

Woody biomass carbon stock estimation using allometric equations

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0. Introduction

Carbon is the building block of life on Earth. All living beings, whether still alive or dead, contain carbon. Carbon moves between atmosphere, oceans, land and living organisms in a process called carbon cycle (Figure 1). Bulk of the carbon is stored in rocks and sediments. Oceans store around 50 times more carbon than the atmosphere, and terrestrial soils and vegetation store around 2.5 to 4 times more carbon than the atmosphere.

Human activities have altered the carbon cycle and carbon pools. Burning of fossil fuels and clearing of vegetation has increased the carbon in the atmosphere. Increased CO₂ in the atmosphere is a core driver of global warming. It is estimated that 60 % of the anthropogenic CO₂ emissions has been sequestered and stored to oceans and terrestrial ecosystems, while the rest has remained in the atmosphere.

Terrestrial carbon sequestration and storage are recognised crucial for mitigating climate change. However, while anthropogenic CO₂ emissions have been increasing, the global terrestrial carbon stocks have been declining, mostly caused by deforestation and forest and land degradation. Multiple initiatives and agreements have been established to promote facilitating terrestrial carbon sequestration and protecting existing carbon stocks. These include, among others, REDD+, Kyoto Protocol, Paris Agreement.

Understanding how much carbon is stored in terrestrial ecosystems is important for climate change mitigation, land management and in supporting policies and initiatives. Reliable estimates of carbon stocks enable a) assessing ecosystem contribution to climate change mitigation, b) comparing ecosystems' carbon storage and thus climate change mitigation potential, and c) detecting changes in carbon storage, both positive and negative, in time.

Woody vegetation represents the largest carbon pool in terrestrial vegetation and thus, plays a key role in carbon sequestration and storage. This learning material provides practical guidance on estimating woody carbon stocks through allometric equations. It is divided into 5 Sections:

1. Background introducing basic concepts, processes and approaches in woody carbon stock inventory
2. Introduction to allometric equations to estimate aboveground woody carbon stocks
3. Introduction to root-to-shoot ratios in estimating belowground woody carbon stocks
4. Step-by-step examples on how to calculate, individual tree, plot and land-use level carbon stocks using allometric equations and root-to-shoot ratios
5. Guidance on how to use carbon stock estimations on determining carbon sequestration rate. The material is supplemented with recommended reading and other relevant materials and reference list.

1 Background

1.1 Basic terminology and concepts

Carbon stock refers to the amount of carbon stored in a (eco)system at a given time. It is presented as the amount of carbon per unit area, usually megagrams of carbon per hectare: MgC ha^{-1} . Terrestrial carbon stocks include living and dead biomass, soil organic carbon, soil inorganic carbon, and long-lasting biomass products

Carbon sequestration refers to the process of capturing and storing carbon over time. It is presented as a sequestered carbon per unit area per time, usually megagrams of carbon per hectare per year $\text{MgC ha}^{-1} \text{y}^{-1}$.

Allometric equation is a mathematic equation that estimates woody individual (or stand) biomass based on one or more tree characteristics, usually diameter, height, and/or wood specific density.

Carbon sink is an ecosystem that absorbs more carbon than it releases (i.e. carbon sequestration rate is positive).

Carbon source is an ecosystem that releases more carbon than it absorbs, (i.e. carbon sequestration rate is negative)

Carbon turnover time refers to the time between carbon being sequestered in and released from the system, i.e. the time carbon stays in the system.

Carbon stock saturation refers to the finite capacity of ecosystems and soil to increase carbon stocks. Carbon stock saturation is reached when the carbon inflow and outflow are equal and, thus carbon stocks are not increasing nor decreasing but remains stable (until disturbance or other change in the system)

