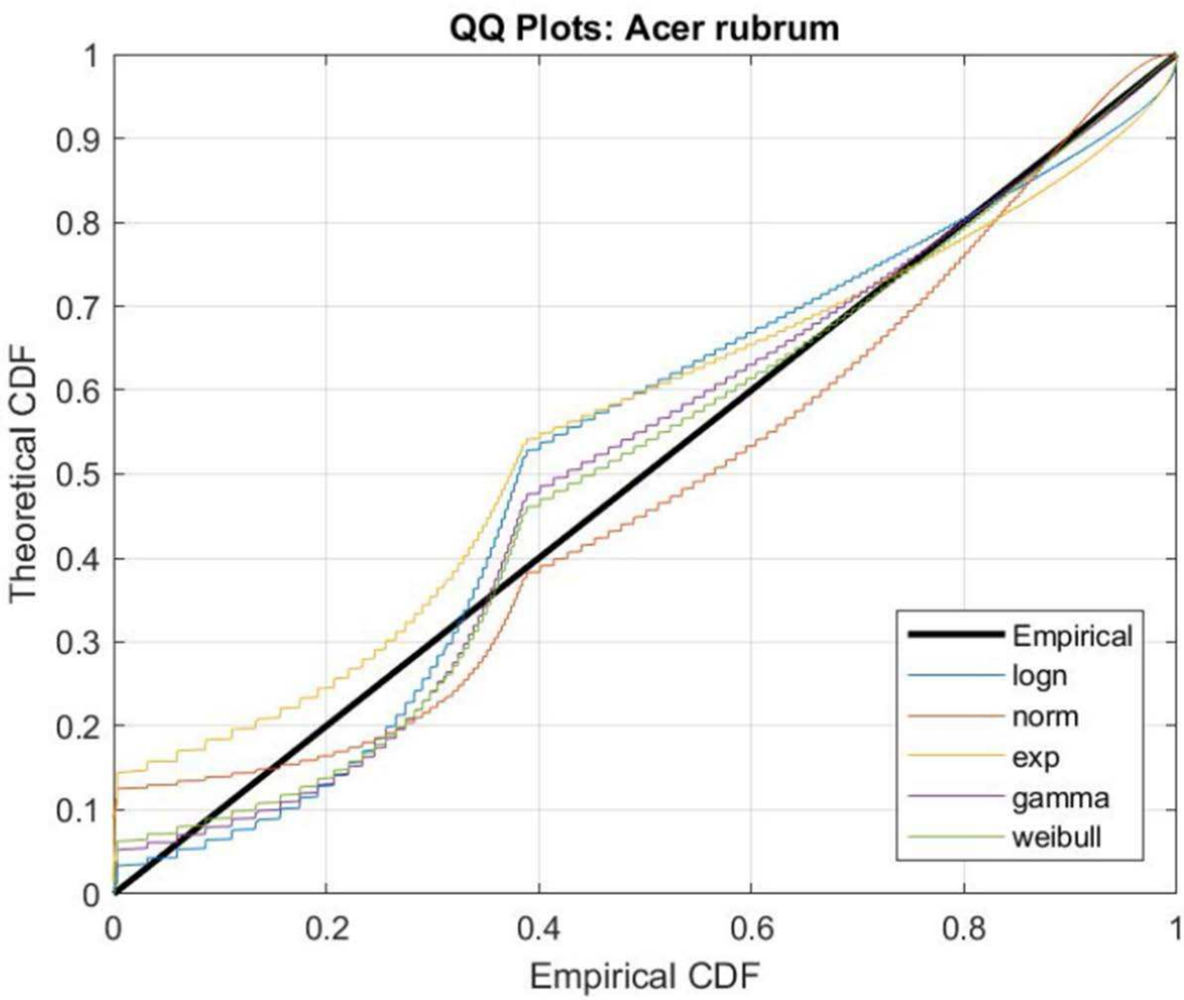
Appendix A: Tree Species used in Study Cities

The following table shows the tree species used in the study cities. Trees were chosen based on design manuals, available datasets and personal communication with urban forestry experts.

New York City	Philadelphia	Baltimore	Denver	Portland
American elm	American Elm	Eastern white pine	American elm	Bald cypress
Eastern red cedar	Crabapple	Flowering dogwood	Austrian pine	Bigleaf maple
Flowering dogwood	East Asian cherry	Loblolly pine	Blue spruce	Black tupelo
Ginkgo	Eastern red cedar	Northern red oak	Bur oak	Dawn redwood
Honeylocust	Ginkgo	Pin oak	Goldenrain tree	Douglas fir
Japanese flowering cherry	Honeylocust	Red maple	Honeylocust	Grand fir
Littleleaf linden	Littleleaf linden	River birch	Kentucky coffeetree	Honeylocust
London planetree	London planetree	Silver maple	London planetree	Japanese zelkova
Northern red oak	Red maple	Sweetgum	Narrowleaf cottonwood	Northern hackberry
Pin oak	Red oak	Water oak	Northern catalpa	Oregon ash
Silver maple	River birch	White oak	Northern Red oak	Oregon white oak
Sweetgum	Southern magnolia	Willow oak	Ponderosa pine	Paperbark maple
Willow oak	Sugar maple		Scots pine	Red alder
	Swamp Spanish oak		Siberian elm	Swamp white oak
	Sweetbay magnolia		Silver maple	Western hemlock
	Willow oak			Western red cedar
				Willow oak

Appendix B: DBH QQ Plot

The following figure shows 5 common distributions found with the Maximum Likelihood Estimation Method displayed with the empirical distribution for the DBH distribution of a tree. The best fit distribution was the distribution that best matched the linear trajectory of the empirical data.



Weibull was the best fit equation for this specific tree species as it is closest linearly to the empirical CDF of the DBH for this tree. This analysis was done for all tree species in all cities

Appendix C: Spatial Analysis Assumptions

To find the number of trees used in each city's Stormwater Green Infrastructure, assumptions of tree density for each vegetated GI technology were made based on city Green Infrastructure design manuals. The following are the assumptions for the spatial analysis. Unless noted, for all small scale infrastructure (bioswales, rain gardens) which was 1 tree per 100 sq. ft. and larger scale infrastructure (detention ponds) which require more spacing for trees (1 tree per 200 sq. ft.)

Philadelphia

Spatial datasets for the Green Infrastructure in Philadelphia were obtained from the open data portal for Philadelphia. Datasets included public and private SGI. SGI considered include Bioinfiltration, Bioretention, Tree Trench, Rain Garden and Swales. The number of units of each SGI technology were in the datasets. It was assumed that each unit of GI had one tree planted per design manuals for SGI.

The building footprint layer was found on Philly's open data website. Using the "Generate Near Table" tool in ArcGIS, the closest distance between the trees and the buildings were found and recorded for each SGI unit.

Denver

Spatial datasets were obtained from Denver's open data portal for stormwater detention and water quality infrastructure. A selected portion of the infrastructure had the tree database supplied with the amount of trees in each technology(Bell, 2020). SGI considered include Detention Pond, Grass Swale, Rain Garden and Porous Landscape Detention.

The tree density data had been collected and the average amount of trees per sq. ft. were used for all of the water quality infrastructure. The building outlines were obtained from the Denver open data website.

Baltimore

Spatial datasets were obtained from SWM Facility Data through Baltimore's open database. SGI technologies that were included in this analysis were bioswales, rain gardens and detention ponds. The selected SGI had their area attached to their spatial datasets. The tree ratios were based on assumptions from looking at other cities' spacing for trees. For small scale infrastructure (bioswales, rain gardens) which was 1 tree per 100 sq. ft. and larger scale infrastructure (detention ponds) which require more spacing for trees (1 tree per 200 sq. ft.)

Portland

Spatial datasets were obtained from Portland's shared database. The facility data available did not include area. Only Vegetated Ditches, Water Quality Swales, Roadside Treatment Facility, Vegetated Filters and Swales all use Vegetation were included in the analysis.

