Measuring carbon sequestration in urban riparian areas: Method development and testing.

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Abstract

The Grow Zone Program was established in 2012 to remove mowing along creeks and allow riparian succession to proceed along them in City of Austin parks. Given that tree growth plays a role in mediating climate change by capturing atmospheric carbon and storing it as organic carbon biomass, quantifying carbon stored in local riparian areas is a key measure to document. The purpose of this study was to develop and test a repeatable methodology for quantifying carbon storage provided by this approach of riparian restoration. Baseline data were collected from Reference sites with no recent history of disturbance as well as Degraded sites undergoing restoration. The amount of carbon stored in Reference sites is higher than in Degraded sites. Although no significant additional carbon gains were documented in Degraded sites within the short term of two years of measurement, the expectation is that tree growth will continue accruing carbon to achieve similar values as undisturbed, Reference sites.

Introduction

In 2012 the Grow Zone Program was established with an agreement between the Parks and Recreation and the Watershed Protection Departments to remove mowing and allow forest growth along creeks in City of Austin (COA) parks. Both passive and active management are used in Grow Zones to encourage the growth and establishment of healthy riparian forests. This will contribute to the Imagine Austin Priority Programs 2 and 4: Sustainably Manage Our Water Resources and Use Green Infrastructure to Protect Environmentally Sensitive Areas and Integrate Nature into the City, respectively. In addition, healthy riparian areas should contribute to the Watershed Protection Department's (WPD's) Key Performance Indicators and Strategic Direction 2023 measures for miles of eroding stream channels restored and stabilized, tons of pollution removed annually from stormwater runoff, and number and percentage of creeks and lakes in good or excellent health.

The benefits of healthy riparian forests include improved water quality, water quantity and erosion protection. Stream banks are stabilized through root structure, rain energy interception and boundary roughness (Sweeney and Newbold 2014; Palmer et al. 2014; Allen et al. 2018). Water quality is improved through the filtering and processing of debris, nutrients and pollutants as stormwater and groundwater are routed through floodplain vegetation and soils (Boulware et al. 2002; Vidon et al. 2010; Weller et al. 2011). Other environmental co-benefits include moderation of surface water temperatures, stabilization of terrestrial/aquatic habitat and food webs, and carbon sequestration (Lovell and Sullivan 2006; Roy et al. 2006; Scoggins 2014). Urban benefits of healthy riparian forests include access to nature and its associated human health benefits, potential pedestrian corridors and cooler air temperatures (e.g., Bratman et al. 2011; Keniger et al. 2013).

Given that tree growth plays a role in mediating climate change by capturing atmospheric carbon and storing it as plant biomass, quantifying carbon stored in local riparian areas will provide insight on how much Austin riparian areas potentially contribute to the mediation of climate change. The purpose of this study was to develop and test a repeatable methodology for quantifying carbon storage provided by restoration at Grow Zones. Although WPD's Riparian Functional Assessment assesses vegetative succession and several other measures of ecological function (Duncan 2012; Duncan and Richter 2012), it did not include a protocol for quantifying the amount of carbon sequestration resulting from existing and newly established trees within Grow Zones. The U.S. Forest Service's (USFS) Forest Inventory and Assessment (FIA) program has developed an extensive set of species-specific allometric equations that can be used to compute tree volume, biomass, and carbon mass by identifying each tree to species, measuring tree height and diameter, and estimating the amount of volume missing/rotten and (if dead) the decay class (Domke et al. 2011; Woodall et al. 2011; Harmon et al. 2013; O'Connell et al. 2014). Using these equations, this study attempted to develop a reliable measure of average carbon sequestration per unit area in Grow Zones prior to restoration, as well as in Reference, undisturbed sites. In addition, this study attempted to develop a repeatable methodology appropriate for quantifying carbon in Austin's urban riparian forests so that WPD staff could monitor and track the carbon sequestration in WPD Grow Zone locations.

Methods

Site Description

Carbon Offset (CO) data were collected at Riparian Functional Assessment (RFA) locations (Figure 1). The RFA study (COA WPD Monitoring Project # 540) tracks the ecological function improvements of Degraded riparian sites undergoing facilitated restoration in relation to sites considered Reference. Reference sites are those still influenced by an urban context but with vegetation that has remained relatively undisturbed in the last 20+ years and which exhibited full canopy conditions in 1997 aerial photographs. Each RFA location consists of a 100m transect (measured down the center of the creek), with a total of six 10m-by-10m plots: laid out at 0m-10m, 45m-55m, and 90m-100m on both right and left banks (Figure 2). At each RFA location, CO data were collected at 3 of the 6 RFA plots where the following conditions were met:

1. The riparian zone was at least 5m (16.4 ft.) wide,
2. The plot did not contain significant artificial structures (bridges, concrete, etc.), and
3. The terrain was accessible to field staff.

The 3 RFA plots within each location were selected randomly prior to fieldwork, with adjustments as necessary if field conditions did not match the criteria listed above. If an RFA location did not have at least 3 plots that fit these criteria, it was removed from the study. The selected RFA plots were designated as the CO sites and will be subsequently referenced as sites. A full site list can be seen in Appendix A. For CO data collection, the boundaries of the sites were reoriented to start at bankfull and run 5m (16.4 ft) perpendicular and 20m (65.6 ft) parallel to the stream (Figure 2).

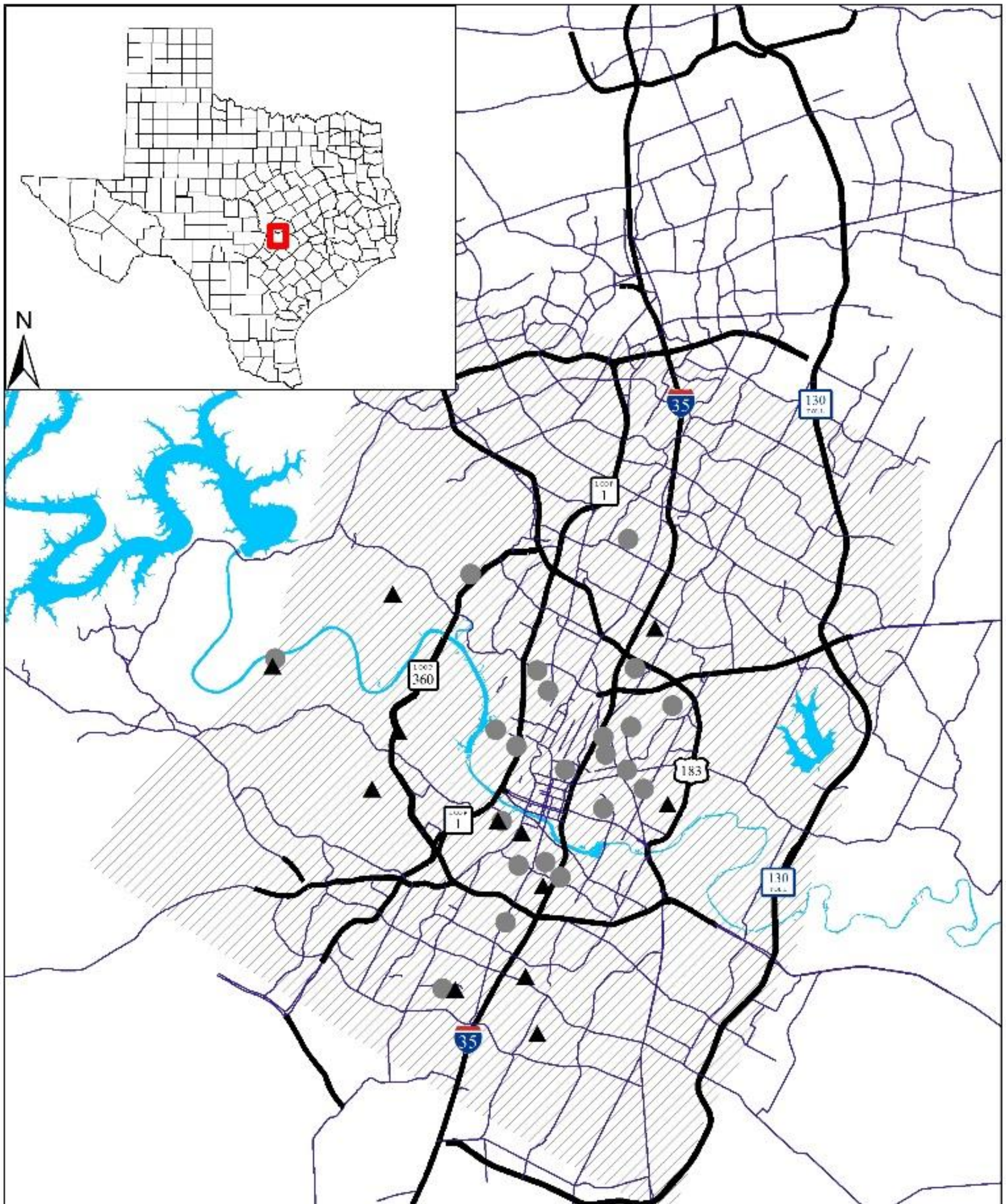

Figure 1. Map showing RFA Degraded locations sampled in even and odd years (gray dots), and Reference locations (black triangles) sampled every year.

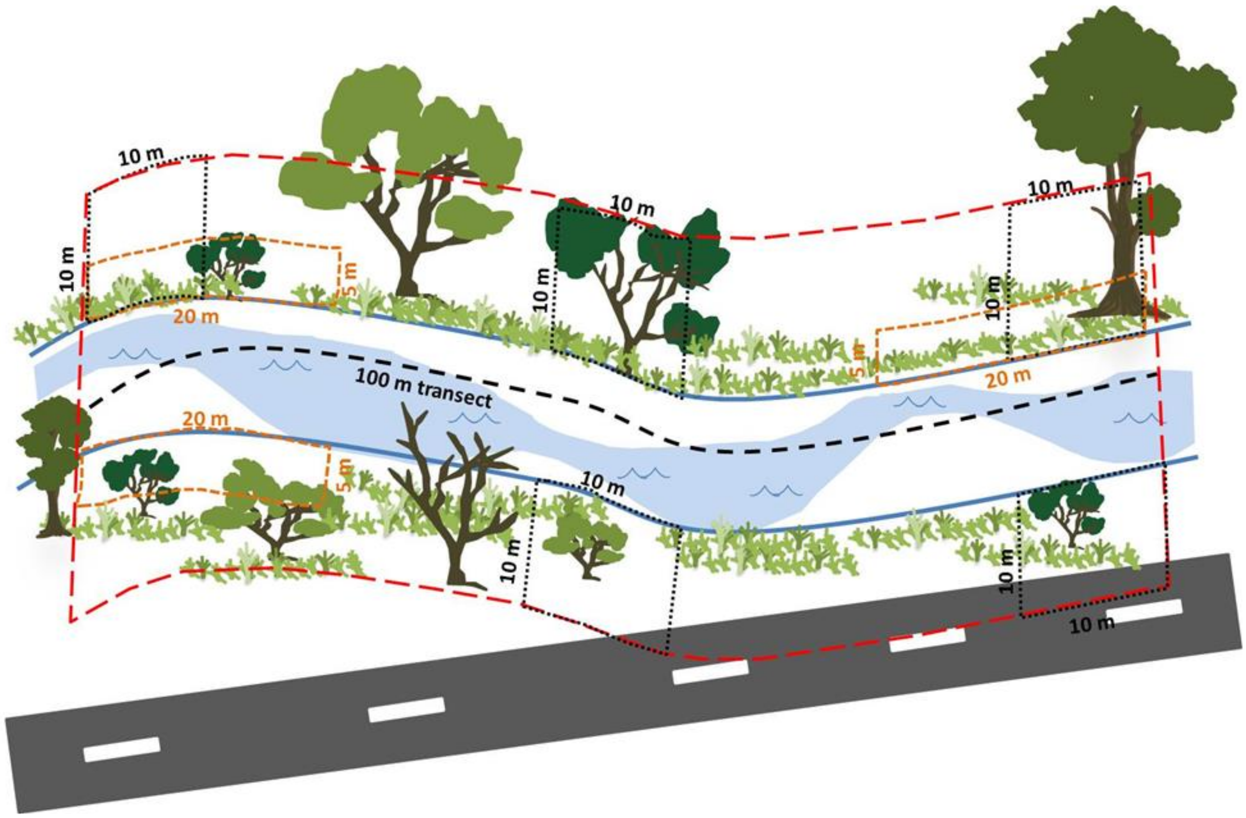

Figure 2. Example of three selected CO sites (dashed orange lines) located within the RFA sampling location (dotted red line). RFA plots are shown in black squares.

