Limitations of existing carbon calculators for riparian forest plantings

How do carbon calculator estimates compare to field-based carbon stock estimates?

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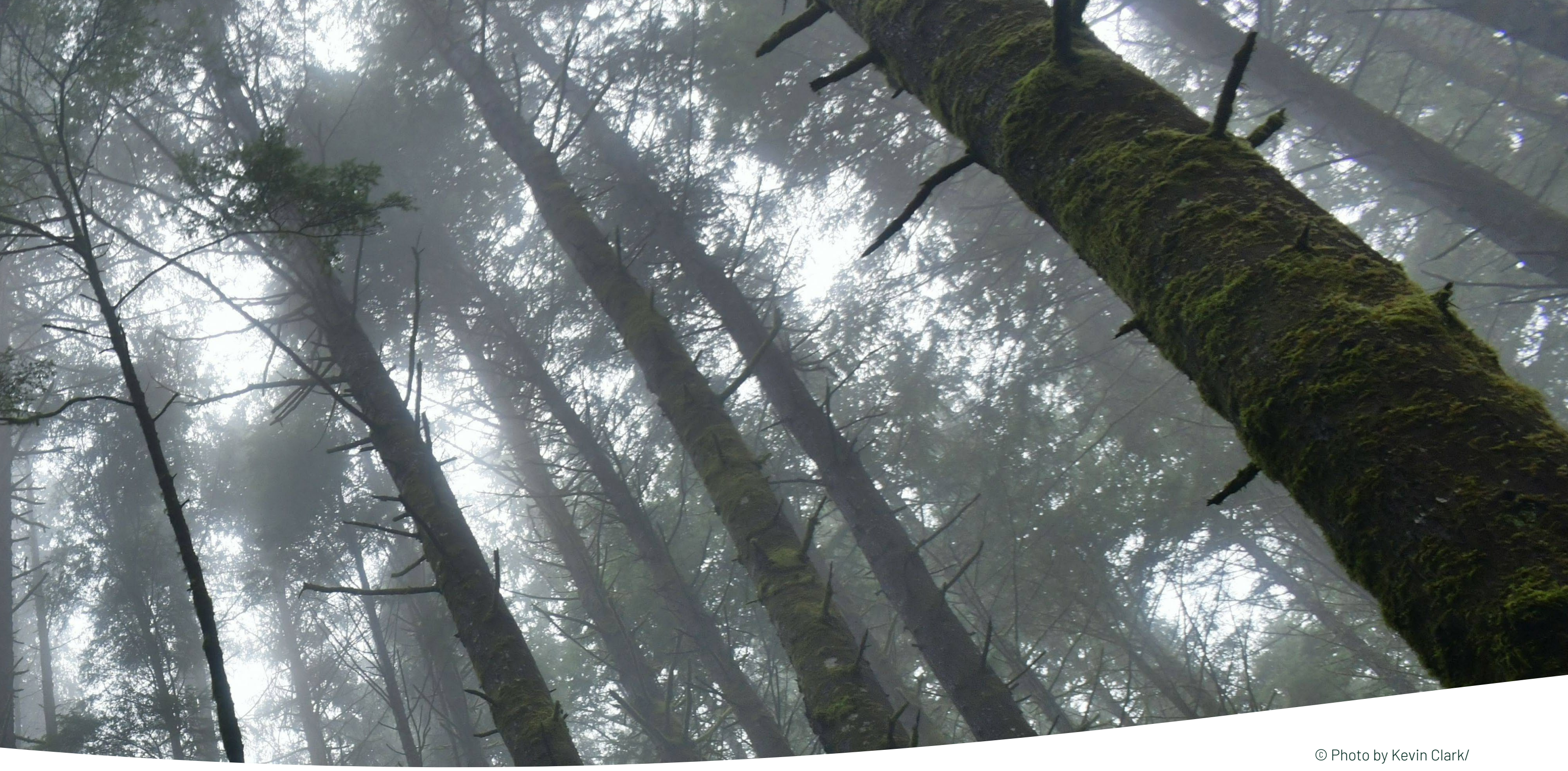


Contents

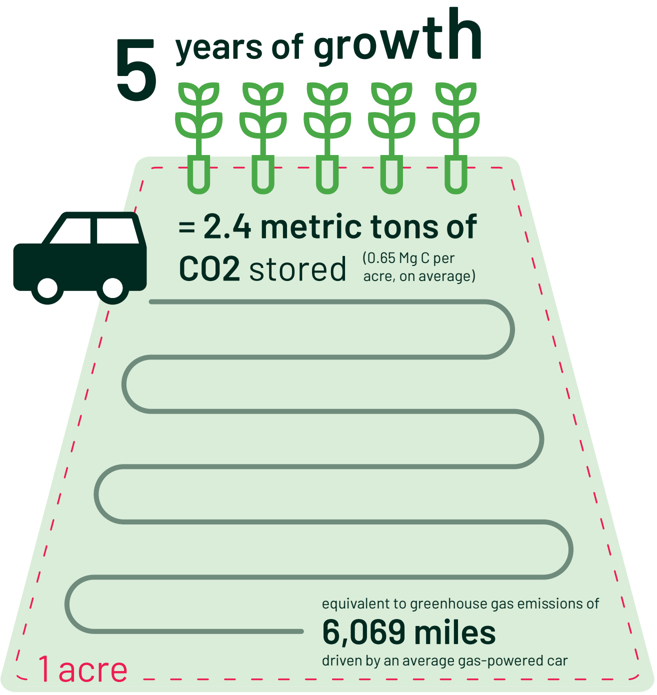
Executive summary

Forests play a critical role in capturing carbon and reducing greenhouse gas concentrations in the atmosphere. Restoration of forest cover provides efficient, cost-effective carbon capture while also supporting biodiversity and providing flood mitigation, nutrient retention, and temperature regulation, especially when planting native forest cover occurs in floodplains and along rivers and streams. Riparian forest restoration projects usually begin with biodiversity or water quality outcomes as their primary goal, but organizations, policies, and programs focused on climate solutions increasingly recognize the role riparian forests and buffers can play in reducing carbon dioxide. To meaningfully measure how these projects contribute to natural climate solution goals, we need transparent, efficient, and robust tools that can estimate the amount of CO_2 sequestered in riparian plantings.

Many tools exist which can quantify carbon sequestration and storage in the forest sector. But fewer of these 'carbon calculators' are applicable outside of upland forests or for woody vegetation types not used for timber production, like riparian forests or buffers. We tested available carbon calculators to see if, using riparian forest project planting plans, we could reliably estimate the carbon benefits of these projects. We measured trees and woody shrubs in 15 plots across a for a 5-year-old, 44-acre riparian forest planting in the southern Willamette Valley. After using allometric equations to estimate the carbon stored in trees and shrubs, we compared the estimates from the carbon calculators to field-based empirical carbon estimates. We expanded upon this case study using data from 5 additional sites, ranging from 5 to 21 years old, for which we had access to planting plans and empirical carbon storage estimates as part of a larger study of carbon in riparian planting in western Oregon.