New York City

Spatial datasets were acquired from NYC Department of Environmental Protection. The following technologies were used for analysis: Bioswale, Green Streets, Green Strip (ROWGS), Rain Gardens and Engineered Soil Pit. ROW bioswale provided tree species used. A frequency analysis was used to determine the frequency of each species to be planted. This will be used to input the species frequency in the overall NYC tree database. The number of trees per technology were all 1 tree per 100 sq. ft. except for Green streets are 200 sq. ft. This is based on the design manual documents. The buildings footprint layer was provided by NYC Open Data

Appendix D: Co-benefit Descriptions

The following are additional co-benefits calculated by i-Tree Eco.

Structural Value

The economic value that the tree brings to the surrounding area is measured by the "structural value." Structural value is calculated in i-Tree Eco as the value of a tree based on the cost of replacing the tree with a similar tree. (Nowak et al., 2002; Nowak et al., 2000).

Oxygen Production

Oxygen is produced through photosynthesis as the tree converts carbon dioxide into biomass (Nowak et al., 2007). The amount of oxygen produced is estimated from carbon sequestration based on atomic weights with Equation 2.

$$Net\ O_2\ release\ \left(\frac{kg}{yr}\right) = net\ C\ sequestration\ \left(\frac{kg}{yr}\right) * \frac{32}{12} \qquad \text{Eq. 2}$$

(Nowak et al., 2007)

Total Annual Benefits

Total Annual Benefits are the monetary value of benefits calculated by i-Tree Eco. Total annual benefits are the converted economic benefit of carbon sequestration, avoided runoff through water captured and pollution removal. The economic values are based on average values seen in US national average costs per unit of these externalities (Forest Service, 2020).

Appendix E: Global Sensitivity Analysis

Global sensitivity analysis using variance based methods have features that make it an appealing method: model independence where sensitivity measures are not model specific, the potential to show the influence of the range of variation of each input factor and interaction effects among input factors. A major drawback to variance-based methods is the computational cost with a large amount of input factors. However, in this case with only 4 model inputs, DBH, CLE, Crown Missing and Crown Health, a variance based global sensitivity model is appropriate.

The variance-based method for global sensitivity analysis used in this study, eFAST, is a model independent method that has the potential to capture the influence of the variations of input parameters (Saltelli 2008). The method uses analysis of variance (ANOVA) decomposition to decompose the variance of a model's output depending on each input and its interactions. (Archer G.E.B., A. Saltelli and I.M. Sobol (1997). Sensitivity measures, ANOVA-like techniques and the use of bootstrap. Journal of Statistical Computation and Simulation, 58, 99–120.

The eFAST method is considered to be more efficient than the method of Sobol, another variance method, when there is a small number of model inputs, due to the fact that eFAST method include the small amount of runs needed compared to the method of Sobol (Primer). The eFAST method has been preferred in different applications including hydrological modelling (Sanadhya 2013)

The eFAST method estimates the expected value and the variance of the output variables to find the contribution of each input parameter of the total variance. The eFAST method uses a Fourier transformation function to describe the distribution of the model output results in terms of one dimensional space rather than multi-dimensional space from the model inputs. The coefficients of the

Fourier series can then be used to estimate the variance and mean of the expected model output. The fraction of variance in the model attributed by a certain parameter is proportional to the coefficients in the Fourier series. The total variance V(Y) of each model output (co-benefit) $Y = f(x_1, x_2,\ldots, x_j)$ is given in terms of the j uncertain individual parameters x_i in equation 1C.

$$V(Y) = V\big(E(Y|x_1)\big) + V\big(E(Y|x_2)\big) + V\big(E(Y|x_3)\big) + \cdots + V\left(E\big(Y|x_j\big)\right) + R \qquad \text{Eq. 1C}$$

Equation 1C shows the total variance of model outputs in Fourier series where $V(E(Y|x_i))$ represents the variance of the expected value of the model output Y with respect to input parameter x_i, and R is a residual corresponding to higher order terms.

The first-order sensitivity index S_i is the fraction of the total output variance attributed to a single input parameter, parameters are the tree input parameters such as DBH, Tree Height, Crown Height, CLE and Crown Base. Equation 2C shows the measure of global sensitivity of Y with respect to x_i for each parameter.

$$S_i = \frac{\mathrm{V}\big(\mathrm{E}(Y|x_i)\big)}{\mathrm{V}(Y)} \qquad \text{Eq. 2C}$$

Equation 2C shows First order sensitivity indices of input parameter x_i

The sum of first order sensitivity indices for all input parameters must add up to one to properly proportion the amount of influence each input variable has on the total amount. In some cases, not all relationships can be attributed to the existing model inputs. In these cases, the sum of first order sensitivity indices will be less than one. This gap in first order sensitivity indices' sum being less than one can be attributed to non-linear interactions which are interactions outside of the influence of linear effects of the model inputs but can still have significant influence on the output variance in first order sensitivity analysis.

The total-order sensitivity index S_T is the fraction of the total output variance not attributed to a single input parameter, this includes interactions among input parameters and higher order variance terms in Equation 1C. Parameters are the tree input parameters such as DBH, Tree Height, Crown Height, CLE and Crown Base. Equation 3C shows the First order sensitivity measures of global sensitivity of Y with respect to x_i for each parameter.

$$S_T = \left(V(Y) - V\big(E(Y|x_{\sim i})\big)\right)/V(Y) \qquad \text{Eq. 3C}$$

Appendix F: Comparative Datasets Assumptions

The following are assumptions of co-benefit values from the US Forest Service's Community Tree Guides. Assumptions were necessary to compare co-benefit values from this study and the Community Tree Guides' units and co-benefits. Each tree species in i-Tree Eco is categorized as either a small, medium or large tree based on the city tree resources. The benefits from the Community Tree Guides are compiled and averaged per the number of different sized trees in each city.

Air pollution

Values of CO removal and $PM_{2.5}$ are the same as PM_{10}

Urban forestry studies have assumed that PM_{10} and $PM_{2.5}$ removal rates are the same, with trees being as effective at removing $PM_{2.5}$ as they are removing PM_{10}. CO and $PM_{2.5}$ have similar equations for removal, so the conservative estimate is made that the CO and PM 2.5 have the same removal rate as PM_{10} in the Community Tree guide. (Conservancy, 2016; Jeanjean et al., 2016; Nowak et al., 2013)

Oxygen Production

Carbon sequestration estimates are given by the Community Tree Guide. The Oxygen production co-benefit is calculated in the same way as i-Tree Eco using the atomic weight conversion from carbon sequestration in Equation 2.