Sites were designated as either Reference, representing relatively undisturbed urban forest areas, or Degraded, representing areas that have been highly altered by human activities such as mowing. The drainage area category of each site was obtained from the publicly available COA GIS creek network, which coincides with the City's regulatory framework and contains the drainage area category as part of the attribute table (City of Austin 2019). Drainage area categories (in acres) are used in the City of Austin as drainage area thresholds at which certain regulations (e.g., creek buffers or Critical Water Quality Zones, CWQZ) apply: 0-64, 65-320, 321-640, and 641-1280 acres. In addition, the percent canopy of each 5m-by-20m site was calculated based on the COA GIS canopy cover 2014 layer using the zonal statistics tool with plots as zones. Each site attribute can be seen in the full site list within Appendix A.

Data Collection

An initial phase of data collection for this project occurred in November 2013; however, data collection following the methods described in this report began in the spring of 2015. Data collected prior to 2015 are substantially different from the current dataset due to differences in sampling methods. As such, this report shall cover data collected from 2015 through 2018. CO data was collected from Reference sites in 2015 to establish an estimate of the amount and variation of carbon that restored sites might be expected to achieve. Due to time constraints, Degraded sites were split into two groups and sampled in alternating years. Roughly half of the Degraded sites were sampled in 2015 and 2017 while the other half were sampled in 2016 and 2018 (Appendix A).

Within each 5m-by-20m (100-m^2, 0.02 acre) site, live and standing dead trees were measured. Small shrubs and woody vines were not measured, since only tree species are currently proposed for carbon sequestration measurement. USFS's FIA program does not define the difference between "tree" and "shrub" (U.S. Forest Service 2014); for our surveys we included all woody species whose mature height is 4.6m (15 ft.) or greater (USDA NRCS 2014). Per the USFS FIA program directives, we included only native species since management plans often target non-native species for removal and thus carbon accrued cannot be credited because it may not be permanently stored. However, sites may contain substantial numbers of invasive species which would contribute to additional carbon sequestration not accounted for within this study.

Tree Measurements

Tree measurements followed the standards established by the USFS's FIA program (U.S. Forest Service 2014). All FIA equations for tree volume and biomass depend on the data being entered in U.S. customary units (inches and feet), rather than metric units (Woodall et al. 2011). Our field measurements were recorded in metric units, and then converted into U.S. customary units for computations. Biomass and carbon mass results in pounds were then converted to kilograms and metric tonnes (1,000 Kg or ~2204 lb) for reporting. Forest carbon stocks are customarily reported in metric tonnes per hectare (International Panel on Climate Change 2006; U.S. Environmental Protection Agency 2012).

Many western North American woodland tree species have multiple stems and are very slow growing, thus the allometric growth formulas are very different for woodland species than for timber species (Woodall et al. 2011). In the Austin area, species designated as "woodland" (Woodall et al. 2011) include *Juniperus ashei* (Ashe juniper), *Vachellia farnesiana* (sweet acacia), *Prosopis glandulosa* (honey mesquite), and *Condalia hookeri* (bluewood). All other non-woodland tree species are considered "timber" species (Domke et al. 2011).

In addition, the method of measuring tree characteristics differs for timber versus woodland tree species. We only collected data from trees and large shrubs that met the following minimum criteria:

Species Type	Status	Height	Cumulative DBH	
Timber	Living	1.4 m (4.5 ft.)	2.5 cm (1 in.)	
	Dead	1.4 m (4.5 ft.)	12.7 cm (5 in.)	leaning < 45 degrees from vertical

Species Type		Height	Diameter at 0.3 m height
Woodland	Living/Dead	0.3 m (1 ft.)	2.5 cm (1 in.)

Timber Species: Diameter at Breast Height (DBH) Measurement

In the United States, DBH is defined as the average stem diameter, outside bark, at 1.4 m (4.5 ft.) above the ground on the high side of the tree. For consistent measurement, the diameter tape must be level and pulled taut. For trees with swellings, deformities, or branches that occur at 1.4 m (4.5 ft.) above the ground, the DBH is measured above the irregularity, where the normal stem shape ceases to be affected. DBH measurements for timber species with multiple trunks followed USFS'S FIA 2014 protocol.

Woodland Species: Diameter at Root Collar (DRC) Measurement

Many western woodland tree species, such as Ashe juniper and mesquite, have multiple stems and are very slow growing. Clumps of stems with a single crown and common above-ground root stock are measured as a single tree (U.S. Forest Service 2014). For these species, Diameter at Root Collar (DRC) is measured at the ground line or stem root collar, whichever is higher.

For a single-stemmed woodland tree, the DRC is equal to the single diameter measured, to the nearest centimeter. For a multi-stemmed woodland tree, DRC is computed as the square root of the sum of the squared stem diameters.

$$DRC = \sqrt{\sum stem\ diameter^2}$$

Height Measurement
Total height for all measured trees was recorded to the nearest 0.1m (4 in.). For shorter trees, total tree height was measured directly, with the use of a stadia telescoping rod or tape measure. For taller trees, we used either a rangefinder or measuring tape to measure distance to tree and a clinometer to estimate the height as a percent of that distance, or we visually estimated tree height based on known-height metrics.

Tree Status
Live: Trees were considered alive if they had any living parts (leaves, buds, or cambium) at or above the diameter measurement (DBH or DRC) (U.S. Forest Service 2014).

Dead: To be counted as a standing dead tree (U.S. Forest Service 2014), dead timber trees were required to:

1) have a DBH of at least 12.7cm (5.0 in.),
2) have a bole of unbroken length of at least 1.4m (4.5 ft.), and
3) lean less than 45 degrees from vertical.

For woodland species with multiple stems, a dead tree was considered standing if at least 1/3 of the volume was still attached or upright (not including cut or removed volume). For woodland species with single stems to qualify as a standing dead tree (U.S. Forest Service 2014), dead trees were required to:

1) have a diameter of at least 12.7cm (5.0 in.),
2) have an unbroken length of at least 0.3m (1.0 ft.), and
3) lean less than 45 degrees from vertical.

Dead standing trees did not have to be self-supported. They may have been supported by other trees, branches, or their crown (U.S. Forest Service 2014).

Rotten and Missing Volume
For live and dead trees >= 12.7cm (5 in.) DBH or DRC, we recorded the percentage of rotten and missing volume on the merchantable bole/portion of the tree (from a 0.3m (1 ft.) stump to a 10cm (4 in.) diameter top) to the nearest 5 percent. For woodland species, the merchantable portion is between the point of DRC measurement to a 4cm (1.5 in.) diameter top (U.S. Forest Service 2014).

For live saplings < 12.7cm (5 in.) DBH or DRC, we recorded the percent of rotten and missing whole-sapling volume, to the nearest 5 percent.

Decay Class
For all standing dead trees, we used Table 1 to categorize the tree by decay class.

Table 1. Standing woody debris decay class descriptions (U.S. Forest Service 2014).

Decay class stage (code)	Limbs and branches	Top	% Bank Remaining	Sapwood presence and condition*	Heartwood condition*
1	All present	Pointed	100	Intact; sound, incipient decay, hard, original color	Sound, hard, original color
2	Few limbs, no fine branches	May be broken	Variable	Sloughing; advanced decay, fibrous, firm to soft, light brown	Sound at base, incipient decay in outer edge of upper bole, hard, light to reddish brown
3	Limb stubs only	Broken	Variable	Sloughing; fibrous, soft, light to reddish brown	Incipient decay at base, advanced decay throughout upper bole, fibrous, hard to firm, reddish brown
4	Few or no stubs	Broken	Variable	Sloughing; cubical, soft, reddish to dark brown	Advanced decay at base, sloughing from upper bole, fibrous to cubical, soft, dark reddish brown
5	None	Broken	Less than 20	Gone	Sloughing, cubical, soft, dark brown, OR fibrous, very soft, dark reddish brown, encased in hardened shell

*Characteristics are for Douglas-fir. Dead trees of other species may vary somewhat. Use this only as a guide.

<u>Data Management</u>

Computations of tree biomass and carbon followed the standards established by the U.S. Forest Service's FIA program. For trees of timber species having DBH >=12.7cm (5 in.), FIA estimates tree biomass using the Component Ratio Method (Zhou and Hemstrom 2009; O'Connell et al. 2014).

The following sites were dropped from the data set prior to any analysis:

- Sites 11174, 11176, and 11177 - Sites within Eanes Creek at Zilker Disc Golf were Degraded sites that were dropped from this study because restoration plans could not be secured and management of the sites continues to include mowing.
- Sites 11256 - South Boggy @ Latteridge and Almondsbury (90mLB) and 11220 - West Bull @ Long Canyon (90mLB), initially categorized as Reference, were dropped from this study because they were found to be Degraded after further field evaluation.
- Site 11289 - Blunn Creek @ Rosedale (90mRB) was initially categorized as a Degraded site that was initially sampled in 2015 but found to have Reference conditions; therefore, the site was substituted by site 11290 – Blunn Creek @ Rosedale (90mLB) for the sampling event in 2017 because it was consistent with the definition of Degraded undergoing restoration.
- Site 11203 –Little Walnut Creek @ Dottie Jordan Park (10mRB) and Site 11207 – Little Walnut Creek @ Dottie Jordan Park (90mRB) were categorized as Degraded and initially sampled in 2015; however, the sites were substituted by 11204 – Little Walnut Creek @ Dottie Jordan Park (10mLB) and 11208 – Little Walnut Creek @ Dottie Jordan Park (90mLB) for the sampling event in 2017 because the active bank erosion was deemed too dangerous to access them.
- Site 11212 – Bull Creek @ Bull District Park (Lakewood Dr) (50mLB) was a Degraded site that was initially sampled in 2015; however, the site was switched to 11213 – Bull Creek @ Bull

District Park (Lakewood Dr) (90mRB) for the sampling event in 2017 because restoration efforts were occurring only on the right bank.

- Site 11216 - West Bull @ Long Canyon and Standing Rock (10mLB) was a Reference site that was initially sampled in 2015; however, after field evaluation it was concluded that the site did not conform to Reference conditions.

In addition, data collection issues arose during the 2018 sampling event which led to multiple sites left unsampled for the year: field data collector issues, staffing constraints in mid fall of 2018, and the beginning of leaf-off season ended RFA (and carbon offset) data collection for the year (Table 2). These sites were removed from the dataset prior to performing temporal analyses.

Table 2. List of sites that were not sampled in 2018.

