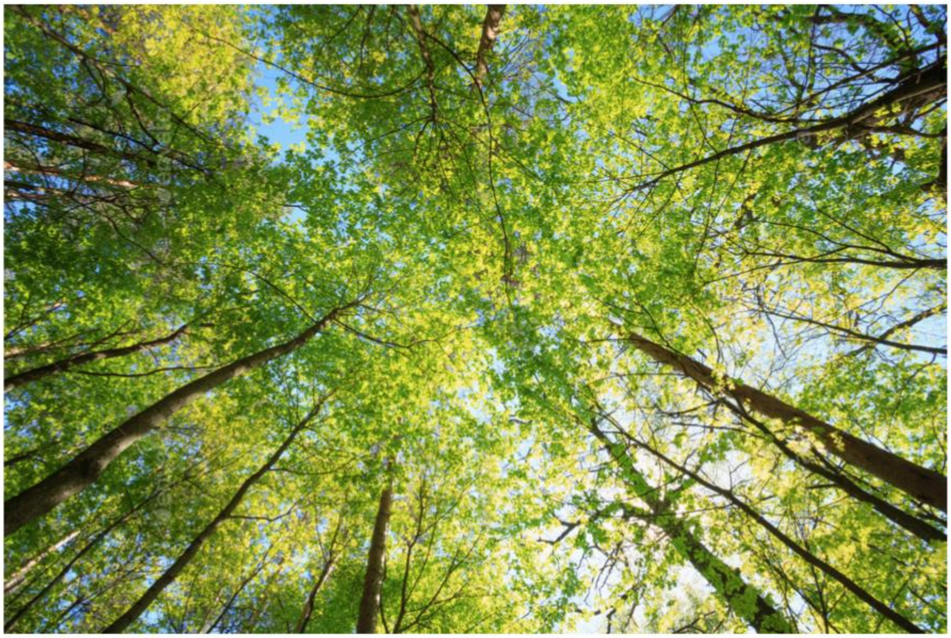

A Two-Part Investigation: Climate Change Mitigation and Adaptation Strategies for Portland's Urban Forests

Recommendations for Portland Parks and Recreation's Department of Urban Forestry

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Executive Summary

This project aims to address the extent to which Portland's urban forest is an effective climate change mitigator, and pinpoint how and where the urban forest could be managed in order to maximize adaptive co-benefits for the city's population. In Chapter 1 we evaluate Portland's current and growing urban growth boundary to determine the land available for canopy expansion, as well as calculate potential solar panel coverage within city limits. We analyze the cost and benefits to find solar is a superior carbon mitigator to trees. In Chapter 2 we conduct an analysis of the social and ecological vulnerabilities of eighty-three Portland parks. This analysis accounts for species richness, mature size diversity, functional diversity, and emphasizes hydraulic diversity's role in buffering the urban forest against drought and uncertain temperature regimes. We translate this analysis into a ranked index for easy comparison between Portland's parks. Finally, we compare this ecological vulnerability index to Portland Bureau of Transportation's Equity Matrix to identify parks that are both socially and ecologically vulnerable. We conclude that there is no correlation between ecological vulnerability and social vulnerability within the parks in our dataset and we make management suggestions to the City of Portland's Parks & Recreation Department based on our findings.

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Introduction

This report assesses the benefits, costs, and equity of Portland's urban forest in order to suggest management practices that prioritize climate change adaptation and mitigation. We aim to answer Urban Forestry's question, "Are we [Portland Urban Forestry] thinking about this problem correctly?" by conducting a comprehensive data analysis of the current and potential canopy and its role in climate change mitigation and adaptation. We hope to provide adaptable frameworks useful to the Department of Urban Forestry that can be updated as new information arises. This report is split into two chapters; Chapter 1 focuses on climate change mitigation, and Chapter 2 concentrates on climate change adaptation.

Climate change mitigation and adaptation are two types of responses that improve the chances of survival for humanity and many of Earth's organisms in the face of climate change. Mitigation entails reducing greenhouse gas emissions to decelerate the rate of warming at the source. Mitigation actions include reducing industrial emissions, switching to renewable energy, and removing carbon dioxide from the atmosphere. Adaptation entails changing infrastructural systems to accommodate for current and future climatic damage. Climate change adaptation includes a wide array of actions, such as switching to crops that are able to withstand higher temperatures, protecting our coasts from sea level rise, and increasing ecosystem resilience.

The urban forest can serve as an opportunity for climate change mitigation, as trees reduce the rate of climate change by sequestering carbon from the atmosphere. In addition, the co-benefits of the urban forest include urban heat island cooling, energy savings from shading, improved air and water quality, stormwater reduction, and psychological well-being, all of which would increase with more canopy cover (Ramsey and DiSalvo, 2018). However, there are certain costs and space limitations associated with the urban forest that restrict the total amount of canopy. We provide the Department of Urban Forestry with an alternative infrastructural carbon mitigation strategy, rooftop solar panels, to consider in comparison with canopy expansion.

Planning for climate change adaptation requires assessment the resilience of Portland's urban forest in its current state. Canopy cover, although essential, is not enough to understand how the urban forest will respond to climate change. In order to offer actionable suggestions to Urban Forestry, we evaluate the current vulnerability/resilience of Portland's city parks. The least ecologically diverse parks are predicted to be the most vulnerable to the consequences of climate change. Therefore, we quantify this vulnerability through development of an ecological vulnerability index and analyze it alongside an existing social vulnerability index to identify parks most in need of urban forest management. In all, we quantified the vulnerability of eighty-three parks, particularly highlighting the factors that drive vulnerability/resilience in each. This index is the first of its kind and can be applied to other parts of the urban forest to guide management decisions.

Chapter 1: Climate Change Mitigation

Introduction

Mitigating climate change is a crucial goal accomplished, in part, by the planting of trees in urban centers. The extent of the urban forest is determined by the costs associated with its establishment and the surface area available for tree planting. We therefore chose to focus the first part of our analysis on updating the potential canopy cover estimates based on a comprehensive suite of variables. While trees can sequester carbon, increasing canopy cover comes with a trade-off of reducing area available for other strategies for climate change mitigation – e.g., solar panels. Considering area available for solar panel installation alongside estimates of potential canopy area will allow for a greater opportunity to balance the trade-offs associated with canopy cover expansion to maximize climate change mitigation. The second part of our analysis assesses the costs and benefits of increasing both tree canopy and solar panel cover in Portland. We constructed a series of calculations that consider the maximum amount of canopy cover available, and the maximum amount of photovoltaic (PV) solar panel cover possible, accounting for long-term development projections regarding housing and commercial needs. We also calculated the financial cost of a tree and a solar panel per year, as well as the carbon savings and outputs of a tree and of a solar panel per kWh per year.

Key Findings

- Our analysis reveals that solar serves as a superior mitigator of carbon compared to trees, based on cost. We estimate that solar panels cost, on average, \$0.63/Kg CO_2 mitigated compared to \$3.16/Kg CO_2 for trees.
- This suggests that discussions regarding expansion of the urban canopy should include the important trade-offs with area for solar energy infrastructure.
- Justifications for expansion of the urban canopy should be based on the many other ecosystem goods and services trees provide in addition to carbon mitigation.
- Our estimates of potential canopy area and potential solar area may be useful to other urban planning discussions in Portland.

Methods

We wrote formulas to calculate the area of land available for canopy and solar panel coverage, as well as the financial and carbon costs of tree and solar panel installation. The variables account for several factors affecting Portland's changing urban growth boundary. All of the variables are listed beneath each equation, and each variable's value in addition to the justification behind why each variable was selected can be found in Appendix 1A.

Total Portland Canopy Cover

We used geospatial mapping tools within ArcGIS to compute the potential canopy cover and PV solar panel cover for the city of Portland.

Equation 1. The total area of potential canopy coverage in Portland

$$(NPB - (BF_F+BF_C+S+T+W+P+G+BGC+BRC-D_{BT}-D_{GT}) = A_c$$

[Total Land Available - Impervious Surfaces - Current Canopy = Potential]

NPB= new Portland boundary

BF_C = current building footprint

BF_F = building footprint future

S = area of land of streets

P= area of PDX primary zone

W = area of waterways

T = area of land of already planted trees

G = area of land of golf courses

D_{BT} = double-counted building trees

D_{GT} = double-counted golf trees

BGC = area around current ground solar panels not suitable for potential tree canopy cover

BRC = area around current roof solar panels and future potential solar roofs not suitable for potential tree canopy cover

A_c = total area of potential canopy coverage

We found the total potential canopy cover to be 41.70-41.76% of Portland's total current and future expansion area, substantially lower than the 52.4% potential that *Tree Canopy and Potential in Portland, Oregon* reported for just the current area.

Total Potential Solar Cover

We then modified Equation 1 to include the housing and building area of Portland to calculate the percentage of available solar panel land, using the same variables as above plus additional variables defined below.

Equation 2. The total area of potential solar panel coverage in Portland

$$NPB - (S+T+W+P-BTG-BTR+BGC+BRC-D_{BT}-D_{GT}) = A_S$$

[Total Land Available - Impervious Surfaces - Current Canopy + Non-shaded Rooftops - Current Solar Cover = Potential]

BTG = area around current trees not suitable for potential ground solar cover

BTR = area around current trees not suitable for potential roof solar cover

A_S= total area of potential solar panel coverage in Portland

Overall, we found the potential solar cover to be 42.79-46.70% of Portland's total future expansion area.

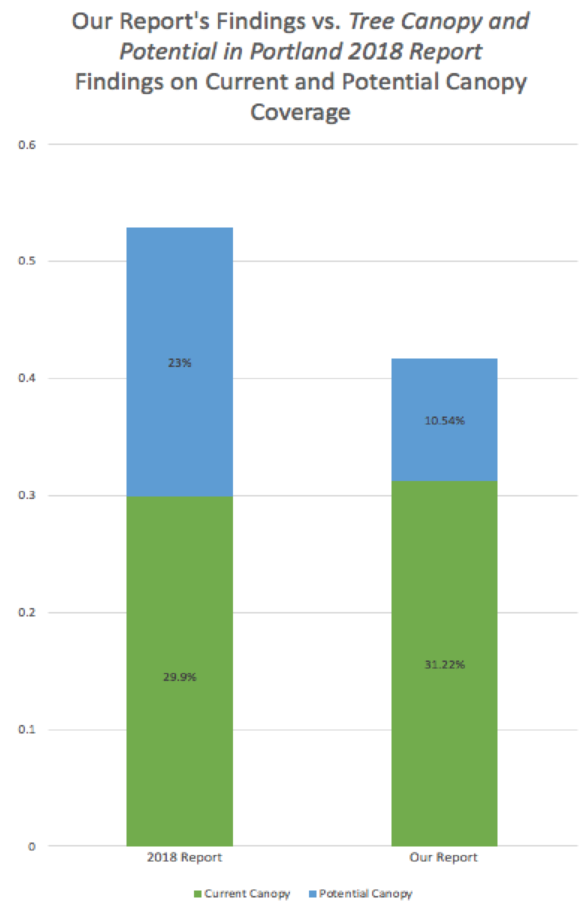

Figure 1. Our potential canopy findings (right) juxtaposed to those in "Tree Canopy and Potential in Portland, Oregon" (left).

Tree Carbon Costs and Benefits

Equation 3. Tree Carbon Costs/Benefits

$$C_{TT} + C_{ST} - C_{MT} = B_T$$

C_{TT} = average carbon sequestered in a Portland tree C_{ST} = shading benefits of trees

C_{MT} = carbon to maintain an urban tree over its lifetime B_T = overall benefits of urban trees

Per year, we calculated that an average Portland tree mitigates 10.7 kg of carbon.

Tree Financial Costs

Equation 4. Tree Financial Costs

$$F_{IT} + F_{MT} = F_T$$

F_{IT} = initial financial cost of tree acquisition and planting F_{MT} = cost of tree maintenance
F_T = total financial cost of urban street tree in Portland.

Table 1. Medium, High, and Low estimates for the financial and carbon costs of trees

MEDIUM	HIGH	LOW
financial tree: $1117.11/tree	financial tree: $1326.80/tree	financial tree: $907.42/tree
carbon tree: 354.0 kg CO_2/tree	carbon tree: 278.9 kg CO_2/tree	carbon tree: 429.1 kg CO_2/tree

Solar Carbon Costs and Benefits

Equation 5. Solar Panel Benefits

$$C_{TP} + C_{SP} - C_{MP} = B_P$$

C_{TP} = average carbon savings from solar in Portland C_{SP} = solar shading benefits
C_{MP} = carbon emissions for a solar panel over its lifetime B_P = overall benefits of solar panels

Solar Panel Financial Costs

Equation 6. Solar Panel Costs

$$F_{IP} + F_{MP} = F_P$$

F_{IP} = initial financial cost of solar panel + installation
F_{MP} = financial cost of solar panel maintenance over solar panel lifespan of 30 years
F_P = total financial cost of solar panel in Portland

Table 2. Medium, High, and Low estimates for the financial and carbon costs of solar panels.

MEDIUM	HIGH	LOW
financial solar: $6,286/kWh system	financial solar: $7,108/kWh system	financial solar: $5,256.9/kWh system
carbon solar: 9,915.7 kg CO2/kWh system	carbon solar: 15,521.9 kg CO2/kWh system	carbon solar: 4,309.4 kg CO2/kWh system

Summarized Results

Table 3. Carbon benefits and financial costs of trees and solar panels in dollars per kilogram of CO_2 mitigated. The high ratio is defined as the most carbon mitigated for the lowest price. The low ratio is defined as defined as the least carbon mitigated for the highest price.

	Solar fiscal to carbon ratio.	Tree fiscal to carbon ratio.
Medium	$0.63/kg CO_2	$3.16/kg CO_2
High	$1.65/kg CO_2	$4.76/kg CO_2
Low	$0.34/kg CO_2	$2.11/kg CO_2

Discussion

The calculations for each section were run using high, low, and medium values for each variable, pulled from the literature. Solar panels proved more cost effective per kilogram of carbon dioxide saved, compared to tree canopy expansion. Street trees can serve as pragmatic mitigators of climate change in Portland, however, considering other climate change mitigation strategies can be more financially sound. The calculations we used can serve as a flexible framework for future cost benefit analyses, as the variable values can be updated as more refined data becomes available. In selecting each variable, we had to operate under various assumptions that could be improved with data more specific to Portland.