How much carbon was stored in the plantings?

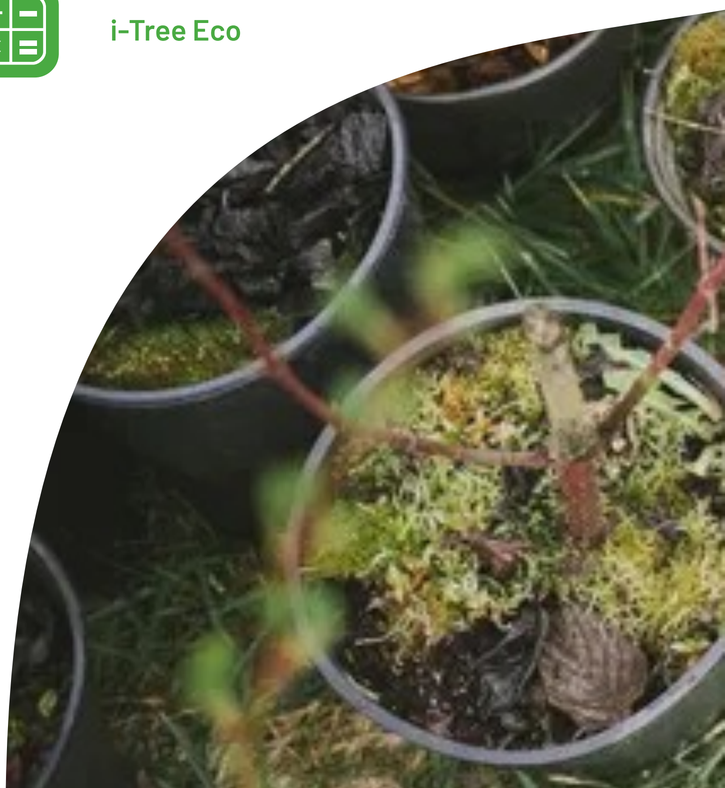
After 5 years of growth, the riparian forest planting at the Willamette Confluence Preserve stored an average of 0.65 Mg C per acre. Plant growth and carbon storage varied considerably across the site, with some of our plots having as little as 0.02 Mg C/acre and others having as much as 1.72 Mg C/acre. The carbon stored in the Willamette Confluence Preserve planting is consistent with estimated carbon stocks in other 5-year-old riparian forest plantings in western Oregon[1]. For the additional sites, field-based carbon storage ranged from 0.14 Mg C per acre in a 5-year-old riparian planting to 36.72 Mg C per acre in a 21-year-old planting.



What carbon calculator tools did we try?

We tested tools which could calculate carbon based on planting plans (either species or groups of species) and are free and relatively easy for restoration practitioners to use. Based on these criteria, we tested the Carbon in Riparian Ecosystems Estimator for California (CREEC), i-Tree Planting, and i-Tree Eco. The i-Tree tools were initially developed to help researchers and practitioners assess urban and peri-urban forest ecosystem service values and functions whereas the CREEC tool was developed for use in California as a Quantification Methodology for riparian forest restoration and other conservation projects.

- Carbon in Riparian Ecosystems Estimator for California (CREEC)
- i-Tree Planting
- i-Tree Eco



How well did the carbon calculators match field estimated carbon stocks for riparian plantings?

Carbon stocks estimated from field measurements were different from carbon calculator estimates, with absolute differences ranging from 0.11 to over 30 Mg C/acre.

At Willamette Confluence Preserve, CREEC estimates were relatively close to field-based carbon storage estimates for the 5-year-old riparian forest planting. Field estimates were 0.11 Mg C/acre greater than carbon stock estimated by CREEC. Conversely, i-Tree Eco overestimated field-based carbon stocks by 3.32 Mg C/acre and i-Tree Planting overestimated by 2.09 – 9.03 Mg C/acre. Across 44-acres, that translates to large overestimates of the potential climate benefits from this planting – claimed effects in excess of 92 Mg C to 397 Mg C in the first 5 years, raising concerns about claimed effects based on carbon calculators.

We found similar mismatches between carbon calculators and field-based carbon stock estimates at riparian reforestation sites ranging from 5 to 21 years post-planting. Mean absolute difference in carbon stocks across all the sites ranged from 8.08 to 17.35 Mg C/acre, depending on the calculator tool used.

Trees to be planted for restoration at Fisher Slough.
© Photo by Don Macanlalay/The Nature Conservancy.

Recommendations for estimating carbon stocks from riparian planting plans

For restoration practitioners who want to estimate the potential carbon stored in riparian plantings, the best estimates are those based sites most similar to where you are planting – similar species mixes, similar climate, similar soils. However, at this time, no carbon calculator has been parameterized based on restoration plantings or riparian forest ecosystems in Oregon.

We found substantial differences between field-estimated carbon stocks in young riparian plantings and the current carbon calculators (CREEC & i-Tree tools). CREEC, with lower absolute differences from field-estimated carbon stocks, could be used for riparian plantings in western Oregon but users should proceed with caution. The tool was parameterized based on California vegetation types, physiographic, and climatic regions. The i-Tree tools tended to provide estimates substantially higher than the field-based estimates and had large absolute differences between field-based carbon stock estimates and those estimated by the tools. Some of those differences are probably due to limitations of the i-Tree tools to represent common riparian plantings used in restoration projects in Oregon. For example, i-Tree tools require plants entered in the planting data to have minimum diameters of 0.5 to 1 inch because the models used for tree growth are not calibrated to include very small diameters. For plantings which start from small bareroot seedlings with small diameters, these models end up performing poorly.

CREEC and i-Tree Planting are relatively easy to use web-based tools. Despite the poor performance, some organizations may still choose to use either the i-Tree Planting tool or CREEC tool to calculate carbon benefits from planting projects. **Users should clearly understand the limitations and describe assumptions or modifications of each tool for their use case, including which species are or are not represented by the tool, choices about mortality rates and/or seedling size and condition.** For example, some organizations continue to use i-Tree Planting using workarounds like reducing the number of years in the growth projections to capture however long it may take for smaller trees to reach the i-Tree minimum diameter. Our case study suggests that, for many species, the i-Tree minimum diameter (1-inch or 2.54 cm) may not be reached for at least 5 years.

Other case study **highlights**

Shrubs play an important carbon sequestration role in riparian plantings.

