Aggregated Methods for Calculating Tree Carbon Stock and Sequestration Rate, and Soil Carbon Stock from Field Collected Fixed Radius Plot Data

Crystal Crown[1], Chloe Hanna[2], Clara Pregitzer[1]

[1] Natural Areas Conservancy, 1234 5th Avenue, New York, NY, USA

[2] Yale School of the Environment, Yale University, New Haven, CT, USA

Description

This document summarizes methods for calculating living and dead tree carbon stock density (Mg C/ha^{-1}), soil carbon stock density (Mg C/ha^{-1}), and annual modeled live tree carbon sequestration rates (Mg C/ha^{-1}/yr^{-1}) in forests using stem data collected in forested natural areas using a fixed-area plot methodology. These methods were aggregated from various literature sources (cited in text), and are a modified form of the methods used in Pregitzer et al. 2021. Differences between those methods and what is outlined here are: 1) updated species coefficients for tree carbon stock; 2) use of measured instead of estimated soil bulk density for soil carbon estimates; 3) modified methods for standing dead tree carbon; 4) removal of by-vigor scaling for carbon sequestration estimates; and 5) correction of the stem bark reduction factor used for Equation 10.

Data Requirements

The below calculations require tree species and size data from fixed area plots for all stems, living and dead, >=2 cm DBH, as well as soil attributes acquired from lab processing of soil cores taken from the same plots.

Plot Attributes

Plot information for use in scaling plot level data to per hectare. Specifics and example data:

Plot ID	Plot Size (ha)
Sample plot unique ID	*Plot size*
x_004	0.0314
x_002	0.0314

Stem Data

Individual stem data from a random sample, fixed-area plot methodology, that includes data for all stems >=2cm and the following attributes for each stem: Species (USDA_Code), DBH (cm), status (living/dead), and decay class (for dead stems). Specifics and example data:

Plot ID	USDA Code	DBH (cm)	Status	Decay Class
Sample plot unique ID	*Species USDA Code*	*DBH of stem*	*Mortality status*	*Decay class for dead stems*
x_004	ROPS	25.4	Living	<null>
x_004	ACPL	34	Dead	2

Soil Data

Soil cores analyzed for bulk density of fine fragments (particles <=2mm), coarse fragment % of sample volume, and % fine fragment organic carbon. The core size we used: 12" long x 1.5" diameter. Specifics and example data:

Plot ID	Core volume (cm^3)	Bulk Density (g/cm^3)	% Organic Carbon	Coarse Fragment (%)
Sample plot unique ID	*Volume of soil core*	*Bulk density of fine fragment/soil component of sample (particles <=2mm)*	*Fine fragment/soil % carbon*	*% of sample volume that is coarse fragment (particles >2mm)*
x_004	292	1.34	9.49	22.33
x_002	292	1.24	1.5	10.1

Calculation Methods

Below are the methods for calculating carbon stock density for live trees, standing dead trees, and soil as well as modeled live tree net carbon sequestration rate. The inputs for the equations presented are color coded by the source of the input as follows: Other equation | Reference table or publication | Field or lab data | Methods dependent

**The supplement table (S1) noted in this section is available for [download](#).

LIVE TREE CARBON STOCK DENSITY: The Megagrams (Mg) Carbon (C) stored in live trees per hectare per plot

---

Equation 1 | Calculate Aboveground Biomass: Calculate the aboveground biomass (kg dry weight) for all living stems >=2cm DBH using the following allometric equation from Jenkins et al. 2003. Species group coefficients to plug into the formula were sourced primarily from Choknacky et al. 2014, with some supplementation as tabulated in *S1*:

$$ABM_t = Exp(\beta_0 + \beta_1 \ln DBH_t)$$
where
ABM_t = aboveground biomass of tree t (kg dry weight)
Exp = exponential function
β_0 and β_1 = species group coefficients (*S1*)
$\ln$ = natural log
DBH_t* = diameter at breast height of tree t (cm)
*equation intended for trees ≥ 2.5 cm DBH