Bottom Line

- Potential additional canopy cover of Portland including the urban growth boundaries is 10.49-10.54%.
- Potential solar panel of Portland including the urban growth boundaries is 42.8-46.7%.
- After a cost/benefit analysis, we find that solar is a superior carbon mitigator to trees in terms of $/kg CO_2.
- The framework we built can be updated with more precise variables to better estimate potential canopy coverage, potential solar coverage, and the costs and benefits of trees and solar panels in the future.

Chapter 2: Climate Change Adaptation

Introduction

Climate change's effects across the city of Portland are far from uniform, and different communities will experience its impacts in varying ways. As inhabitants of a city experiencing a sustained period of growth, Portland residents continue to grow more vulnerable to the environmental impacts of increasing climate variability. While wealthier communities have the resources and time to mitigate and adapt to these effects, lower socioeconomic and minority communities remain the most vulnerable. The access to environmental spaces has become an indicator of these social vulnerabilities, but if one takes a closer look, simply having access to environmental spaces does not solve the issue. In order to ensure that these environmental spaces will benefit all residents of Portland in the future, steps need to be taken to ensure that the urban forest is resilient to climate change and this resilience is equitably distributed across the city.

The National Climate Assessment (2014) predicts what the Pacific Northwest climate will look like in the coming century. Although models referenced by the report disagree on a number of points, one common theme is that an increase in global temperature will drive a decrease in average precipitation during summer months. This will cause a number of problems, such as low streamflow from the Cascades, leading to a reduction in the amount of available water, an increased risk of wildfire, and a higher likelihood of drought (National Climate Assessment, 2014). All of these factors significantly threaten the forested land west of the Cascades. The report also outlines the ways in which climate change will affect the trees of the Northwest, which will become less healthy and at greater risk of mortality as temperature increases and summertime water availability is reduced.

In 2015, Portland developed a Climate Action Plan that outlined strategies for restructuring the community around climate change in an equitable way. Urban forests keep city air clean and minimize pollution while also providing habitats, healthy soils, and controlled temperatures. Action 13A of the Climate Action Plan calls for "tree preservation and maintenance programs and incentives" within the city of Portland, focusing on communities with lower canopy cover and higher vulnerability to hazards like flooding, landslides, and heat waves — all conditions which a robust urban canopy moderates, while 13B advises local officials to "address tree age, species diversity and tree distribution" (Climate Action Plan, 2015, 103). All these actions take under consideration the inequalities associated with modern urban parks. The Action Plan notes that “Low income populations and communities of color in the Portland area are exposed to disproportionately higher levels of air pollution than predominantly White communities and moderate and higher income areas” (Climate Action Plan, 2015, 102).

This project provides an analysis of the ecological and social vulnerability of Portland's urban parks. Our ecological vulnerability index is based on functional diversity, mature tree size, hydraulic diversity, and species richness, and it aims to predict park tree resilience and adaptability to climate change, as well as other stressors. The ecological vulnerability index is then compared to social vulnerability traits in Portland. This two-part research design helps us to account for ecological and social vulnerabilities and create a dual research mandate. This allows us to make clear and actionable recommendations to Urban Forestry regarding the allocation of resources and spending that will have the greatest ecological and social impact.

Key Findings

- Our analysis reveals which parks have the highest combination of ecological and social vulnerability, traits that may be used to prioritize urban forest management in these parks.
- In general, ecological vulnerability is evenly distributed across the city suggesting that, unlike canopy cover, there is little inequity in this attribute of Portland’s urban parks.
- The Ecological Vulnerability Index (EVI) developed here may be used to assess vulnerability/resilience in other parts of the urban forest using additional data sources—e.g., street tree inventory data.

Methods

Our research allows for the interdisciplinary identification of at-risk parks in Portland based on indices of social and ecological vulnerability. In order to estimate the social vulnerability of the communities surrounding each of our 83 focus parks, we juxtaposed our park locations over the Portland Bureau of Transportation’s (PBOT) 2016 equity matrix. This is a simplified matrix that focuses on three factors, race, income, and limited english proficiency, as summarized by 5 year estimates of the US Census and the American Community Survey (Portland Bureau of Transportation, 2016). We decided to use this existing matrix instead of creating our own measure of social vulnerability or using another available database due to the

PBOT matrix's institutional support within the city of Portland. This matrix is based on national best practice, and on the guidance of Portland's Office of Equity and Human Rights. PBOT has been including equity considerations in their work for many years, but their website notes the difficulty of standardizing and comparing results based on different measurements of equity. In this research it is our goal to provide analysis that can be integrated into larger equity goals and frameworks that exist in the city (Portland Parks and Recreation 2018).

We compare PBOT's social equity scores to a combined index of ecological vulnerability traits. This index includes species richness, diversity in mature tree size, functional diversity, and hydraulic diversity. Below we outline the methods used to score and rank each park based on our four variables of interest.

Mature Size Diversity

As with functional diversity, the literature does not suggest an ideal distribution of mature tree size for climate change adaptation or even resiliency. In this case we will again rely on the assumption that a greater distribution of traits in urban parks will allow for the greatest climate change resiliency. Each park's tree size score is based on how close that park falls to an equal distribution: that is, one third small form trees, one third medium form trees, and one third large form trees.

Functional Diversity

The Portland Park Trees data set categorizes each individual tree based on broad traits, with a total of four categories. Trees are categorized as either conifer or broadleaf, and evergreen or deciduous. This creates a total of four categories; coniferous evergreen (CE), coniferous deciduous (CD), broadleaf evergreen (BE), and broadleaf deciduous (BD). Coniferous evergreen and deciduous broadleaf are most common and make up the majority of trees in Portland parks. The literature is inconclusive when it comes to the ideal distribution of each of these four functional categories, however it is clear that when preparing for the uncertain effects of climate change diversity is key. For this reason we ranked parks based on how close they come to an equal 25% split between these categories. This was done because we felt that given the lack of consensus in the literature it would be inappropriate for us to make a value judgment, beyond the more diverse the better approach. As our goal was to create a broad and inclusive index of important ecological traits we felt it was most important to diversify our areas of focus and make use of the information already available from the Park Tree Inventory.

Species Richness

Species diversity has been calculated using a common measure of species richness. This was done by finding the total number of species represented in a park and weighting that score by the number of trees in that park. This means that if two parks have the same number of species, the park with less trees will receive a higher species richness score than a park with more trees but the same number of species.

Hydraulic Diversity

Hydraulic diversity is defined in Anderegg et al. 2018 as "standard deviation in Hydraulic Safety Margin" across all the trees in a given area. Hydraulic Safety Margin refers to the proximity of a given tree to critical levels of drought-induced water transport failure that often lead to limb failure or even death. Different species of trees are variably adapted to assorted drought conditions and as such demonstrate a wide array of different capacities for dealing with drought. Because of this diversity of evolved strategies, a stand of trees with higher hydraulic diversity will be better adapted to dealing with stressful conditions.. Calculations of hydraulic diversity were completed using a combination of Portland Park Tree Inventory data and Liu et al. 2019's database of taxa-specific hydraulic functional trait values. For each park site with sufficient data, 83 in total, the community-weighted mean and standard deviation in tree-level Hydraulic Safety Margin were calculated, and each park was given a score from 1-4 based on its hydraulic diversity relative to other parks.

Each of our ecological vulnerability variables is scored from 1 to 4. Each of these values represents a quartile. A score of 1 denotes that the park in questions ranks among the lowest 25% of Portland parks, while a 4 is the highest 25%. Each park score for each category has been summed to create the final index score, which ranges from 4 to 16. A score of 4 implies that the park in question falls within the lowest quartile for every ecological vulnerability trait, and is in desperate need of attention. A score of 16 implies that the park with that score ranks in the highest quartile for each trait, and is therefore more likely to be resilient to climate change stressors.

Results

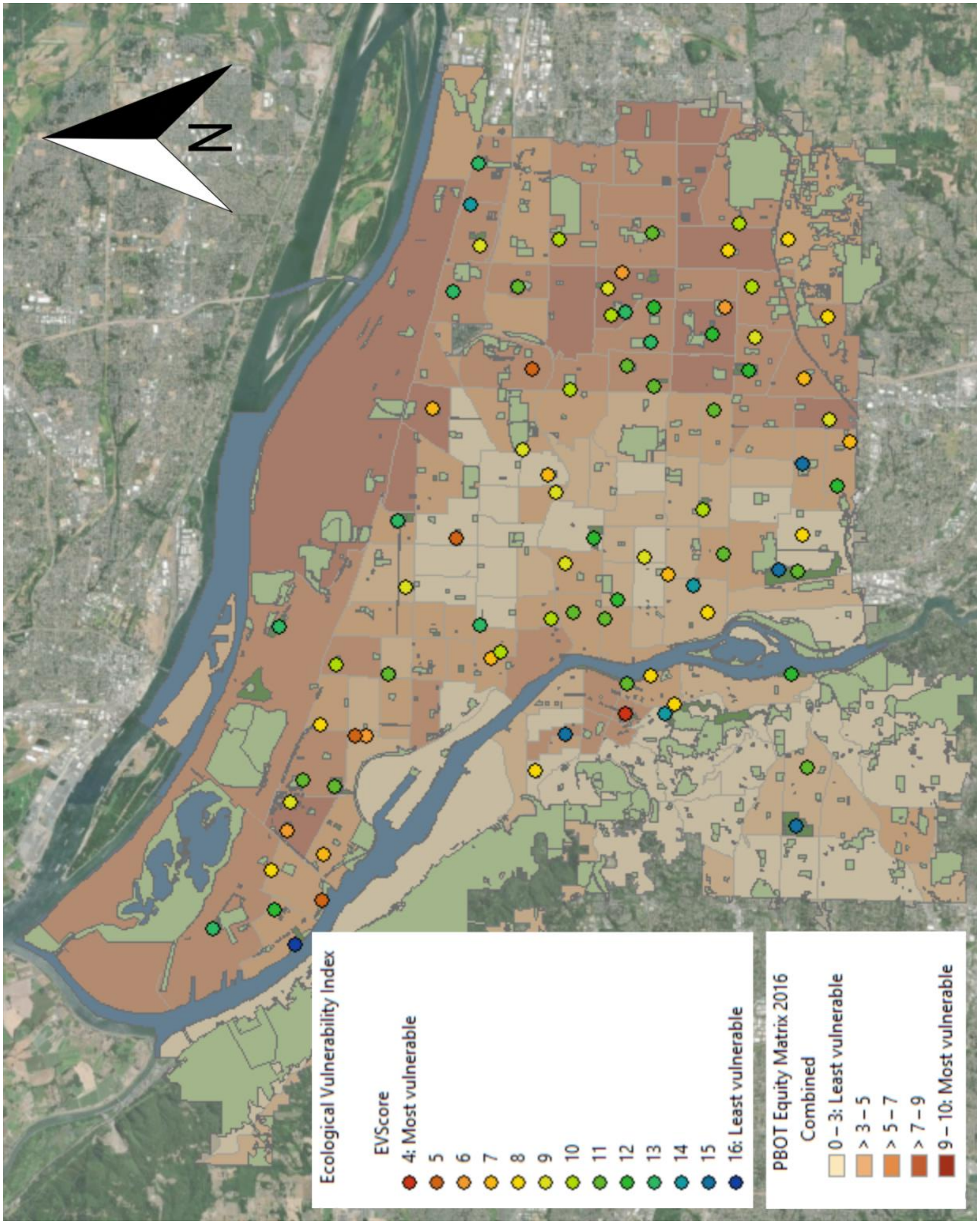

Figure 2. Our Ecological Vulnerability Index overlayed with the PBOT Equity Matrix.

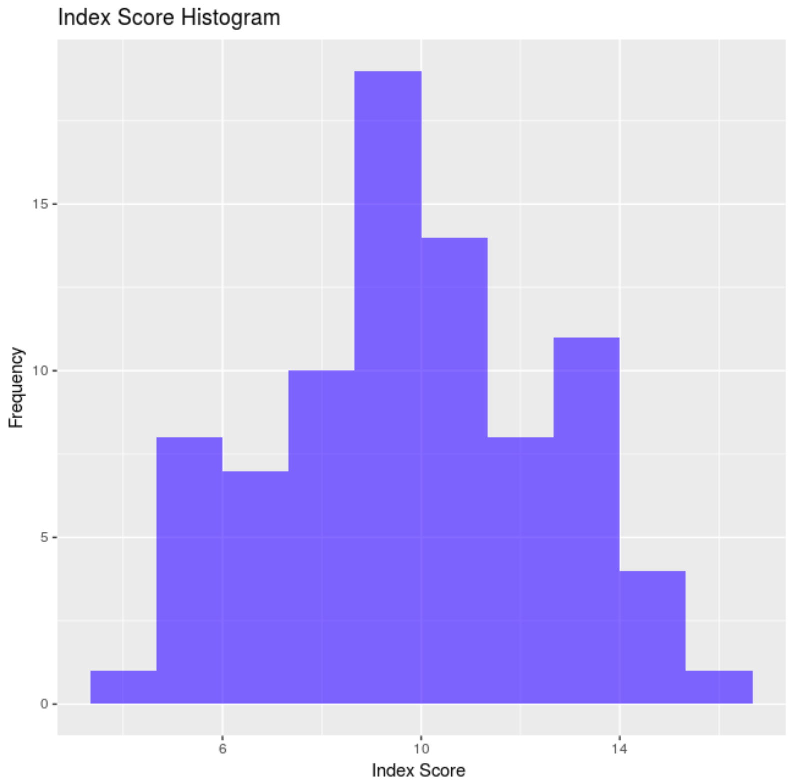

Figure 3. Histogram of Ecological Vulnerability Index Score frequency.