Site #	**Site Name**	**Source of Error**
13645	SHL Trib @ Crestmont (10m RB)	field data collector issues
13646	SHL Trib @ Crestmont (50m RB)	field data collector issues
13647	SHL Trib @ Crestmont (90m RB)	field data collector issues
13648	SHL @ Shady Oak Court (10m LB)	Staffing, beginning of leaf off season
13649	SHL @ Shady Oak Court (50m LB)	Staffing, beginning of leaf off season
13650	SHL @ Shady Oak Court (90m LB)	Staffing, beginning of leaf off season
13672	TYS in Reed Park @ Footbridge (10m LB)	Staffing, beginning of leaf off season
13673	TYS in Reed Park @ Footbridge (50m LB)	Staffing, beginning of leaf off season
13674	TYS in Reed Park @ Footbridge (90m RB)	Staffing, beginning of leaf off season
13678	EBO @ Gillis Gabion (10m RB)	Staffing, beginning of leaf off season
13679	EBO @ Gillis Gabion (90m RB)	Staffing, beginning of leaf off season
13680	EBO @ Gillis Gabion (90m LB)	Staffing, beginning of leaf off season

Data Analysis

Carbon and biomass are calculated per individual tree, so the initial step was to sum carbon and biomass from each individual tree within a site followed by calculating a total carbon and total biomass for each location.

Develop a Reliable Measure of Average Carbon/ Unit Area

To develop reliable estimates of carbon storage in trees, staff first attempted to discern if any variables contributed to significant differences in the average carbon per unit area. A generalized linear model was built in SAS9.4 using PROC GENMOD to determine if the total carbon within a site was dependent on the condition (Reference, Degraded) or drainage area category (1 = 0-64, 2 = 65-320, 3 = 321-640, 4 = 641-1280 acres). Total carbon is a positive, continuous variable with a long tail in the distribution which supports the use of either a lognormal distribution or gamma distribution for modeling in order to obtain better parameter estimates when compared to a normal distribution (McGill et al. 2006). Thus, a generalized linear model was used and not a linear model which would assume that the distribution of total carbon was normal. Drainage area category and site condition were treated as classification levels within the model while the total carbon was modeled assuming a gamma distribution. An alpha level of 0.05 was used to determine the statistical significance of site condition and drainage area category on total carbon.

Locally estimated scatterplot smoothing (LOESS) regression was used to examine the effect of percent canopy at a site on the total carbon using PROC LOESS in SAS9.4. LOESS is a nonparametric regression technique used to capture general patterns in noisy, non-linear data (Cleveland 1979).

Monitor and Track Carbon Sequestration
The amount of carbon sequestered within each site during the study period was calculated by subtracting the total carbon in the site during the initial visit from the total carbon in the site during the follow-up visit. This equates to the amount of carbon a site might sequester in a two-year period. The distribution of the differences was shown to be close to normal and a general linear model was built in SAS9.4 using PROC GLM to estimate the average difference in total carbon from the initial visit to the follow-up visit. A second model incorporated the percent canopy cover in 2014 to determine if the temporal difference was dependent on the canopy cover at the beginning of restoration.

The amount of carbon sequestered at each site was depicted graphically. A summary of the tree species found in each site along with the amount of carbon related to that species can be seen in Appendices B and C.

Results and Discussion
Develop a Reliable Measure of Average Carbon/ Unit Area
To develop reliable estimates of carbon storage in trees, staff first attempted to discern if any variables contributed to significant differences in the average carbon per unit area. As described in the methods above, the variables considered included site condition, drainage area, and percent canopy cover. There was a significant difference in average total carbon stored based on the site condition ($p = 0.002$). Reference sites contained an average of 2,264.42 g/100 m^2 of carbon (95% confidence interval of the mean 1,480.07-3,464.44 g/100 m^2) while Degraded sites contained an average of 904.49 g/100 m^2 of carbon (95% confidence interval of the mean 610.96-1,339.04 g/100 m^2) (Figure 3). The total carbon was not significantly different between the different drainage area categories ($p > 0.26$) and does not appear to be an important variable to consider when developing an average carbon sequestration per unit area estimate (Figure 4).

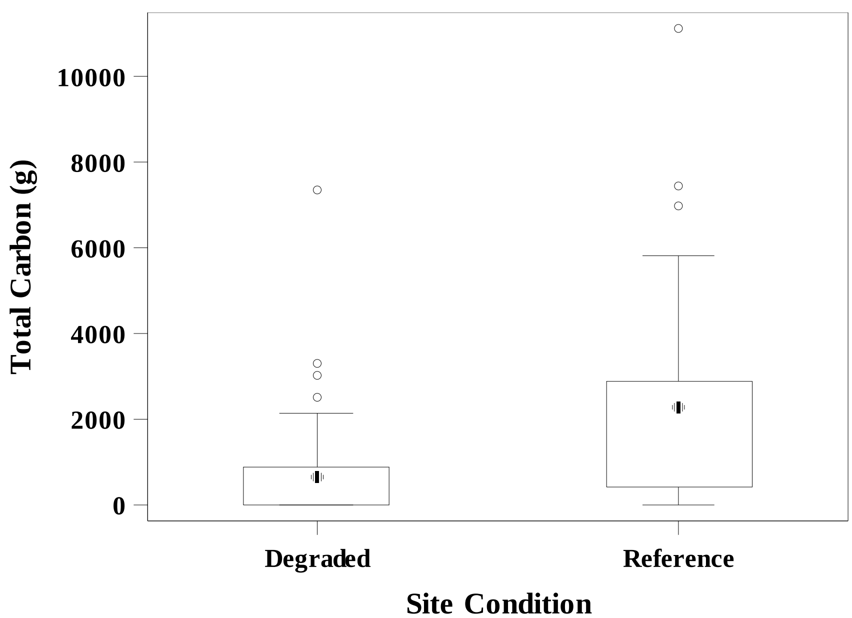

Figure 3. Boxplot of total carbon (g/100m^2 site) at Degraded and Reference sites

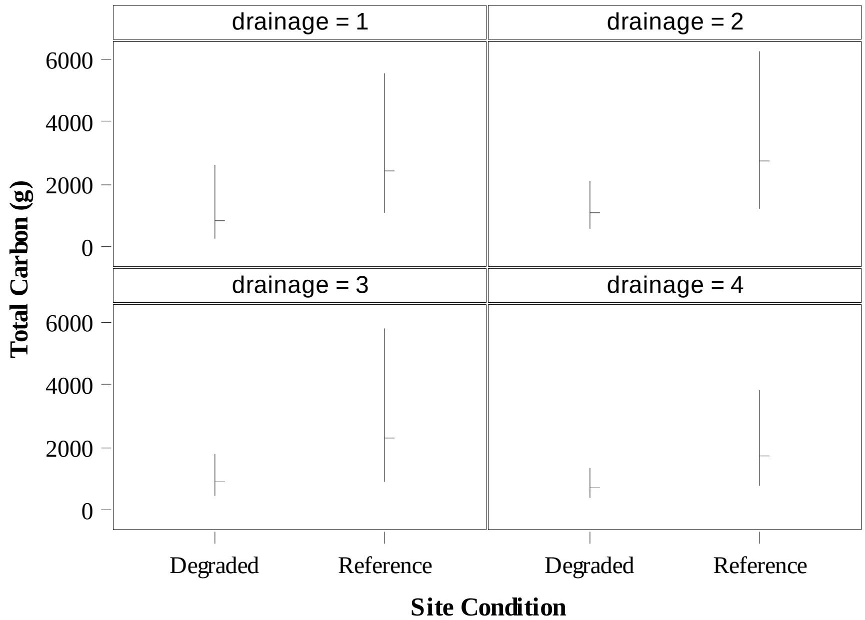

Figure 4. Plot of total carbon (g/100m²site) at Degraded and Reference sites within each drainage area category (1 = 0-64, 2 = 65-320, 3 = 321-640, 4 = 641-1280 acres). Vertical bars represent the 95% confidence interval of the mean and the horizontal tick marks represent the estimated mean total carbon within each drainage category and site condition.

Canopy cover ranged from 0-100 % in the Degraded sites while the canopy cover was always over 80% in the Reference sites (Figure 5). The mean total carbon in the Degraded sites was not significantly more than 0 for the majority of the range of GIS-measured canopy cover; however, the LOESS regression indicated that total carbon was higher in Degraded sites as percent canopy cover approached 100% GIS-measured canopy cover. The total carbon in Reference sites was highly variable and there was no clear correlation between percent canopy cover and total carbon at a site (Figure 5). Variation in total carbon among sites is likely impacted by the presence and abundance of non-native invasive woody species which were not accounted for in this study. Examination of the RFA data shows that *Ligustrum lucidum* dominates the understory in some of Reference sites. Because this study does not account for carbon stored in non-native species, their presence at a site would lead to increased variability of carbon among sites with relatively similar values of canopy cover. There is some evidence that GIS canopy cover could be an important variable when developing estimates of carbon per unit area in Austin; however, additional sampling which includes non-native invasive woody species may be needed to lower the variability of carbon estimates seen in the current data prior to developing an accurate model.

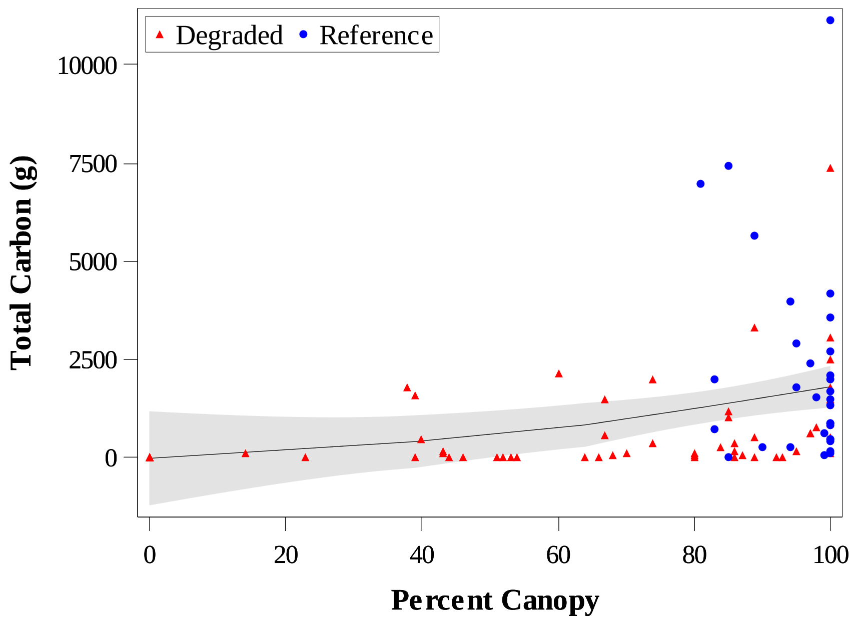

Figure 5. Total carbon (g)/100m^2 site versus the percent canopy cover at each site location. Triangles represent site considered to be Degraded while circles represent Reference condition sites. The black line is a LOESS regression line using data from both Degraded and Reference sites. The gray band is the 95% confidence interval of the LOESS regression.

In addition, the amount of carbon stored at a site depended on what species of trees were present. Each species of tree within the study had a different carbon per unit area (Table 3) with *Juniperus ashei*, *Platanus occidentalis*, *Ulmus crassifolia*, and *Carya illinoinensis* having the greatest grams of carbon per square meter in sites under Reference conditions while *Carya illinoinensis*, *Ulmus crassifolia*, *Quercus fusiformis*, and *Salix nigra* had the greatest grams of carbon per square meter in sites under Degraded conditions. Thus, sites which contained these tree species typically had higher amounts of carbon storage than sites which did not contain these species.

Table 3. List of all species found within the initial visits to Degraded and Reference sites in this study. The total count of each species within Degraded/Reference sites is given along with the grams of carbon per square meter of each species.

