_black*	Asian (%) *P_asian*	White (%) *P_white*	Native American Indian (%) *P_natamer*	Native Hawaiin & Pacific Islander (%) *P_nathawa*	Other & Two or More Races (%) *P_other*	Total Street Length (US feet) *streetlength*
Bayview	43155	586201	32%	33%	12%	1%	3%	20%	583588
Bernal Heights	85607	747500	5%	16%	59%	1%	0%	19%	210187
Castro/Upper Market	92237	946246	2%	10%	80%	0%	0%	8%	129424
Chinatown	17630	781746	2%	84%	12%	0%	0%	2%	26772
Crocker Amazon	68705	623471	2%	58%	22%	0%	0%	18%	80005
Diamond Heights	90510	918255	6%	14%	70%	0%	0%	9%	39548
Downtown/Civic Cente	24491	497297	10%	28%	46%	1%	0%	15%	137115
Excelsior	67398	624593	3%	49%	26%	1%	0%	21%	261697
Financial District	45221	942568	6%	47%	39%	1%	0%	7%	129854
Glen Park	90510	918255	6%	14%	70%	0%	0%	9%	65430
Golden Gate Park									115758
Haight Ashbury	85539	943062	5%	10%	77%	0%	0%	8%	120187
Inner Richmond	69861	941194	2%	38%	51%	0%	0%	8%	206569
Inner Sunset	85696	883481	2%	33%	58%	0%	0%	7%	182671
Lakeshore	62904	901153	5%	34%	49%	0%	0%	11%	306254
Marina	102442	1836082	1%	11%	84%	0%	0%	4%	150511
Mission	63627	738529	4%	13%	57%	1%	0%	25%	340004
Nob Hill	53283	702632	2%	39%	53%	0%	0%	6%	60571
Noe Valley	105807	998187	2%	12%	77%	0%	0%	9%	167234
North Beach	70067	844444	3%	37%	54%	0%	0%	5%	92930
Ocean View	67475	609976	12%	49%	27%	0%	0%	11%	209927
Outer Mission	79477	674346	2%	49%	31%	1%	0%	17%	314721
Outer Richmond	72459	835293	2%	48%	44%	0%	0%	7%	168848
Outer Sunset	73728	726851	1%	57%	35%	0%	0%	5%	324453
Pacific Heights	109307	2300281	2%	13%	81%	0%	0%	5%	97035
Parkside	83131	720247	1%	58%	35%	0%	0%	6%	219896
Potrero Hill	98182	836252	9%	13%	66%	0%	1%	10%	179825
Presidio	116807	883333	2%	8%	80%	0%	1%	9%	230367
Presidio Heights	96542	1963021	2%	17%	75%	0%	0%	5%	52464
Russian Hill	84537	1245448	1%	21%	74%	0%	0%	4%	103206
Seacliff	162903	2301282	2%	38%	54%	0%	0%	6%	60942
South of Market	67572	679924	9%	33%	48%	1%	0%	9%	312352
Twin Peaks	99449	831868	6%	19%	66%	0%	0%	8%	73623
Visitacion Valley	44373	575983	13%	55%	12%	1%	3%	17%	149288
West of Twin Peaks	125027	952703	2%	31%	59%	0%	0%	7%	292530
Western Addition	53990	690196	15%	20%	55%	0%	0%	9%	221724

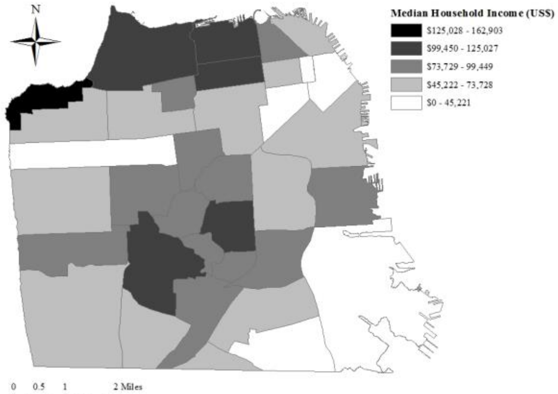

Figure A1. Spatial distribution of median household income (US$).