Equation 2 | Calculate Below-ground Component Ratios: Calculate the below-ground component ratios using the Jenkins et al. (2003) ratio equation. Duplicate equation for coarse and fine roots using below coefficients:

Component	β_0	β_1
Fine Roots	-1.8629	-0.77534
Coarse Roots	-1.4485	-0.03476

Table 1: Coefficients for calculating belowground component ratio for fine and coarse roots. Sourced from Chojnacky et al., 2014.

$$R_{ct} = Exp(\beta_0 + \beta_1 * LN(DBH_t))$$
where
R_{ct} = ratio of component c to aboveground biomass of tree t
Exp = exponential function
β_0 and β_1 = Belowground component coefficients (table 1)
DBH_t = diameter at breast height of tree t (cm)

Equation 3 | Calculate Total Stem Biomass: Calculate the total biomass of a stem. To do this you will calculate the biomass of each belowground component by multiplying the ratio of each component (coarse and fine roots, from Equation 2) by the tree's aboveground biomass, and then add these values to the aboveground biomass from Equation 1:

$$TBM_t = ABM_t + R_{frt}*ABM_t + R_{crt}*ABM_t$$
where
TBM_t = total biomass of tree t (kg dry weight)
ABM_t = aboveground biomass of tree t (kg) – Eq. 1
R_{frt} = fine root component ratio of tree t - Eq. 2
R_{crt} = coarse root component ratio of tree t – Eq. 2

Equation 4 | Calculate Live Tree Carbon Stock Density: Determine the live tree biomass per unit area in megagrams/hectare by calculating the total live tree biomass in the plot (the sum of all trees) and converting from kilograms to megagrams then dividing by the plot area. Carbon content is assumed to be 50% (Woodall et al., 2011).

$$C_t = (0.50*\Sigma(TBM_t/1000))/x$$
where
C_t = carbon stored in live trees for plot x (Mg/ha)
TBM_t = total biomass of tree t in plot (kg) – Eq. 3
0.50 = conversion to carbon
1000 = conversion from kg to Mg
x = plot size in Ha

Equation 5 | Calculate the Potential Relative Increment (PRI): To calculate net carbon sequestration, we first estimated DBH in year 2 using the potential relative increment (PRI) method. The following formula from Bragg 2001 calculates the PRI for an individual tree based on its DBH and species:

$$PRI_t = b_1 \, DBH_{t1}^{\,b2} \, b_3^{\,DBHt1}$$
where
PRI_t = potential relative increment of tree t (ratio)
DBH_{t1} = year 1 DBH of tree t (cm)
b_1, b_2, b_3 = species-specific coefficients

Coefficients are assigned as per Bragg, 2005. These coefficients are specific to the northeastern U.S. If a tree's species was not included in the table, we substituted an average for its genus. If a genus was not included, we substituted the average for hardwoods or softwoods. This method may underestimate growth of fast-growing non-native trees. PRI is the *maximum* increment a tree is likely to grow, as such, the resulting values are the maximum potential. Reduction factors based on tree condition were not included because condition was not available for all cities.

Equation 6 | Calculate the projected DBH in Year 2: The projected DBH of a stem one year from the date it was measured. This is an idealized calculation that does not take into account tree or habitat conditions which could influence growth rate. Use the following formula to calculate DBH in year 2:

$$DBH_{t2} = (PRI_t {}^*DBH_{t1}) + DBH_{t1}$$
where
PRI_t = potential relative increment of tree t – Eq 5
DBH_{t1} = year 1 DBH of tree t (cm)
DBH_{t2} = year 2 DBH of tree t (cm)

Calculate Biomass in Year 2: To calculate projected biomass in year 2, follow the same steps for calculating live tree biomass (Equations 1-3), replacing the measured DBH with the projected DBH from **Equation 6**.