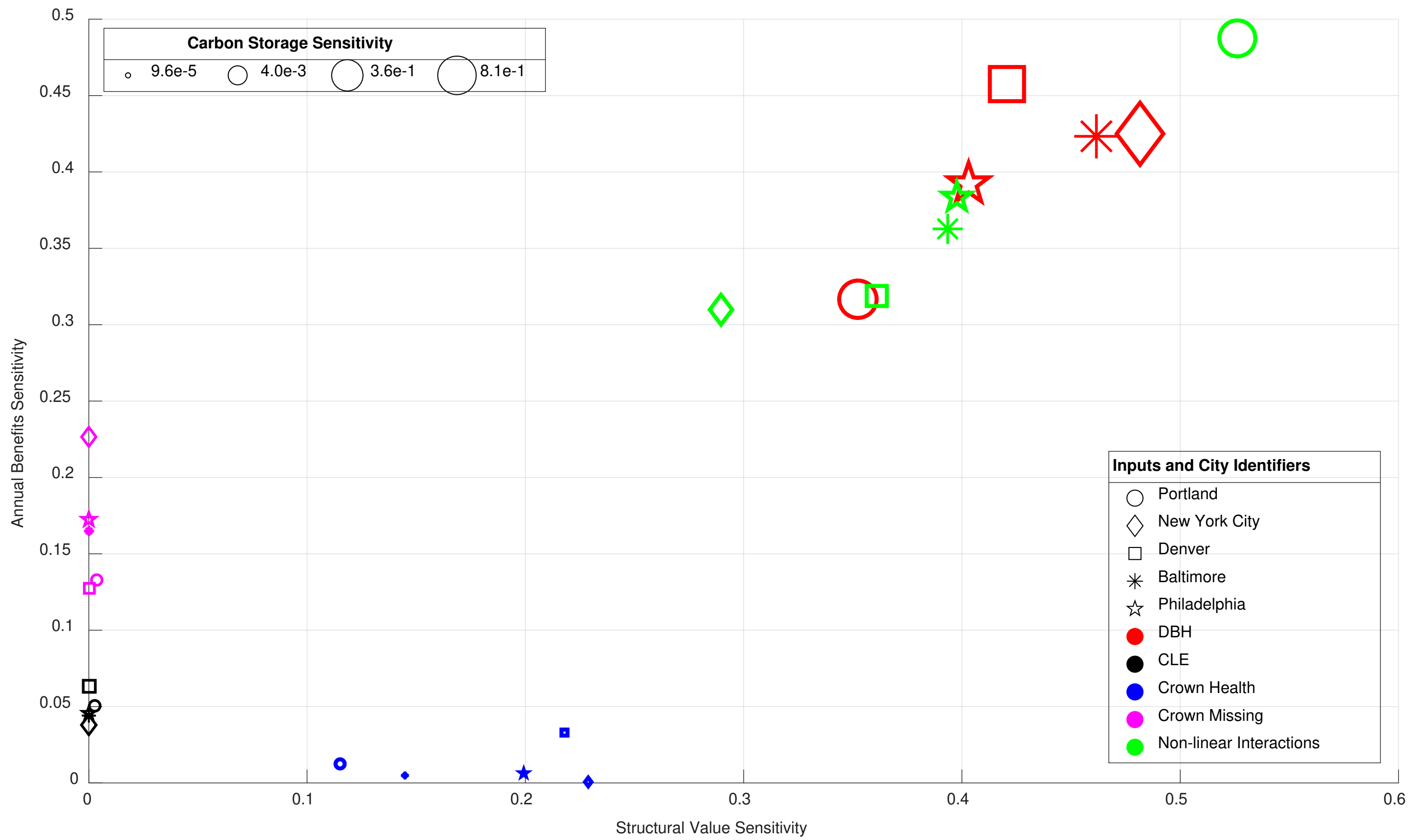
Total Annual Benefits

Total annual benefits in i-Tree are the monetary benefits associated with avoided runoff, gross carbon sequestration, and pollution removal. This is compared to the Community Tree Guide's monetary value of rainfall interception, net CO_2 and air pollution uptake +avoidance of O_3, NO_2, SO_2, and PM_{10}. (Hirabayashi et al., 2011)

Structural Value

Structural value in i-Tree Eco is the cost to replace a tree. The Community Tree Guide's structural value is calculated as the value of the tree, planting cost and removal cost.

Appendix G: Additional Sensitivity Analysis



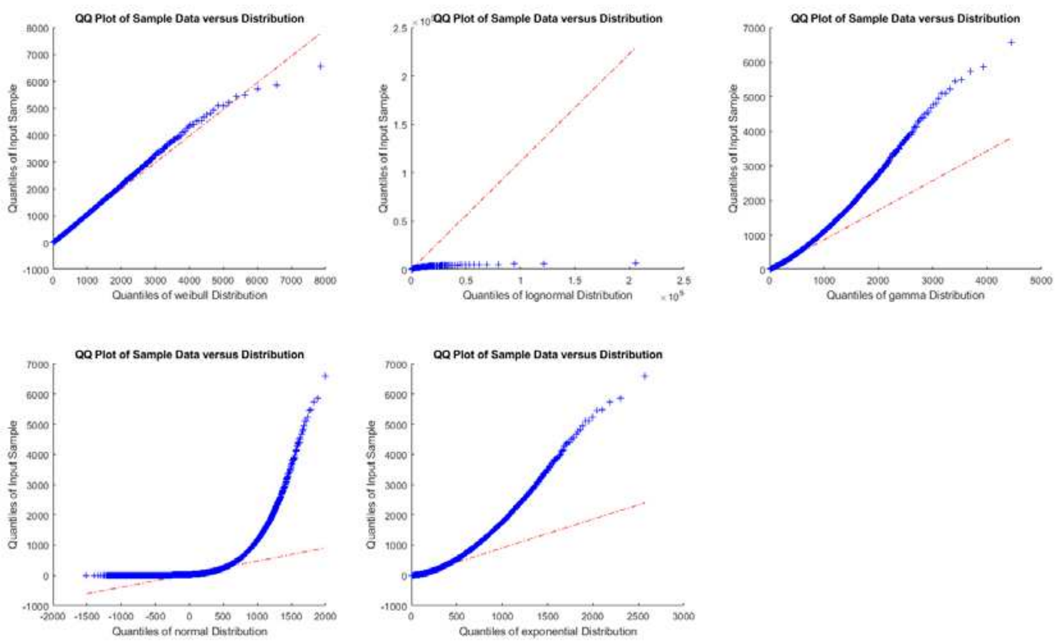
The following is additional sensitivity analysis results of Total Annual Benefits, Carbon Storage and Structural Value.

Appendix H: QQ Plots of Co-benefits Distributions

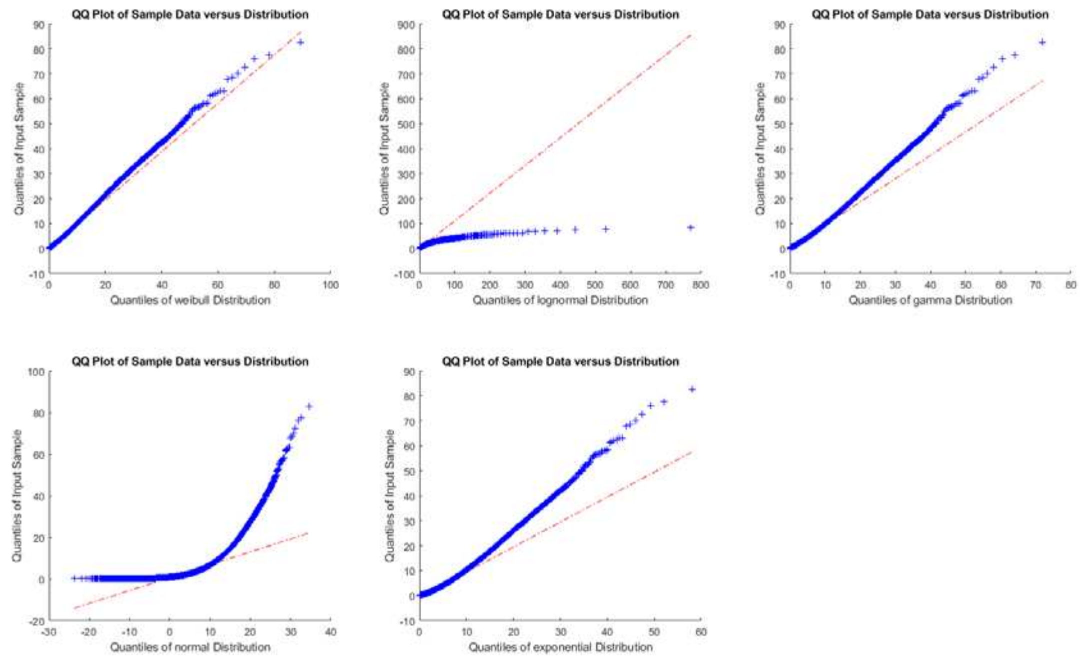
The following plots show the quantiles of common distributions plotted against the empirical data of different co-benefits for the city of Philadelphia's composite tree co-benefits.