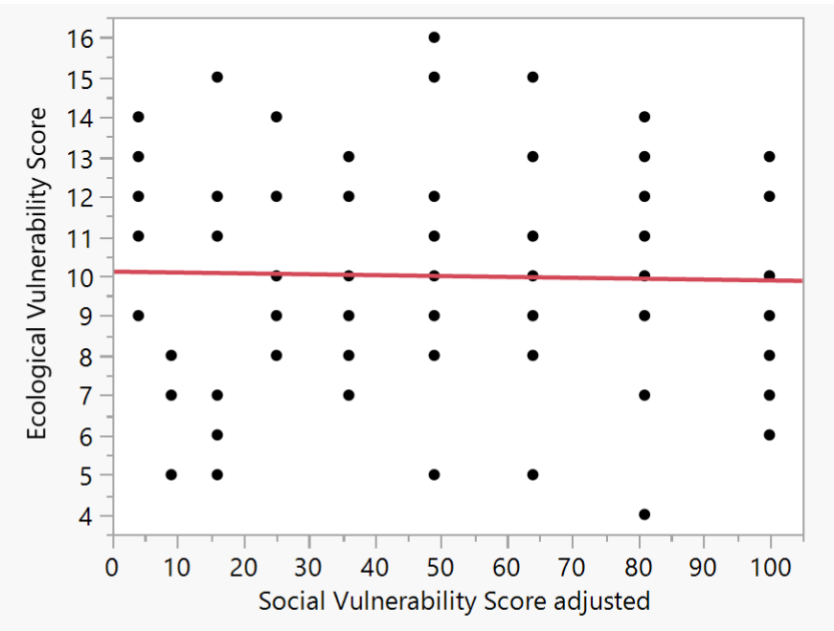

Figure 4. Linear regression of Ecological Vulnerability Score vs. Social Vulnerability score (adjusted for left skew). R^2 *was calculated at 0.000564, demonstrating little to no relationship between the two variables.*

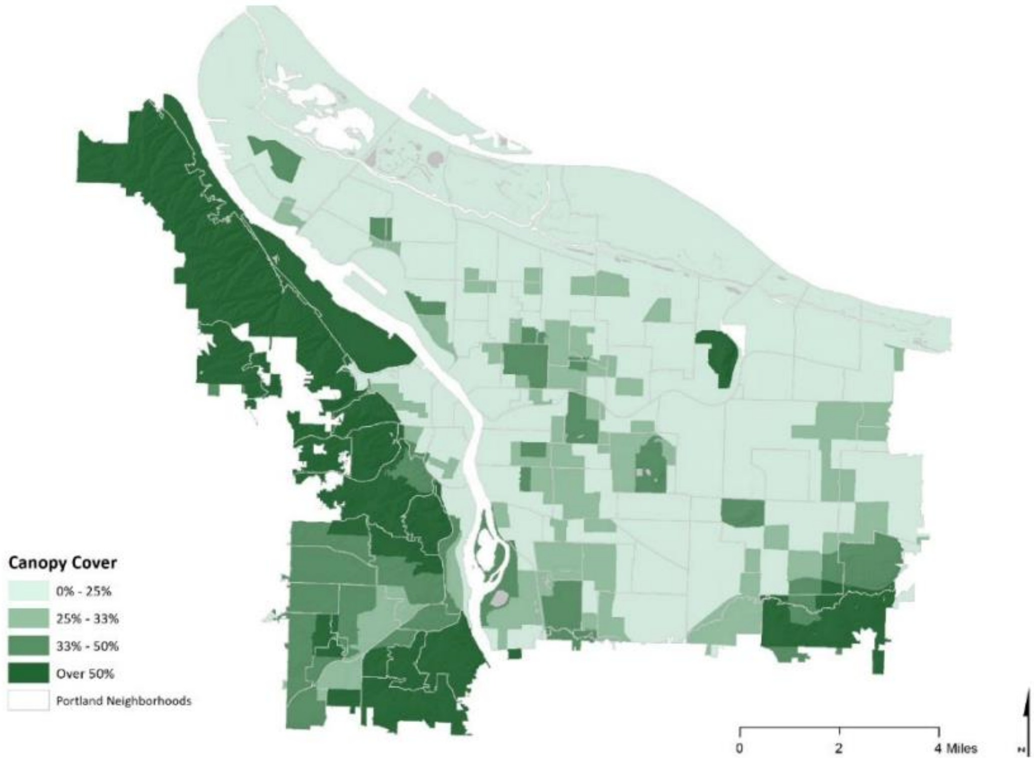

Figure 5. Percent canopy cover distributed throughout Portland as reported in Portland's Citywide Tree-Planting Strategy 2018. While climate-resilient parks as predicted by our index are distributed evenly throughout the city, overall canopy cover is still very inequitable.

Table 4. Five parks with lowest overall vulnerability.

Park	Ecological Vulnerability Score (4 - 16 Most to Least vulnerable)	Social Vulnerability Score (0 - 10 Least to Most vulnerable)
Gabriel Park	15	4
Cathedral Park	16	7
Crystal Springs Rhododendron Garden	15	7
Brentwood City Park	15	7
Couch Park	15	8

Table 5. Five parks with highest overall vulnerability.

Park	Ecological Vulnerability Score (1 - 16 Most to Least vulnerable)	Social Vulnerability Score (0 - 10 Least to Most vulnerable)
South Park Blocks	4	9
Hancock Park	5	8
N. Crawford St. N. Polk Ave. Property	5	7
Gammans City Park	5	4
Wilshire Park	5	3

Discussion

Both projects are informed by research on climate change its effects on urban and forested environments. The research done on mitigation relies on data gathered by the City of Portland and elsewhere to ground calculations of the cost effectiveness of investing in trees versus investing in solar energy and predictions on how these two forms of climate change mitigation will change in Portland in the coming years. We put estimates, government reports, and policy in conversation to provide a realistic view of the state of Portland trees and solar panels and their futures as the City continues to grow, and we use straightforward calculations to determine if tree planting or solar panel installation is more effective. We also provide insights on where existing literature could be improved in order to make future calculations and projections more accurate. The research on adaptation is inspired by research done on equity and urban parks throughout the United States. These studies suggest that economic and social disparities between communities are often mirrored in access to healthy parks. Our research adds to existing literature by offering a concrete evaluation of Portland park health and equity, comparing the two to determine which parks in the city need the most attention.

Both research groups have developed useful tools that can be implemented by Portland Parks and Recreation and by others. The scoring system developed by the adaptation group offers a clear ranking of parks in terms of their need for resources. The mitigation group provides an analysis of the effectiveness of tree planting versus solar through flexible calculations. The variables for these calculations are clearly explained, and their sources are given so that anyone who is interested can do the calculations themselves or use the variables or calculations for other potential purposes. Our research is useful to city planners as well as to organizations offering funding for park development and to citizens of Portland interested in changing their city for the better.

The guiding questions for our research come from Jeff Ramsay and the Urban Forestry division of the Portland Parks and Recreation Department. Our projects have attempted to adequately answer these questions, provide the scholarly background from which we have based our research, and suggest areas in which further research can be carried out. Our team of researchers is interdisciplinary, and our projects reflect our diversity of specialities. By using our individual expertise, we provide research which unites a variety of fields in the goal of preparing the city of Portland for its climatological future.

The Bottom Line

Although addressing the quantitative relationship between social vulnerability score and ecological vulnerability score was not the core focus of our analysis, we were pleased to see that there was not a clear spatial correlation between these variables across the city. This means that Portland Parks and Recreation has a strong foundation from which to build equitable and ecologically conscious monitoring and investment plans to maximize the adaptability of Portland's parks to an uncertain climate future. Our use of hydraulic diversity as an indicator puts this index on the forefront of climate impact resilience analysis. There are still areas of concern related to the equitable distribution of green space in Portland. Analysis by Portland Parks and Recreation shows that the distribution of trees and tree canopy cover on private property is significantly higher in Portland's west side. Our research can serve as a tool to aid in future policy making decisions by providing a simplified system for ranking parks. There is a lot of nuance and social context that we were not able to capture in our analysis, which is both something to be aware of, and something to consider if future work of this type is done.

Summary of Key Findings and Policy Recommendations

Our analysis updated potential additional canopy cover of Portland from the previously reported 23% to a much lower estimate, 10.49-10.54%, and established a potential PV solar panel cover of 42.8-46.7%, taking into account the future size of Portland. A cost/benefit analysis showed that solar energy is a superior carbon mitigator to trees in terms of $/kg CO_2.

Parks were given individual scores based on indices of ecological and social vulnerability, and parks with poor scores in both categories were identified for further action. No overall correlation was found between the spatial distribution of ecological and social vulnerability in Portland's parks, but overall city-wide canopy cover is still very unevenly distributed.

When considering about how best to prepare Portland for the influence of climate change in the present and future, solar energy as well as other types of climate mitigation strategies should be taken into account in addition to canopy coverage. While other types of climate mitigation techniques may not be in the purview of the Portland Parks & Recreation Urban Forestry, our findings suggest collaborative approaches with other departments may help decide how best to balance increasing canopy cover with other climate mitigation technologies.

However, when weighing the benefits of various strategies for climate mitigation that Portland could adopt in the future, the adaptive value of the urban forest's co-benefits for disadvantaged populations should not be discounted. Our park tree adaptation analysis offers a framework from which the Portland Urban Forestry Department can locate and manage specific parks demonstrating higher ecological and social vulnerability than others in order to decrease vulnerability to climate change within the city, especially in socially disadvantaged areas. The visual nature of our GIS analysis makes it applicable for communication to the public, ranging in accessibility from volunteers to school groups to neighborhood associations.

Our approaches to both mitigation and adaptation provide new frameworks and analytical tools that Portland Parks and Recreation can use in the future when considering how best to manage an urban forest affected by the trials of climate change. These frameworks can be updated with new and increasingly accurate data as it becomes available, and provide insight into the kinds of variables that should be considered when surveying urban tree health and resiliency, such as site-level hydraulic diversity, and the future parameters that should be considered when building tree canopy cover goals, such as solar potential and population growth.

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Appendices

Mitigation A: Discussion of Variables and Limitations

Mitigation variable value and discussion of variables for each equation

Calculating total area of potential canopy and solar covers in Portland

Currently, Portland reports the percentage of Portland land available for potential canopy cover as 52.4% (Ramsey and DiSalvo, 2018). We hypothesize this would increase with the projected increase in Portland's Urban Growth Boundary to include more land and decrease when we subtract land alloted for redevelopment and housing. Below is a description of every variable used in equations 1 and 2 and the sources of their data.

We calculated potential canopy cover with Equation 1 with the variables defined below. Data for variables without a source are compiled from Metro Regional Government's RLIS, Portland Park and Recreation Street Tree Inventory, and iTree data. We also used ArcGIS to estimate each of the areas needed from those data sets.

Table 6. Variables for Equation 1, the total area of potential canopy coverage in Portland.

Data	Time Period	Source
Canopy	2014	Metro RLIS
Waterbodies	2016	Metro RLIS
Building Footprints	2019	Portland Maps-Open Data
Buildable Lands Index	2019	Portland Maps-Open Data
Streets	2019	Metro RLIS
PDX Primary Zone	2014	Port of Portland
Golf Courses (ORCA)	2019	Metro RLIS
Park and Street Trees	2019	Portland Maps-Open Data
Solar Data		

Table 7. Summarized variables included in equations 1 and 2.

Potential	No Potential
Pervious Surfaces	Area Under Tree Canopy Cover
Parking Lots	Buildings
Sidewalks	Water
	Streets
	PDX Primary Zone
	Future Building Footprint
	Ground Solar Buffer Area
	Building Solar Buffer Area

NPB= new portland boundary

389.76 km^2

To predict which areas will be annexed into Portland from the UGB and possible UGB extensions, the Buildable Lands Inventory and Growth Allocation GIS model (Oregon Metro 2018) was layered on top of a current map of Portland. The future building footprints falling within Portland's UGB were assumed to be on land that would be annexed, and were given a 13.7 meter buffer region in order that the Polygon surrounding them would make a cohesive block. These new extensions were then connected to the city using the Union geoprocessing tool.

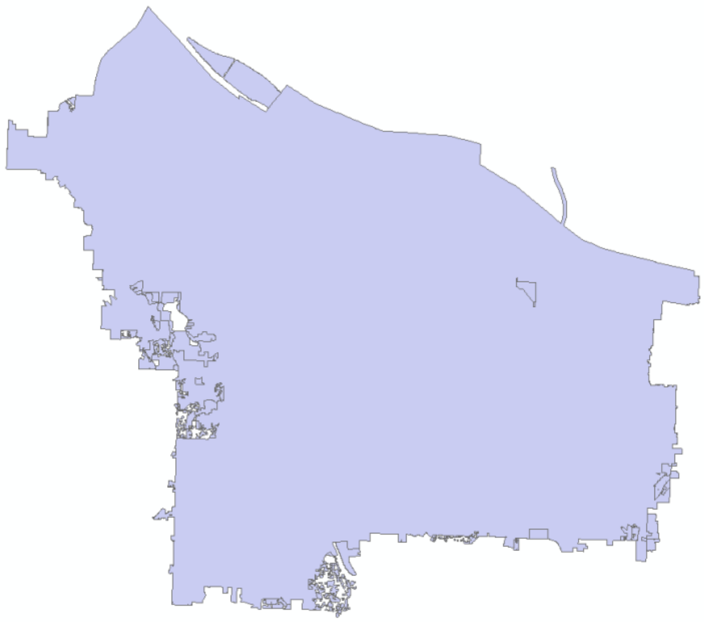

Figure 6. Picture of New Portland Boundary.

BF_C = building footprint future

148.87 km^2

Area of the footprint of buildings predicted to be built or redeveloped by 2036, as shown in Portland's Buildable Lands Inventory and Growth Allocation GIS model (Oregon Metro 2018). Boundary set to fit Portland Urban Growth Boundary expansions. The total area of the attribute BLDGFT_SQFT was then taken.

BF_F = building footprint current

5.89 km^2

Area of land of current houses, residencies, and all other buildings which intersect the NPB, shown on the 'Buildings' GIS file on PortlandMaps-Open Data. The total area was added by adding the Shape_Area attribute.

S = area of land of streets

19.09 km^2

This variable was found by taking the length of all streets on the ‘streets’ PortlandMaps-Open Data file laying inside the NPB, and multiplying by the average width of streets in ‘Street Plan’ file. This roundabout method was used because Portland’s streets are only coded as a line, so the streets planned to be built in Gateway, Central City South Waterfront, and Hayden Island polygons were used and averaged. This estimate is then likely low considering the larger streets in the city center and highways, but that effect is mitigated since canopy often hangs over streets.