Despite comprising a small proportion of overall carbon stocks in mature riparian forests, shrubs comprise a substantial proportion of the carbon stocks in early plantings and can help to jump start carbon sequestration by quickly accumulating biomass carbon. Shrubs also provide critical riparian habitat. Riparian planting projects should include dense areas of and diverse mixes of shrubs as well as trees to provide important wildlife habitat value and increase early planting C benefits.

Young, heterogenous stands are highly variable in stand density and carbon stocks, which makes precise estimates of carbon stocks challenging.

For organizations interested in field-based monitoring, sufficient staff or contract time should be included in project planning and project budgets. Our case study provides insight into the capacity required for measuring and monitoring carbon stocks in riparian plantings over time. Using our case study data, estimating carbon stocks with a 20% margin of error would require increased sampling intensity – an additional 5-6 field days for this 44-acre site. Precision is anticipated to improve as stands mature and homogenize so reassessing the sample power with data as sites age should be used to guide monitoring. Given clear tradeoffs between precision of carbon stock estimates and data collection effort, organizations and program managers should carefully consider the goals of and needs for carbon stock monitoring over time. Remote sensing data may also be useful for monitoring growth of trees and shrubs and tracking carbon stocks in riparian plantings over large areas, though limited use cases are available for riparian ecosystems in the Pacific Northwest. Developing and validating remote sensing-based models for riparian reforestation in the Pacific Northwest could decrease effort needed to track climate mitigation benefits from these activities into the future.

Introduction

Restoration of riparian forest cover provides multiple benefits, from supporting biodiversity to providing flood mitigation, nutrient retention, and temperature regulation. Indeed, most riparian forest restoration projects are initiated with biodiversity or water quality outcomes as their primary goal. Restoration of riparian forest cover can also provide meaningful carbon sequestration benefits, however carbon accounting in woody vegetation types not used for timber production (e.g., riparian forests and riparian buffers) is lacking and there are limited tools available that can inform estimates of the eventual climate mitigation benefit from these projects. At the same time, given increased demand for and funding opportunities associated with carbon sequestration and storage in natural and working lands, people engaged in riparian forest restoration efforts have a demonstrated need for transparent, efficient, and robust approaches to estimate the carbon sequestration potential of riparian planting projects.

Young trees growing at Willamette Confluence Preserve. © Photo by Melissa Olson.

Many tools exist which can quantify carbon sequestration and storage in the forest sector. However, due to a variety of constraints, fewer of these 'carbon calculators' are applicable outside of upland forests or for woody vegetation types not used for timber production (e.g., riparian forests and riparian buffers). We reviewed several available carbon calculators to determine which could be used to estimate riparian forest carbon based on planting plans and compared estimated carbon storage from carbon calculators to field-based empirical estimates. Here, we describe our findings first from a case study at the Willamette Confluence Preserve (WCP) in Eugene, OR where we measured trees and woody shrubs in 15 plots across a 5-year-old riparian forest planting. We used allometric equations to estimate the carbon stored in those trees and shrubs and compared the empirical estimates with estimates from the carbon calculators. We expanded upon this case study using estimates of carbon stocks at 5 sites sampled as part of a chronosequence study in western Oregon[2]. For these sites, ranging from 5 to 21 years old, we had access to planting plans which described the species and number of plants installed and were able to compare field estimates with estimates from carbon calculators. For two projects, we only had information on trees planted but not the shrubs.

Carbon Calculator Descriptions

We assessed freely available tools for projecting the carbon stocks from reforestation planting projects. We specifically focused on tools which could take user planting plans and project carbon stocks over time and initially identified three potential tools. The i-Tree suite of tools, developed to help researchers and practitioners assess forest ecosystem service values and functions, includes a simple web-based tool, i-Tree Planting, and a more advanced desktop software tool, i-Tree Eco. The Carbon in Riparian Ecosystems Estimator for California (CREEC) is a web-based tool developed for use in California as a Quantification Methodology for riparian forest restoration and other conservation projects. While i-Tree and CREEC both provide estimates of above- and belowground carbon stocks in trees and understory shrubs, they differ in the methodologies used and data required to estimate carbon stocks in riparian planting projects.

CREEC is a simple web-based tool that predicts changes in carbon stocks in riparian forests from their planting at year zero through year 100. CREEC provides carbon stock estimates for tree, coarse woody debris, forest floor, understory, and soil carbon pools. To use CREEC, users must identify the regeneration type (i.e., planted community), region, type of site preparation, and prior land use for the project. Carbon stocks in CREEC are estimated by converting user's planting plans, entered as plants per acres or percentage by species, into density classes for vegetation functional groups and then matching those to one of five vegetation types which are then matched with look-up tables[3]. The carbon look-up tables were developed based on relationships between age, live tree biomass, and other carbon stocks in a large database of riparian forest measurements in California[4]. Using CREEC to estimate carbon stored in planted riparian forests in Oregon requires important simplifying assumptions – namely, that planted riparian communities in Oregon can be adequately mapped to one of the

vegetation types included in CREEC and that growth and biomass accumulation in those vegetation types follows similar trajectories. For example, we assume that the plantings at WCP follow similar growth curves to riparian ecosystems in the Coast Range and Foothills of northern California.

i-Tree Planting and i-Tree Eco model future carbon stocks based on user entered data on the species and number of plants (e.g., the planting plan), the initial size of plants (e.g., diameter at the time of planting), the condition of the trees (if known), the amount of sun and shade (based on project location and user entered data), estimated mortality and the project lifetime. Growth is then estimated based on several parameters, such as growing season length determined by nearby meteorological data, and species-specific growth rates based on over 100 species-specific or aggregate allometric equations[5]. The online tool, i-Tree Planting, allows users to enter plants in groups of the same species (e.g., 100 black cottonwood seedlings can be entered using 1 line of data entry) whereas i-Tree Eco requires each plant to be entered individually. Recent updates to the i-Tree Planting Calculator limits data entry to plants with dbh > 2.54 cm (1 inch), which is larger than planting stock used in our case study, whereas i-Tree Eco allows users to enter plants with a minimum of 1.27 cm dbh, or 0.5 inch. i-Tree Eco also recommends entering initial heights for all plants for more accurate estimate. Since restoration planting plans vary considerable (e.g., gallon pots, bare root stock, plugs, stakes), planting stock may or may not meet these minimum limits and data requirements. Where planting stock is considerably less than the minimum diameters, we'd expect these tools to overestimate the initial starting condition of riparian plantings. Because i-Tree Eco requires users to enter initial plant diameter and information for each individual plant, it is more data entry intensive for practitioners than i-Tree Planting or CREEC. We only tested i-Tree Eco for Willamette Confluence Preserve but tested i-Tree Planting and CREEC for WCP and the expanded dataset of sites.