Philadelphia

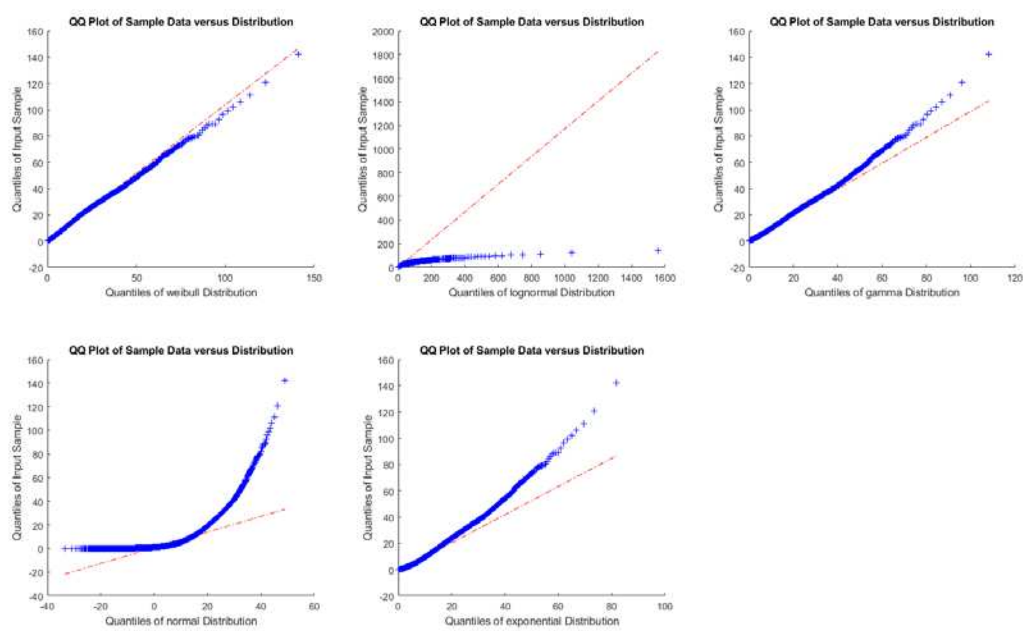
Carbon Storage



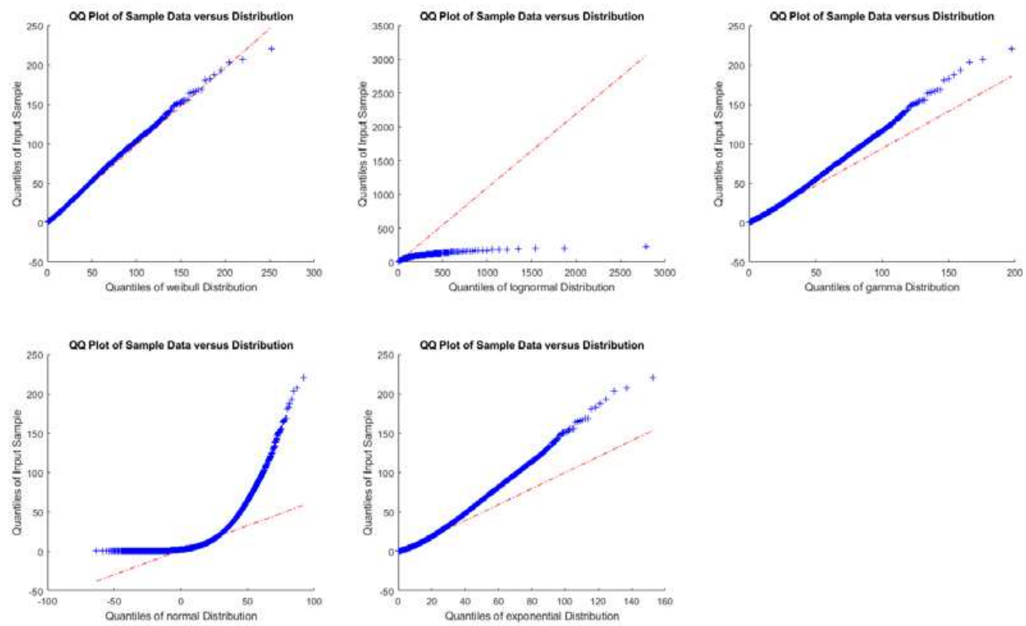
Carbon Sequestration



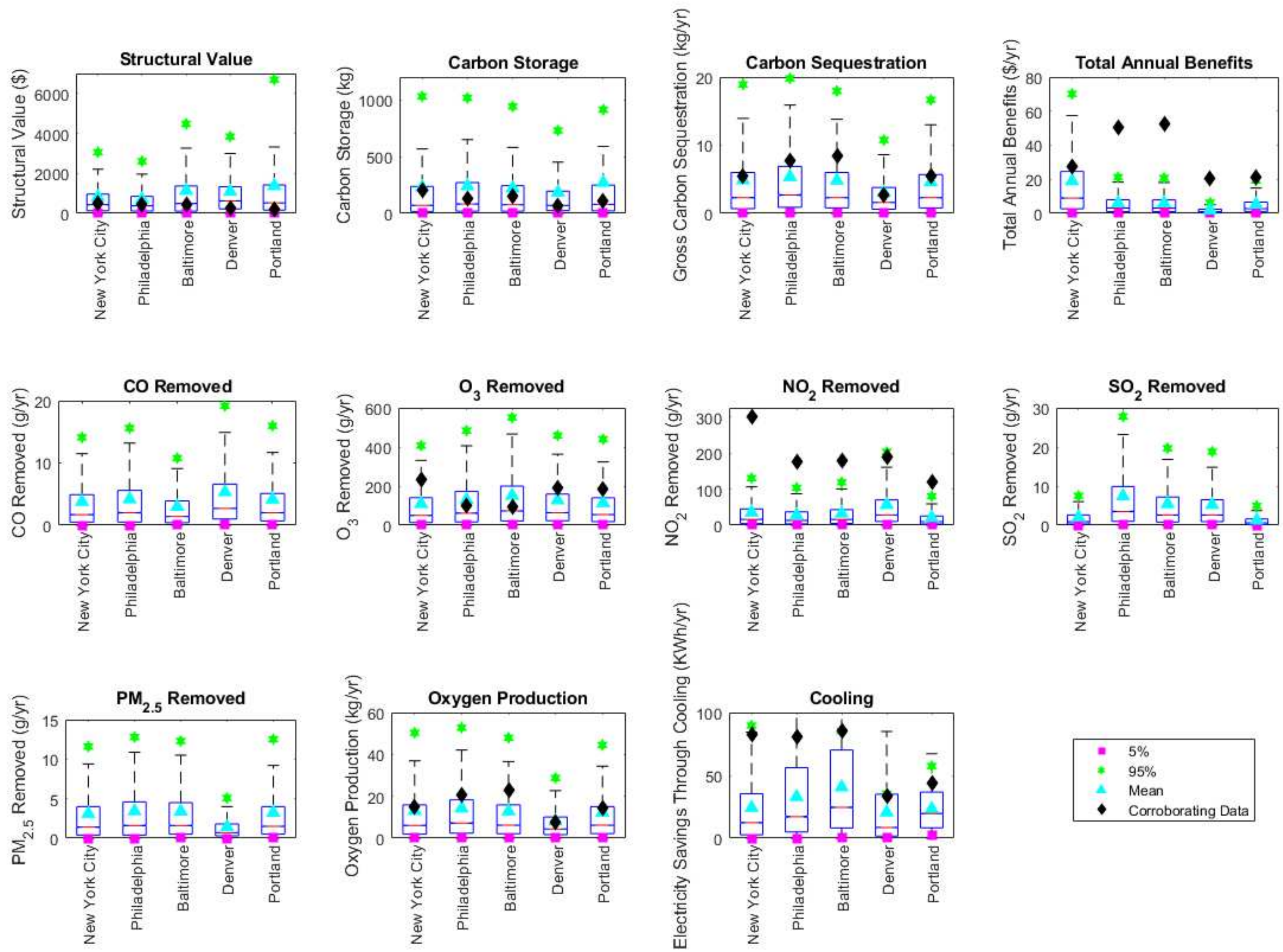
$PM_{2.5}$ Removal



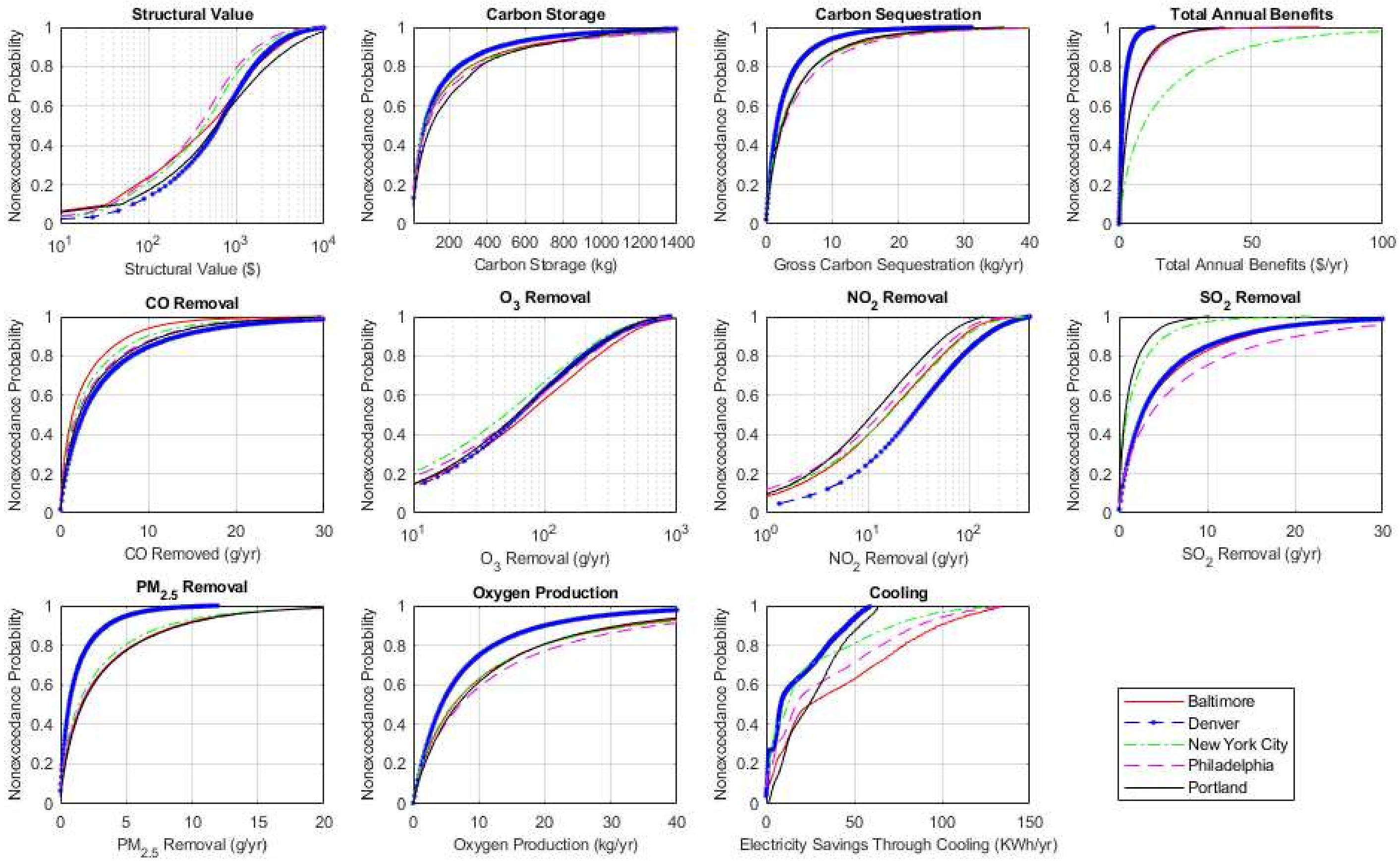
Cooling


QQ Plot of Sample Data versus Distribution
Quantiles of Input Sample
Quantiles of weibull Distribution
QQ Plot of Sample Data versus Distribution
Quantiles of Input Sample
Quantiles of lognormal Distribution
QQ Plot of Sample Data versus Distribution
Quantiles of Input Sample
Quantiles of gamma Distribution
QQ Plot of Sample Data versus Distribution
Quantiles of Input Sample
Quantiles of normal Distribution
QQ Plot of Sample Data versus Distribution
Quantiles of Input Sample
Quantiles of exponential Distribution