P= area of PDX primary zone

0.33 km^2

This is an area outside of the PDX airport that must be without tree canopy, data from PDX Primary Zone shapefile on PortlandMaps-Open Data.

W = area of waterways

33.25 km^2

To find this variable ‘the streams (POLY)’ file from RLIS was intersected with the NPB boundary.

T = area of land of already planted trees

121.68 km^2

The 2014 canopy file was downloaded from RLIS, and set to only show where its data intersected with the NPB. The area was found by taking a count of all the pixels that were found in the dataset to have canopy cover and multiplying by the area of one pixel.

S_{R+G} = ground and rooftop solar arrays

High Estimate = 2.23 km^2

Average Estimate = 0.85 km^2

Low Estimate = 0.12 km^2

The area of land with already installed ground and rooftop solar panels (Derek Miller solar data given directly to our group), with requisite buffer area (see **BTR** for buffer distance calculation). In short, the minimum area of non-rooftop land necessary for solar panels to not be shaded by canopy cover was calculated.

G = area of land of golf courses

25.87 km^2

This variable was found by using 2019 Outdoor Recreation and Conservation Sites (ORCA) RLIS shapefile, and selecting all features labeled as a golf course. The area was then found.

D_{BT} = double-counted building trees

0.88 km^2

Because some of the areas that have canopy cover were also counted as areas where there will be future building development, this overlap was needed to be subtracted out of the equation. Portland's existing canopy cover was intersected on ten randomly selected areas of the BF_F map, and the percentage of building footprint intersected by canopy cover was found. These percentages were averaged and then multiplied by the total BF_F.

D_{GT} = double-counted golf trees

6.29 km^2

Because golf courses are areas that don't have the potential for more canopy cover, but do have an existing canopy, this canopy must be subtracted out of the equation. That way, all golf courses can be summarily subtracted without counting their trees twice. A sample of over two-thirds of golf courses falling within the BF_F was taken to find what percentage of the courses were covered with tree canopy. This percentage was then multiplied by the total area of golf courses.

BGC = area around current ground solar panels not suitable for potential tree canopy cover

0.0077952 km^2 / 0.0591453 km^2 / 0.17118014 km^2

Same buffer zone calculation method as BTR discussed below. In GIS, the area was found by selecting all solar panels not intersecting with buildings, and applying the small, medium, and high estimate buffer zones. The area of the buffer zones was then taken and multiplied by half, to account for the panel's ability to get full light even if the space behind it is shaded.

BRC = area around current roof solar panels not suitable for potential tree canopy cover

0 km² / 0.00051157 km² / 0.03538258 km²

Same buffer zone calculation method as BTG discussed below. In GIS, the buffer was applied by intersecting all solar panels with Portland buildings to see which were placed on rooftops. The buffer distance was added, and all area of buffer that intersected the rooftop was subtracted from the area not suitable for canopy cover. This number was then divided in half because a buffer is only necessary on the South side of the solar panel as that is the most face.

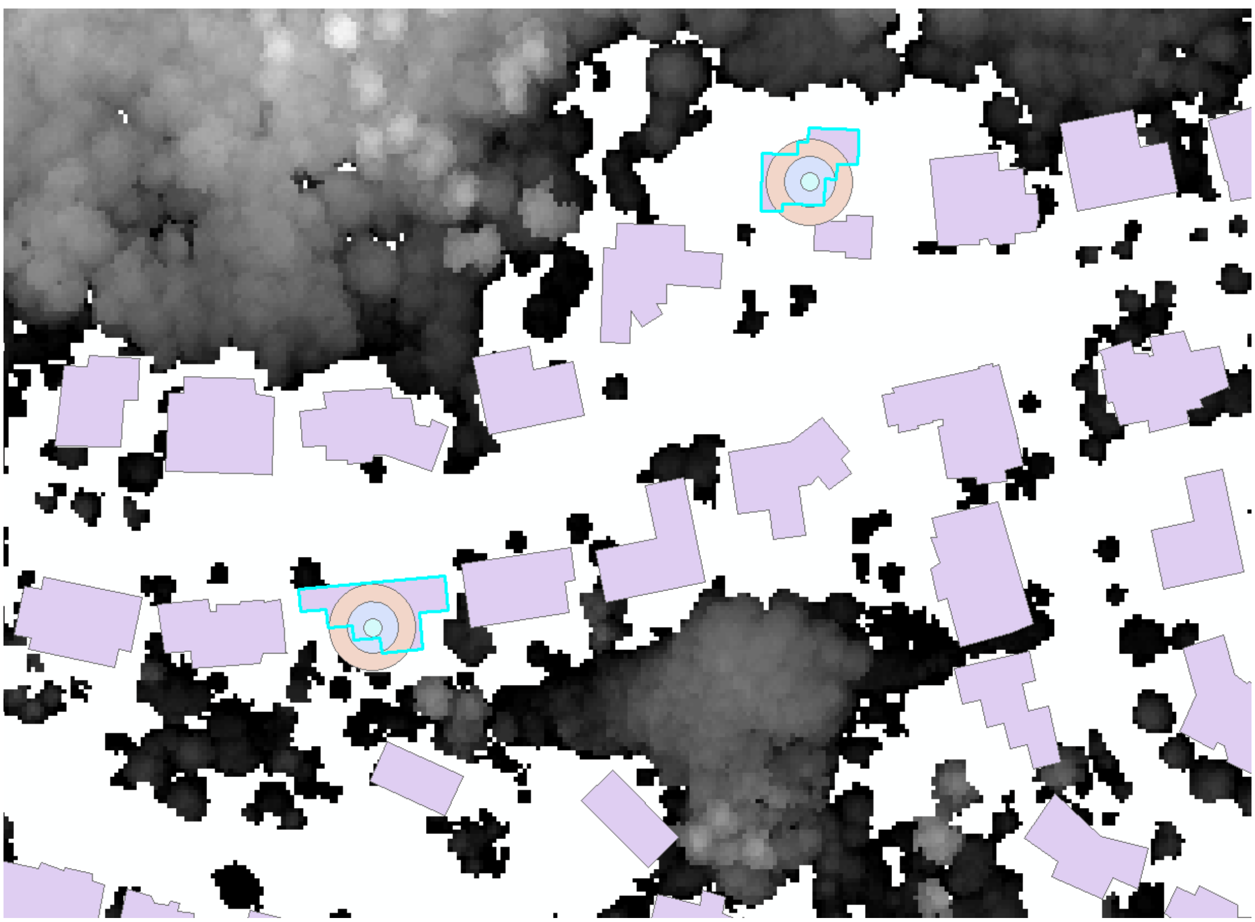

Figure 7. Photo of GIS showing buildings with solar panels' buffer areas.

BRS = area around current trees not suitable for potential roof solar cover

0 km²/ 7.2330634 km² / 12.085639 km²

Each polygon of roof solar panels was given a 2.3 m (medium estimate), and 4.9 m (high estimate) buffer zone, the areas of which are not counted as potential solar cover because a tree's canopy up to that point would shade the panel. The low estimate is 0 m buffer zone, meaning that trees would not impact solar panels on roofs. Each current solar panel, and roof that could potentially have solar in the future, was given a buffer area so that the shade from canopy area would not overlap potential places for solar installation, rendering those panels useless. These same buffers were put around roofs already containing solar panels, and were marked as areas with no potential canopy cover. The buffer zone (s) plus the crown radius of the tree (r) equals the whole shading area, which is the distance away from a solar panel that a tree should be planted.

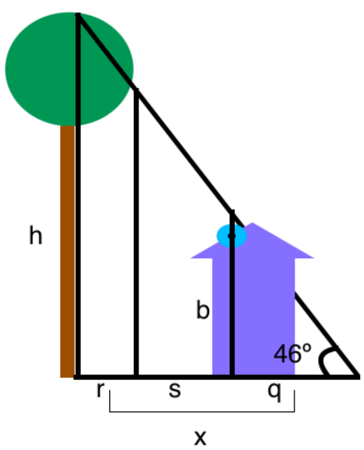

Figure 8. Calculating buffer zone around roof solar not suitable for trees and around trees not suitable for roof solar.

The buffer zone was calculated using an average height (h) of all inventoried Portland street trees as 19.16m as calculated from the Portland Parks Tree Inventory. The (n-1) standard deviation of that value is 11.43m, so the high (30.59m) and low (8.14m) ranges were calculated using the high and low standard deviation from the average. We wanted to calculate the shading of such a tree (s in the Figure 6). We assumed the angle of the average angle of the sun to be 46º in Portland (Rhodes et al. 2014; Marsh 2018), which is the angle solar panels are optimally placed in Portland and roughly equivalent to Portland's latitude. We used the tangent function to calculate tan(46º)=19.16 meters/ x, where x equals $r+s_1+q$, where r is the crown radius of the tree, s_1 is the buffer zone, and q is the shading area of the tree that would be blocked by the building and need not be counted as shading area (see Figure 6). The variable x was calculated by tan(46º) = h/x, which using the three estimates of building height, worked out to 7.86m for a low estimate, 18.50 meters for a medium estimate, and 29.54 meters for a high estimate. Because the edge of a tree's crown and not the tree's trunk can be found in GIS, we subtracted the crown radius from the shading zone to arrive at the buffer zone. The crown radius was calculated using the average of the average of the North-South crown radius for all Portland street trees inventoried and the average of the East-West crown radius for all Portland street trees inventoried. The standard deviation (n-1) for each average was the same, 5.8m, and so the low estimate for crown radius used was 5.12 m, the medium estimate was 10.91 m, and the high estimate was 16.70m. The q variable was calculated from tan(46º) = b/q, where b is average building height in Portland from GIS data. The average of the middle ⅓ of building heights was found to be 5.48m, the average of the smallest ⅓ of buildings were found to be 3.68 meters, and the average of the tallest ⅓ of buildings were found to be 8.22m. Cut-off heights, used to separate buildings into three groups, were found by adding the standard deviation of all building heights multiplied by 0.16 to the mean of all building heights, and then subtracting the standard deviation of all building heights multiplied by 0.16 from the mean. This gave the 33rd and 66th percentile of building heights, which were used to split the dataset into tertiles. Finally, the buffer zone, s_1, was calculated by subtracting q and the low, average, and high r estimates from the low, average, and high x estimates, respectively. So, buffer zone was found to be non-existent at the low estimate, 2.3 meters in the medium estimate, and 4.9 meters on the high estimate.

Furthermore, to find how much rooftop area in Portland exists within s (where shade from canopy cover would disqualify the use of solar panels), a sample of forty randomly selected buildings from throughout the city were chosen in GIS, and given randomly placed solar panels. These panels were then given the medium and high estimate buffer zone, and the amount of potential canopy cover overlapped with the buffer zone was calculated. The percentage of overlap taken from this sample was then used to find how much overlap existed per square foot of potential roof solar. This factor was then multiplied by the roof area of all Portland buildings to see how much roof area was unfit for solar panels because of canopy shading.

BTG = area around current trees not suitable for potential ground solar cover (same value for each)

N/A / 6.5087564 km^2 / 12.085639 km^2

Each Polygon of ground solar panels (s_2) was given a 2.74m (low estimate), 7.59m (medium estimate), and 12.85m (high estimate) buffer zone, the area of which is not counted as potential canopy cover because a tree's canopy up to that point would shade the panel. Each current tree was given the same buffers because the buffer area around them is not suitable for potential ground solar cover due to the tree's shade. The buffer zone plus the crown radius of the tree equals the whole shading area, which is the distance away from a ground solar panel that a tree should be planted. Because the edge of a tree's crown and not the tree's trunk can be found in GIS, we subtracted the crown radius from the shading zone to arrive at the buffer zone, s_2. The s_2 variable was found by calculating $\tan(46^o) = h/(r+ s_2)$, using the same h and r variables as in the previous h and r variable explanations.

To apply the buffer in GIS, the percentage of rooftop area too shaded for solar panels was found. Next, the ratio between s_1 and s_2 was taken, which revealed how much more likely ground area is to be shaded by the same height tree as rooftop area. The percentage of ground area shade per square foot was then found and multiplied by the square feet of ground area available for solar panels (A_C).

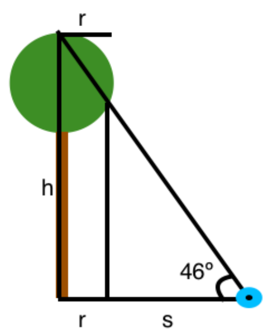

Figure 9. Calculating buffer zone around ground solar not suitable for trees and around trees not suitable for ground solar.

A$_S$= total area of potential solar panel coverage in Portland

40,236.16 acres of Solar Potential

41.78% of City Land

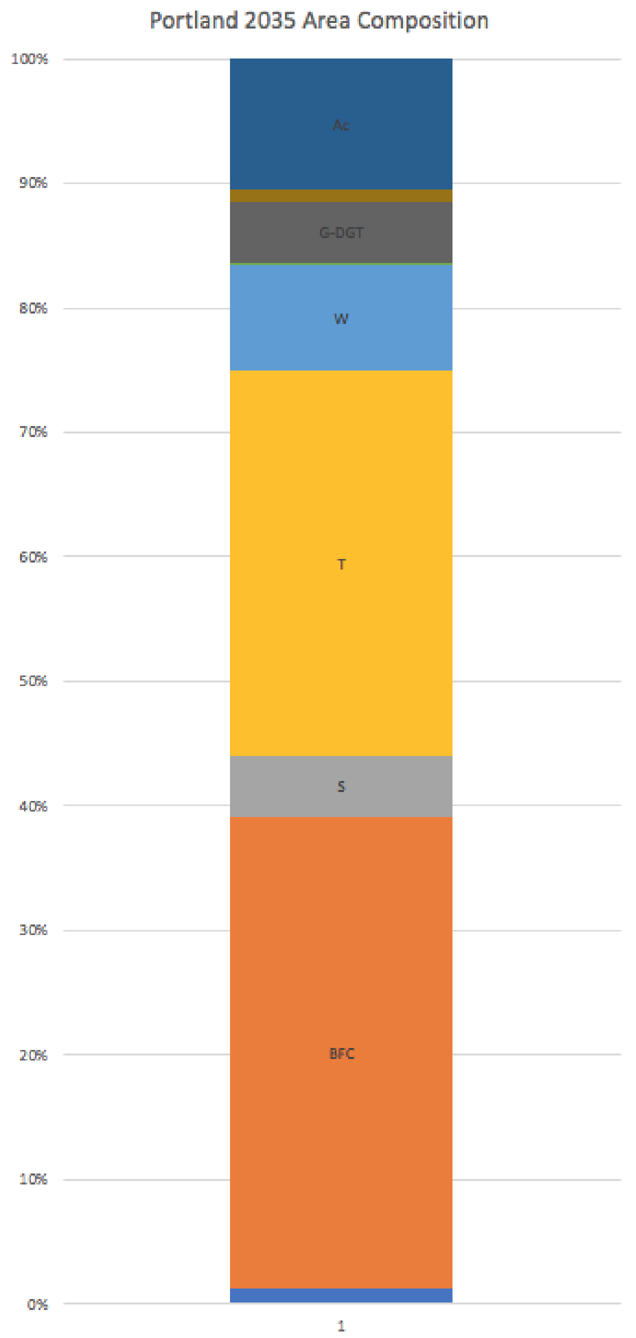

Figure 10. Percentage of Portland's Future land area by variable.