Species Name	Degraded		Reference	
	Count	Carbon/m^2	Count	Carbon/m^2
Juniperus ashei	0	0.0000	14	11.2279
Platanus occidentalis	2	0.0162	4	2.6538
Ulmus crassifolia	8	1.8069	19	2.5631
Carya illinoinensis	12	2.4699	10	1.8271
Quercus fusiformis	2	1.6231	2	0.7821
Salix nigra	11	1.2182	4	0.7599
Celtis spp.	7	0.2963	14	0.7494
Ulmus americana	6	0.0692	5	0.5643
Populus deltoides	1	0.0771	1	0.5465
Quercus texana	0	0.0000	2	0.2996
Ilex vomitoria	0	0.0000	6	0.2239
Fraxinus spp.	21	0.9033	12	0.2051
Morus spp.	6	0.1331	2	0.1927
Acer negundo	3	0.0094	7	0.0964
Fraxinus texensis	0	0.0000	2	0.0944
Ilex decidua	0	0.0000	5	0.0385
Juniperus virginiana	0	0.0000	3	0.0384
Taxodium distichum	1	0.0031	2	0.0365
Diospyros texana	0	0.0000	7	0.0346
Maclura pomifera	1	0.0365	2	0.0196
Juglans nigra	2	0.0223	2	0.0126
Ungnadia speciosa	0	0.0000	2	0.0093
Garrya ovata ssp. lindheimeri	0	0.0000	2	0.0063
Viburnum rufidulum	0	0.0000	1	0.0040
Acacia farnesiana	3	0.0149	2	0.0036
Cornus drummondii	1	0.0043	3	0.0035
Unknown tree species	0	0.0000	1	0.0028
Aesculus pavia	0	0.0000	1	0.0021
Catalpa speciosa	3	0.0856	1	0.0012
Ptelea trifoliata	0	0.0000	2	0.0011
Cercis canadensis var. texensis	2	0.0006	1	0.0002
Sideroxylon lanuginosum	0	0.0000	1	0.0002
Celtis occidentalis	5	0.1121	0	0.0000
Morus rubra	9	0.0534	0	0.0000
Parkinsonia aculeata	1	0.0021	0	0.0000
Prunus mexicana	1	0.0002	0	0.0000
Sapindus saponaria var. drummondii	1	0.0028	0	0.0000

Monitor and Track Carbon Sequestration

In order to track how much carbon accrued at Degraded sites within a short time span (2 years), staff visited each Degraded site in a follow-up visit in 2017-2018. The same method used in the initial site visit was used in the follow-up visit with the goal of determining if a significant amount of carbon had accrued. There was no significant increase in total carbon from the initial visit of a Degraded site (2015-2016) compared to the follow up visit (2017-2018) ($p = 0.5648$). The estimated difference in total carbon was 172.7 g of carbon/100 m^2 (95% confidence interval of the mean -81.6 to 427.0 g/100 m^2). In addition, the amount of GIS-measured canopy cover present at the site during 2014 did not have a significant effect on the difference in carbon between the site visits ($p = 0.9612$) (Figure 6).

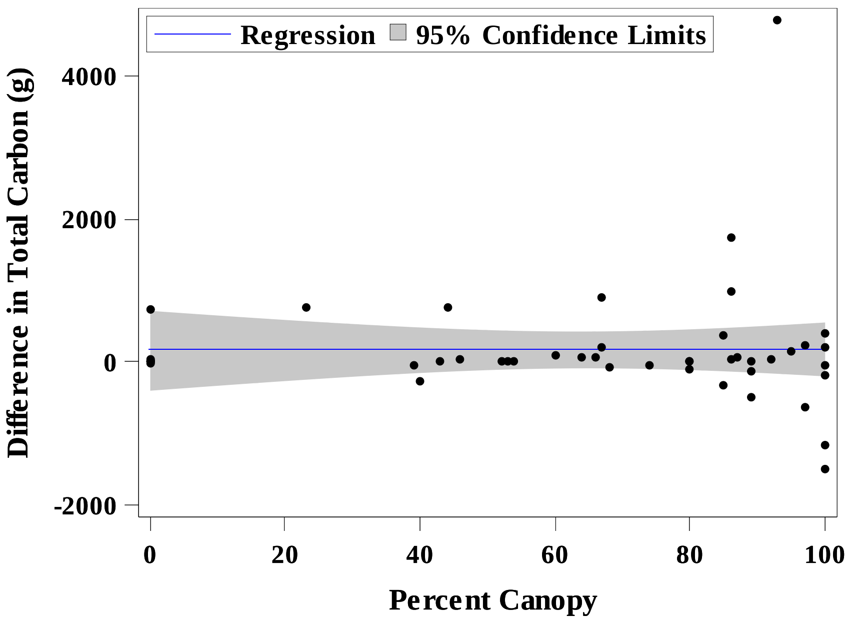

Figure 6. Difference between 2017-2018 and 2015-2016 calculated total carbon (g/100m^2 site) along a percent canopy gradient.

All Degraded sites experienced natural recruitment of trees and shrubs while some sites received supplemental tree sapling plantings. These saplings take about four to five years to reach the minimum size to have been included in the carbon protocol measurements (2.5 cm DBH) and were not likely represented in these data. Growth of all individuals within a site, not just planted individuals, in two years was thought to be small; however, if there was some recruitment from the understory in most sites and each individual tree that was sampled in the initial visit grew any in the two-year time frame then it was thought that this could lead to a small, significantly positive accrual of carbon.

In the data, some sites experienced losses of carbon between the initial and follow-up sampling (e.g. 11246 and 11248) which is the most likely reason we did not see a significant increase in carbon (Figure 7). Field measurement errors account for some of these discrepancies. Some trees had DBH estimated rather than directly measured with a DBH tape due to poison ivy access barriers. A larger problem was that sites could not be laid out in exactly the same location for the follow-up visit. Therefore, a tree that may have been within the site in the initial year may have not been in the follow-up data collection or vice versa. Case in point, site 11246 contained an individual *Carya illinoinensis* that was 65 cm DBH in 2015 but only had an individual with a 50 cm DBH in 2017. This is most likely not the same individual. Site 11248 contained an individual *Carya illinoinensis* that was 49.5 cm DBH in 2015 but no trees were recorded for the site in 2017. It was not noted that the tree was removed or fell and it is thought that the site location just did not have the same individual within the sample area. Site 11197 is an example of the opposite trend. In 2015, this site contained no trees; however, in the follow up sample just two years later, a *Carya illinoinensis* with a 54.3 cm DBH was reported. Trees do not grow this quickly and it must be the case that the site locations were different between the sampling events. This is a weakness of the field methods of this study, especially given the ratio of site edge relative to the internal area in a 5m-by-20m site. Nevertheless, it was not feasible to have better site configuration given the linear and narrow nature of the riparian corridors where restoration is taking place.

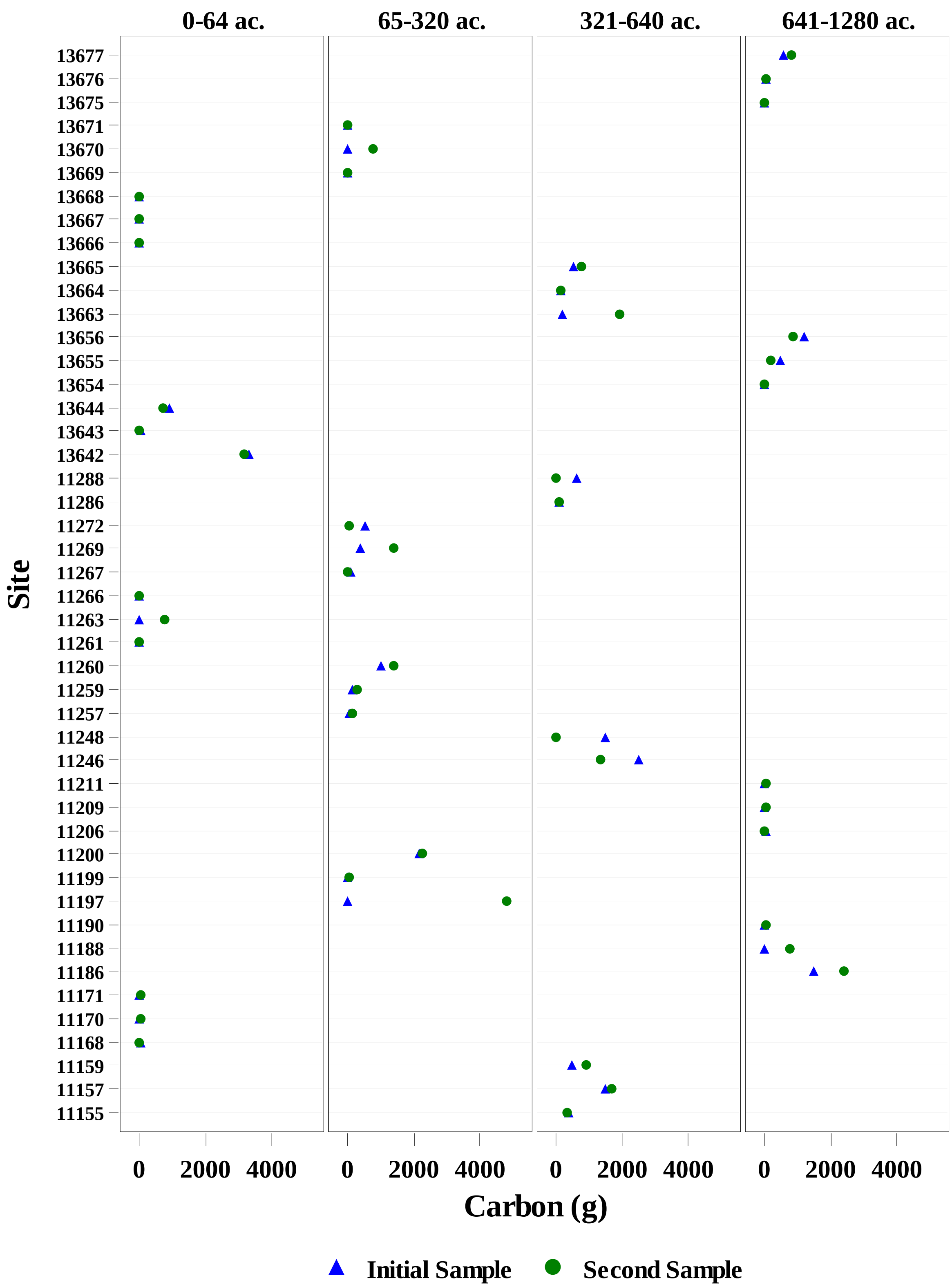

Figure 7. Difference in grams of carbon per 100 m² site in the initial site visit vs the follow-up site visits two years later for each Degraded site.

Conclusions

Reference sites have significantly larger amounts of carbon stored when compared to Degraded sites given the higher density of mature trees present. The expectation is that, over time, Degraded sites undergoing restoration within the Grow Zone Program will achieve similar vegetation structure dominated by mature trees as Reference sites and thus accrue similar amounts of carbon as held in Reference sites. The average carbon stored in Reference sites was 2,264.42 g/100 m^2. In many climate change discussions, carbon dioxide or carbon dioxide equivalent is referenced as metric tons. In this context, average carbon stored in Reference sites was 0.002264 metric tons/100 m^2. Thus, 44,161.42 m^2 of Reference condition riparian area is needed to store one metric ton of carbon. This equates to 0.017 square miles or 10.9 acres (Yao et al. 2012; Liu et al. 2016). However, there is high variability around this average carbon stored likely due to different species composition among reference sites but also due to the presence and dominance of invasive non-native species in some Reference sites (because only native species' carbon is counted per the study's protocol, sites dominated by invasive non-native species are likely to have lower total carbon reported).