Equation 7 | Calculate Net Sequestration Per Stem: To calculate net carbon sequestration for each tree, subtract the year 1 biomass (kg) from the projected year 2 biomass (kg) and then multiply the difference by 50% to convert this difference to (projected) net carbon sequestered.

$$NS_t = (TBM_{t2} - TBM_{t1}){}^*0.50$$
where
NS_t = net sequestration of tree t (kg)
TBM_{t2} = year 2 DBH of tree t (cm)- Eq 6
TBM_{t1} = year 1 DBH of tree t (cm)
0.50 = conversion to carbon

Equation 8 | Calculate Annual Sequestration Rate: The above sequestration per stem is then extrapolated to a Mg C / Ha / Year using the following formula:

$$SeqC_x = (\,\Sigma(NS_t)/1000)/x$$
where
$SeqC_x$ = C sequestered annually by trees in plot x (Mg/ha)
NS_t = net sequestration of tree t (kg)
1000 = conversion from kg to Mg
x = plot size in hectares

Calculate Aboveground Biomass for Dead Stem: Using Equation 1, calculate the Aboveground biomass for each dead stem. Note codes in *S1* that address unknown dead stems (USDA Codes 2TB, 2TE).

Calculate Component Ratios: A component ratio is a ratio of the biomass in a tree component to total tree biomass. You will calculate these ratios for several tree components using the formulas below. Note there are different formulas for different tree components.

Equation 9a | Calculate the Ratios for Belowground Components: Coarse and fine root ratio formula- the same formula used for live tree calculations (equation 2), and the coefficients in Table 1:

$$R_{ct} = Exp(\beta_0 + \beta_1 * LN(DBH_t))$$
where

R_{ct} = ratio of component c to Belowground biomass of tree t
Exp = exponential function
β_0 **and** β_1 = Belowground component coefficients (Table 1)
DBH_t = diameter at breast height of tree t (cm)

Equation 9b | Calculate the Ratios for Aboveground Components: Stem Bark, Stem Wood, Coarse Roots, and Foliage ratio formula (Jenkins 2003).

$$R_{ct} = Exp(\beta_0 + \beta_1 / DBH_t)$$
where

R_{ct} = ratio of component c to aboveground biomass of tree t
Exp = exponential function
β_0 and β_1 = Aboveground component coefficients (Table 2)
DBH_t = diameter at breast height of tree t (cm)

Wood Type:	Hardwood		Softwood	
Component	β_0	β_1	β_0	β_1
Stem Bark	-2.0129	-1.6805	-2.098	-1.1432
Stem Wood	-5.424	-2.0129	-0.3737	-1.8055
Coarse Roots (aboveground)	-1.6911	0.816	-1.5619	0.6614
Foliage	-4.0813	5.8816	-2.9584	4.4766

Table 2: Coefficients for calculating aboveground component ratios for stem bark, stem wood, coarse roots, and foliage, associated with the stem by wood type (Jenkins 2003).

Equation 9c | Calculate the branch ratio: Using the branch ratio formula (Jenkins 2003), calculate the ratio of branches as the remainder after other aboveground biomass components are subtracted from the whole:

$$R_{brn} = 1 - (R_{sb} + R_{sw} + R_{fol})$$
where

R_{brn} = ratio branches to aboveground biomass, *Eq. 9c*
R_{sb} = ratio stem bark to aboveground biomass, *Eq. 9b*
R_{sw} = ratio stem wood to aboveground biomass, *Eq. 9b*
R_{fol} = ratio foliage to aboveground biomass, *Eq. 9b*

Equation 10 | Calculate the Adjusted Biomass of Each Component: Calculate the component biomass by multiplying the Aboveground Biomass (Equation 1) by the ratio for each component, then multiply the product by the SLA factors (Table 3).

$$ACBM_{ct} = (ABM_t * R_{ct}) * SLA_c$$
where

$ACBM_{ct}$ = adjusted biomass of component c of SDT t (kg)
ABM_t = total aboveground biomass of SDT t (kg) – Eq. 1
R_{ct} = ratio of component c to total biomass of SDT t – Eq. 9a-c
SLA_c = structural loss adjustment for component c (Table 3)

To account for volume loss, reduce component biomass using structural loss adjustment (SLA) factors (Table 3) from Domke 2011 with modifications: a) Foliage and fine roots assumed to be present only in decay class 1 with 75% reduction from live tree. b) To account for

height loss, stem wood and bark SLAs are reduced (the Domke 2011 SLAs are for biomass calculated with the Component Ratio Method, which includes height). For decay classes 2-4, stem wood and bark SLAs are reduced by 50% of the previous class SLA.