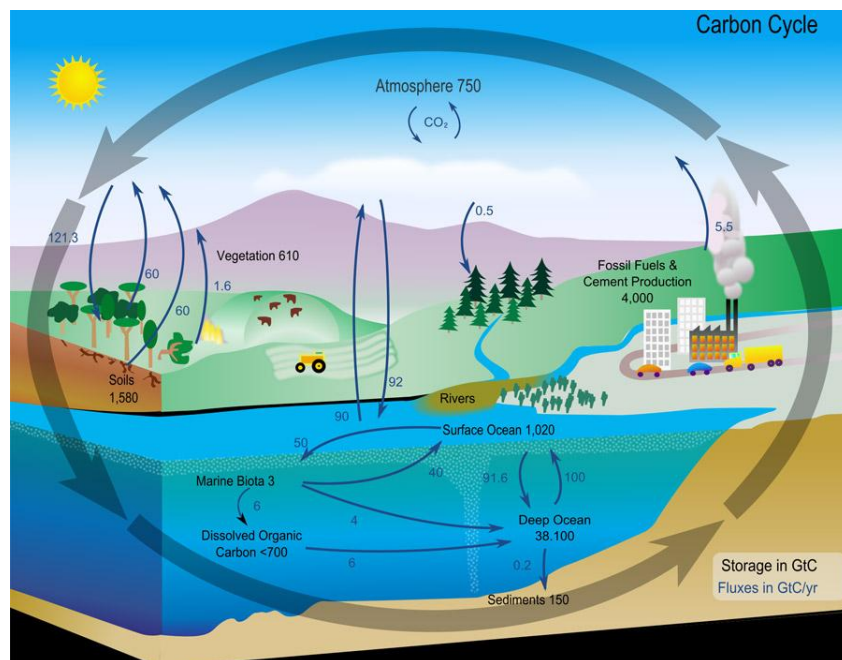


Figure 1. Illustration of global carbon cycle. Figure by NASA, Public domain, via Wikimedia Commons. This figure is not covered by the CC BY-NC license of this publication.

1.2 Organic carbon in a forest

Carbon enters ecosystems through photosynthesis: plants sequester carbon from the atmosphere and deposit it in their biomass. Part of biomass carbon is transformed into soil organic carbon through soil fauna decomposing organic matter. Most of soil carbon consists of humus.

A forest, or any landscape, contains different “compartments” or pools of organic carbon (Figure 2). It depends on the study and objectives which compartments are accounted for in the carbon stock inventory. Carbon is located both aboveground (aboveground carbon) and belowground (belowground carbon).

Aboveground carbon (AGC) consists of carbon in the tree trunks, branches, and leaves, herbaceous layer, and litter.

Belowground carbon consists of carbon in the plant roots and in soil organic carbon.

This learning material will, in the next chapters, focus solely on measuring carbon stocks in woody biomass, mainly trees, both above- and belowground.

However, it is worth of noting that soil carbon stock is larger than carbon in terrestrial vegetation. Thus, the importance of soil carbon stocks cannot be undermined in the ecosystem carbon stock estimations and accounting.