Case study

The Willamette Confluence Preserve

The Willamette Confluence Preserve (WCP) rests between the Coast Fork and Middle Fork of the Willamette River. In the last century, the site was a source of gravel and other aggregate materials used to build the roads and buildings of Eugene and Springfield. In 2010, The Nature Conservancy purchased the property with financial support from the Bonneville Power Administration (BPA), the Oregon Watershed Enhancement Board (OWEB), and the Doris Duke Charitable Foundation. For a decade after its purchase, The Nature Conservancy in Oregon led site restoration projects to improve water quality, fish and wildlife habitat, and ecological integrity at the WCP. After more than a decade of restoration work, The Nature Conservancy transferred the property to McKenzie River Trust in 2023 to support the long-term care and and stewardship of this special place.

Coyote Field shown during photo point monitoring, two years before planting in 2017 (left), and the same location three years post-planting, in 2022 (right). © Photo by Melissa Olson.

Riparian forest plantings occurred over multiple years and in multiple areas of the WCP as part of restoring the site from its former use as a gravel mine. These plantings varied in species composition and planting density depending on the site conditions. Between 2015 and 2019, riparian plantings were installed in small areas around Pudding Ponds and the Lower Middle Fork area of WCP. Coyote Field, a 44-acre area, was the largest riparian forest planting area and was planted in 2019. Coyote Field was planted using bareroot stock trees and shrubs, less than 18" tall on average (from soil to tip after planting) but actual heights varied (10" - 20") depending on how well individual species grew during the nursery grow out period. At the time of planting, project managers expected no more than 25% mortality. The planting designs for Coyote Field included over 80,000 plants of 19 species (7 tree species and 12 shrub species). Shrubs comprised 75% of the planting design, with snowberry *(Symphoricarpos albus)* being most abundant. Black cottonwood *(Populus trichocarpa)* and big-leaf maple *(Acer macrophyllum)* comprised most of the trees planted.

In the spring of 2024, we conducted a field survey of tree and shrub biomass in the Coyote Field planting. We used published allometric equations to estimate the amount of carbon stored in the planting and compared the field-based estimates to carbon stocks projected by potential 'carbon calculators'. We used information from the original planting plans for Coyote Field alongside consultation with the planting project manager, Melissa Olson, to parameterize each of the tools and calculate the expected carbon storage at 5 years post-planting. Each tool required us to make choices during data entry/scenario parameterization, described in more detail in the Methods section, which likely impact the accuracy of carbon estimates.

Melissa Olson stands in front of a 5-year-old black cottonwood at Willamette Confluence Preserve in 2024. © Photo by Jason Nuckols.

Case Study Results

We recorded 102 trees (> 3 cm dbh), 198 seedlings (< 3 cm dbh), and 59 shrubs across 15 plots. Three species had grown enough in 5 years to have 3 cm diameters: black cottonwood, big-leaf maple, and Douglas fir *(Pseudotsuga menziesii)*. Two plots had no trees that had reached the 3 cm minimum dbh. Overall, mean woody stem density was 1185 (+/- 489) stems/acre with high variability among plots in tree, seedling, and shrub density.

The trees, seedlings, and shrubs planted in Coyote Field store an estimated average of 0.65 (+/- 0.6) Mg C/acre with plot level carbon stocks varying from 0.02 Mg C/acre to 1.72 Mg C/acre. Trees and shrubs both contributed substantially to the carbon stocks within the riparian forest planting. Shrubs comprised an average of 51% of the total woody carbon stocks, while trees comprised 44% and tree seedlings comprised the remaining 5%. At the plot level, the percent of carbon stocks stored in shrubs, trees, and seedlings ranged from 0 – 96%, 0-92%, and 1 – 16%, respectively.

At 5-years post planting, shrubs and trees dominate the carbon stocks at Coyote Field. Few tree species had reached our minimum diameter requirement to be counted as trees (> 3 cm dbh). As the planting continues to mature, and current seedlings shift into the tree size class, tree carbon stocks are expected to comprise a higher proportion of the overall carbon stocks.