It may take a few decades for a Degraded site to achieve a vegetative structure similar to that of a site under Reference conditions (Matzek et al. 2016; Dybala et al. 2018; Dybala et al. 2019) and, as noted in this study, large amounts of carbon do not seem to be stored in short time frames (2 years). Based on growth rates of other *Juniperus* species (Mcpherson et al. 2016), it may take 15 to 20 years for an individual to grow to a size equal to that of trees in Austin Reference sites. Similar time frames existed for *Platanus* species while time frames of 10 to 15 years were estimated for *Ulmus* species and *Quercus* species to reach the DBH present in Reference sites (Mcpherson et al. 2016). Assuming linear growth rates of the trees and the average carbon in Reference sites of 2,264.42 g/100 m^2, an annual accrual of carbon might be 113 to 151g/100 m^2 with a time from of 15 to 20 years, respectively. These two values are higher than the average annual accrual rate from this study (172.7 g/100 m^2 every two years); however, recall that the follow-up site visits may not have actually sampled the same site location and it is difficult to extrapolate accurate accrual rates from this data set. Many linear equations exist which predict the DBH of a tree from its age so the assumption that this is a linear transition may not be wrong; however, there are also equations which use a log-log, quadratic, or cubic relationship. Putting the growth rates into the context of mitigating efforts for carbon emissions and climate change, and assuming the higher sequestration rate of 151 g/100 m^2 annually, 662,251.7 m^2 of Degraded riparian area would need to undergo restoration to capture one metric ton of carbon each year. This equates to 0.256 square miles or 163.65 acres. Restoring riparian areas as forested corridors may constitute one among many tools for supporting carbon neutrality goals in the City of Austin if conducted at relevant scales along the entire creek network over the long term. Efforts to protect the already forested corridors will help ensure the carbon stored in these areas remains sequestered.

The Grow Zone program described in this paper and others (Gonzalez and Richter 2014; Gonzalez and Richter 2015) promotes forest growth along creeks located on land owned by the City of Austin; currently 237.9 acres of land are part of the Grow Zone program. However, most riparian zones within the City are located on private land: 83% of the total area established as regulatory creek buffers (CWQZ) is private. When broken out by jurisdiction type, private ownership constitutes 71% of the total CWQZ area within the city limits (full purpose jurisdiction) and 95% of the total CWQZ area in the extraterritorial jurisdiction (ETJ). The amount of canopy cover along CWQZ is contrasting between the two ecoregions, Eastern Edwards Plateau and the Blackland Prairie: Eastern Edwards Plateau CWQZ have higher canopy cover values than those of the Blackland Prairie. Protection of Edwards Plateau CWQZ areas from canopy loses would support securing the carbon accrued in those areas. The Blackland Prairie ecoregion has generally low levels of canopy cover along their creeks given the mostly agricultural and pastureland land use often encroaching to the top of creek banks thus representing carbon accrual potential if reforested.

Watershed regulations apply within the city limits and ETJ and prohibit most development within the CWQZ. However, general landscape maintenance—including mowing, gardening, and tree care—is not defined as development by the Land Development Code and is thus allowed in riparian areas. Watershed regulations also prohibit large-scale clearing of dense vegetation, but there is currently no proactive inspection or enforcement of this provision for private development once permitted development projects are complete. Enforcement of this provision relies on complaint-based investigations, which typically occur only after vegetation clearing has occurred. In addition, tree regulations also prohibit the removal of protected and heritage trees, but these regulations only apply to projects within the city limits and rely on complaint-based investigations for enforcement over time. Finally, existing development regulations do not require vegetation in the CWQZ to be restored if current conditions are Degraded thus providing no mechanism to address potential restoration of these creek buffers within the framework of development activities.

To maximize the amount of carbon sequestered and achieve relevant scales of restoration on private land, the City could consider strengthening watershed regulations to restrict mowing and allow establishment trees and shrubs within the CWQZ; developing a proactive inspection program to monitor riparian zones over time; extending tree regulations to the extra-territorial jurisdiction; and/or creating an incentive programs similar to the Grow Zone program to encourage private landowners to restore Degraded riparian areas. Any regulatory changes would need to be developed in coordination with public stakeholders, other City departments, and policymakers. In addition, any proposed changes to the tree regulations would need to be led by the City Arborist. Beyond development regulations, programmatic approaches to incentivize preservation of existing wooded floodplains and CWQZs and restoration of those without a forested plant community can help achieve additional carbon storage gains.

Monitoring carbon accrual based on field measurements is time intensive and not feasible at the scale of the entire City of Austin jurisdiction. To work appropriately, it is imperative to sample the same site location and individual trees over long time periods to accurately track the amount of carbon sequestered at a site. This adds a level of complexity to field measurements as tagging a tree may not be appropriate for a growing tree and less permanent flagging can be lost. Although substantial variation can be introduced with GIS-based monitoring of sites, this method may provide a surrogate for more field-intensive methods at larger scales, and merits further evaluation and testing.

Recommendations

- Given the substantial field effort required to measure individual tree stems and the inherent difficulty of scaling up this method for substantially large areas like those targeted for riparian restoration, we recommend evaluating an alternative GIS based quantification which might consider both canopy cover and tree species. Existing canopy verification methods are used by organizations like City Forest Credits (City Forest Credits 2018).
- If it is desired to form a more accurate model of GIS canopy cover to stored carbon in a site, then non-native invasive species should be recorded in future sample collection.
- When considering a field-based method for tracking carbon accrual, a non-destructive method for tagging individual trees within the plot is recommended to reduce uncertainty with respect to tracking individual trees over time.
- WPD staff should work with the City Arborist and other City departments to evaluate watershed regulation changes to support increases in canopy cover and riparian function in the CWQZ as part of the development rules.
- WPD should consider incentive tools to increase canopy cover within the CWQZ in public and private parcels in the full purpose and ETJ jurisdictional boundaries.
- For approaches that require tracking carbon as forest succession takes place, plot delineation markers with high visibility for easy relocation are recommended, and potentially high-precision GPS tools that were not feasible at the time of this study. In addition, long-term data collection, at least 20 years, is recommended.

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Appendix A. Carbon offset sites with condition, drainage area, and percent canopy cover. The drainage area categories include: 1 = 0-64, 2 = 65-320, 3 = 321-640, 4 = 641-1280 acres.

Site #	Site Name	Condition	Drainage Area Category	Year Sampled	Percent Canopy Cover
11155	Little Walnut Creek Upstream of Mearns Meadow(10mRB)	Degraded	321-640	2015/2017	74
11157	Little Walnut Creek Upstream of Mearns Meadow(50mRB)	Degraded	321-640	2015/2017	100
11159	Little Walnut Creek Upstream of Mearns Meadow(90mRB)	Degraded	321-640	2015/2017	100
11168	Barton Creek Trib @ Lund and Robert E. Lee(10mLB)	Degraded	0-64	2015/2017	68
11170	Barton Creek Trib @ Lund and Robert E. Lee(50mLB)	Degraded	0-64	2015/2017	86
11171	Barton Creek Trib @ Lund and Robert E. Lee(90mRB)	Degraded	0-64	2015/2017	66
11174*	Eanes @ Zilker Disc Golf(10mLB)	Degraded	0-64	2015	--
11176*	Eanes @ Zilker Disc Golf(50mLB)	Degraded	0-64	2015	--
11177*	Eanes @ Zilker Disc Golf(90mRB)	Degraded	0-64	2015	--
11186	Boggy Creek @ 10th St(10mLB)	Degraded	641-1280	2015/2017	67
11188	Boggy Creek @ 10th St(50mLB)	Degraded	641-1280	2015/2017	44
11190	Boggy Creek @ 10th St(90mLB)	Degraded	641-1280	2015/2017	92
11197	Boggy Creek @ Airport(10mRB)	Degraded	65-320	2015/2017	93
11199	Boggy Creek @ Airport(50mRB)	Degraded	65-320	2015/2017	64
11200	Boggy Creek @ Airport(50mLB)	Degraded	65-320	2015/2017	60
11204**	Little Walnut Creek @ Dottie Jordan Park(10mLB)	Degraded	641-1280	2017	56
11206	Little Walnut Creek @ Dottie Jordan Park(50mLB)	Degraded	641-1280	2015/2017	39
11208**	Little Walnut Creek @ Dottie Jordan Park(90mLB)	Degraded	641-1280	2017	71
11209	Bull Creek @ Bull District Park (Lakewood Dr)(10mRB)	Degraded	641-1280	2015/2017	0
11211	Bull Creek @ Bull District Park (Lakewood Dr)(50mRB)	Degraded	641-1280	2015/2017	46
11213**	Bull Creek @ Bull District Park (Lakewood Dr)(90mRB)	Degraded	641-1280	2017	19
11220*	West Bull @ Long Canyon and Standing Rock(90mLB)	Degraded	321-640	2015	--

Site #	Site Name	Condition	Drainage Area Category	Year Sampled	Percent Canopy Cover
11246	South Boggy @ Dittmar Park near Strickland(10mLB)	Degraded	321-640	2015/2017	100
11248	South Boggy @ Dittmar Park near Strickland(50m LB)	Degraded	321-640	2015/2017	100
11256*	South Boggynear Latteridge Almondsbury(90mLB)	Degraded	321-640	2015	--
11257	Johnson Creek in Tarrytown Park(10mRB)	Degraded	65-320	2015/2017	87
11259	Johnson Creek in Tarrytown Park(50mRB)	Degraded	65-320	2015/2017	95
11260	Johnson Creek in Tarrytown Park(50mLB)	Degraded	65-320	2015/2017	85
11261	Oak Springs Trib Downstream of Tillery Street(10mRB)	Degraded	0-64	2015/2017	0
11263	Oak Springs Trib Downstream of Tillery Street(50mRB)	Degraded	0-64	2015/2017	23
11266	Oak Springs Trib Downstream of Tillery Street(90mLB)	Degraded	0-64	2015/2017	0
11267	Boggy @ Willowbrook Huisache Crossing(10mRB)	Degraded	65-320	2015/2017	80
11269	Boggy @ Willowbrook Huisache Crossing(50mRB)	Degraded	65-320	2015/2017	86
11272	Boggy @ Willowbrook Huisache Crossing(90mLB)	Degraded	65-320	2015/2017	89
11286	Blunn Creek @ Rosedale(10mLB)	Degraded	321-640	2015/2017	100
11288	Blunn Creek @ Rosedale(50mLB)	Degraded	321-640	2015/2017	97
11290**	Blunn Creek @ Rosedale(90mLB)	Degraded	321-640	2017	97
13642	WLN @ N Star Greenbelt (50m RB)	Degraded	0-64	2016/2018	89
13643	WLN @ N Star Greenbelt (90m LB)	Degraded	0-64	2016/2018	0
13644	WLN @ N Star Greenbelt (10m RB)	Degraded	0-64	2016/2018	100
13645	SHL Trib @ Crestmont (10m RB)	Degraded	321-640	2016	98
13646	SHL Trib @ Crestmont (50m RB)	Degraded	321-640	2016	51
13647	SHL Trib @ Crestmont (90m RB)	Degraded	321-640	2016	74
13648	SHL @ Shady Oak Court (10m LB)	Degraded	641-1280	2016	100
13649	SHL @ Shady Oak Court (50m LB)	Degraded	641-1280	2016	38
13650	SHL @ Shady Oak Court (90m LB)	Degraded	641-1280	2016	39