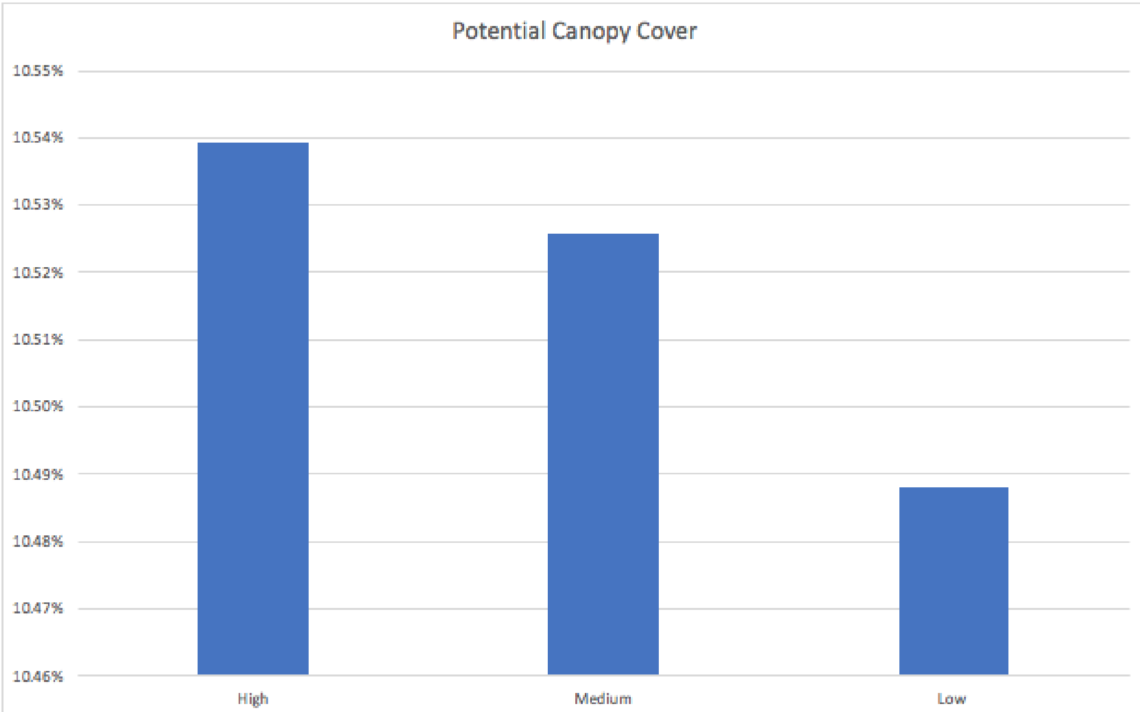

Figure 11. Three predictions of Potential Canopy Cover available in the year 2035, as deduced from our low, medium, and high buffer estimates for solar panels.

Variables for Equation 3: Tree carbon benefits

C_{TT} = average carbon sequestered in a Portland tree

Medium: 369.6 kg CO_2/tree

High: 448 kg CO_2/tree

Low: 291.2 kg CO_2/tree

Per year, 11.2 kg CO_2 is sequestered by an average Portland tree. The Portland Urban Forestry department used i-Tree Eco software to determine the carbon sequestration values of all park trees in Portland. This value is the average of all park trees in Portland that were in the Parks Tree Inventory dataset compiled by the Portland Urban Forestry department. There was a high degree of variation in the values with a standard deviation of 10.1 kg CO_2/year/tree. Additionally, there were no carbon sequestration values for street trees in Portland and the continuation of this project would benefit from i-Tree Eco analysis of these trees as well. To obtain our final values, we multiplied the 11.2 kg CO_2/tree/year by the medium, high, and low estimated tree lifespans, 33 years, 40 years, and 26 years, respectively.

C_{ST} = shading benefits of trees

Medium: 49.731 kg CO2 saved/tree

High: 60.28 kg CO2 saved/tree

Low: 39 kg CO2 saved/tree

Per year, 1.507 kg CO_2 is mitigated due to the shading of buildings by a single average tree. The shading benefits of trees are defined as the carbon savings of an average size household from less air conditioning due to the shading of trees. Avoided overall electricity usage due to tree shading was calculated by the Western Washington and Oregon Community Tree Guide using average energy mixes and emissions data from the Western Washington and Oregon regions. I modified their value for tree energy savings to match current energy mixes of Multnomah County (44% coal, 24% natural gas) and different carbon emissions associated with each type of energy (1.460 lbs CO_2/kWh for coal, 0.116 lbs CO_2/kWh for natural gas) (McPherson et al. 2002, Deisner 2009). The values for tree energy savings were based on simulations of the shading effects of three different tree size classes at three different distances from buildings taking into account leaf densities and cardinal direction (McPherson et al., 2002). Park trees were excluded because they were assumed to not have any shading benefits on building energy use. The energy savings for each tree size class (3.1 kWh/year/small tree, 4.65 kWh/year/medium tree, 6.25/year/large tree) were used to calculate the weighted average energy savings per tree using Portland specific street and park tree size proportions (McPherson et al., 2002, Park Tree Inventory, Street Tree Inventory). To obtain our final values, we multiplied the 1.507 kg CO_2/tree/year by the medium, high, and low estimated tree lifespans, 33 years, 40 years, and 26 years, respectively.

C_{MT} = carbon used to maintain an urban tree over its lifetime

Medium: 65.34 kg CO_2/tree

High: 79.2 kg CO_2/tree

Low: 51.48 kg CO_2/tree

Per year, 1.98 kg CO_2 is emitted in the maintenance of an average tree. This value is the carbon emitted due to the maintenance of trees in Orlando, FL (Horn et al. 2015). To obtain estimates, Horn et al. distributed surveys to determine the most common tree maintenance activities in Orlando. Vegetation maintenance practices, specific maintenance equipment, and landscape characteristics were determined for residential parcels and were separated into tree, lawn, garden, and shrub maintenance categories. Determining the maintenance equipment type, frequency of use, and carbon (C) emissions of the equipment, allowed them to calculate the C emissions associated with the maintenance of one standard tree. These emissions calculations are specific to residential trees in Orlando, FL and likely differ with Portland's different tree compositions and maintenance routines. However, much of the canopy in Portland is maintained by residents so these numbers may be comparable to these residential tree maintenance estimates. To obtain our final values, we multiplied the 1.98 kg CO_2/tree/year by the medium, high, and low estimated tree lifespans, 33 years, 40 years, and 26 years, respectively.

B_T = overall benefits of urban trees

Medium: 354.0 kg CO_2/tree

High: 429.1 kg CO_2/tree

Low: 278.9 kg CO_2/tree

Per year, we calculated that an average Portland tree mitigates 10.7 kg of carbon. The lifespan of a street tree is between 26 and 40 years (Roman and Scatena, 2011). This was the range we used to calculate the total amount of carbon sequestered, carbon emitted from maintenance, and avoided emissions from electricity savings for a tree. However, this is a conservative estimate for all trees in Portland; park trees are likely to have longer lifespans because their environmental conditions mimic their natural conditions more closely (McPherson & Kendall, 2014). To obtain our final values, we multiplied the 10.7 kg CO_2/tree/year by the medium, high, and low estimated tree lifespans, 33 years, 40 years, and 26 years, respectively.

Variables for Equation 4: Tree financial costs

F_{IT} = initial financial cost of tree acquisition and planting

Medium: $600/tree

High: $700/tree

Low: $500/tree

The initial financial cost of tree acquisition and planting per tree in Portland as reported by Jeff Ramsey in a personal correspondence is $500-$700.

F_{MT} = financial cost of tree maintenance

Medium: $517.11/tree

High: $626.8/tree

Low: $407.42/tree

Per year, we calculated that an average Portland tree costs $15.67 to maintain. This value, the average maintenance cost of public and private trees, was calculated from costs reported by the Western Washington and Oregon Community Tree Guide (2002). Maintenance includes pruning, irrigation, and removal and disposal. The values were reported for small, medium, and large tree classes (small: 28 ft tall and 25ft spread, medium: 38 ft tall and 31 ft spread, large: 46 ft tall and 41 ft spread) (McPherson et al. 2002). The 2019 Portland specific costs were calculated by accounting for inflation using the U.S. inflation calculator and by weighting the averages by Portland's small, medium, and large tree class compositions as reported by the Parks Tree Inventory and the Street Tree Inventory from PortlandMaps - OpenData. To obtain our final values, we multiplied the $15.67/tree/year by the medium, high, and low tree life spans, 33 years, 40 years, and 26 years, respectively.

F_{T} = total financial cost of urban street tree in Portland

Medium: $1117.11/tree

High: $1326.80/tree

Low: $907.42/tree

Final tree fiscal to carbon ratio calculation

MEDIUM

financial tree: $\$1117.11/tree$

carbon tree: $354.0\ kg\ CO_2/tree$

$$\left(\frac{\$1117.11}{tree}\right)\times\left(\frac{tree}{354.0\ kg\ CO_2}\right)=\left(\frac{\$1117.11}{354.0\ kg\ CO_2}\right)$$
$$=\frac{\boldsymbol{\$3.16}}{\boldsymbol{kg\ CO_2}}$$

Medium Cost: $\$3.16/kg\ CO_2$

HIGH *defined as the least carbon mitigated for the highest price*

financial tree: $\$1326.80/tree$

carbon tree: $278.9\ kg\ CO_2/tree$

$$\left(\frac{\$1326.80}{tree}\right)\times\left(\frac{tree}{278.9\ kg\ CO_2}\right)=\left(\frac{\$1326.80}{278.9\ kg\ CO_2}\right)$$
$$=\frac{\boldsymbol{\$4.76}}{\boldsymbol{kg\ CO_2}}$$

High Cost: $\$4.76/kg\ CO_2$

LOW *defined as the most carbon mitigated for the lowest price*

financial tree: $\$907.42/tree$

carbon tree: $429.1\ kg\ CO_2/tree$

$$\left(\frac{\$907.42}{tree}\right)\times\left(\frac{tree}{429.1\ kg\ CO_2}\right)=\left(\frac{\$907.42}{429.1\ kg\ CO_2}\right)=\frac{\boldsymbol{\$2.11}}{\boldsymbol{kg\ CO_2}}$$

Low Cost: $\$2.11/kg\ CO_2$

Variables for Equation 5: Solar panel benefits

C_{TP} = average carbon savings (carbon not emitted) from solar (per 1 kWh) in Portland

Medium: 9,590.11 kg CO2/kWh system

High: 15,012.29 kg CO2/kWh system

Low: 4,167.94 kg CO2/kWh system

The U.S. Energy Information Administration reports that the average carbon dioxide emissions from electricity is 1,009 lbs CO_2/MWh or 1.009 lbs CO_2/kWh in its United States Electricity Profile 2017. We use this value for the high end of the range. To make the data more usable and universal, we converted this new value to the metric system where (1.009 lbs of CO_2/kWh)*(0.4536 kg/lb) = 0.4577 kg CO_2/kWh. When electricity does not come from fossils fuels and instead comes from renewable sources, 0.4577 kg CO_2/kWh is not emitted, and thus is mitigated. Portland's own electricity profile inevitably varies from the national average, therefore we multiplied the potential carbon mitigated by the percent of Portland's electricity that comes from non-renewable sources. Natural gas and coal account for 68% of Portland's energy mix (*Sustainability at Work*), resulting in the potential amount of 0.3112 kg CO_2/kWh not emitted through the use of PV solar energy. This value may not be a completely accurate reflection of Portland's true energy mix, as Portland is supplied by two main energy companies, Portland General Electric and Pacific Power, and each have different energy mixes and sources. For example, Portland General Electric (PGE) in their break down of their energy mix claim that 33% of their energy is "purchased power," but they do not break down this category further into renewable or non-renewable sources (*Portland General Electric*). Additionally, in Pacific Power's break down of their energy mix, they have a vague "other" category that also can create confusion in finding the exact amount of Portland's energy that stems from fossil fuels. In summary, while Portland General Electric and Pacific Power report some of their percentages of electricity generated from fossil fuels, there is a possibility that these values should be higher, as the vagueness of the 'purchased power' and 'other' categories could potentially contain fossil fuel-derived electricity.

The same type of data from the Oregon Electricity Profile 2017 reports 0.280 lbs/kWh which converts to 0.1270 kg CO_2/kWh. We use this value for our low boundary. Natural gas and coal account for 68% of Portland's energy mix (*Sustainability at Work*), resulting in the potential amount of 0.0864 kg CO_2/kWh not emitted through the use of PV solar energy using the low boundary. The average of the high and low boundaries calculates to 0.1988 kg CO_2/kWh. These medium, high, and low values where then multiplied by the potential amount of energy that could be harvested from the sun in Portland, OR using the Weather Underground solar calculator (Weather Underground). In this calculator, The system size was a ~1 kWh system, with a randomly chosen panel type (Kyocera KD205GX-LP panel with 15% efficiency) and an address in SE Portland. With these specifications, approximately 1,608 kWh/year of energy can be harvested from the sun. To obtain the lifetime carbon mitigated, we multiplied this second value by 30 years (Jordan and Kurtz, 2012). There may be some limitations to these calculations as not every spot in Portland may get the same amount of sunlight hours (thus, the 1,608 kWh/year of energy value could fluctuate) and also as the age of the solar panel system increases, it is possible that the solar capture efficiency could decrease, also affecting these values.