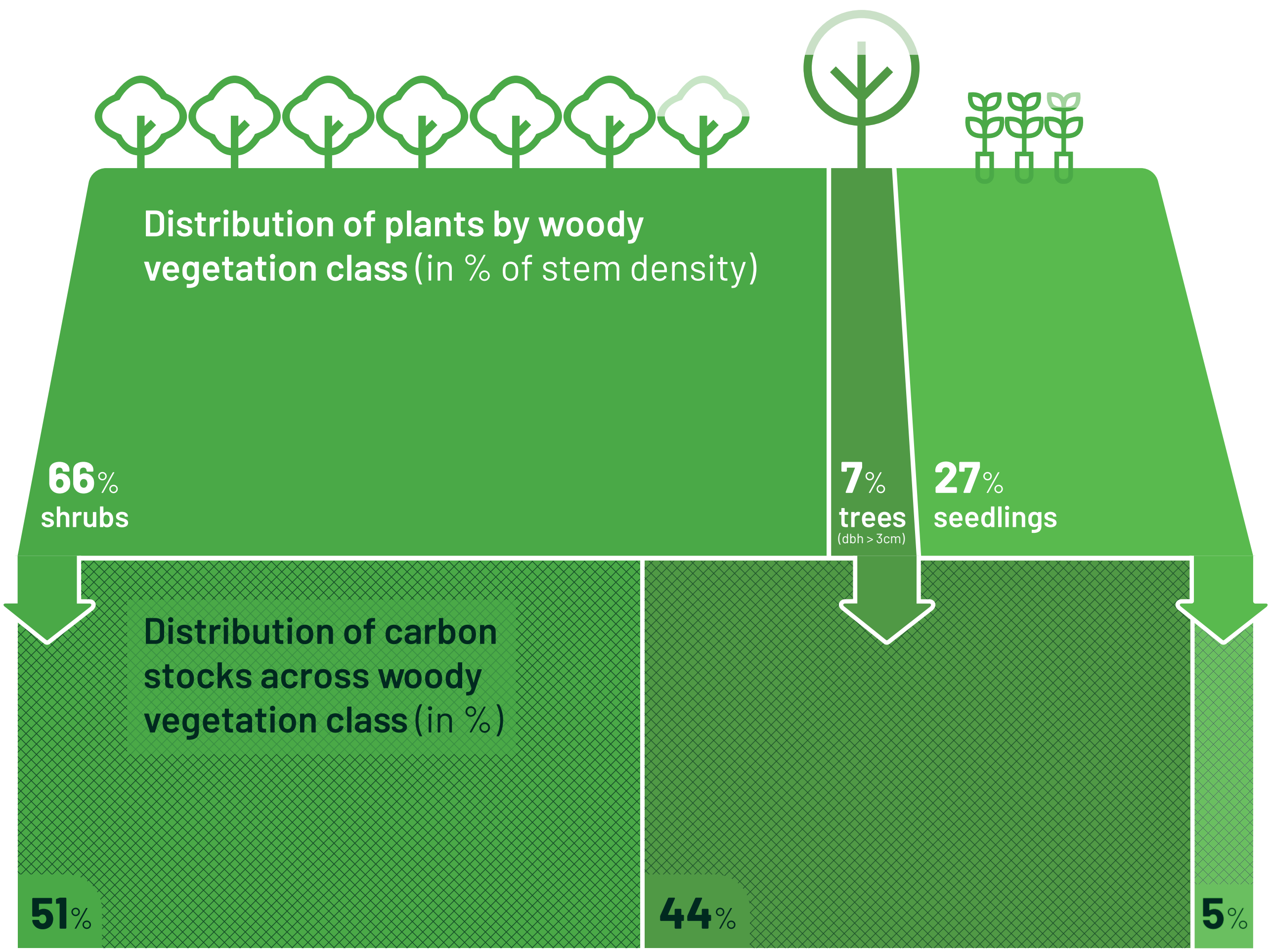


Figure 1. Shrubs, trees, and seedlings comprise different proportions of the stem density and carbon stocks in a 5-year old riparian planting at Willamette Confluence Preserve.

Tree and seedling carbon stocks were dominated by black cottonwood, consistent with the rapid growth rate of black cottonwood and the planting plan. Black cottonwood trees averaged 3.65 +/- 2.46 kg C per tree.

Shrubs vary widely in their estimated carbon stocks, depending on species and size. In this planting, black elderberry *(Sambucus nigra)* had the highest carbon stocks per plant. However, we caution against generalizing the per plant carbon stocks from this case study – for 7 species these estimates are based on less than five individual shrubs. Given extensive browse pressure on some of those species (i.e., vine maple), the size measured at Coyote Field is unlikely to represent growth under average or good conditions.

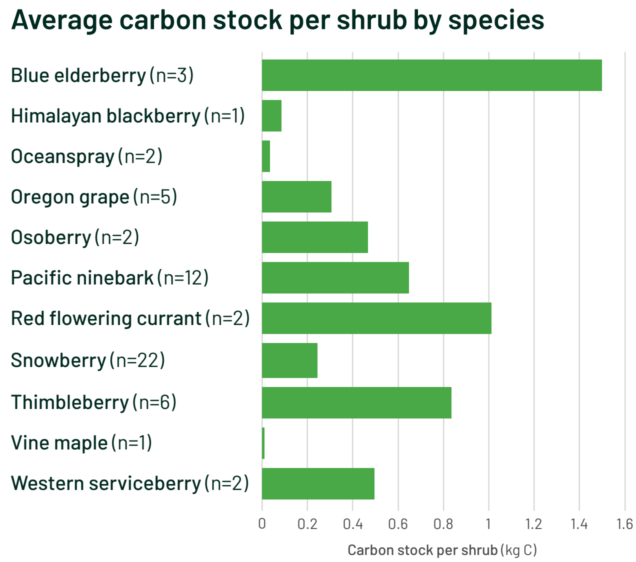


Figure 2. Estimated carbon stocks by species for shrubs measured in this case study.

Five-year old riparian planting in Lane County, OR.

Shrubs like snowberry *(Symphoricarpos albus)* contributed substantial cumulative carbon to plots due to their abundance despite their smaller stature and lower per shrub carbon stocks.

Distribution of shrub carbon stocks by species (in %)

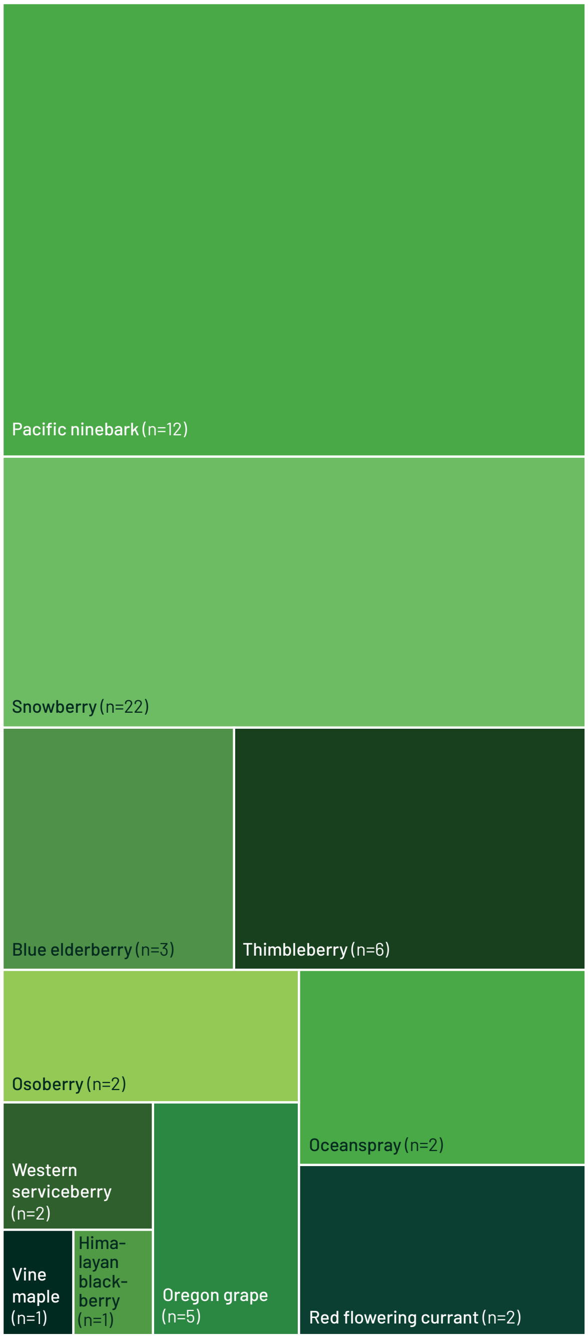


Figure 3. At Willamette Confluence Preserve, shrub carbon stocks were comprised of many species. This figure shows estimated average percent of shrub carbon stocks attributable to each species.

TNC scientist, Rose Graves, measures woody carbon in a riparian planting.
© Photo by Kammy Kern-Korot.

Carbon calculator estimates based on the Coyote Field planting plans were different than carbon stock estimates based on field data. Neither i-Tree nor CREEC provide uncertainty estimates for carbon stock projections.