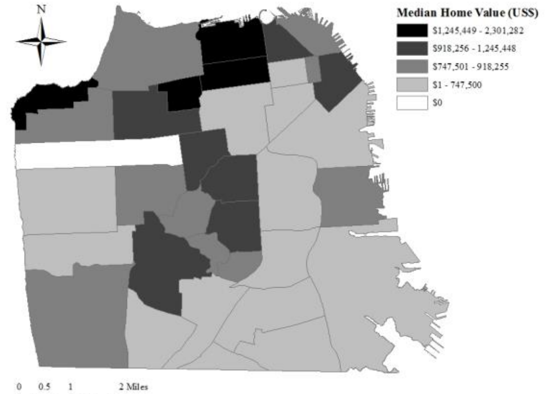

Figure A2: Spatial distribution of median home value (US$).

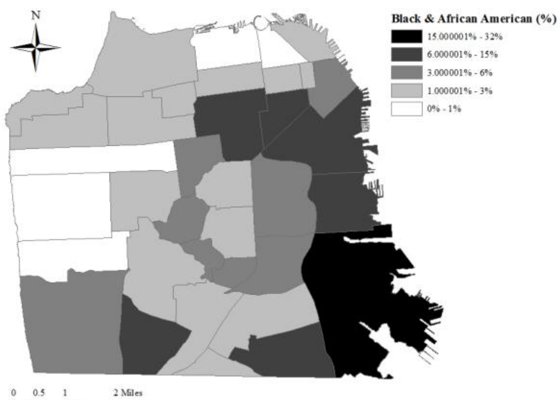

Figure A3: Spatial distribution of the proportion of Black & African American residents.

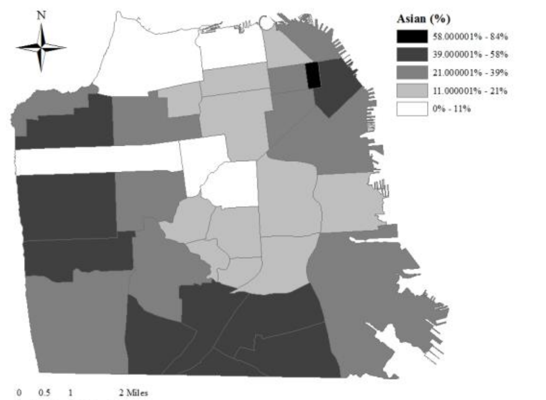

Figure A4: Spatial distribution of the proportion of Asian residents.

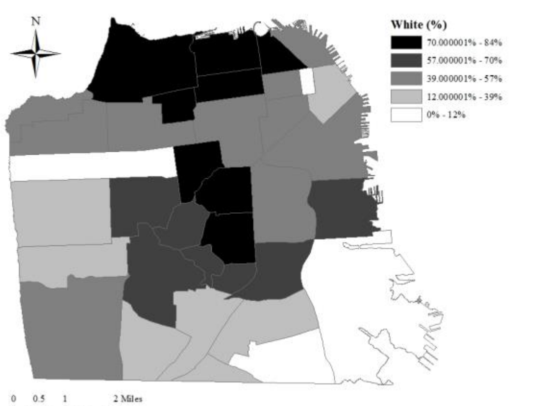

Figure A5: Spatial distribution of the proportion of White residents.

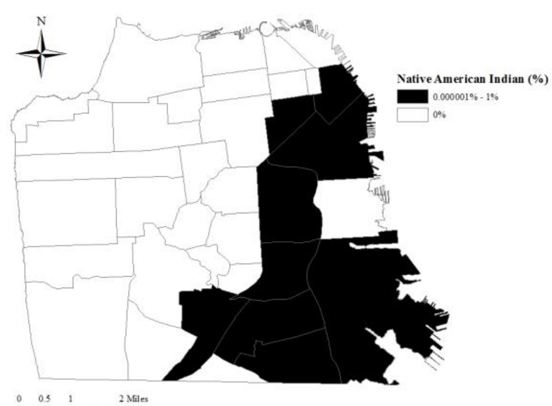

Figure A6: Spatial distribution of the proportion of Native American Indian residents.