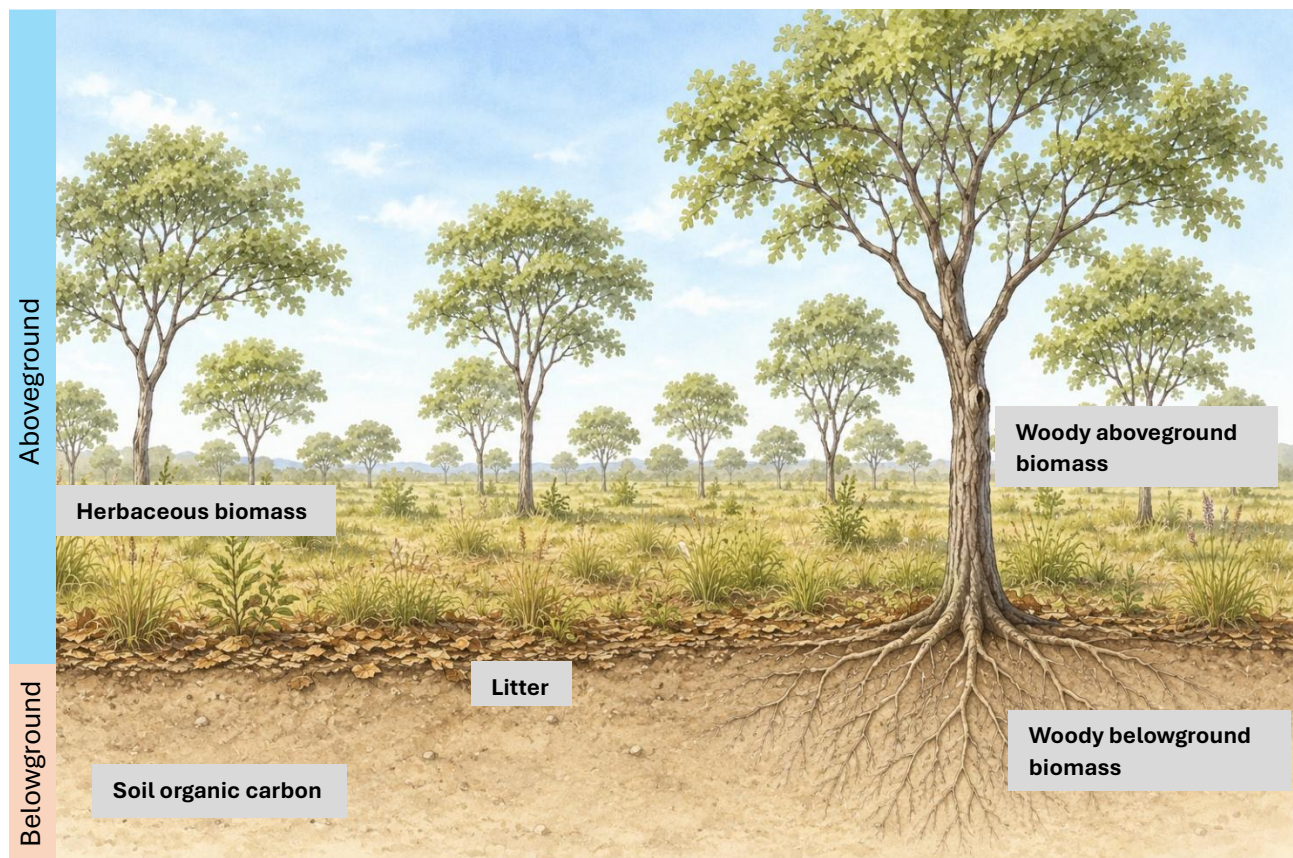


Figure 2. Organic carbon pools in the landscape. Aboveground carbon consists of carbon in the (i) **woody biomass**: trunk, branches and leaves, (ii) **herbaceous layer**, and (iii) **litter**. Belowground carbon consists of carbon in the (iv) woody and herbaceous **plant roots**, and **soil organic carbon**. Image generated by AI, annotations added by the author.

1.3 Approaches for woody carbon stock inventory

There are three common methods to estimate and measure carbon stock in a given system or a carbon pool.

Modelling

There are specific modelling software developed for carbon stock estimations. The models are based on ecological processes and land management.

✓ **Advantages:** No fieldwork required, low-time consuming, promising results.

⚠ **Disadvantages:** Depend on input data (to set the parameters of modelling), which sometimes or in some places may be difficult to acquire.

Remote sensing

Remote sensing-based estimations are based on interpretations from satellite images, e.g. number of trees or canopy coverage.

✓ **Advantages:** Can be used to estimate carbon stocks from very large areas.

⚠ **Disadvantages:** Provide rather simplified, default values.

Field-based measurements

Field-based measurements are based on actual biomass inventory in the field.

✓ **Advantages:** They provide the most accurate results.

⚠ **Disadvantages:** Time- and resource-consuming.

The three most used field-based methods for woody carbon inventory are:

Laser scanning (Light Detection and Ranging, LiDAR) through terrestrial, airborne, or mobile laser scanning, which creates 3D maps and can visualize individual trees. Based on specific algorithms, LiDAR can be used to estimate biomass. Laser scanning is a rather accurate and low-time consuming method (compared to other field-based methods). Yet requires specific knowledge and technological skills and is still rather expensive.

Whole tree harvesting (and combustion) provides the most accurate estimate of the carbon pool. It is based on cutting down the tree to determine the dry weight of tree parts (stem, leaves, branches etc.) This method destroys the tree and thus, also the carbon stock. This method is used to create allometric equations to enable biomass and carbon estimation based on specific characteristics of the woody individual.

Allometric equations are currently the most common (field-based) method for above-ground woody carbon stock assessment. **Root-to-shoot ratios** and equations can be used to estimate root biomass based on the aboveground biomass.

The usage of these allometric equations and root-to-shoot ratios is explained in detail, and some equations are presented, in the chapters below.