Decay Class	Stem Wood*	Stem Bark	Foliage*	Coarse Roots ^	Fine Roots**	Branches
1	1.0	0.92	0.25	1.0	0.25	1.0
2	0.50	0.46	0.00	0.95	0.00	0.50
3	0.25	0.23	0.00	0.80	0.00	0.20
4	0.13	0.12	0.00	0.65	0.00	0.10
*Domke SLA = 1 for all classes, alteration to account for height loss is a reduction of 50% from previous class for classes 2-4. **Author additions, not from Domke 2011. ^Domke Roots SLA factor applied to both above and below ground coarse roots.						

Table 3: Structural loss adjustment factors by decay class and tree component.

Equation 11 | Calculate Total Biomass of Dead Tree: To calculate the total biomass of the standing dead tree, sum all of the component biomass estimates from Equation 10, and multiply the total by a decay reduction factor (Table 4)to account for density loss:

$$TBM_{sdt} = DRF * \Sigma ACBM_{ct}$$

where

TBM_{sdt} = total biomass of SDT t adjusted for decay loss (kg)

DRF = decay reduction factor (Table 4)

Σ = sum all components of SDT t

$ACBM_{ct}$ = adj. biomass of component c of SDT t (kg.) – Eq. 1

Wood Type	Decay Class 1	Decay Class 2	Decay Class 3	Decay Class 4
Hardwood	0.99	0.80	0.54	0.43
Softwood	0.97	1	0.92	0.55

Table 4: Decay reduction factors sources obtained from Harmon et al. 2011. Assigned to the stem by wood type and decay class. Wood type classifications can be found in *S1*.

Equation 12 | Calculate SDT Carbon Stock Density: The above biomass per stem is then extrapolated to a Mg C / Ha by summing the TBM (kg) of all stems from Equation 11 for the plot, dividing that sum by 1000 to convert kg to Mg. Then dividing the plot total by the plot size in hectares, and finally multiplying that output by 0.5 to convert the biomass measurement to carbon. SDT carbon is assumed to be 50% of biomass (Harmon et al., 2008).

$$C_{sdt} = 0.50 * ((\Sigma(TBM_t)/1000)/x)$$

where

C_{sdt} = carbon stored in dead trees for plot x (Mg/ha)

0.50 = conversion to carbon

TBM_t = total biomass of standing dead tree t in plot x (kg) - Eq. 11

1000 = conversion from kg to Mg

x = plot size in hectares

Calculations in this section are based on soil analysis of 30cm depth cores taken at each plot.

Equation 13 | Calculate Volume of Belowground Roots Per Plot: To start, calculate the volume of coarse roots estimated in the top 30 cm of soil in a plot, using the specific gravity for the species, and the outputs from equations 1 and 2-- assuming that 60% of coarse roots are in the top 30 cm of soil (Jackson et al 1996):

$$V_{crt} = \Sigma(R_{crt} * ABM_t * 0.6) / SPG_{sp}$$

where

V_{crt} = volume (cm^3) of coarse roots in plot x

R_{crt} = coarse root component ratio of tree t in plot x– Eq. 2
ABM_t = aboveground biomass of tree *t in plot x* (kg))- Eq. 1
0.6 = Proportion of coarse roots in top 30cm (Jackson et al 1996)
SPG_{sp} = Specific gravity of species of tree t in plot x (table x)
x = plot size in Ha

Equation 14 | Calculate the Volume of Mineral Soil Per Plot: Using the output from Equation 13, calculate the volume of mineral soil per plot, by subtracting volume of roots (Eq. 2) and coarse fragment (pieces >2mm, as determined in the lab) from the volume of soil in the plot:

$$V_{sx} = (V_{p30} - V_{xr})*(1 - CF_x)$$

where

V_{sx} = volume of soil in plot x to 30 cm depth (cm^3)