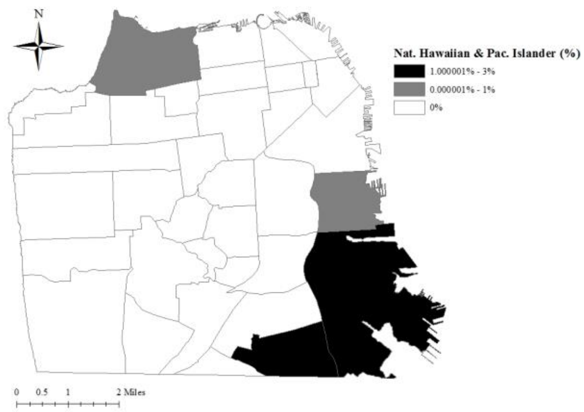

Figure A7: Spatial distribution of the proportion of Native Hawaiian & Pacific Islander residents.

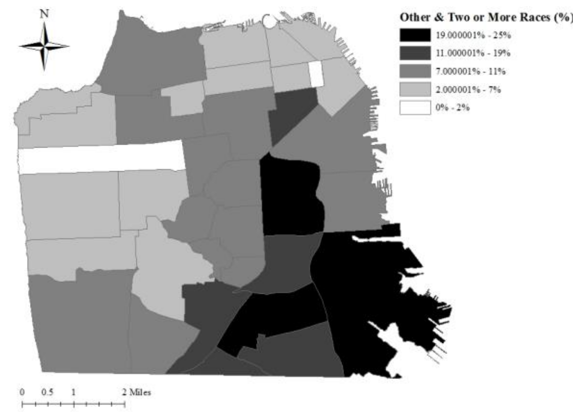

Figure A8: Spatial distribution of the proportion of Other & Two or More Races residents.

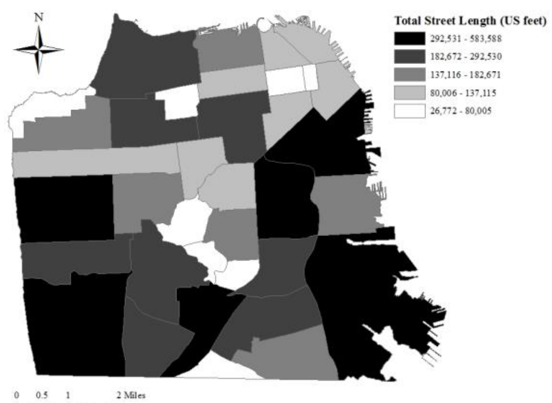

Figure A9: Spatial distribution of the proportion of total street length (US feet).

APPENDIX B: Neighborhood Amenity Values

Table B1. Street tree benefit values for the city of San Francisco and its neighborhoods. Calculated in iTree Streets using inventory data for 64,583 street trees gathered from the Urban Forest Map. Neighborhoods are ordered from largest to smallest total annual benefit.