Site #	Site Name	Condition	Drainage Area Category	Year Sampled	Percent Canopy Cover
13654	TAN us storm pipe @ Givens Pk (10m LB)	Degraded	641-1280	2016/2018	80
13655	TAN us storm pipe @ Givens Pk (50m LB)	Degraded	641-1280	2016/2018	40
13656	TAN us storm pipe @ Givens Pk (90m LB)	Degraded	641-1280	2016/2018	85
13663	TAN @ Bart Park nr Berkman (10m RB)	Degraded	321-640	2016/2018	86
13664	TAN @ Bart Park nr Berkman (90m LB)	Degraded	321-640	2016/2018	43
13665	TAN @ Bart Park nr Berkman (90m RB)	Degraded	321-640	2016/2018	67
13666	Seabrook Spg (50m RB)	Degraded	0-64	2016/2018	54
13667	Seabrook Spg (90m RB)	Degraded	0-64	2016/2018	53
13668	Seabrook Spg (90m LB)	Degraded	0-64	2016/2018	52
13669	BMK @ Buttermilk Pk (10m RB)	Degraded	65-320	2016/2018	0
13670	BMK @ Buttermilk Pk (50m RB)	Degraded	65-320	2016/2018	0
13671	BMK @ Buttermilk Pk (90m LB)	Degraded	65-320	2016/2018	0
13672	TYS in Reed Park @ Footbridge (10m LB)	Degraded	65-320	2016	43
13673	TYS in Reed Park @ Footbridge (50m LB)	Degraded	65-320	2016	100
13674	TYS in Reed Park @ Footbridge (90m RB)	Degraded	65-320	2016	100
13675	CMF ds xing @ CMF Ranch (10m LB)	Degraded	641-1280	2016/2018	89
13676	CMF ds xing @ CMF Ranch (50m LB)	Degraded	641-1280	2016/2018	80
13677	CMF ds xing @ CMF Ranch (90m LB)	Degraded	641-1280	2016/2018	97
13678	EBO @ Gillis Gabion (10m RB)	Degraded	65-320	2016	70
13679	EBO @ Gillis Gabion (90m RB)	Degraded	65-320	2016	14
13680	EBO @ Gillis Gabion (90m LB)	Degraded	65-320	2016	84
11149	Barton @ Key West from Cape Coral(10mRB)	Reference	0-64	2015	83
11152	Barton @ Key West from Cape Coral(50mLB)	Reference	0-64	2015	95
11153	Barton @ Key West from Cape Coral(90mRB)	Reference	0-64	2015	100
11161	Little Walnut Trib @ Gus Garcia Park(10mRB)	Reference	321-640	2015	100
11164	Little Walnut Trib @ Gus Garcia Park(50mLB)	Reference	321-640	2015	100

Site #	**Site Name**	**Condition**	**Drainage Area Category**	**Year Sampled**	**Percent Canopy Cover**
11165	Little Walnut Trib @ Gus Garcia Park(90mRB)	Reference	321-640	2015	100
11180	Barton Creek Ephemeral 3(10mLB)	Reference	0-64	2015	100
11182	Barton Creek Ephemeral 3(50mLB)	Reference	0-64	2015	85
11183	Barton Creek Ephemeral 3(90mRB)	Reference	0-64	2015	100
11191	Fort Branch @ Tura Lane LISI 1(10mRB)	Reference	641-1280	2015	85
11192	Fort Branch @ Tura Lane LISI 1(10mLB)	Reference	641-1280	2015	99
11195	Fort Branch @ Tura Lane LISI 1(90mRB)	Reference	641-1280	2015	94
11216*	West Bull @ Long Canyon and Standing Rock(10mLB)	Reference	321-640	2015	12
11217	West Bull @ Long Canyon and Standing Rock(50mRB)	Reference	321-640	2015	89
11221	Bee Creek DS Loop 360(10mRB)	Reference	65-320	2015	100
11224	Bee Creek DS Loop 360(50mLB)	Reference	65-320	2015	94
11226	Bee Creek DS Loop 360(90mLB)	Reference	65-320	2015	90
11227	Commons Ford Trib US Bridge @ Commons Ford Ranch(10mRB)	Reference	641-1280	2015	100
11229	Commons Ford Trib US Bridge @ Commons Ford Ranch(50mRB)	Reference	641-1280	2015	81
11230	Commons Ford Trib US Bridge @ Commons Ford Ranch(50mLB)	Reference	641-1280	2015	83
11233	Williamson Creek @ Wagon Bed Trl(10mRB)	Reference	0-64	2015	100
11235	Williamson Creek @ Wagon Bed Trl(50mRB)	Reference	0-64	2015	100
11238	Williamson Creek @ Wagon Bed Trl(90mLB)	Reference	0-64	2015	99
11240	Onion Creek @ Nuckols and Thaxton(10mLB)	Reference	65-320	2015	100
11241	Onion Creek @ Nuckols and Thaxton(50mRB)	Reference	65-320	2015	100
11244	Onion Creek @ Nuckols and Thaxton(90mLB)	Reference	65-320	2015	98
11249	South Boggy @ Dittmar Park near Strickland(90mRB)	Reference	321-640	2015	100
11251	South Boggy near Latteridge Almondsbury(10mRB)	Reference	321-640	2015	100

Site #	Site Name	Condition	Drainage Area Category	Year Sampled	Percent Canopy Cover
11252	South Boggy near Latteridge Almondsbury(10mLB)	Reference	321-640	2015	95
11273	West Bouldin Creek in West Bouldin (10mRB)	Reference	641-1280	2015	100
11275	West Bouldin Creek in West Bouldin (50mRB)	Reference	641-1280	2015	100
11276	West Bouldin Creek in West Bouldin (50mLB)	Reference	641-1280	2015	95
11279	Blunn Creek US of Cow Trough Spring(10mRB)	Reference	65-320	2015	100
11282	Blunn Creek US of Cow Trough Spring(50mLB)	Reference	65-320	2015	97
11284	Blunn Creek US of Cow Trough Spring(90mLB)	Reference	65-320	2015	100

*Sites that were removed from data set. See Data Management section for details.
**Sites that were changed during the project. See Data Management section for details.

Appendix B. List of species found at each Reference site with the count, median diameter at base height (DBH) or diameter at root collar (DRC), and total carbon for that species.

Site Number	Tree ID	Species	Date	Count	Median DBH or DRC (cm)	Total Carbon (g)
11149	AEPA	*Aesculus pavia*	18Mar2015	2	4.75	7.15
11149	DITE3	*Diospyros texana*	18Mar2015	2	5.8	15.35
11149	GAOVL	*Garrya ovata spp. lindheimeri*	18Mar2015	2	6.05	16.21
11149	ILDE	*Ilex decidua*	18Mar2015	4	4.85	22.49
11149	ILVO	*Ilex vomitoria*	18Mar2015	21	5.4	235.46
11149	JUAS	*Juniperus ashei*	18Mar2015	1	19	775.69
11149	PLOC	*Platanus occidentalis*	18Mar2015	1	36	440.34
11149	QUTE	*Quercus texana*	18Mar2015	1	28.7	464.55
11152	CAIL2	*Carya illinoinensis*	18Mar2015	1	4.5	4.94
11152	FRAXI	*Fraxinus spp.*	18Mar2015	1	17	74.29
11152	ILVO	*Ilex vomitoria*	18Mar2015	11	3.2	26.35
11152	JUAS	*Juniperus ashei*	18Mar2015	4	21.05	2641.23
11152	QUFU	*Quercus fusiformis*	18Mar2015	3	15.1	171.12
11153	CELTI	*Celtis spp.*	18Mar2015	2	9.7	54.34
11153	FRAXI	*Fraxinus spp.*	18Mar2015	1	11.9	47.41
11153	FRTE	*Fraxinus spp.*	18Mar2015	3	13.8	313.99
11153	ILDE	*Ilex decidua*	18Mar2015	1	3.3	1.89
11153	JUAS	*Juniperus ashei*	18Mar2015	1	10.9	22.75
11161	ACNE2	*Acer negundo*	19Mar2015	1	2.9	1.79
11161	CAIL2	*Carya illinoinensis*	19Mar2015	7	12.3	438.62
11161	CECAT	*Cercis canadensis var. texensis*	19Mar2015	1	2.5	0.81
11161	FRAXI	*Fraxinus spp.*	19Mar2015	1	4	3.12
11161	ULCR	*Ulmus crassifolia*	19Mar2015	1	2.6	0.86
11164	CAIL2	*Carya illinoinensis*	19Mar2015	5	17.8	712.19
11164	CELTI	*Celtis spp.*	19Mar2015	3	9.6	68.88
11164	CODR	*Cornus drummondii*	19Mar2015	2	2.9	2.49
11164	FRAXI	*Fraxinus spp.*	19Mar2015	6	3.9	19.63
11164	ILDE	*Ilex decidua*	19Mar2015	2	3.45	4.39
11164	JUVI	*Juniperus virginiana*	19Mar2015	1	2.9	1.03
11164	MAPO	*Maclura pomifera*	19Mar2015	2	10.55	63.1
11164	ULAM	*Ulmus americana*	19Mar2015	1	5.7	6.43
11165	ACNE2	*Acer negundo*	19Mar2015	1	3.5	2.85
11165	FRAXI	*Fraxinus spp.*	19Mar2015	1	5.6	7.26
11165	ILDE	*Ilex decidua*	19Mar2015	15	3.7	48.6
11165	JUVI	*Juniperus virginiana*	19Mar2015	1	3.3	1.42
11165	ULCR	*Ulmus crassifolia*	19Mar2015	1	16.5	68.47

Site Number	Tree ID	Species	Date	Count	Median DBH or DRC (cm)	Total Carbon (g)
11165	UNKNOWN	Unknown	19Mar2015	2	4.85	9.39
11180	JUAS	*Juniperus ashei*	20Mar2015	3	26.5	2523.63
11180	ULCR	*Ulmus crassifolia*	20Mar2015	3	10	175.49
11182	JUAS	*Juniperus ashei*	20Mar2015	8	23.55	6515.66
11182	ULCR	*Ulmus crassifolia*	20Mar2015	13	7.9	930.26
11183	DITE3	*Diospyros texana*	20Mar2015	5	5.5	32.2
11183	JUAS	*Juniperus ashei*	20Mar2015	1	24	627.63
11183	QUFU	*Quercus fusiformis*	20Mar2015	1	82.8	2487.93
11183	ULCR	*Ulmus crassifolia*	20Mar2015	4	15.1	429.97
11191	CASP8	*Catalpa speciosa*	24Mar2015	1	4.6	3.98
11191	FRAXI	*Fraxinus spp.*	24Mar2015	2	5.6	14.83
11192	FRAXI	*Fraxinus spp.*	24Mar2015	2	8.3	56.04
11192	ULCR	*Ulmus crassifolia*	24Mar2015	1	3.5	1.88
11195	FRAXI	*Fraxinus spp.*	24Mar2015	4	9.85	113.51
11195	JUVI	*Juniperus virginiana*	24Mar2015	5	9.3	128.1
11195	MAPO	*Maclura pomifera*	24Mar2015	1	4.4	3.56
11195	ULCR	*Ulmus crassifolia*	24Mar2015	1	3.6	2.02
11216	CELTI	*Celtis spp.*	26Mar2015	1	18.3	95.91
11216	DITE3	*Diospyros texana*	26Mar2015	1	3.5	1.99
11216	FRAXI	*Fraxinus spp.*	26Mar2015	1	6.3	9.75
11216	FRTE	*Fraxinus spp.*	26Mar2015	1	3.3	1.9
11216	ILVO	*Ilex vomitoria*	26Mar2015	1	3.5	2.21
11216	JUAS	*Juniperus ashei*	26Mar2015	6	7.1	3942.69
11217	DITE3	*Diospyros texana*	26Mar2015	1	4.5	3.77
11217	GAOVL	*Garrya ovata spp. lindheimeri*	26Mar2015	3	3.2	5.31
11217	ILVO	*Ilex vomitoria*	26Mar2015	2	4.45	8.27
11217	JUAS	*Juniperus ashei*	26Mar2015	9	20.4	5650.63
11221	ILVO	*Ilex vomitoria*	01Apr2015	35	4.9	340.4
11221	JUNI	*Juglans nigra*	01Apr2015	2	5.9	20.1
11221	JUAS	*Juniperus ashei*	01Apr2015	4	16.35	1631.74
11221	PLOC	*Platanus occidentalis*	01Apr2015	2	30.25	904.15
11221	ULCR	*Ulmus crassifolia*	01Apr2015	3	26.4	1242.69
11221	VIRU	*Viburnum rufidulum*	01Apr2015	1	7.5	13.51
11224	CAIL2	*Carya illinoinensis*	01Apr2015	1	5.4	7.73
11224	ILVO	*Ilex vomitoria*	01Apr2015	10	3.25	20.06
11224	JUAS	*Juniperus ashei*	01Apr2015	5	21.8	3924.14
11226	FRTE	*Fraxinus spp.*	01Apr2015	1	5.5	6.94
11226	ILVO	*Ilex vomitoria*	01Apr2015	33	3.9	130.68
11226	JUNI	*Juglans nigra*	01Apr2015	1	17.1	22.7