CREEC estimated that Coyote Field plantings would store 0.54 Mg C/acre in trees and woody shrubs after 5 years. Understory carbon stocks in CREEC include herbs, vines, and saplings modeled as a function of the live tree carbon. The category reported as “tree carbon” in CREEC estimator output represents trees and woody shrubs in riparian forest communities and is a closer representation of our field estimated carbon stocks. The CREEC projection for tree carbon was lower than our field estimated carbon stock for trees, shrubs, and saplings by 0.11 Mg C/acre, well within the 90% CI of our field estimated carbon stocks.

i-Tree Eco Forecast estimated 3.97 Mg C/acre and i-Tree Planting estimated 9.68 Mg C/acre, 6.94 Mg C/acre in trees and 2.74 Mg C/acre in shrubs. i-Tree Eco and i-Tree Planting estimates were substantially higher than field estimated carbon stocks (+2.71 Mg C/acre and +9.03 Mg C/acre). Over the 44-acre project area, this translates to a potential overestimate of project benefits by 119 to 397 Mg C in the first 5 years. This is the equivalent of the CO2 emissions from the consumption of 46,210 to 175,350 gallons of gasoline.

Comparisons of Carbon Stock Estimates: Additional Sites

At 5 additional sites, field-based carbon stock estimates ranged from 0.14 Mg C per acre for a 5-year-old riparian planting to 36.72 Mg C per acre for a 21-year-old planting. Carbon calculator carbon stock estimates had little agreement with the field-based carbon stock estimates and were often outside the 90% confidence interval of those estimates.

Estimated Carbon Stocks at sites ranging from 5 to 21 years in age

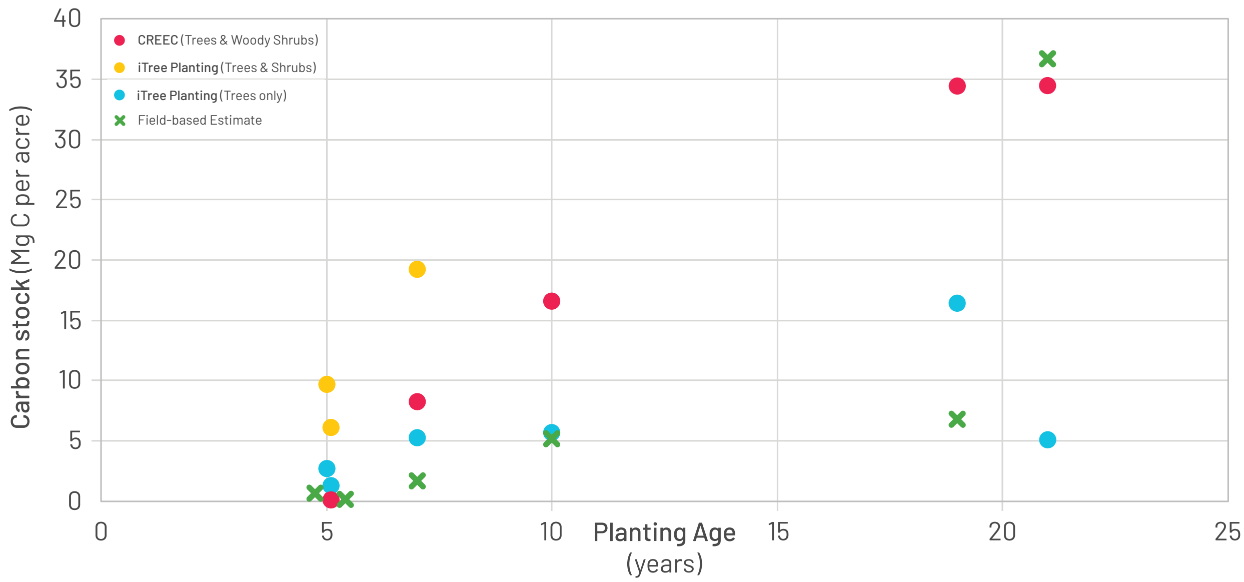


Figure 4. Carbon stocks (Mg C per acre) estimated at 6 riparian planting project sites using field-based estimates and two carbon calculators (CREEC and i-Tree Planting) plotted against the age of the planting project.

Table 1. Site information, carbon stocks estimated from field data and carbon calculators and field measured stand characteristics for the Willamette Confluence Preserve (WCP) Coyote Field planting and 5 additional sites surveyed as part of a chrono sequence study of riparian planting carbon stocks in western Oregon (O'Kelley et al. *in prep*).

Site Information					Field-based Estimated Carbon Stocks (Mg C/acre)		Calculator Estimated Carbon Stocks (Mg C/acre)			Field Measured Stand Characteristics		
Site	Years	Planting Area (acres)	Initial Planting Density (plants/acre)	Number of plots sampled	Average Carbon Stored in Trees, Saplings, & Shrubs	90% Confidence Interval	CREEC Trees & Woody Shrubs	iTree Planting Trees & Shrubs	iTree Planting Tree Only	Average Tree Density (stems/acre)	Average Shrub Density (shrubs/acre)	Average Tree & Shrub Density (plants/acre)
WCP	5	44	1820	15	0.65	0 - 1.63	0.54	9.68	5.67	89	796	1185
LF05a	5	41	1362	3	0.14	0 - 0.31	0.54	6.08	2.31	0	1268	1268
LC05c	7	2.5	2068	3	1.72	0 - 6.0	8.24	19.22	7.66	108	702	810
LF10b	10	50	431*	3	5.14	1.41 - 8.87	16.61	NA	5.69	364	135	499
LF15b	19	3	1183	3	6.76	1.68 - 11.84	34.44	43.68	22.12	357	783	1140
LF20b	21	4.5	467*	3	36.72	28.20 - 45.25	34.44	NA	5.09	256	1673	1930

Case Study Insights for Future Monitoring

Our sample of the 44-acre WCP was based on fifteen 10-m radius plots, while the other sites were based on three 8-m radius plots. We highlight a well-known tradeoff between monitoring effort and precision: more precise estimates of carbon stocks will typically require a larger sample size especially if based on smaller plots (<0.1 ha). Precision is anticipated to improve with subsequent measurements as stands mature and homogenize. Depending on the monitoring goals, high precision estimates may be needed – for example, participation in carbon offset programs.

We used data from WCP and 43 additional sites sampled as part of the western Oregon riparian planting chronosequence[6]. We estimated the sample sizes needed to meet a precision target of +/-20% total woody biomass carbon (Mg C/acre) with 90% confidence using the equation: N = (t2 * (CV2))/E2 where E is equal to the margin of error (0.20) and t is equal to 1.645 (90% confidence interval).

Our results confirm recommendations that younger plantings (< 10 years old) are highly variable and require increased sample sizes. At Coyote Field, woody carbon stocks (Mg C/acre) had 91% coefficient of variation and, across western Oregon, sites between 5 and 10-years old averaged 103% coefficient of variation. For sites over 15 years old, coefficient of variation dropped to 70% and 64% for sites over 20 years old. Based on these estimates, for a maximum 20% error with 90% confidence, sampling would require substantial time.