C_{SP} = shading benefits of solar panels

Medium: 325.6 kg CO2/kWh system

High: 509.7 kg CO2/kWh system

Low: 141.5 kg CO2/kWh system

This variable is defined as the carbon savings of an average size household from less energy usage due to the shading of solar panels. Because this calculation has to be in units of CO2/kWh, we use the same value as the amount of carbon mitigated (not emitted) by using solar to calculate the approximate annual carbon savings that shade from solar panels can provide. Using a base temp of 70 degrees (F) for cooling degree days, there are on average 109 cooling degree day units per year in Portland, OR (*Western Regional Climate Center*). Using the value from Dominguez (2011) of 0.501 kWh of less energy used per day per one degree increase in temperature we get: (109 cooling degree day units)*(0.501 kWh saved)= 54.6 kWh per year in Portland, OR. 54.6 kWh per year was multiplied by the medium, high, and low values of carbon mitigated: 0.3112 kg CO_2/kWh, 0.0864 kg CO_2/kWh, and 0.1988 kg CO_2/kWh, respectively. These new values were then multiplied by the approximate lifespan of a solar panel, 30 years, to obtain the carbon savings from shade for a lifetime of a solar panel (Medium: 325.6 kg CO2/kWh system; High: 509.7 kg CO2/kWh system; Low: 141.5 kg CO2/kWh system). The 0.501 kWh saved value was from a study conducted in San Diego. Because of the variations in temperature and weather between San Diego and Portland, this value might not accurately reflect what the true shade savings that a house in Portland might experience. Additionally, while it was not found to be as significant as cooling savings, the study also found that solar panels have the potential to provide heat savings during heating degree days by insulting roofs and trapping heat between the panel and the roof. Further analysis should be conducted to pinpoint the accurate cooling and heating savings PV solar can have on buildings in Portland.

C_{MP} = carbon emissions for a solar panel over its lifetime

Medium: 0.0345 kg CO2-eq/kWh system

High: 0.045 kg CO2-eq/kWh system

Low: 0.018 CO2-eq/kWh system

Values for this variable were borrowed from Fthenakis (2008), wherein they conducted an analysis of lifetime greenhouse gas emissions (GHG) for four types of photovoltaic solar technologies--multicrystalline silicon, monocrystalline silicon, ribbon silicon, and thin-film cadmium telluride. The values for these four types of solar were obtained from the Case 3 scenario (U.S. grid mixture and Franklin database). The four values were averaged together and then converted to kg to match other variables--resulting in a value of 0.0345 kg CO2-eq./kWh. This is reported in kg CO2-equivalents instead of just kg CO2. This could slightly affect our final carbon calculations in that this carbon cost and maintenance value increase the amount of CO2 it reports because it includes other greenhouse gases in it. Future analysis for Portland should use updated data that reports in just CO2, not CO2-eq, and it should further analyze the types of photovoltaic technology most utilized in Portland in order to report the most correct lifetime GHG emissions correlated with the right technologies. Thus, the carbon cost of solar panels in Portland, OR can be recorded with the new values. The high value was calculated to be 0.045 kg CO2-eq/kWh based off of the monocrystalline silicon emissions values, and the low value was 0.018 CO2-eq/kWh based off of the thin-film cadmium telluride emissions values.

B_P = overall benefits of urban solar panels

Medium: 9,915.7 kgC/kWh system

High: 15,521.9 kgC/kWh system

Low: 4,309.4 kgC/kWh system

Variables for Equation 6: Solar panel costs

F_{IP} = initial financial cost of solar panel and installation

Medium: $4,673/kWh system

High: $5,008/kWh system

Low: $3,807/kWh system

Lowest cost/kWh in PDX: $300/kWh system

Highest cost/kWh PDX: $8192/kWh system

Using data from Derek Miller that was given directly to our group, we took the average financial cost of a PV system in Portland. We only included data that was labelled ‘photovoltaic’ or ‘photovoltaics.’ We subtracted the tax rebate from the initial cost to obtain what peoples’ end payment was. This value (cost-rebate in $) was plotted against the system size/capacity in kWh. We excluded about 30 data points reported as kWh generated instead of kWh system capacity, as well excluded unknowns. The slope of the best fit line of kWh system versus cost showed relatively linear trend ($R^2 = 0.6358$). The average system size was 2.975 kWh, and the (n-1) standard deviation from that average was +/-1.31 kWh. Inserting the average system size (then the high end average+standard deviation and low end average-standard deviation) for the kWh system in the equation for this line (y=5769.9x-3264.4) and then dividing by the system size inserted in the equation (average, low, high) to find the cost per kWh gave us the average financial cost of PV solar, $4673/kWh. We did not use the average of the cost/kWh directly because of the large standard deviation in the cost/kWh (2109) when calculated directly from the average cost and average kWh system, so instead use the best fit line to better account for this deviation. Some potential issues with this analysis is that this fiscal calculation does not take into account any grants individuals may have obtained. Also, the nature of the data is such that we are unsure if monetary inflation was taken into account for the inputs from the early 2000s, or if that is something that needs to be done in future versions of this project to take into consideration changing values of money.

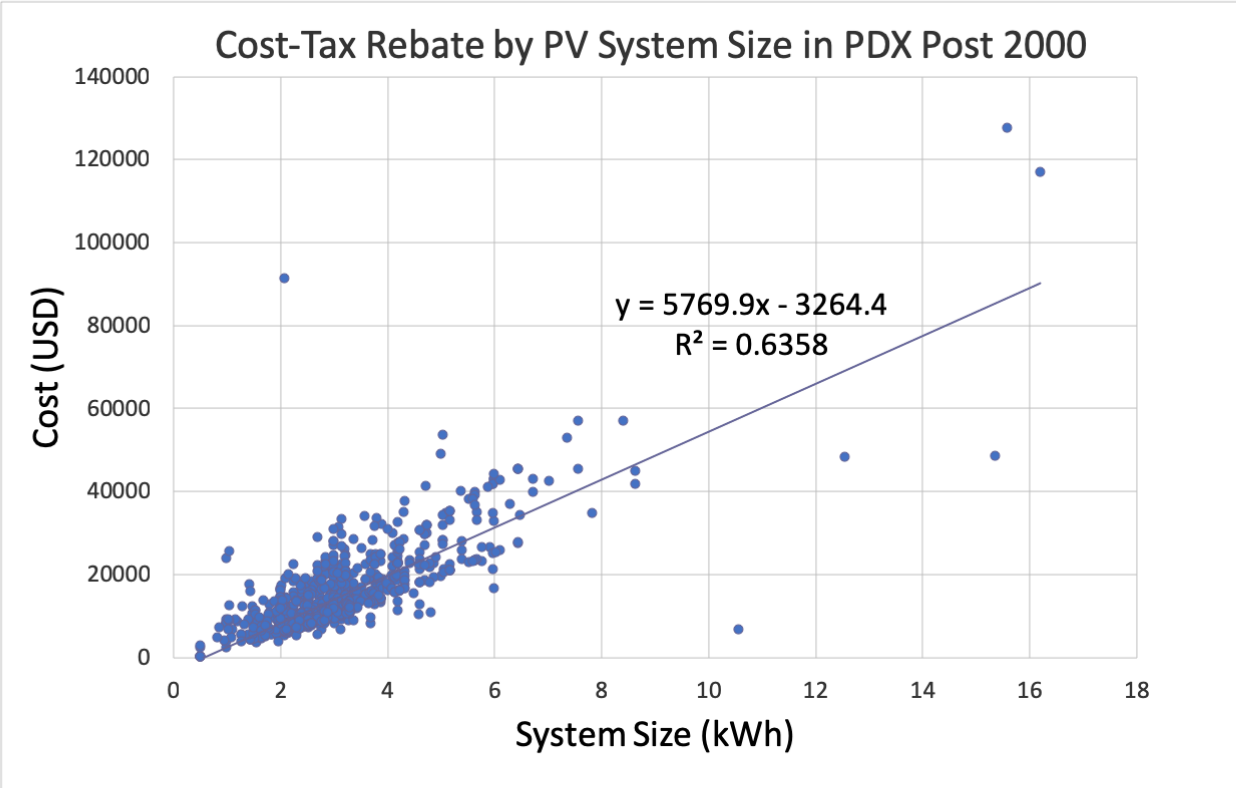

Figure 12. Solar Panel System Size in kWh versus the cost of each solar system in Portland since 2000 minus the tax rebate received for that solar system, with best fit line and its equation shown.

F_{MP} = financial cost of solar panel maintenance over solar panel lifespan of 30 years

Medium: $1613/kWh system

High: $2100/kWh system

Low: $1450/kWh system

We borrow previously calculated averages of maintenance fees from Power From Sunlight to include into our design (*What Are The Operational Costs…)*. They report that for a five kWh photovoltaic system, one can expect an annual maintenance fee to cost $200 and a cleaning fee to cost $125-$150 every one to three years. We calculated an average fiscal maintenance amount from this to be $53.75/kWh/year. Also calculated were the high and low values to create a range; low = $48.33/kWh/year and high = $70/kWh/year. The low value of this range could be even lower if a solar panel owner executed their own maintenance and cleaning, eliminating the need to call in outside companies to carry out these actions. These values were multiplied by an estimated solar panel lifespan of 30 years to obtain the lifetime financial maintenance cost of solar panels. We used a lifespan of 30 years because PV cells have been found to degrade linearly up until 30 years and exponentially after 30 years (Jordan and Kurtz, 2012). Most warranties for solar panels last 25-30 years. The degradation rates in Oregon have been estimated to be 0.6%-1.5% per year (Vignola et al., 2009), which would yield 82% to 45% efficiency after 30 years, a decrease that we estimate most solar panel owners would want to replace their panels if they experienced. Solar panel degradation is related to the quality, and thus sometimes the price, of the solar panel, so high-end priced solar panels may be less likely to degrade as quickly.

F_P = total financial cost of solar panel in Portland

Average: $6,286/kWh system

High: $7,108/kWh system

Low: $5,257/kWh system

Final solar fiscal to carbon ratio calculations.

MEDIUM

financial solar: $6,286/kWh system

carbon solar: 9,915.7 kg CO2/kWh system

$$\left(\frac{\$6286}{kWh\ system}\right)\times\left(\frac{kWh\ system}{9{,}915.7\ kg\ CO_2}\right)=\left(\frac{\$6286}{9{,}915.7\ kg\ CO_2}\right)$$

$$=\frac{\$0.63}{kg\ CO_2}$$

Medium Cost: $0.63/kg CO2

HIGH *defined as the least carbon mitigated for the highest price*

financial solar: $7,108/kWh system

carbon solar: 4,309.4 kg CO2/kWh system

$$\left(\frac{\$7{,}108}{kWh\ system}\right)\times\left(\frac{kWh\ system}{4{,}309.4\ kg\ CO_2}\right)=\left(\frac{\$7{,}108}{4{,}309.4\ kg\ CO_2}\right)$$
$$=\frac{\$1.65}{kg\ CO_2}$$

High Cost: $1.65/kg CO2

LOW *defined as the most carbon mitigated for the lowest price*

financial solar: $5,256.9/kWh system

carbon solar: 15,521.9 kg CO2/kWh system

$$\left(\frac{\$5{,}257}{kWh\ system}\right)\times\left(\frac{kWh\ system}{15{,}521.9\ kg\ CO_2}\right)=\left(\frac{\$5{,}257}{15{,}521.9\ kg\ CO_2}\right)$$
$$=\frac{\$0.34}{kg\ CO_2}$$

Low Cost: $0.34/kg CO2

Interpretation and Contribution to the City

The data proved solar panels victorious over canopy expansion in terms of fiscal to carbon ratios. We thereby recommend considering alternative climate change mitigators within Portland and its ever-expanding city limits.

These calculations provide a flexible framework for quantitatively considering other methods of climate change mitigation. The values selected in our estimation rest in the middle of found literature value ranges, and the results can be assessed using values at the high and low end of each variable to establish a range of fiscal to carbon ratios for both solar panels and trees. As more refined data for some of the variables factored into the equation's surface, the estimation will grow increasingly more reflective of Portland's unique urban environment.

Our project was structured around Jeff Ramsey's question of whether Portland Parks & Recreation Urban Forestry canopy goal of 33.3% is the most environmentally and financially sound goal, or if there are other considerations, namely solar panels, they should prioritize. By recalculating the potential canopy cover and calculating potential solar panel cover, Urban

Forestry can be more equipped to know if the 33.3% goal is an obtainable target or needs to be reevaluated based on percent of that goal already met or that will be met easily with the added land that Portland will have in the future. Using data that accounts for the carbon and monetary costs and benefits of both solar panels and canopy cover, this project suggests that Portland should consider other options before relying solely on tree canopy expansion to mitigate the city's climate change impact. These practices will put climate change mitigation at the forefront of the City of Portland's agenda in its tree planting decisions.

Adaptation A: Complete Park Vulnerability Score Listing

Table 8. Complete list of park vulnerability scores.