	Annual Energy Benefits (US$)	Annual CO2 Benefits (US$)	Annual Air Quality Benefits (US$)	Total Annual Benefits (US$)
OLS				
City of San Francisco	997216	101994	-76580	1161018
GWR				
Western Addition	132450	13944	-8909	146394
Mission	81628	7442	16272	105342
Bayview	78657	9394	-54626	88051
South of Market	53199	4813	-1116	58012
Outer Sunset	38471	4053	10541	53065
Castro/Upper Market	46437	4522	-846	50959
Bernal Heights	42524	4390	-10589	46914
Inner Richmond	42266	4503	-8878	46769
Outer Mission	36350	3807	-518	40157
Downtown/Civic Cente	35993	3415	-4680	39408
Haight Ashbury	33331	3769	-304	37100
Noe Valley	29212	2752	3237	35201
Parkside	22646	2446	7406	32498
Outer Richmond	27630	2732	1772	32134
Financial District	25148	2270	3147	30565
Excelsior	21944	1871	5498	29313
West of Twin Peaks	23519	2932	-13234	26451
Potrero Hill	23404	2049	830	26283
Ocean View	23195	2452	-284	25647
Pacific Heights	19682	1908	2951	24541
Russian Hill	17586	1623	4865	24074
North Beach	19952	1636	763	22351
Presidio Heights	18194	2096	-4085	20290
Marina	15681	1597	2638	19916
Lakeshore	17132	1995	-6286	19127
Inner Sunset	15720	1608	-397	17328
Glen Park	13071	1738	-14951	14809
Visitacion Valley	12214	1446	-8708	13660
Nob Hill	11073	1024	631	12728
Diamond Heights	7513	768	-214	8281
Crocker Amazon	4783	426	1296	6505
Seacliff	2548	251	348	3147
Twin Peaks	1299	132	-237	1431
Chinatown	1294	112	-5	1406
Golden Gate Park	807	78	276	1161
Presidio	663	64	-184	727

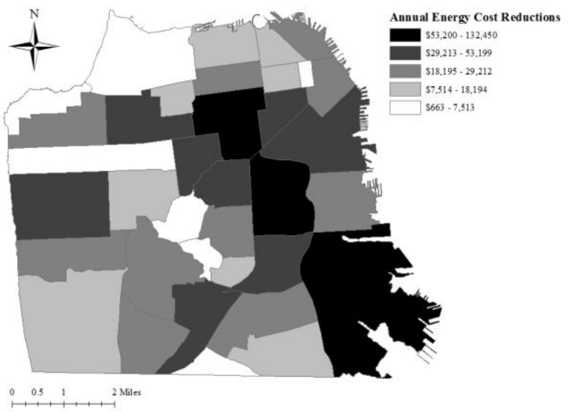

Figure B1: Spatial distribution of Annual Energy Cost Reductions (US$).

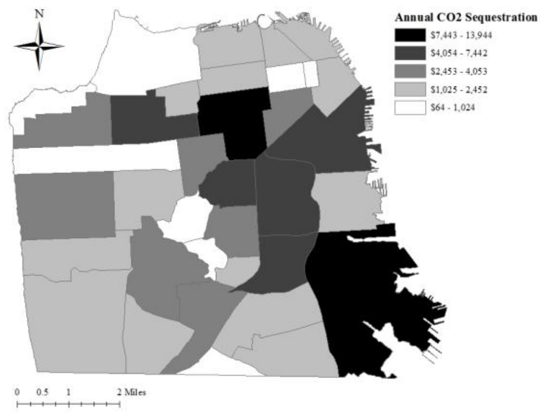

Figure B2: Spatial distribution of Annual CO2 Sequestration (US$).

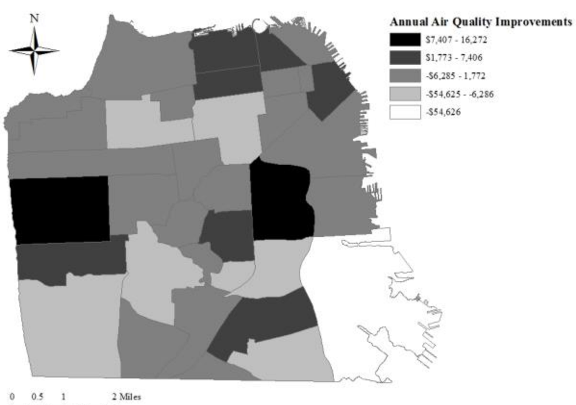

Figure B3: Spatial distribution of Annual Air Quality Improvements (US$).