Table 2. Sampling data from this case study and a larger study of sites in western Oregon indicate high sampling effort would be needed to meet precision goals of a maximum 20% error with 90% confidence, especially in the earlier years post-planting.

Site	Years	Sampling effort and summary statistics				Sampling effort needed based on current data	
		No. Plots Sampled	Plot Size (Acres)	Mean	Coefficient of Variation	Estimated sample size	Estimated sample acres
WCP	5	15	0.08	0.65	0.91	57	4.52
Pooled Sites	5-10 years	3	0.05	6.46	1.03	72	3.57
Pooled Sites	10-15 years	3	0.05	22.40	0.85	48	2.41
Pooled Sites	15-20 years	3	0.05	32.70	0.70	33	1.64
Pooled Sites	20+ years	3	0.05	75.10	0.64	28	1.38

Detailed Methods

Field-based carbon stock estimates

Field sampling at Willamette Confluence Preserve

We inventoried trees and shrubs at the Coyote Field planting during May 2024. We used simple random sampling to locate clusters of five 10-meter radius (0.03 ha) circular plots. The inventory employed cluster sampling to reduce variability and achieve greater precision. Each cluster of plots was arranged in a cross configuration oriented in the cardinal directions. The center plot was located using random coordinates generated within the planting area. The remaining plot centers were located using a 50-m tape laid out in each cardinal direction (N,E,S,W). Plot center coordinates were recorded using a handheld GPS. No permanent plots are installed in this project.

Sampling tools ©
Photo by Rose Graves.

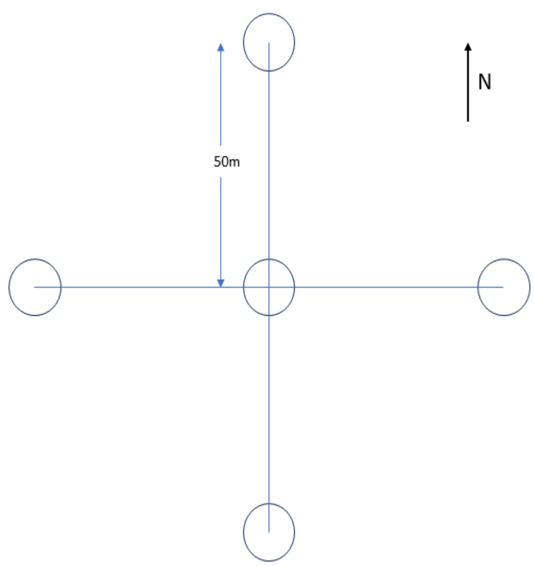


Figure 5. Diagram of plot cluster array. Each plot in the array has a radius of 10-m. The 2.5-m radius subplots are nested within the plots using the same plot center.

At each plot, we established a 10-m radius tree and seedling plot and a 2.5-m radius shrub plot. All trees (> 3 cm dbh) within the 10-m plot were recorded by species and we measured the diameter at 1.3 m (dbh) and height of each tree. We tallied seedlings (tree species < 3 cm dbh) by species. Shrub biomass was measured in 0.002 ha subplots (2.5-m radius). For shrubs, we recorded the species, height, width, and orthogonal width.

Field sampling at additonal sites

We used simple random sampling to locate three sample plots at each site. Plot center coordinates were recorded using a handheld GPS. No permanent plots were installed in this project. At each plot, we established an 8-m radius tree plot, a 4-m radius understory plot, a 15-m coarse woody debris transect, and 3 soil sampling locations. Data collection differed slightly from the more intensive sampling at the Willamette Confluence Preserve. Trees were measured only if they had reached 5 cm dbh, and shrubs were measured and seedlings tallied in the 4-m radius understory plot. Data collected for each tree and shrub was the same as described above.

Field data analysis and carbon stock estimates

We applied allometric equations to the field data to calculate carbon stocks for trees (live and dead), shrubs, and seedlings. To compare to the carbon calculator tools, we calculate both aboveground and belowground carbon stocks. All analyses were done in R[7].

Tree Biomass and Carbon

Tree carbon stocks were estimated using the National Scale Volume and Biomass Estimators (NSVB) method[8]. The NSVB method is a recent replacement of the Component Ratio Method (CRM) used by the Forest Inventory Analysis (FIA) and offers more precise and accurate representations of forest aboveground biomass and carbon compared to the CRM. NSVB uses both diameter (dbh) and height (h) measurements to estimate individual tree biomass and carbon. Belowground biomass was calculated applying equations for coarse root and fine root component ratio[9]. These tree-level estimates are then aggregated to plots and expanded to a hectare basis. Analysis was done in R, modifying open source NSVB R code[10].

Seedling biomass was calculated following Johnson et al.[11], using the formula:

$$SB_x = b1 + b2 * SD_x$$

where: SB_x = aboveground seedling biomass in plot x (Mg/ha), SD_x = seedling density (stems/ha) in plot x, and *b1* and *b2* = forest type coefficients. Johnson et al. provide seedling biomass coefficients for only one forest type in the Pacific Northwest so we used the b1 and b2 coefficients for that forest type. We calculated aboveground seedling C stocks for each species by multiplying biomass by species-specific live tree carbon factors[12]. Belowground C stocks were assumed to be 10% of aboveground stocks[13].

Woody Shrub Biomass and Carbon

Measurements of shrub structure were collected for all shrubs within the 2.5-m radius subplots. These included: height (h, defined as the maximum vertical distance from the ground surface to the height of the shrub), longest width (w1) and orthogonal width (w2). Allometric equations to calculate aboveground biomass in multi-stemmed small trees, woody and semi-woody shrubs were chosen from published literature based on a variety of factors. We placed preference on equations which: 1) use parameters available in our dataset, 2) provide total aboveground biomass estimates, and 3) that are developed for a location as close as possible to the study. Whenever possible, we chose to use allometric equations that were species specific. However, where allometric equations were not available for a species we chose allometric equations from the same genus or family. For species in the *Rosaceae* family, which has many growth forms, we modified the specificity criteria to include similar growth form (e.g., small tree, woody versus semi-woody shrub) at the genus and family level. For several species, we used multispecies models developed by Verschuyl et al. 2018. The applicability of multispecies models to predict total AGB for single genus and species has been shown for shrubs[14]. Belowground C stocks were assumed to be 10% of aboveground stocks[15].