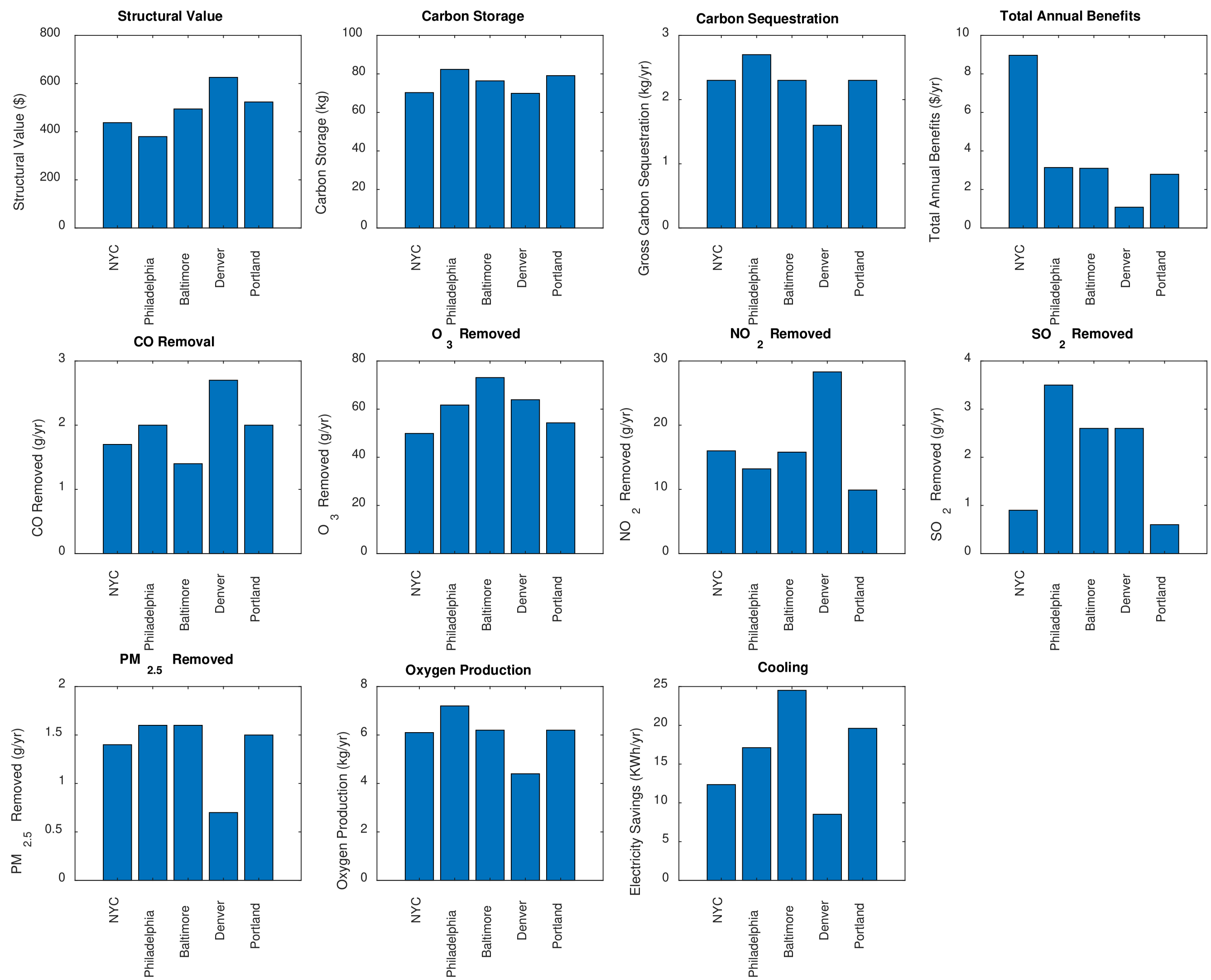
Appendix I: All Composite Trees Boxplot



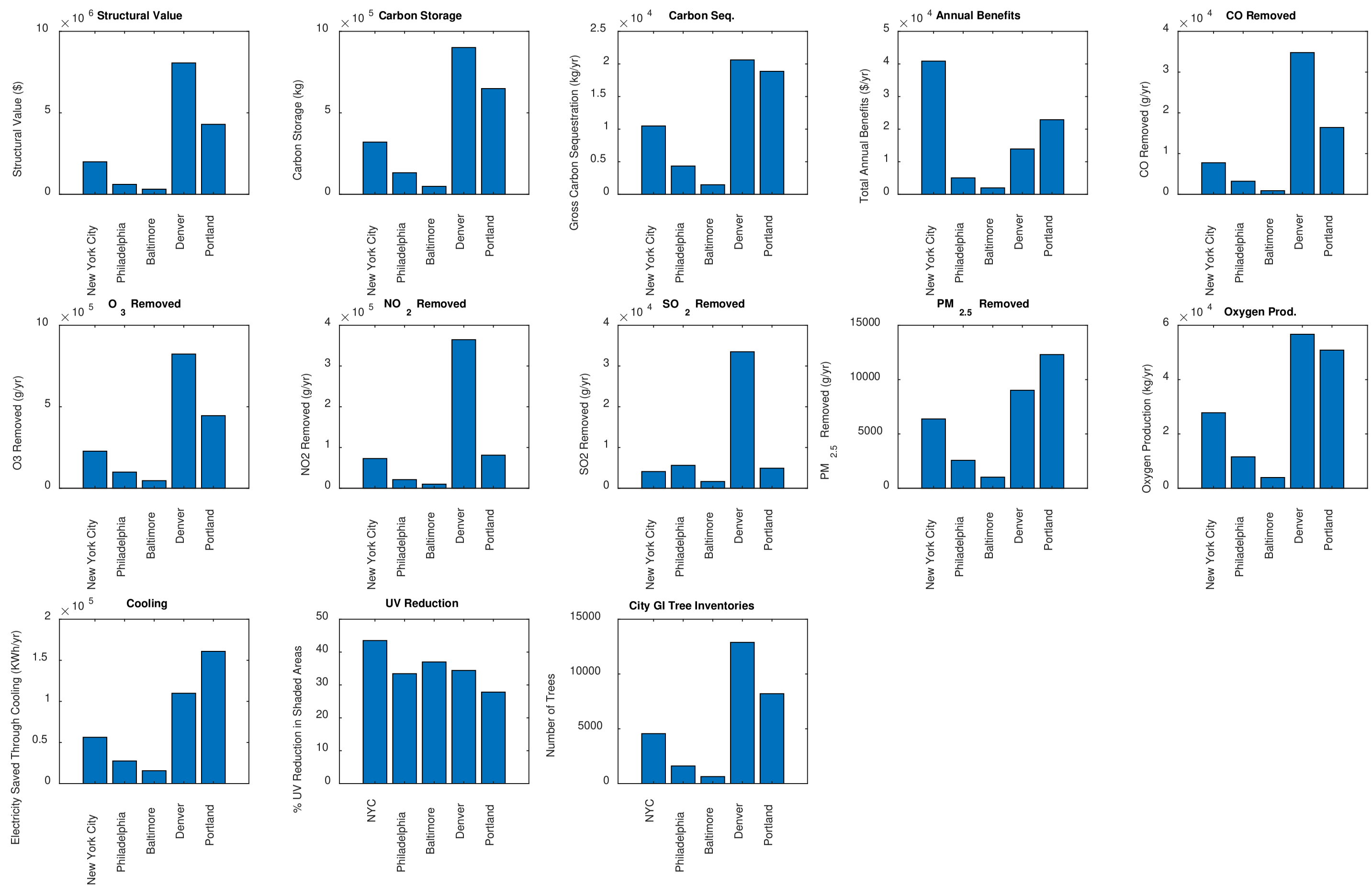
Appendix J: All Composite Trees CDFs



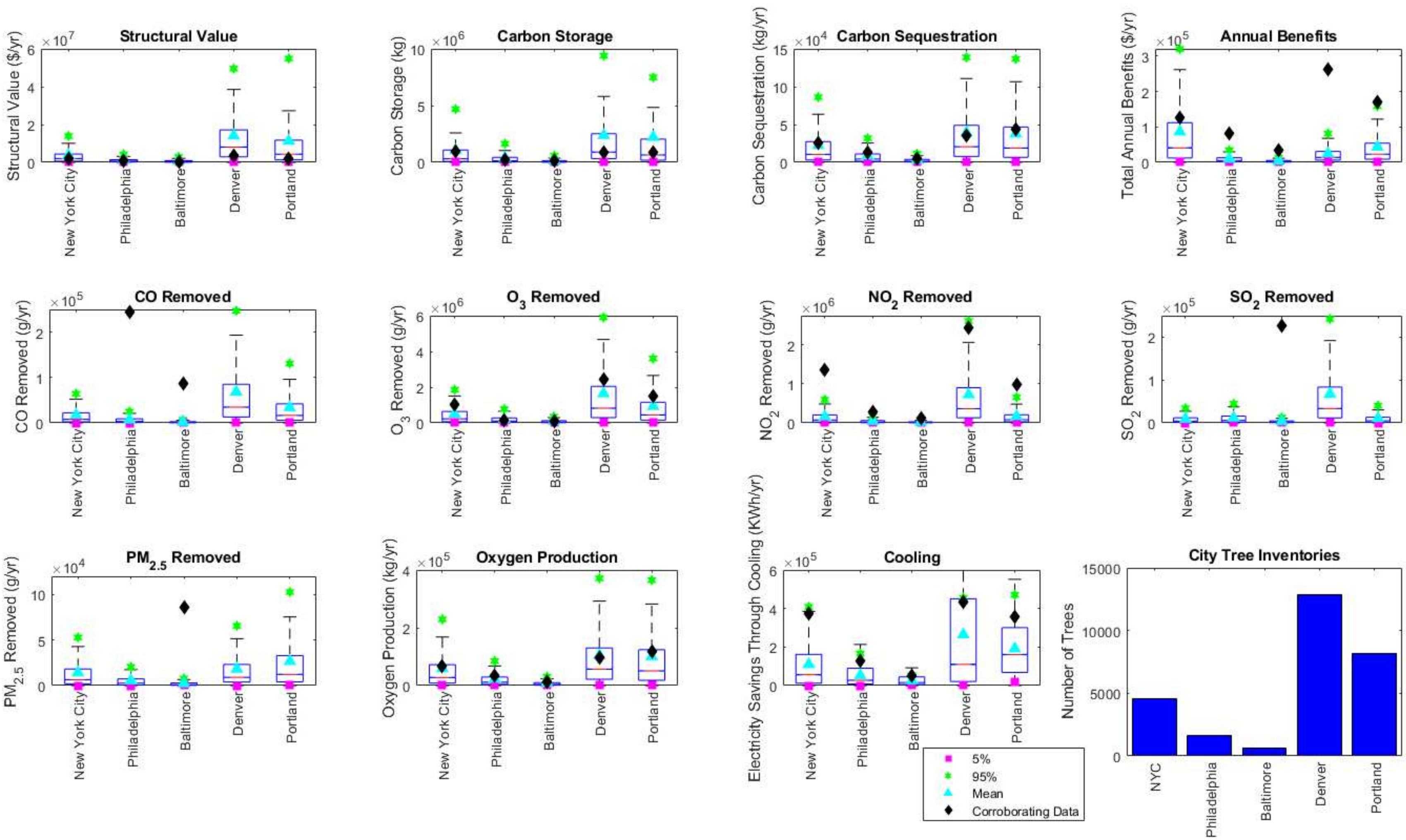
Appendix K: Composite Tree Median Co-benefits for all Cities