Site Number	Tree ID	Species	Date	Count	Median DBH or DRC (cm)	Total Carbon (g)
11226	SANI	*Salix nigra*	01Apr2015	2	18.4	123.02
11227	CAIL2	*Carya illinoinensis*	01Apr2015	2	23.45	455.34
11227	CELTI	*Celtis spp.*	01Apr2015	3	3.9	57.18
11227	DITE3	*Diospyros texana*	01Apr2015	4	6.95	51.25
11227	JUAS	*Juniperus ashei*	01Apr2015	2	17	784.75
11227	ULCR	*Ulmus crassifolia*	01Apr2015	10	7.9	328.95
11229	PLOC	*Platanus occidentalis*	01Apr2015	4	60.7	6978.54
11230	CELTI	*Celtis spp.*	01Apr2015	4	2.85	5.23
11230	DITE3	*Diospyros texana*	01Apr2015	1	2.9	1.22
11230	PLOC	*Platanus occidentalis*	01Apr2015	1	43.6	699.89
11233	ULCR	*Ulmus crassifolia*	02Apr2015	35	6.7	872.02
11235	CELTI	*Celtis spp.*	02Apr2015	3	6.5	31.83
11235	JUAS	*Juniperus ashei*	02Apr2015	1	14.8	113.63
11235	ULCR	*Ulmus crassifolia*	02Apr2015	2	35.85	1342.52
11238	CELTI	*Celtis spp.*	02Apr2015	4	10.8	147.05
11238	ULCR	*Ulmus crassifolia*	02Apr2015	1	44.4	452.82
11240	DITE3	*Diospyros texana*	02Apr2015	3	3.6	5.75
11240	ULCR	*Ulmus crassifolia*	02Apr2015	3	5.8	118.83
11241	ACFA	*Acacia farnesiana*	02Apr2015	1	4.1	5.78
11241	CELTI	*Celtis spp.*	02Apr2015	5	3.3	19.02
11241	DITE3	*Diospyros texana*	02Apr2015	3	4	8.22
11241	PTTR	*Ptelea trifoliata*	02Apr2015	2	2.55	1.72
11241	ULCR	*Ulmus crassifolia*	02Apr2015	6	5.75	360.21
11241	UNSP	*Ungnadia speciosa*	02Apr2015	8	3.15	16.71
11244	ACFA	*Acacia farnesiana*	02Apr2015	1	4.4	6.54
11244	CELTI	*Celtis spp.*	02Apr2015	3	2.9	11.99
11244	FRAXI	*Fraxinus spp.*	02Apr2015	1	7.6	15.55
11244	JUAS	*Juniperus ashei*	02Apr2015	1	26.3	1076.9
11244	PTTR	*Ptelea trifoliata*	02Apr2015	1	3.5	1.99
11244	SILA20	*Salix nigra*	02Apr2015	1	2.5	0.81
11244	ULCR	*Ulmus crassifolia*	02Apr2015	12	7.75	423.11
11244	UNSP	*Ungnadia speciosa*	02Apr2015	8	3.2	15.01
11249	ACNE2	*Acer negundo*	03Apr2015	2	14.4	105.27
11249	CAIL2	*Carya illinoinensis*	03Apr2015	1	72	3824.81
11249	CELTI	*Celtis spp.*	03Apr2015	9	3	10.57
11249	ILDE	*Ilex decidua*	03Apr2015	20	3.35	53.6
11249	PODE3	*Populus deltoides*	03Apr2015	1	55.1	1858.1
11251	CAIL2	*Carya illinoinensis*	03Apr2015	1	4.7	5.5
11251	CELTI	*Celtis spp.*	03Apr2015	1	8.6	17.9
11251	JUAS	*Juniperus ashei*	03Apr2015	1	30	896.18

Site Number	Tree ID	Species	Date	Count	Median DBH or DRC (cm)	Total Carbon (g)
11251	ULCR	*Ulmus crassifolia*	03Apr2015	4	15.5	415.95
11252	CAIL2	*Carya illinoinensis*	03Apr2015	6	6.3	359.74
11252	CELTI	*Celtis spp.*	03Apr2015	14	11.75	1360.62
11252	ULCR	*Ulmus crassifolia*	03Apr2015	3	5.7	49.97
11273	ACNE2	*Acer negundo*	09Apr2015	2	2.75	3.16
11273	CELTI	*Celtis spp.*	09Apr2015	8	5.2	639.65
11273	MORUS	*Morus spp.*	09Apr2015	7	8.8	300.59
11273	ULAM	*Ulmus americana*	09Apr2015	2	26.55	967.04
11273	ULCR	*Ulmus crassifolia*	09Apr2015	2	15.9	202.21
11275	ACNE2	*Acer negundo*	09Apr2015	1	3	1.95
11275	CELTI	*Celtis spp.*	09Apr2015	3	7.4	53.78
11275	FRAXI	*Fraxinus spp.*	09Apr2015	1	16	72.03
11275	QUTE	*Quercus texana*	09Apr2015	1	30.1	554.05
11275	ULCR	*Ulmus crassifolia*	09Apr2015	2	38.45	1296.23
11276	ACNE2	*Acer negundo*	09Apr2015	4	4.55	25.51
11276	CAIL2	*Carya illinoinensis*	09Apr2015	2	15.85	207.68
11276	MORUS	*Morus spp.*	09Apr2015	2	22.9	354.43
11276	ULAM	*Ulmus americana*	09Apr2015	3	25.2	901.87
11279	ACNE2	*Acer negundo*	10Apr2015	1	25.8	187.19
11279	CODR	*Cornus drummondii*	10Apr2015	3	4.1	8.29
11279	FRAXI	*Fraxinus spp.*	10Apr2015	3	9	239.02
11279	SANI	*Salix nigra*	10Apr2015	2	40.15	287.27
11279	TADI2	*Taxodium distichum*	10Apr2015	5	6.5	90.08
11279	ULAM	*Ulmus americana*	10Apr2015	1	5.9	7
11282	CAIL2	*Carya illinoinensis*	10Apr2015	2	16.3	195.46
11282	CELTI	*Celtis spp.*	10Apr2015	3	8.5	70.03
11282	CODR	*Cornus drummondii*	10Apr2015	1	2.7	1.01
11282	SANI	*Salix nigra*	10Apr2015	3	55	2092.95
11282	ULAM	*Ulmus americana*	10Apr2015	1	13.3	36.36
11284	FRAXI	*Fraxinus spp.*	10Apr2015	1	10.5	34.74
11284	JUAS	*Juniperus ashei*	10Apr2015	9	27	10990.39
11284	SANI	*Salix nigra*	10Apr2015	1	19.4	80.56
11284	TADI2	*Taxodium distichum*	10Apr2015	1	10.8	33.96

Appendix C. List of each species found at Degraded sites with the date, count, diameter at breast height (DBH) or diameter at root collar (DRC), and total carbon of the species.

Site Number	Tree ID	Species	Initial				Follow-up			
			Date	Count	DBH or DRC (cm)	Total Carbon (g)	Date	Count	DBH or DRC (cm)	Total Carbon (g)
11155	CELTI	*Celtis spp.*	19Mar2015	1	15	85.25	24May2017	1	18.5	107.31
11155	MORUS	*Morus spp.*	19Mar2015	12	9	299.43	24May2017	7	10.5	242.98
11157	CELTI	*Celtis spp.*	19Mar2015	4	28.55	1093.45	24May2017	4	19	1159.99
11157	FRAXI	*Fraxinus spp.*	19Mar2015	3	4.6	375.36	24May2017	3	7.3	518.15
11159	CELTI	*Celtis spp.*	19Mar2015	2	5	9.43	24May2017	5	3.5	10.33
11159	FRAXI	*Fraxinus spp.*	19Mar2015	5	12.1	312.98	24May2017	10	12.85	703.2
11159	SANI	*Salix nigra*	19Mar2015	3	25	177.84	24May2017	3	23	201.63
11168	MORUS	*Morus spp.*	20Mar2015	27	3.5	69.23				
11168	No trees	No trees					15May2017	0	0	0
11170	MORUS	*Morus spp.*	20Mar2015	1	2.5	0.9	15May2017	5	4.2	35.81
11171	CELTI	*Celtis spp.*					15May2017	3	2.7	2.85
11171	No trees	No trees	20Mar2015	0	0	0				
11171	ULCR	*Ulmus crassifolia*					15May2017	23	3.5	53.16
11186	ACNE2	*Acer negundo*					19May2017	1	5.2	7.41
11186	CAIL2	*Carya illinoinensis*	24Mar2015	1	50	1467.29	19May2017	1	60	2373.51
11186	CECAT	*Cercis canadensis var. texensis*	24Mar2015	1	2.8	1.11				
11186	FRAXI	*Fraxinus spp.*					19May2017	2	3.15	3.56
11188	ACFA	*Acacia farnesiana*					19May2017	1	24.1	771.68
11188	CAIL2	*Carya illinoinensis*					19May2017	3	3.8	8.65
11188	CELTI	*Celtis spp.*					19May2017	1	3.9	2.47
11188	CECAT	*Cercis canadensis var. texensis*	24Mar2015	1	3.2	1.58				
11188	SILA20	*Salix nigra*					19May2017	1	2.5	0.81
11188	ULCR	*Ulmus crassifolia*	24Mar2015	2	3.85	4.83				
11190	CAIL2	*Carya illinoinensis*					19May2017	1	4.1	3.92
11190	CELTI	*Celtis spp.*					19May2017	1	5	4.63
11190	ILDE	*Ilex decidua*					19May2017	3	3.5	5.32
11190	No trees	No trees	24Mar2015	0	0	0				
11190	ULAM	*Ulmus americana*					19May2017	3	7	34.2
11197	CAIL2	*Carya illinoinensis*					22May2017	3	54.3	4766.75
11197	FRAXI	*Fraxinus spp.*					22May2017	2	2.8	2.32
11197	MORUS	*Morus spp.*					22May2017	6	3.6	14.26
11197	No trees	No trees	25Mar2015	0	0	0				
11199	CELTI	*Celtis spp.*					22May2017	3	4	7.44