Park	Mature Size Diversity Score	Functional Diversity Score	Species Richness Score	Hydraulic diversity Score	Overall Ecological Vulnerability Index Score 4 - 16 (highest - lowest vulnerability)	PBOT Social Vulnerability Score 0 - 10 (lowest - highest vulnerability)
Alberta Park	1	3	2	3	9	5
Arbor Lodge Park	2	1	2	1	6	4
Argay Park	3	3	4	4	14	9
Berkeley Park	2	1	2	3	8	7
Berrydale Park	1	4	3	3	11	9
Bloomington Park	1	4	2	2	9	9
Brentwood Park	4	4	3	4	15	7
Brooklyn School Park	2	2	2	2	8	5
Buckman Field	3	3	3	2	11	7
Cathedral Park	4	4	4	4	16	7
Cherry Blossom Park	4	2	3	4	13	9
Cherry Park	2	3	4	3	12	9
Chimney Park	2	3	4	4	13	8
Colonel Summers Park	2	3	4	3	12	5
Columbia Children's Arboretum	3	3	4	3	13	8
Columbia Park	1	3	3	4	11	8
Couch Park	4	3	4	4	15	8
Creston Park	1	3	2	4	10	5
Crystal Springs Rhododendron Garden	4	4	4	3	15	7
Custer Park	4	2	1	4	11	4

Dawson Park	3	1	1	2	7	6
Duniway Park	3	4	3	4	14	2
Earl Boyles Park	1	3	1	1	6	10
East Holladay Park	4	1	2	3	10	9
Eastmoreland Garden	3	4	3	1	11	2
Ed Benedict Park	3	2	4	3	12	10
Essex Park	4	2	2	3	11	7
Farragut Park	1	4	3	2	10	9
Fernhill Park	3	4	4	2	13	6
Flavel Park	3	2	2	2	9	10
Floyd Light Park	4	3	4	2	13	10
Frazer Park	3	2	3	1	9	7
Gabriel Park	4	4	4	3	15	4
Gammans Park	1	2	1	1	5	4
Gates Park	2	2	2	4	10	8
George Park	3	2	2	1	8	7
Gilbert Heights Park	3	1	1	3	8	10
Gilbert Primary Park	3	2	2	1	8	6
Glenwood Park	1	1	2	3	7	9
Gov Tom McCall Waterfront Park	4	4	1	2	11	8
Hancock Park	1	1	1	2	5	8
Harney Park	3	1	1	2	7	6
Harrison Park	3	4	2	2	11	9
Hazeltine Park	4	2	3	3	12	6
Holladay Park	2	3	3	2	10	7
Irving Park	4	4	3	2	13	2

Kenilworth Park	2	4	3	2	11	7
Kenton Park	2	3	2	1	8	7
Knott Park	3	1	4	3	11	8
Lair Hill Park	1	2	4	1	8	6
Laurelhurst Park	2	4	4	2	12	2
Lents Park	1	4	4	3	12	9
Lincoln Park	2	4	1	4	11	9
Luuwit View Park	3	3	1	2	9	8
Matt Dishman Community Center & Pool	4	1	1	4	10	6
McCoy Park	4	2	2	1	9	10
McKenna Park	3	2	1	1	7	6
Midland Park	2	2	1	1	6	10
Montavilla Park	4	2	2	2	10	8
N Crawford St and N Polk Ave Property	1	1	2	1	5	7
Normandale Park	1	2	1	3	7	3
Northgate Park	2	1	2	1	6	10
Oregon Park	2	3	1	3	9	6
Peninsula Park	2	3	4	2	11	4
Piccolo Park	1	1	1	4	7	4
PlayHaven Park	1	1	2	4	8	8
Powell Park	4	4	3	3	14	5
Raymond Park	4	2	3	1	10	8
Rose City Park	2	2	3	2	9	6
Sacajawea Park	1	1	1	4	7	10
Senns Dairy Park	2	4	4	3	13	9
Sewallcrest Park	2	1	2	4	9	2

South Park Blocks	1	1	1	1	4	9
South Waterfront Park	1	4	2	1	8	6
St Johns Park	4	2	4	2	12	7
Stark Street Island	2	2	2	4	10	10
University Park	4	2	3	2	11	8
Ventura Park	1	3	4	1	9	10
Wallace Park	3	1	3	1	8	3
Washington Monroe Property	3	1	3	4	11	7
Wilkes Park	2	3	4	4	13	9
Willamette Park	3	3	3	3	12	4
Wilshire Park	1	2	1	1	5	3

Adaptation B: Additional Maps and Figures

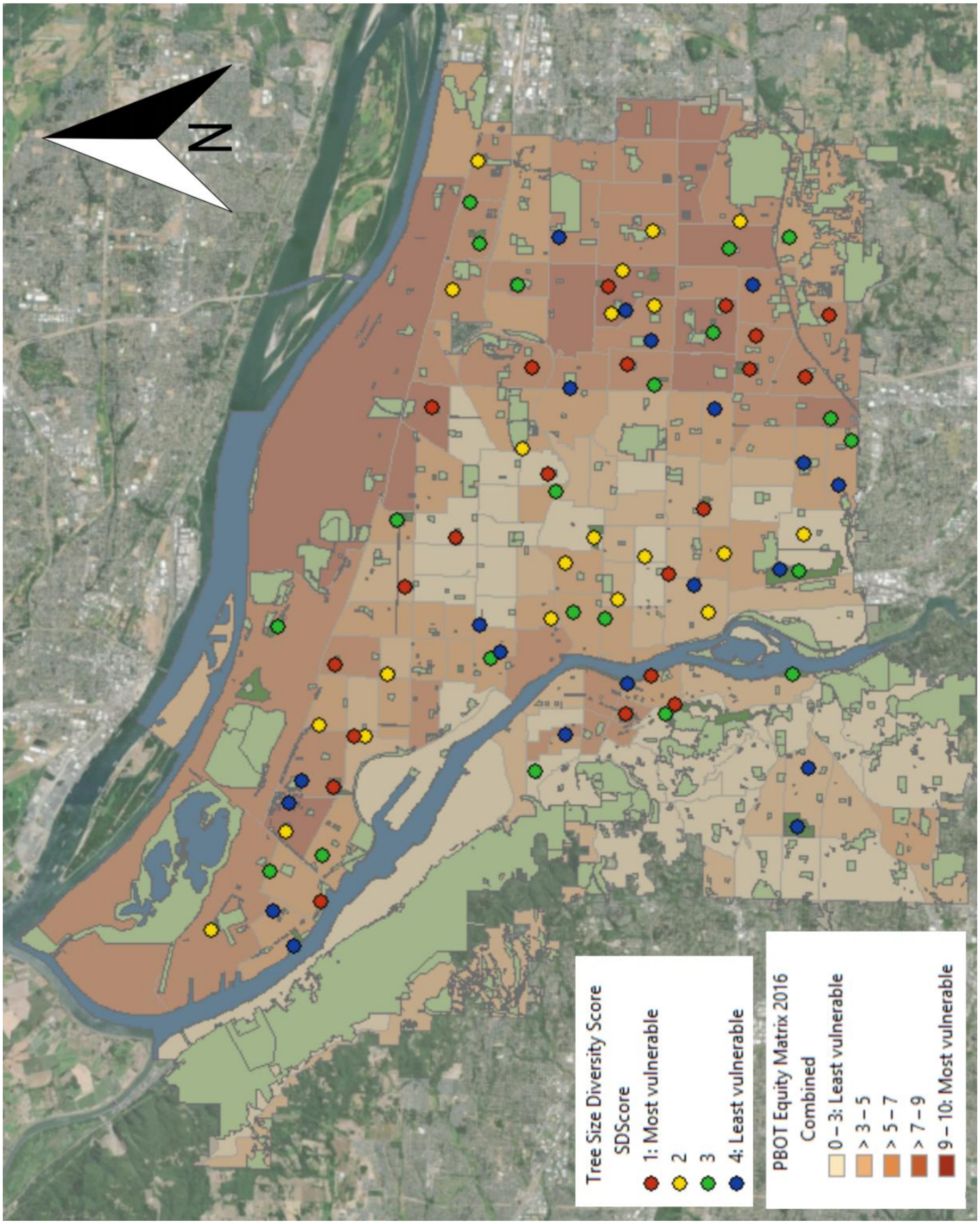

Figure 13. Map of Tree Size Diversity scores.

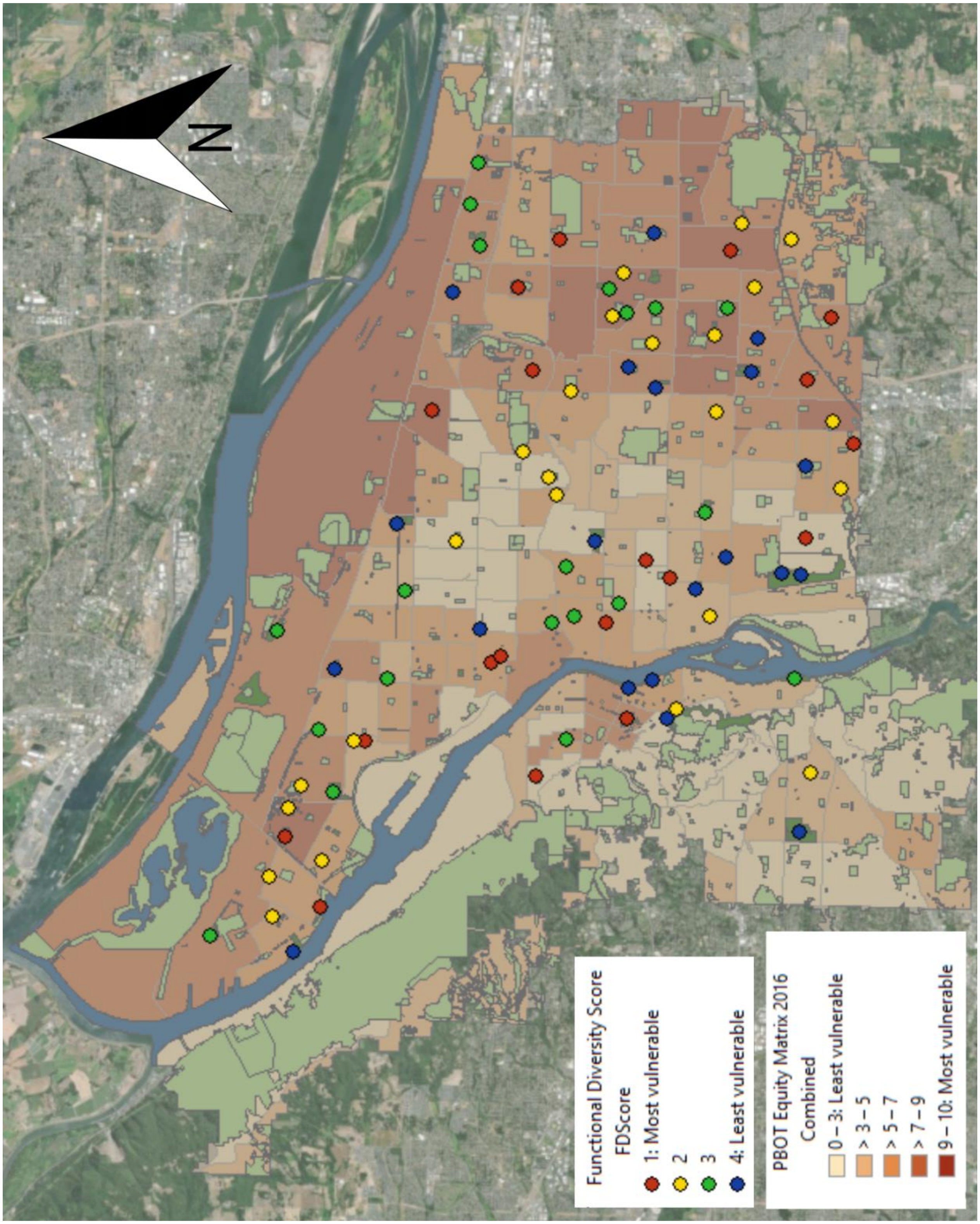

Figure 14. Map of Functional Diversity scores.

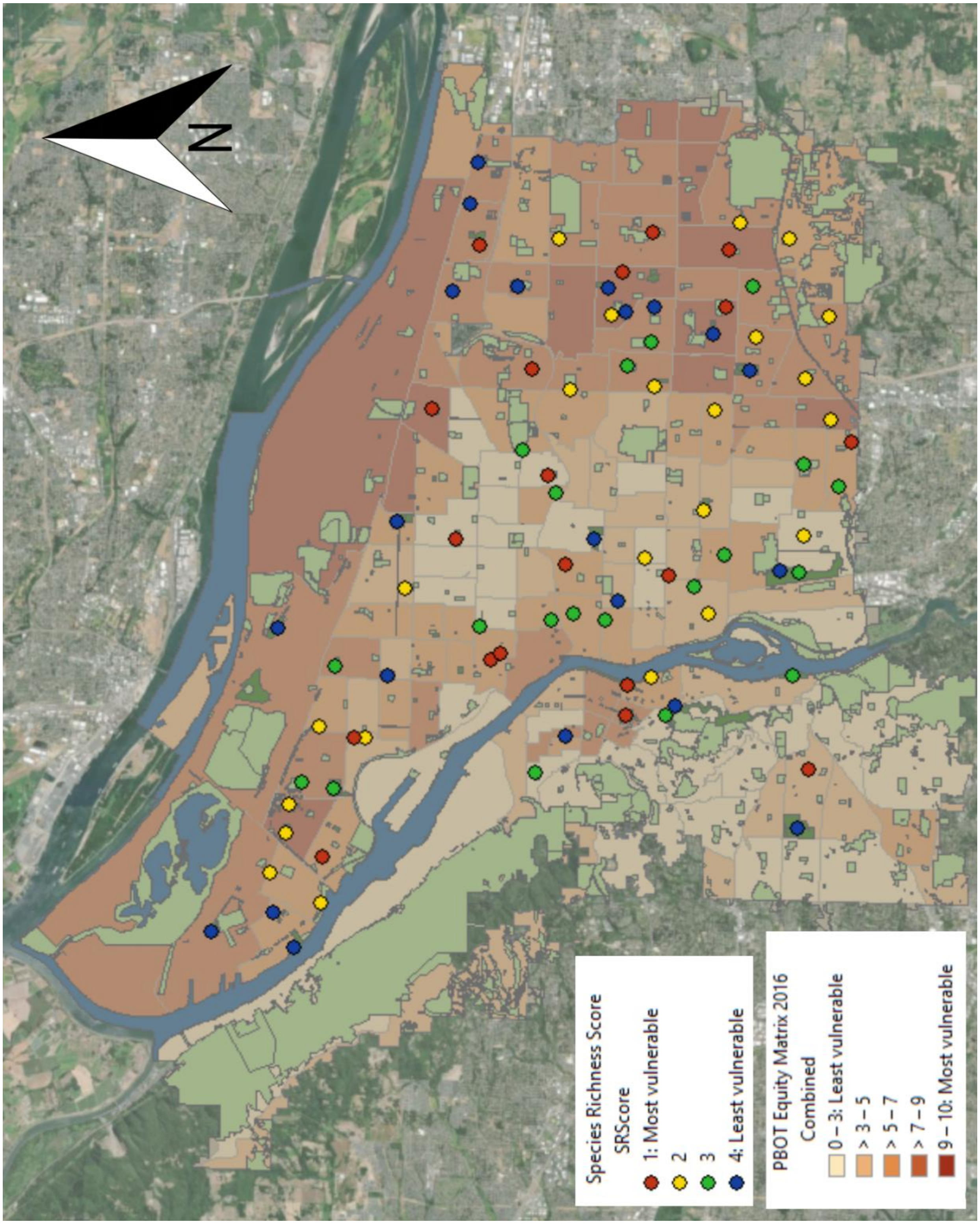

Figure 15. Map of Species Richness scores.