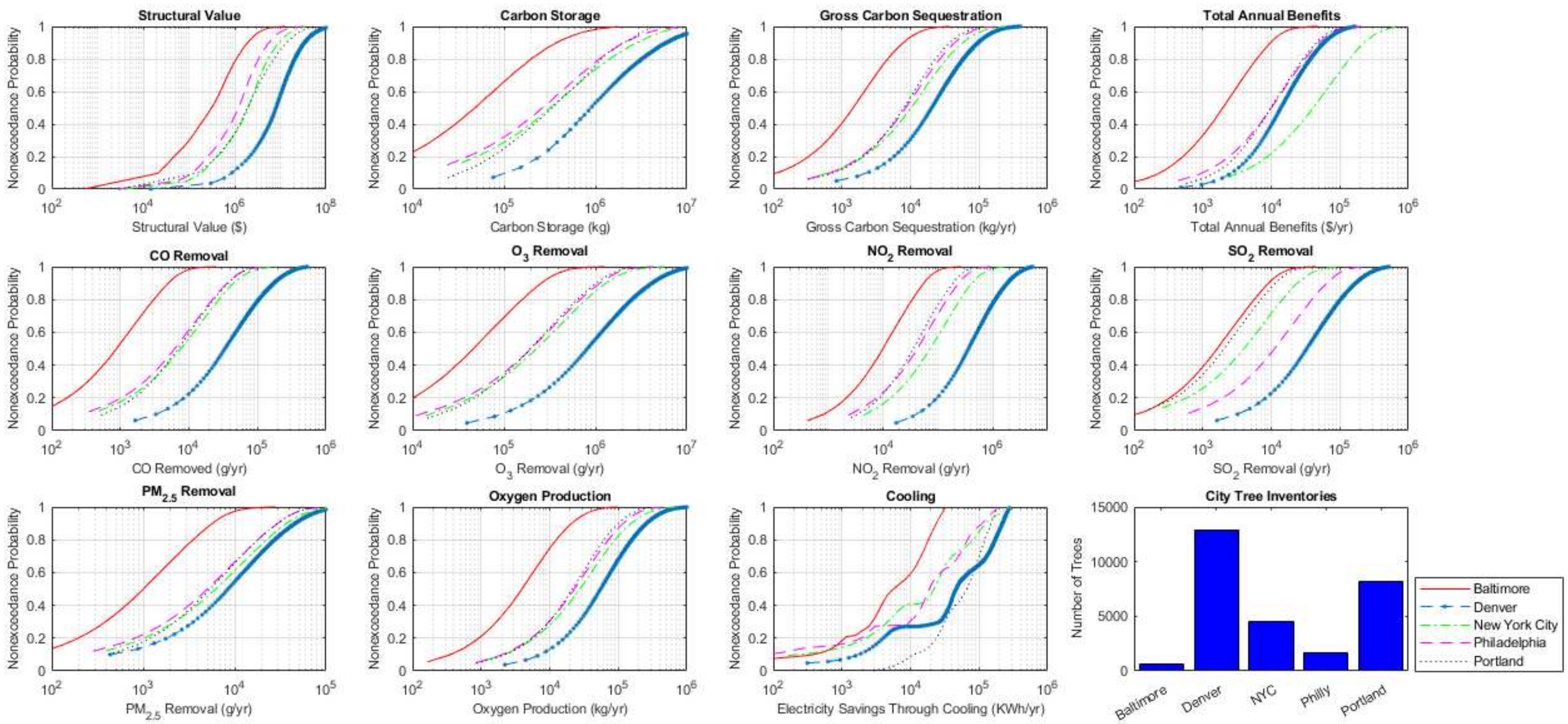
Appendix L: Median Co-benefits for all Cities



Appendix M: Boxplot of Municipal Level Co-benefits for all Cities



Appendix N: CDF of Municipal Level Co-benefits for all Cities



Appendix O: Tabular Co-benefit results

The following tables show the mean, median, 5th percentile and 95th percentile for the composite tree and the total amount of trees in each city's tree inventory. The composite tree is based on the frequency of tree species in each city. The composite tree is then multiplied by the number of trees in the SGI tree inventory to show the municipal level of SGI tree co-benefits.

Portland-Composite Tree

Co-benefits	Mean	Median	5th Percentile	95th Percentile
Structural Value ($)	1377.33	523.47	21.17	5749.15
Carbon Storage (kg)	270.66	79.10	2.60	1114.97
Gross Carbon Sequestration (kg/yr)	4.60	2.30	0.10	16.70
Total Annual Benefits ($/yr)	5.29	2.79	0.24	18.09
CO Removed (g/yr)	4.14	2.00	0.10	14.90
O_3 Removed (g/yr)	113.74	54.30	2.60	409.10
NO_2 Removed (g/yr)	20.74	9.90	0.50	74.60
SO_2 Removed (g/yr)	1.29	0.60	0	4.60
$PM_{2.5}$ Removed (g/yr)	3.24	1.50	0.10	11.70
Oxygen Production (kg/yr)	12.27	6.20	0.30	44.40
Cooling (KWh/yr)	23.39	19.61	0.38	58.28

Portland- All Trees

Co-benefits	Mean	Median	5^{th} Percentile	95^{th} Percentile
Structural Value ($)	1.13E+07	4.29E+06	1.74E+05	4.72E+07
Carbon Storage (kg)	2.22E+06	6.49E+05	2.13E+04	9.15E+06
Gross Carbon Sequestration (kg/yr)	3.77E+04	1.89E+04	8.20E+02	1.37E+05
Total Annual Benefits ($/yr)	4.34E+04	2.29E+04	1.97E+03	1.48E+05
CO Removed (g/yr)	3.40E+04	1.64E+04	8.20E+02	1.22E+05
O_3 Removed (g/yr)	9.33E+05	4.45E+05	2.13E+04	3.36E+06
NO_2 Removed (g/yr)	1.70E+05	8.12E+04	4.10E+03	6.12E+05
SO_2 Removed (g/yr)	1.05E+04	4.92E+03	0	3.77E+04
$PM_{2.5}$ Removed (g/yr)	2.66E+04	1.23E+04	8.20E+02	9.60E+04
Oxygen Production (kg/yr)	1.01E+05	5.09E+04	2.46E+03	3.64E+05
Cooling (KWh/yr)	1.92E+05	1.61E+05	3.15E+03	4.78E+05

Philadelphia- Composite Tree

Co-benefits	Mean	Median	5^{th} Percentile	95^{th} Percentile
Structural Value ($)	707.62	379.69	18.15	2606.30
Carbon Storage (kg)	240.55	82.35	1.30	1016.64
Gross Carbon Sequestration (kg/yr)	5.35	2.70	0.10	19.80
Total Annual Benefits ($/yr)	5.96	3.14	0.14	21.23
CO Removed (g/yr)	4.18	2.00	0	15.60
O_3 Removed (g/yr)	129.37	61.70	1.40	483.65
NO_2 Removed (g/yr)	27.70	13.20	0.30	103.56
SO_2 Removed (g/yr)	7.44	3.50	0.10	27.80
$PM_{2.5}$ Removed (g/yr)	3.42	1.60	0	12.80
Oxygen Production (kg/yr)	14.26	7.20	0.30	52.77
Cooling (KWh/yr)	32.87	17.12	0	103.12