Carbon calculator parametrization

CREEC Parameters

CREEC does not require information on plant size. Instead, users must identify the regeneration type (i.e., planted community), region, type of site preparation, and prior land use for the project. We chose the Coast Range and Foothills (<1000 m elevation) region as most likely to be similar to the WCP site and the additional sites. The other options available in the CREEC tool are: Central Valley, Sierra/Klamath/Cascades (>1000 m elevation), and Southern California. For all sites, site prep was low, non-mechanical and prior land use was degraded/invaded or grassland, depending on reported prior condition. Plantings were entered using a percent composition or number of plants per acre by species based on the planting plans available.

i-Tree Planting & i-Tree Eco Forecast Parameters

The i-Tree tools require input on plant size using diameter at breast height (dbh). For i-Tree Eco, all plants were assigned initial dbh of 0.5 cm. i-Tree Eco also requires users to input the height of each plant, which we entered as 0.45 m for all plants. These likely overestimate the initial starting condition of the planting, given that bareroot stock plants used in the restoration plants had not reached 1.37 m (4.5 feet or "breast height"). However, entering height and not dbh is not accepted.

Additional information needed to run the i-Tree tools included location (e.g., Eugene, Lane County, Oregon), mortality rate, and sun exposure (full sun). For the WCP case study, we modified mortality rates in i-Tree Eco forecast to have a maximum cumulative estimate of 25% for the 5-year period.

Percent crown dieback was assumed to be 0% for all initial plantings. i-Tree Planting allows users to enter groups of the same species using a single line of data, whereas i-Tree Eco requires a separate line of data for each individual plant which requires more data entry. Given this time limitation, we did not run i-Tree Eco for the additional sites. For i-Tree Planting, we limited mortality to 3% annual mortality (the default) and assumed all plants were in 'good' condition.

Species Data Entry

No tool allowed us to enter all species which were planted at Coyote Field or the other sampled sites. For species which were not available in CREEC, we chose either the next closest species/genera (i.e., Quercus spp. versus Quercus garryana) or the generic "Other understory woody shrub" or "Other canopy tree" as appropriate. In i-Tree planting, we often used a genus level (i.e., Holodiscus spp.) or chose a next closest genera. The i-Tree Eco tool allowed entry of all species except mockorange *(Philadelphus lewisii)*. We chose to substitute osoberry *(Oemlaria cerasiformis)* based on the similar growth form of the two species. Table 3 provides species lists from the sites' planting plans included in this report and how each species was entered into each tool.

Table 3. Species list for the plantings included in this study, the assumed growth form, and how each species was entered into the i-Tree Planting and CREEC carbon calculators.

Species Scientific Name (common name)	Growth Form	WCP: Coyote Field	LF05a	LC05c	LF10b	LF15b	LF20b	iTree Planting	CREEC
Abies grandis (grand fir)	Tree		X	X	X		X	Abies grandis	Other canopy tree
Acer circinatum (vine maple)	Shrub	X	X					Acer palmatum	Acer (other)
Acer macrophyllum (big leaf maple)	Tree	X	X	X	X	X		Acer macrophyllum	Acer (other)
Alnus rubra (red alder)	Tree		X	X	X	X		Alnus rubra	Alnus (other)
Alnus rhombifolia (white alder)	Tree				X			Alnus rhombifolia	Alnus rhombifolia
Amelanchier alnifolia (w. serviceberry)	Shrub	X	X	X		X		Amelanchier spp	Other understory woody shrub
Calocedrus decurrens (incense cedar)	Tree		X	X	X			Calocedrus decurrens	Other canopy tree
Cornus sericea (red osier dogwood)	Shrub		X	X		X		Cornus sericea	Other understory woody shrub
Crataegus douglasii (black hawthorn)	Tree			X		X		Crataegus spp	Other canopy tree
Frangula purshiana (cascara)	Tree	X	X	X		X		Fangula spp	Other canopy tree
Fraxinus latifolia (Oregon ash)	Tree	X	X	X	X	X	X	Fraxinus latifolia	Fraxinus latifolia
Holodiscus discolor (oceanspray)	Shrub	X	X			X		Holodiscus spp	Other understory woody shrub
Lonicera involucrate (twinberry)	Shrub		X	X		X		Lonicera spp	Other understory woody shrub
Mahonia aquifolium (Oregon Grape)	Shrub	X	X	X				Mahonia spp	Other understory woody shrub
Malus fusca (crabapple)	Shrub		X			X		Malus spp	Other understory woody shrub
Oemleria cerasiformis (osoberry)	Shrub	X	X	X		X		Oemleria spp	Other understory woody shrub
Philadelphus lewisii (mock orange)	Shrub	X	X	X				Oemleria spp	Other understory woody shrub
Physocarpus capitatus (Pacific ninebark)	Shrub	X	X	X		X		Rosa spp	Physocarpus capitatus
Pinus ponderosa (ponderosa pine)	Tree			X	X			Pinus ponderosa	Other canopy tree
Populus trichocarpa (black cottonwood)	Tree	X		X	X			Populus balsamifera ssp. trichocarpa	Populus (other)
Prunus virginiana (choke cherry)	Tree			X		X		Prunus virginiana	Other canopy tree

Species Scientific Name (common name)	Growth Form	WCP: Coyote Field	LF05a	LC05c	LF10b	LF15b	LF20b	iTree Planting	CREEC
Pseudotsuga menziesii (Douglas fir)	Tree	X	X		X	X	X	Pseudotsuga menziesii	Other canopy tree
Quercus garryana (Oregon white oak)	Tree	X						Quercus garryana	Quercus (other)
Quercus kellogii (California black oak)	Tree	X						Quercus kellogii	Quercus (other)
Ribes sanguineum (red flowering currant)	Shrub	X		X				Rubus spp	Other understory woody shrub
Rosa nutkana (Nootka rose)	Shrub			X		X		Rosa spp	Rosa sp
Rosa pisocarpa (cluster rose)	Shrub		X					Rosa spp	Rosa sp
Rubus parviflorus (thimbleberry)	Shrub	X	X	X				Rubus spp	Rubus sp
Rubus spectabilis (salmonberry)	Shrub		X	X		X		Rubus spp	Rubus sp
Salix lasiandra (Pacific willow)	Shrub			X				Salix spp	Salix sp
Salix sitchensis (Sitka willow)	Shrub			X				Salix sitchensis	Salix sp
Salix scouleriana (Scouler's willow)	Shrub		X					Salix scouleriana	Salix sp
Sambucus cerulea (blue elderberry)	Shrub	X	X			X		Sambucus nigra	Sambucus sp
Sambucus racemose (red elderberry)	Shrub		X	X				Sambucus racemosa	Sambucus sp
Spirea douglasii (Western Spirea)	Shrub			X		X		Rosa spp	Other understory woody shrub
Symphoricarpos albus (snowberry)	Shrub	X	X	X		X		Rosa spp	Symphoricarpos albus
Thuja plicata (western red cedar)	Tree	X	X	X		X	X	Thuja plicata	Other canopy tree
Tsuga heterophylla (western hemlock)	Tree					X	X	Tsuga heterophylla	Other canopy tree

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