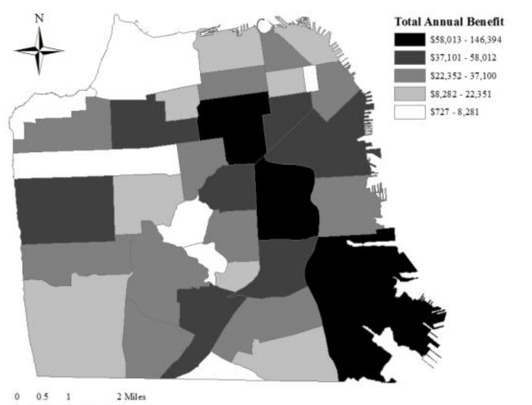

Figure B4. Spatial distribution of Total Annual Benefit (US$) from amenity values.

APPENDIX C: Regression Output

Table C1. Adjusted R2 under OLS for San Francisco and GWR for its neighborhoods. Neighborhoods ordered by magnitude of Adjusted-R2.

	Adjusted-R2
OLS	
City of San Francisco	0.482
GWR	
North Beach	0.646
Russian Hill	0.632
Chinatown	0.623
Financial District	0.623
Marina	0.621
Nob Hill	0.614
Pacific Heights	0.597
South of Market	0.594
Bayview	0.593
Downtown/Civic Center	0.592
Presidio	0.583
Potrero Hill	0.581
Western Addition	0.567
Presidio Heights	0.561
Mission	0.550
Visitacion Valley	0.548
Bernal Heights	0.533
Inner Richmond	0.528
Castro/Upper Market	0.526
Haight Ashbury	0.524
Excelsior	0.522
Noe Valley	0.509
Glen Park	0.501
Seacliff	0.495
Outer Richmond	0.484
Crocker Amazon	0.484
Diamond Heights	0.483
Twin Peaks	0.482
Golden Gate Park	0.468
Inner Sunset	0.468
Outer Mission	0.466
West of Twin Peaks	0.441
Ocean View	0.417
Outer Sunset	0.410
Parkside	0.383
Lakeshore	0.355

Table C2. Standardized coefficients for explanatory variables. Measures relative magnitudes and direction of predicted effect of explanatory variables on street tree amenities. A one standard deviation increase in an explanatory variable has a predicted standard coefficient change in standard deviations of the dependent variable.