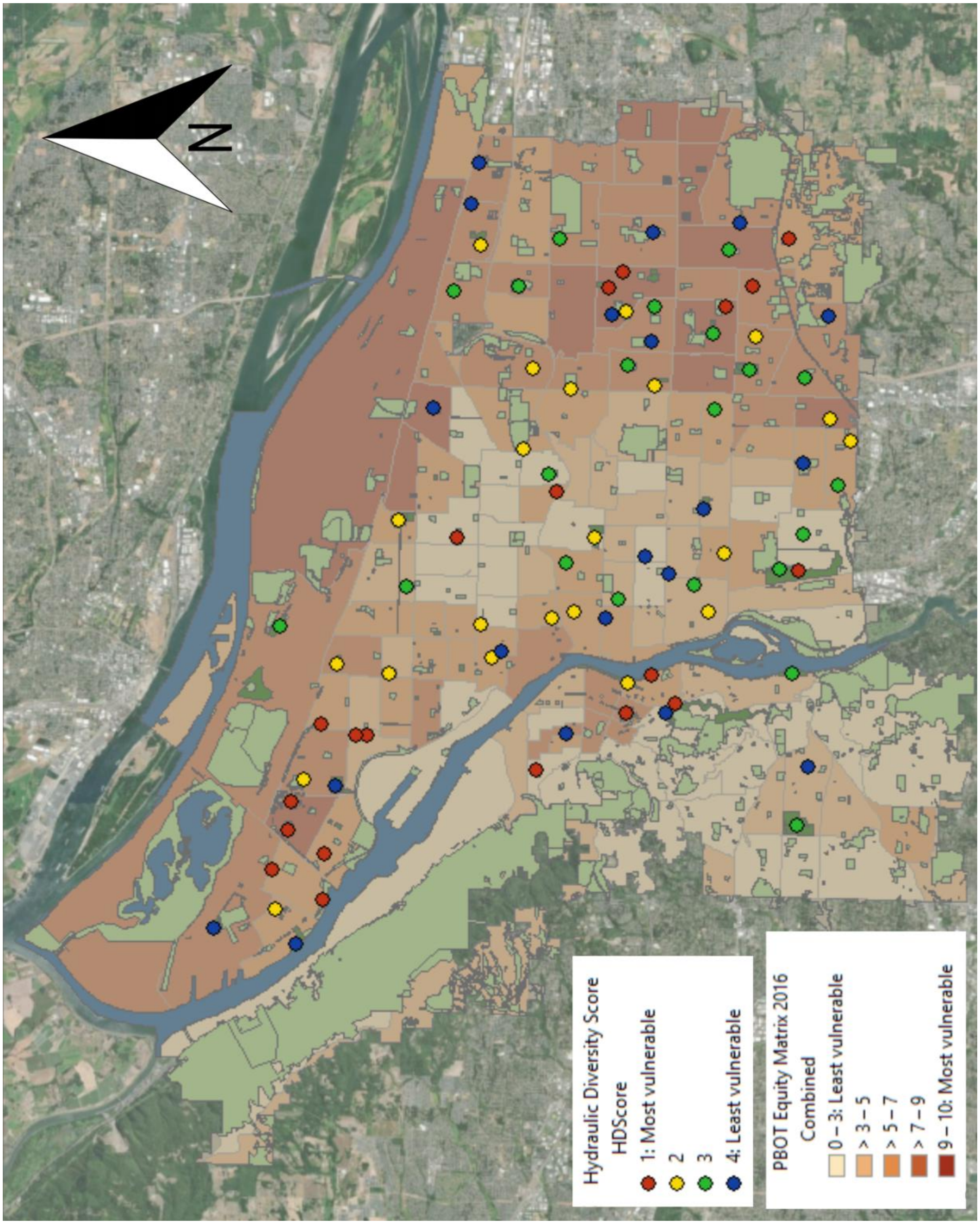

Figure 16. Map of Hydraulic Diversity scores.

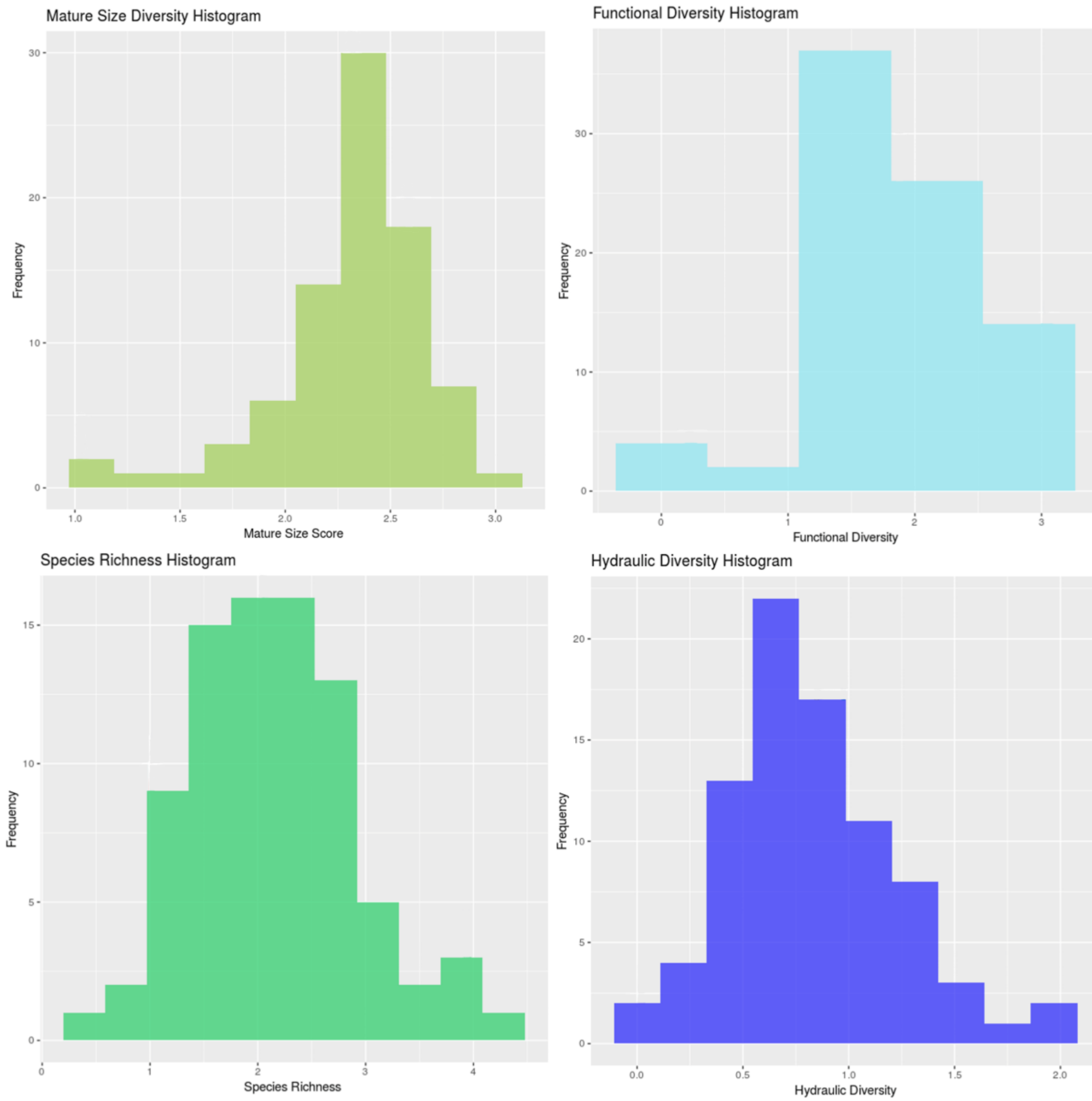

Figure 17. Score frequency for each ecological vulnerability variable.

Adaptation C: Justification of Variables

Lack of Biological Diversity Leads to Ecosystem Vulnerability

The relatively haphazard planting and maintenance practices in the early days of Portland's park system have had lasting impacts on the climate resiliency of the city's urban forest. One of these negative impacts is a lack of evenly distributed species richness in Portland's parks. For example, tight clumps of large, mature Douglas firs dominate many public spaces. Of the 15,854 park trees inventoried by Urban Forestry, 3,540 are identified as Douglas fir alone. That number represents more than 20% of total individuals recorded among 280 different possible species across the city (Portland Parks and Recreation 2018). Other common large-form trees native to the Pacific Northwest include Western redcedar, Sitka spruce, Western hemlock, and Ponderosa pine, along with assorted deciduous broadleaf trees like Red alder and Bigleaf maple, but these trees are nowhere near as common in the urban forest as Douglas Fir (Waring 1979, 1382). Other common monocultures in the Portland park system include homogenous stands of Elm and Ash, both of which are highly vulnerable to disease, insect infestation, and fungal invasion.

Dearborn and Kark (2010) explore the value of conserving overall species richness in the urban forest. They list seven possible motivations for urban biodiversity conservation and argue that urban areas can serve as an important venue for conservation biology. Their motivations include "preserving local biodiversity, creating stepping stones to non-urban habitats, understanding and facilitating responses to environmental change, conducting environmental education, providing ecosystem services, fulfilling ethical responsibilities, and improving human well-being" (2010, 1). With these motivations in mind, Dearborn and Kark aim to preserve biodiversity of all forest ecosystems, both species and functional, urban or otherwise.

An understanding of hydraulic traits, the mechanisms through which water and nutrients are transported throughout a plant, is key to developing a model that accurately represents the interactions between communities of trees and their surrounding environments. Recent studies have found hydraulic diversity, defined as “higher standard deviation in hydraulic safety margin” across the trees in a given site, to be one of the most important up-and-coming predictors of a forest ecosystem’s response to changes in water availability (Anderegg et al. 2018, 538). Diversity in hydraulic traits plays a critical role in providing ecological stability to forest ecosystems, especially during periods of drought. According to Anderegg’s team, “higher hydraulic diversity buffers variation in ecosystem flux during dry periods across temperate and boreal forests” (Anderegg 2018, 538). This means that even as environmental conditions and levels of nutrient availability change in a forest, the ecosystem can still maintain itself if the individuals within it are in possession of a wide range of strategies for dealing with those changing conditions. Their findings demonstrate that the hydraulic diversity of plants within an ecosystem is the primary determining factor that mediates a given ecosystem’s resilience to drought.

Social Vulnerability

Our project is driven by the question of whether or not ecological vulnerability in Portland parks occurs in the same areas as social vulnerability. The effects of a community’s environment on human wellbeing is documented many studies, with research showing that a higher level of ecological health corresponds with a higher level of human health. Brown and Grant (2005) explore the human and ecological health benefits derived from urban biodiversity policies by focusing on ecological services provided by nature as well as benefits derived from human interaction with nature. Their research demonstrates clear links between human health and nature, particularly in urban areas. In analyses of the relationships between race, income, and urban forests, Watkins and Gerrish (2018) find significant inequity in the distribution of urban forests. These findings are especially concerning because they imply that socially vulnerable groups do not have access to the same positive co-benefits of urban forests that more privileged social groups do. A variety of studies find significant racial and socioeconomic inequality in urban park distribution both at the neighborhood and city level (Rigolon 2016; Rigolon et al. 2018; Hughey et al 2016). Cities with higher proportions of ethnic minority and low-income individuals have less access to higher quality parks, especially in communities with a majority latino population (Rigolon et al. 2018). These studies demonstrate the importance of using an environmental justice lens to investigate urban parks and park funding, showing that funding practices have created disparities among urban parks throughout the United States. It was one of our goals in this project to investigate whether or not these inequities in public access to resilient green infrastructure are present in Portland's park system, as well.

Adaptation D: Expanded Hydraulic Diversity Methods

Key terms

Hydraulic traits: Physiological mechanisms of water and nutrient transport within a plant.

Psi_{min}: Minimum normal stem water potential.

P_{50}: Water potential at which 50% of stem xylem conductivity is lost.

Hydraulic safety margin: The difference between naturally occurring xylem pressure values and pressure values that would lead to hydraulic dysfunction, subsequent loss of conductivity, and potential limb failure or mortality. Calculated as the difference of Psi_{min} and P_{50} (Choat et al. 2012).

Hydraulic diversity: Communiy weighted standard deviation in hydraulic safety margin (Anderegg et al. 2018).

Calculating Park Hydraulic Diversity

We calculated hydraulic diversity at the park level by:

1. Using the Park Tree Inventory dataset to identify all of the tree species present in a given park.
2. Retrieving data on Psi_{min} and P_{50} for each species present in that park using a recently published global trait dataset (Liu et al. 2019).
3. Calculating Hydraulic Safety Margin for each species from the difference between Psi_{min} and $P_{50.}$
4. Compiling a dataset of tree-level Hydraulic Safety Margins for each park.
5. Taking the community-weighted standard deviation for each park.
6. Dividing the city-wide range of standard deviations into quantiles.
7. Assigning a score 1-4 to each park depending on which quantile its SD falls into.

Lit. Cited:

H. Liu et al., Hydraulic traits are coordinated with maximum plant height at the global scale. Science Advances. 5, eaav1332 (2019).
B. Choat et al., Global convergence in the vulnerability of forests to drought. Nature. 491, 752–755 (2012).
W. R. L. Anderegg et al., Hydraulic diversity of forests regulates ecosystem resilience during drought. Nature. 561, 538–541 (2018).