Site Number	Tree ID	Species	Initial				Follow-up			
			Date	Count	DBH or DRC (cm)	Total Carbon (g)	Date	Count	DBH or DRC (cm)	Total Carbon (g)
11199	Desert	*Chilopsis linearis*					22May2017	4	2.9	7.6
11199	MORUS	*Morus spp.*					22May2017	10	4.35	42.99
11199	No trees	No trees	25Mar2015	0	0	0				
11200	CAIL2	*Carya illinoinensis*	25Mar2015	1	58.24	2147.65	22May2017	1	57	2247.59
11206	CASP8	*Catalpa speciosa*	25Mar2015	6	4.5	30.18				
11206	No trees	No trees					22May2017	0	0	0
11209	No trees	No trees	26Mar2015	0	0	0				
11209	TADI2	*Taxodium distichum*					17May2017	1	13.7	39.31
11211	TADI2	*Taxodium distichum*	26Mar2015	1	7.3	13.89	17May2017	1	14.3	42.06
11211	ULAM	*Ulmus americana*					17May2017	2	4.85	8.86
11246	CAIL2	*Carya illinoinensis*	03Apr2015	1	65	2513.18	18May2017	1	50	1359.56
11248	CAIL2	*Carya illinoinensis*	03Apr2015	1	49.5	1481.79				
11248	No trees	No trees					18May2017	0	0	0
11257	ACNE2	*Acer negundo*					25May2017	1	3.5	2.85
11257	FRAXI	*Fraxinus spp.*	08Apr2015	4	6.4	53.16	25May2017	7	4.4	121.56
11259	SANI	*Salix nigra*	08Apr2015	6	10.05	155.69	25May2017	6	15.55	304.41
11260	FRAXI	*Fraxinus spp.*	08Apr2015	7	3.2	62.23	25May2017	7	5.2	106.98
11260	SANI	*Salix nigra*	08Apr2015	1	14.2	59.6	25May2017	1	20	126.91
11260	ULCR	*Ulmus crassifolia*	08Apr2015	2	37.65	912.14	25May2017	2	39.1	1184.07
11261	No trees	No trees	08Apr2015	0	0	0	16May2017	0	0	0
11263	No trees	No trees	08Apr2015	0	0	0				
11263	PODE3	*Populus deltoides*					16May2017	1	60.2	763.07
11266	No trees	No trees	08Apr2015	0	0	0	16May2017	0	0	0
11267	CELTI	*Celtis spp.*	09Apr2015	1	3.5	1.88	19May2017	1	3.1	1.37
11267	MORUS	*Morus spp.*	09Apr2015	4	9.7	111.28				
11267	QUFU	*Quercus fusiformis*	09Apr2015	1	4.1	4.91				
11267	QUMA2	*Quercus macrocarpa*					19May2017	1	8	20.93
11269	ACNE2	*Acer negundo*	09Apr2015	1	4.5	5.24	19May2017	3	6.8	40.94
11269	CAIL2	*Carya illinoinensis*	09Apr2015	1	35	100.55				
11269	CELTI	*Celtis spp.*	09Apr2015	8	5.15	133.94	19May2017	10	4.5	240.1
11269	FRAXI	*Fraxinus spp.*					19May2017	8	13.25	441
11269	MORUS	*Morus spp.*	09Apr2015	2	16.3	104.11	19May2017	1	15.4	79.41
11269	PLOC	*Platanus occidentalis*	09Apr2015	1	2.5	0.77	19May2017	1	3.1	1.37
11269	PRME	*Prunus mexicana*	09Apr2015	1	2.6	0.91				

Site Number	Tree ID	Species	Initial				Follow-up			
			Date	Count	DBH or DRC (cm)	Total Carbon (g)	Date	Count	DBH or DRC (cm)	Total Carbon (g)
11269	SANI	*Salix nigra*					19May2017	3	29	513.9
11269	ULAM	*Ulmus americana*	09Apr2015	1	10.6	30.11	19May2017	2	8.6	61.97
11272	CAIL2	*Carya illinoinensis*					19May2017	1	2.5	1.1
11272	CELTI	*Celtis spp.*	09Apr2015	3	2.5	3.03	19May2017	5	4	41.2
11272	FRAXI	*Fraxinus spp.*	09Apr2015	2	5.8	15.89				
11272	QUMU	*Quercus muehlenbergii*					19May2017	1	3.7	3.14
11272	ULCR	*Ulmus crassifolia*	09Apr2015	1	34.5	519.08				
11286	ACNE2	*Acer negundo*	14Apr2015	3	4.5	31.52				
11286	CELTI	*Celtis spp.*	14Apr2015	2	4.3	6.43	25May2017	2	5.1	9.79
11286	CODR	*Cornus drummondii*	14Apr2015	5	4.6	19.41	25May2017	7	4.3	29.42
11286	FRAXI	*Fraxinus spp.*	14Apr2015	5	3.2	22.03				
11286	MORUS	*Morus spp.*	14Apr2015	3	3.2	14.07	25May2017	1	3	1.48
11286	ULAM	*Ulmus americana*	14Apr2015	1	10.7	30.82	25May2017	1	13.2	35.84
11288	FRAXI	*Fraxinus spp.*	14Apr2015	2	16.8	252.43				
11288	No trees	No trees					25-May-17	0	0	0
11288	SANI	*Salix nigra*	14Apr2015	1	31.5	362.97				
11288	ULAM	*Ulmus americana*	14Apr2015	1	5.4	5.61				
13642	FRAXI	*Fraxinus spp.*	20May2016	1	4.6	4.43	15Jun2018	8	7.85	196.11
13642	JUNI	*Juglans nigra*	20May2016	1	16.4	70.13				
13642	MORU2	*Morus rubra*	20May2016	6	5	50.79				
13642	MORUS	*Morus spp.*					15Jun2018	5	6	66.05
13642	PODE3	*Populus deltoides*	20May2016	1	28.5	346.92	15Jun2018	1	33	494.56
13642	SANI	*Salix nigra*	20May2016	15	18	2845.92	15Jun2018	7	32	2432.45
13643	CELTI	*Celtis spp.*					15Jun2018	2	3.3	3.31
13643	GLTR	*Gleditsia triacanthos*					15Jun2018	4	3.65	10.07
13643	JUNI	*Juglans nigra*	20May2016	1	10.2	30.11				
13644	CASP8	*Catalpa speciosa*	20May2016	1	20.8	108.63	15Jun2018	2	14.25	109.93
13644	CEOC	*Celtis occidentalis*	20May2016	1	7.7	13.6				
13644	CELTI	*Celtis spp.*					15Jun2018	2	6.6	26.51
13644	FRAXI	*Fraxinus spp.*	20May2016	5	7	85.85	15Jun2018	6	6.25	89.22
13644	SANI	*Salix nigra*	20May2016	6	14.35	687.4	15Jun2018	2	21.25	500
13654	ACFA	*Acacia farnesiana*					11Jun2018	1	5	8.16
13654	FRAXI	*Fraxinus spp.*					11Jun2018	2	4.9	10.79
13654	No trees	No trees	20May2016	0	0	0				
13655	ACFA	*Acacia farnesiana*	20May2016	1	5	8.16	11Jun2018	4	6.25	60.12
13655	FRAXI	*Fraxinus spp.*	20May2016	9	3.2	23.97	11Jun2018	10	3.7	37.32

Site Number	Tree ID	Species	Initial				Follow-up			
			Date	Count	DBH or DRC (cm)	Total Carbon (g)	Date	Count	DBH or DRC (cm)	Total Carbon (g)
13655	MORU2	*Morus rubra*	20May2016	7	4.8	31.34				
13655	MORUS	*Morus spp.*					11Jun2018	17	4.3	117.79
13655	PRUNU	*Prunus spp.*	20May2016	1	2.8	.				
13655	ULCR	*Ulmus crassifolia*	20May2016	1	29.6	414.93				
13656	ULCR	*Ulmus crassifolia*	20May2016	2	34.95	1181.28	11Jun2018	2	35.15	855.74
13663	ACFA	*Acacia farnesiana*	13May2016	6	4.25	36.32	12Jun2018	4	16.6	1885.11
13663	FRAXI	*Fraxinus spp.*	13May2016	1	3.2	1.76	12Jun2018	5	4.5	24.95
13663	MORU2	*Morus rubra*	13May2016	3	3.5	7.29				
13663	SANI	*Salix nigra*	13May2016	5	8	127.63	12Jun2018	1	2.7	1.13
13664	CODR	*Cornus drummondii*					12Jun2018	5	3.4	10.2
13664	FRAXI	*Fraxinus spp.*	13May2016	3	5.1	17.5	12Jun2018	9	4	68.87
13664	SANI	*Salix nigra*	13May2016	2	18.15	120.85	12Jun2018	1	21.6	63.12
13664	ULAM	*Ulmus americana*	13May2016	1	3.4	1.74	12Jun2018	2	3.2	3.11
13665	CEOC	*Celtis occidentalis*	13May2016	2	15.5	206.49				
13665	CELTI	*Celtis spp.*					12Jun2018	3	13	292.29
13665	FRAXI	*Fraxinus spp.*	13May2016	4	5.2	28.38	12Jun2018	3	6.5	24.22
13665	GLTR	*Gleditsia triacanthos*					12Jun2018	2	3.2	3.5
13665	MAPO	*Maclura pomifera*	13May2016	2	15	164.37				
13665	MORU2	*Morus rubra*	13May2016	3	5.1	25.06				
13665	MORUS	*Morus spp.*					12Jun2018	13	4.4	76.65
13665	PAAC3	*Parkinsonia aculeata*	13May2016	1	6.5	9.46				
13665	SANI	*Salix nigra*	13May2016	3	7	44.54	12Jun2018	5	8.5	117.85
13665	ULAM	*Ulmus americana*	13May2016	5	3.5	71.76	12Jun2018	10	4.9	233.04
13665	ULCR	*Ulmus crassifolia*					12Jun2018	1	2.7	0.95
13666	No trees	No trees	11May2016	0	0	0				
13666	PODE3	*Populus deltoides*					12Jun2018	1	4.8	4.1
13666	SANI	*Salix nigra*					12Jun2018	2	4.2	7.32
13667	No trees	No trees	11May2016	0	0	0				
13667	SANI	*Salix nigra*					12Jun2018	2	5.85	15.37
13668	MORUS	*Morus spp.*					12Jun2018	3	3.2	7.16
13668	No trees	No trees	11May2016	0	0	0				
13668	SANI	*Salix nigra*					12Jun2018	1	5	5.19
13669	CELTI	*Celtis spp.*					13Jun2018	3	3.6	10.05
13669	No trees	No trees	11May2016	0	0	0				
13670	ACFA	*Acacia farnesiana*	11May2016	5	3.5	22.45	13Jun2018	1	25.5	750.83
13671	No trees	No trees	11May2016	0	0	0				
13671	ULAM	*Ulmus americana*					13Jun2018	8	2.6	13.18

Site Number	Tree ID	Species	Initial				Follow-up			
			Date	**Count**	**DBH or DRC (cm)**	**Total Carbon (g)**	**Date**	**Count**	**DBH or DRC (cm)**	**Total Carbon (g)**
13675	CAIL2	*Carya illinoinensis*	27May2016	1	3.7	3.04	02Oct2018	3	4.2	14.77
13676	CAIL2	*Carya illinoinensis*	27May2016	4	3.5	42.12	02Oct2018	4	4.75	67.51
13677	CAIL2	*Carya illinoinensis*	27May2016	3	17.8	592.46	02Oct2018	5	3	828.52
13677	CELTI	*Celtis spp.*					02Oct2018	3	3.1	4.4