V_{p30} = total volume (cm^3) of a plot to 30cm depth
V_{xr} = volume of roots in plot x to 30 cm depth (cm^3)- Eq. 13
CF_x = coarse fragment volume of plot x (ratio)

Equation 15 | Calculate Soil Organic Carbon in Plot
Using the soil volume from Eq. 14, calculate the carbon content of the soil in the plot to 30 cm depth by multiplying the soil volume by the % organic carbon and the soil bulk density for the plot (both obtained through laboratory analysis). Divide the product by 1e6 to convert from grams to megagrams.

$$C_{sx} = (V_{sx} * BD_x * PC_x)/1E6$$

where

C_{sx} = SOC in plot x to 30 cm (Mg)

V_{sx} = volume of soil in plot x to 30 cm (cm3/ha) – Eq. 14
PC_x = percent organic carbon for plot x (ratio)
BD_x = soil bulk density for plot x (g/cm3)
1E6 = conversion from g to Mg

Equation 16 | Calculate Soil Organic Carbon Stock Density. Using the per plot soil carbon stock from Equation 15 calculate the megagrams of carbon per hectare of organic soil carbon by dividing the plot stock by the size of the plot in hectares.

$$C_s = C_{sx}/x$$

where

C_s = Extrapolated SOC per hectare at plot x (Mg/ha)

C_{sx} = SOC in plot x to 30 cm (Mg/ha) - Eq. 15
x = plot size in Ha

Equation 17 | Calculate total carbon stock density. USing the outputs from the above calculations, calculate the total carbon stock density per plot using the outputs from the above calculations.

$$C_{stock} = C_t + C_{SDT} + C_s$$
where

C_{stock} = **Carbon stock density (Mg/ha) of carbon at plot x**
C_t = Carbon stock density (Mg/ha) in live trees at plot x Eq. 4
C_{SDT} = Carbon stock density (Mg/ha) in SDTs at plot x Eq. 12
C_s = Carbon stock density (Mg/ha) at soil at plot x Eq. 16

References

Bragg, D.C., 2001. Potential relative increment (PRI): a new method to empirically derive optimal tree diameter growth. Ecological Modeling, 137(1), pp.77-92.

Bragg, D.C., 2003. Optimal tree increment models for the northeastern United States. In Proceedings of the fifth annual forest inventory and analysis symposium (pp. 18-20).

Chojnacky, D.C., Heath, L.S. and Jenkins, J.C., 2014. Updated generalized biomass equations for North American tree species. Forestry, 87(1), pp.129-151.

Domke, G.M., Woodall, C.W. and Smith, J.E., 2011. Accounting for density reduction and structural loss in standing dead trees: Implications for forest biomass and carbon stock estimates in the United States. Carbon Balance and Management, 6, pp.1-11.

Harmon, M.E., Woodall, C.W., Fasth, B. and Sexton, J., 2008. Woody detritus density and density reduction factors for tree species in the United States: a synthesis. USDA For. Serv. Gen. Tech. Rep. NRS-29.

Harmon, M.E., 2011. Differences between standing and downed dead tree wood density reduction factors.

Jackson, R.B., Canadell, J., Ehleringer, J.R., Mooney, H.A., Sala, O.E. and Schulze, E.D., 1996. A global analysis of root distributions for terrestrial biomes. Oecologia, 108, pp.389-411.

Jenkins, J.C., Chojnacky, D.C., Heath, L.S. and Birdsey, R.A., 2003. National-scale biomass estimators for United States tree species. Forest science, 49(1), pp.12-35.

Pregitzer, C.C., Hanna, C., Charlop-Powers, S. and Bradford, M.A., 2022. Estimating carbon storage in urban forests of New York City. Urban Ecosystems, 25(2), pp.617-631.

Woodall, C.W., Heath, L.S., Domke, G.M. and Nichols, M.C., 2011. Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the US forest inventory, 2010. Gen. Tech. Rep. NRS-88. Newtown Square, PA: US Department of Agriculture, Forest Service, Northern Research Station, 30.