	Median Household Income (US$) *HHincome*	**Median Home Value (US$)** *HomeValue*	**Black & African American (%)** *P_black*	**Asian (%)** *P_asian*	**White (%)** *P_white*	**Native American Indian (%)** *P_natamer*	**Native Hawaiian & Pacific Islander (%)** *P_nathawa*	**Other & Two or More Races (%)** *P_other*	**Total Street Length (US feet)** *streetlength*
OLS									
City of San Francisco	-0.409	0.151	0.460	0.027	0.382	-0.072	-0.428	0.196	0.563
GWR									
Bayview	-0.652	0.123	0.252	0.052	0.639	-0.138	-0.261	0.285	0.643
Bernal Heights	-0.573	0.154	0.345	0.036	0.537	-0.125	-0.339	0.258	0.634
Castro/Upper Market	-0.523	0.195	0.496	0.020	0.431	-0.191	-0.487	0.273	0.661
Chinatown	-0.540	0.213	0.647	0.011	0.385	-0.366	-0.688	0.365	0.728
Crocker Amazon	-0.486	0.106	0.261	0.050	0.530	0.017	-0.233	0.161	0.570
Diamond Heights	-0.503	0.165	0.395	0.033	0.469	-0.082	-0.373	0.210	0.619
Downtown/Civic Center	-0.544	0.211	0.595	0.012	0.404	-0.315	-0.618	0.343	0.707
Excelsior	-0.555	0.131	0.285	0.044	0.557	-0.064	-0.271	0.222	0.609
Financial District	-0.556	0.205	0.617	0.014	0.410	-0.357	-0.662	0.367	0.723
Glen Park	-0.531	0.156	0.358	0.035	0.504	-0.088	-0.341	0.225	0.620
Golden Gate Park	-0.409	0.200	0.588	0.026	0.331	-0.112	-0.549	0.172	0.647
Haight Ashbury	-0.494	0.208	0.553	0.015	0.387	-0.205	-0.540	0.268	0.670
Inner Richmond	-0.448	0.222	0.639	0.010	0.323	-0.223	-0.617	0.254	0.684
Inner Sunset	-0.448	0.190	0.511	0.026	0.383	-0.103	-0.480	0.193	0.636
Lakeshore	-0.352	0.101	0.354	0.079	0.421	0.137	-0.304	0.027	0.524
Marina	-0.482	0.233	0.734	0.001	0.308	-0.379	-0.754	0.349	0.738
Mission	-0.571	0.182	0.445	0.025	0.487	-0.205	-0.449	0.298	0.664
Nob Hill	-0.529	0.218	0.654	0.009	0.372	-0.357	-0.686	0.357	0.725
Noe Valley	-0.530	0.175	0.419	0.028	0.473	-0.133	-0.405	0.247	0.638
North Beach	-0.519	0.218	0.708	0.008	0.350	-0.406	-0.760	0.375	0.747
Ocean View	-0.419	0.112	0.314	0.056	0.467	0.065	-0.275	0.105	0.552
Outer Mission	-0.484	0.131	0.315	0.045	0.499	-0.007	-0.287	0.168	0.585
Outer Richmond	-0.389	0.208	0.648	0.025	0.297	-0.135	-0.605	0.170	0.662
Outer Sunset	-0.376	0.167	0.517	0.050	0.355	0.004	-0.468	0.093	0.601
Pacific Heights	-0.498	0.228	0.678	0.004	0.338	-0.338	-0.692	0.336	0.721
Parkside	-0.374	0.142	0.438	0.061	0.391	0.063	-0.390	0.067	0.569
Potrero Hill	-0.618	0.166	0.404	0.032	0.541	-0.225	-0.422	0.322	0.670
Presidio	-0.436	0.238	0.743	0.001	0.273	-0.317	-0.728	0.295	0.721
Presidio Heights	-0.468	0.228	0.666	0.005	0.322	-0.282	-0.658	0.294	0.703
Russian Hill	-0.511	0.224	0.706	0.006	0.341	-0.390	-0.744	0.365	0.740
Seacliff	-0.373	0.210	0.687	0.025	0.275	-0.147	-0.640	0.163	0.670
South of Market	-0.582	0.192	0.524	0.020	0.463	-0.294	-0.552	0.346	0.696
Twin Peaks	-0.486	0.182	0.457	0.027	0.428	-0.110	-0.434	0.216	0.633
Visitacion Valley	-0.572	0.111	0.236	0.051	0.595	-0.051	-0.224	0.222	0.604
West of Twin Peaks	-0.453	0.154	0.393	0.040	0.444	-0.018	-0.359	0.156	0.595
Western Addition	-0.514	0.217	0.603	0.010	0.378	-0.282	-0.608	0.315	0.697

Table C3. P-values for explanatory variables. Values less than 0.05 are considered statistically significant.