Philadelphia- All Trees

Co-benefits	Mean	Median	5th Percentile	95th Percentile
Structural Value ($)	1.14E+06	6.10E+05	2.92E+04	4.19E+06
Carbon Storage (kg)	3.87E+05	1.32E+05	2.09E+03	1.63E+06
Gross Carbon Sequestration (kg/yr)	8.59E+03	4.34E+03	1.61E+02	3.18E+04
Total Annual Benefits ($/yr)	9.58E+03	5.05E+03	2.25E+02	3.41E+04
CO Removed (g/yr)	6.72E+03	3.21E+03	0	2.51E+04
O_3 Removed (g/yr)	2.08E+05	9.92E+04	2.25E+03	7.77E+05
NO_2 Removed (g/yr)	4.45E+04	2.12E+04	4.82E+02	1.66E+05
SO_2 Removed (g/yr)	1.20E+04	5.62E+03	1.61E+02	4.47E+04
$PM_{2.5}$ Removed (g/yr)	5.49E+03	2.57E+03	0	2.06E+04
Oxygen Production (kg/yr)	2.29E+04	1.16E+04	4.82E+02	8.48E+04
Cooling (KWh/yr)	5.28E+04	2.75E+04	0	1.66E+05

New York City- Composite Tree

Co-benefits	Mean	Median	5th Percentile	95th Percentile
Structural Value ($)	818.43	437.57	20.21	3062.12
Carbon Storage (kg)	230.82	70.30	1.00	1029.53
Gross Carbon Sequestration (kg/yr)	4.88	2.30	0.10	18.90
Total Annual Benefits ($/yr)	19.00	8.97	0.32	70.11
CO Removed (g/yr)	3.79	1.70	0	14.10
O_3 Removed (g/yr)	109.01	49.90	1.30	406.61
NO_2 Removed (g/yr)	34.97	16.00	0.40	130.46
SO_2 Removed (g/yr)	2.02	0.90	0	7.50
$PM_{2.5}$ Removed (g/yr)	3.10	1.40	0	11.60
Oxygen Production (kg/yr)	13.02	6.10	0.20	50.32
Cooling (KWh/yr)	24.20	12.36	0	89.62

New York City- All Trees

Co-benefits	Mean	Median	5th Percentile	95th Percentile
Structural Value ($)	3.73E+06	1.99E+06	9.21E+04	1.40E+07
Carbon Storage (kg)	1.05E+06	3.20E+05	4.56E+03	4.69E+06
Gross Carbon Sequestration (kg/yr)	2.23E+04	1.05E+04	4.56E+02	8.61E+04
Total Annual Benefits ($/yr)	8.66E+04	4.09E+04	1.46E+03	3.20E+05
CO Removed (g/yr)	1.73E+04	7.75E+03	0	6.43E+04
O_3 Removed (g/yr)	4.97E+05	2.27E+05	5.93E+03	1.85E+06
NO_2 Removed (g/yr)	1.59E+05	7.29E+04	1.82E+03	5.95E+05
SO_2 Removed (g/yr)	9.21E+03	4.10E+03	0	3.42E+04
$PM_{2.5}$ Removed (g/yr)	1.41E+04	6.38E+03	0	5.29E+04
Oxygen Production (kg/yr)	5.94E+04	2.78E+04	9.12E+02	2.29E+05
Cooling (KWh/yr)	1.10E+05	5.63E+04	0	4.08E+05

Baltimore- Composite Tree

Co-benefits	Mean	Median	5th Percentile	95th Percentile
Structural Value ($)	1137.57	494.46	18.15	4501.95
Carbon Storage (kg)	223.96	76.40	1.40	945.30
Gross Carbon Sequestration (kg/yr)	4.81	2.30	0.10	18.10
Total Annual Benefits ($/yr)	5.94	3.10	0.18	20.88
CO Removed (g/yr)	2.98	1.40	0.10	10.84
O_3 Removed (g/yr)	151.58	73.10	2.60	552.24
NO_2 Removed (g/yr)	32.69	15.80	0.60	119.10
SO_2 Removed (g/yr)	5.43	2.60	0.10	19.80
$PM_{2.5}$ Removed (g/yr)	3.39	1.60	0.10	12.40
Oxygen Production (kg/yr)	12.83	6.20	0.30	48.20
Cooling (KWh/yr)	40.66	24.51	0.10	115.12

Baltimore- All Trees

Co-benefits	Mean	Median	5^{th} Percentile	95^{th} Percentile
Structural Value ($)	7.26E+05	3.15E+05	1.16E+04	2.87E+06
Carbon Storage (kg)	1.43E+05	4.87E+04	8.93E+02	6.03E+05
Gross Carbon Sequestration (kg/yr)	3.07E+03	1.47E+03	6.38E+01	1.15E+04
Total Annual Benefits ($/yr)	3.79E+03	1.98E+03	1.15E+02	1.33E+04
CO Removed (g/yr)	1.90E+03	8.93E+02	6.38E+01	6.92E+03
O_3 Removed (g/yr)	9.67E+04	4.66E+04	1.66E+03	3.52E+05
NO_2 Removed (g/yr)	2.09E+04	1.01E+04	3.83E+02	7.60E+04
SO_2 Removed (g/yr)	3.47E+03	1.66E+03	6.38E+01	1.26E+04
$PM_{2.5}$ Removed (g/yr)	2.17E+03	1.02E+03	6.38E+01	7.91E+03
Oxygen Production (kg/yr)	8.19E+03	3.96E+03	1.91E+02	3.08E+04
Cooling (KWh/yr)	2.59E+04	1.56E+04	6.25E+01	7.34E+04

Denver- Composite Tree

Co-benefits	Mean	Median	5^{th} Percentile	95^{th} Percentile
Structural Value ($)	1097.7488	625.62	32.2585	3861.9265
Carbon Storage (kg)	184.7366	69.9	4.1	755.3
Gross Carbon Sequestration (kg/yr)	3.0491	1.6	0.1	10.9
Total Annual Benefits ($/yr)	1.8976	1.08	0.12	6.37
CO Removed (g/yr)	5.3249	2.7	0.1	19.4
O_3 Removed (g/yr)	127.3843	63.9	3.4	463.9
NO_2 Removed (g/yr)	56.3208	28.3	1.5	205.1
SO_2 Removed (g/yr)	5.2258	2.6	0.1	19
$PM_{2.5}$ Removed (g/yr)	1.4204	0.7	0	5.2
Oxygen Production (kg/yr)	8.1316	4.4	0.3	29
Cooling (KWh/yr)	20.5902	8.528	0.12	69.941

Denver- All Trees

Co-benefits	Mean	Median	5^{th} Percentile	95^{th} Percentile
Structural Value ($)	1.41E+07	8.06E+06	4.16E+05	4.98E+07
Carbon Storage (kg)	2.38E+06	9.01E+05	5.28E+04	9.73E+06
Gross Carbon Sequestration (kg/yr)	3.93E+04	2.06E+04	1.29E+03	1.40E+05
Total Annual Benefits ($/yr)	2.45E+04	1.39E+04	1.55E+03	8.21E+04
CO Removed (g/yr)	6.86E+04	3.48E+04	1.29E+03	2.50E+05
O_3 Removed (g/yr)	1.64E+06	8.23E+05	4.38E+04	5.98E+06
NO_2 Removed (g/yr)	7.26E+05	3.65E+05	1.93E+04	2.64E+06
SO_2 Removed (g/yr)	6.73E+04	3.35E+04	1.29E+03	2.45E+05
$PM_{2.5}$ Removed (g/yr)	1.83E+04	9.02E+03	0	6.70E+04
Oxygen Production (kg/yr)	1.05E+05	5.67E+04	3.87E+03	3.74E+05
Cooling (KWh/yr)	2.65E+05	1.10E+05	1.55E+03	9.01E+05

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