	Median Household Income (US$)	**Median Home Value (US$)**	**Black & African American (%)**	**Asian (%)**	**White (%)**	**Native American Indian (%)**	**Native Hawaiin & Pacific Islander (%)**	**Other & Two or More Races (%)**	**Total Street Length (US feet)**
	HHincome	*HomeValue*	*P_black*	*P_asian*	*P_white*	*P_natamer*	*P_nathawa*	*P_other*	*streetlength*
OLS									
City of San Francisco	0.06429	0.43158	0.02926	0.87794	0.12132	0.72626	0.02796	0.32609	0.00224
GWR									
Bayview	0.0036	0.4729	0.1768	0.7383	0.0088	0.4540	0.1328	0.1076	0.0002
Bernal Heights	0.0053	0.3525	0.0562	0.8123	0.0172	0.4862	0.0439	0.1394	0.0001
Castro/Upper Market	0.0076	0.2386	0.0070	0.8974	0.0443	0.2871	0.0042	0.1178	0.0001
Chinatown	0.0085	0.2170	0.0013	0.9459	0.0807	0.0711	0.0003	0.0604	0.0000
Crocker Amazon	0.0216	0.5297	0.1649	0.7511	0.0215	0.9295	0.1832	0.3773	0.0006
Diamond Heights	0.0108	0.3190	0.0284	0.8301	0.0309	0.6453	0.0253	0.2239	0.0001
Downtown/Civic Center	0.0070	0.2142	0.0022	0.9370	0.0631	0.1033	0.0007	0.0660	0.0000
Excelsior	0.0078	0.4314	0.1191	0.7756	0.0151	0.7292	0.1132	0.2079	0.0002
Financial District	0.0077	0.2352	0.0020	0.9298	0.0664	0.0781	0.0004	0.0596	0.0001
Glen Park	0.0082	0.3460	0.0469	0.8170	0.0226	0.6241	0.0414	0.1957	0.0002
Golden Gate Park	0.0344	0.2338	0.0021	0.8641	0.1203	0.5356	0.0021	0.3207	0.0001
Haight Ashbury	0.0107	0.2113	0.0032	0.9223	0.0682	0.2551	0.0019	0.1257	0.0001
Inner Richmond	0.0204	0.1860	0.0011	0.9471	0.1273	0.2213	0.0008	0.1492	0.0001
Inner Sunset	0.0198	0.2529	0.0056	0.8634	0.0709	0.5630	0.0048	0.2624	0.0001
Lakeshore	0.0894	0.5733	0.0655	0.6270	0.0562	0.5051	0.0759	0.8867	0.0016
Marina	0.0151	0.1747	0.0004	0.9939	0.1531	0.0603	0.0002	0.0698	0.0000
Mission	0.0049	0.2757	0.0150	0.8691	0.0272	0.2574	0.0080	0.0920	0.0001
Nob Hill	0.0088	0.2030	0.0011	0.9563	0.0878	0.0741	0.0003	0.0626	0.0000
Noe Valley	0.0074	0.2893	0.0204	0.8539	0.0297	0.4538	0.0153	0.1543	0.0001
North Beach	0.0116	0.2110	0.0007	0.9614	0.1142	0.0533	0.0002	0.0615	0.0001
Ocean View	0.0425	0.5143	0.0946	0.7225	0.0361	0.7403	0.1106	0.5665	0.0008
Outer Mission	0.0175	0.4325	0.0851	0.7738	0.0251	0.9694	0.0913	0.3444	0.0003
Outer Richmond	0.0467	0.2196	0.0010	0.8730	0.1664	0.4572	0.0014	0.3339	0.0001
Outer Sunset	0.0535	0.3276	0.0060	0.7500	0.0977	0.9817	0.0066	0.5993	0.0003
Pacific Heights	0.0115	0.1802	0.0007	0.9774	0.1149	0.0828	0.0003	0.0724	0.0000
Parkside	0.0584	0.4124	0.0187	0.6987	0.0702	0.7414	0.0206	0.7097	0.0005
Potrero Hill	0.0040	0.3285	0.0290	0.8345	0.0188	0.2264	0.0136	0.0747	0.0001
Presidio	0.0269	0.1631	0.0003	0.9967	0.2025	0.1002	0.0003	0.1089	0.0000
Presidio Heights	0.0160	0.1750	0.0008	0.9731	0.1289	0.1325	0.0005	0.1022	0.0000
Russian Hill	0.0114	0.1955	0.0006	0.9718	0.1178	0.0576	0.0002	0.0626	0.0000
Seacliff	0.0596	0.2171	0.0007	0.8706	0.2036	0.4251	0.0013	0.3612	0.0001
South of Market	0.0054	0.2587	0.0060	0.8969	0.0384	0.1270	0.0018	0.0637	0.0001
Twin Peaks	0.0123	0.2718	0.0117	0.8599	0.0453	0.5379	0.0096	0.2106	0.0001
Visitacion Valley	0.0079	0.5080	0.2065	0.7459	0.0121	0.7863	0.2013	0.2147	0.0004
West of Twin Peaks	0.0215	0.3578	0.0306	0.7925	0.0402	0.9205	0.0317	0.3728	0.0002
Western Addition	0.0088	0.1963	0.0018	0.9493	0.0767	0.1321	0.0007	0.0815	0.0000