Carbon stock measurements represent the carbon stock only at the time of the measurement. Through carbon sequestration and release, carbon stocks change over time.

2 Allometric equations for aboveground tree biomass and carbon estimations

This learning material focuses solely on allometric equations for biomass and carbon stock estimation.

While acknowledging that proper sampling approach and accurate woody measurement-taking (DBH, height, basal area, etc.) are essential pre-requisite for reliable carbon stock assessment and usage of allometric equations, sampling and tree measurement are out of the scope of this material.



Open access reading materials on sampling and tree measurement taking

Pearson, Timothy; Walker, Sarah; Brown, Sandra (2013). Sourcebook for Land Use, Land-Use Change and Forestry Projects. © World Bank. <http://hdl.handle.net/10986/16491>

Sehmi R, Mbow C, Pitkanen S, Cross H, Berry N, Riddell M, Heiskanen J, Aynekulu E. 2016. Replicable tools and frameworks for bio-carbon developments in West Africa. ICRAF Working paper No. 237. Nairobi, World Agroforestry Centre. DOI: <http://dx.doi.org/10.5716/WP16138.PDF>.

UNFCCC (2015). Measurements for Estimation of Carbon Stocks in Afforestation and Reforestation Project Activities under the Clean Development Mechanism: A Field Manual. https://unfccc.int/resource/docs/publications/cdm_afforestation_field-manual_web.pdf

2.1 Overview of allometric equations

It is commonly assumed that 47 – 50 % of dry biomass consists of carbon. Thus, when inventorying woody carbon stocks in the field, we actually estimate (dry) woody biomass.

This woody biomass is then translated into carbon by a biomass-to-carbon fraction rate of 0.47 - 0.5.

Allometric equations estimate aboveground dry biomass of an individual tree (or a shrub). Allometric equations are based on one or more tree characteristics, namely: (i) diameter breast height, (ii) height, (iii) wood specific density.

There are hundreds of allometric equations developed. The equations can be:

- species-specific
- country-specific
- ecosystem-specific
- climatological zone-specific
- combination of the above

Most allometric equations have limitations, and they are suitable for trees within a certain diameter size range.



It is important to understand that allometric equations provide only estimations, not exact, fully precise values. Thus, the results obtained, while useful approximations, are subjected to a degree of uncertainty.

2.2 Examples of allometric equations

In the table below, there are some commonly used allometric equations for the tropics.

Table 1. Selected multispecies allometric equations estimating tree biomass.

DBH = diameter breast high, H = height, WD = wood density, BA = basal area. Table derived from Mänttinen (2020), see references to the sources within.

Equation	Region	Limitations	Source
$AGB(kg) = 0.0673 * (WD * DBH^2 * H)^{0.976}$	Pantropical	5cm ≤ DBH ≤ 212cm	Chave et al. 2014
$AGB(kg) = 0.0559 * WD * DBH^2 * H$	Pantropical	5cm ≤ DBH ≤ 212cm	Chave et al. 2014
$AGB(kg) = 0.0899 * (DBH^2)^{0.9522} * (H^{0.9522}) * (WD^{0.9522})$	Not specified	Not specified	FAO 2004
$AGB(kg) = 0.112 * (WD * DBH^2 * H)^{0.916}$	Tropical dry forests	5cm ≤ DBH ≤ 63.4cm	Chave et al. 2005
$AGB(kg) = 10^{(-0.535 + \log_{10} * BA)}$	Tropical dry forests	3cm ≤ DBH ≤ 30cm	Brown, 1997
$AGB(kg) = \text{Exp}(-1.996 + 2.232 * \text{Ln} * DBH)$	Tropical dry forests	5cm ≤ DBH ≤ 40cm	Brown, 1997
$AGB(kg) = 34.4703 - 8.0671 * DBH + 0.6589 * DBH^2$	Tropical dry forests	5cm ≤ DBH	Brown, et al., 1989
$AGB(kg) = 0.2035 * DBH^{2.13196}$	Tropical dry forests	DBH ≤ 63cm	Pearson, et al., 2005
$AGB(kg) = WD * \text{Exp}(-0.997 + 1.784 * (\text{Ln}(DBH))^2 - 0.0281 * (\text{Ln}(DBH))^3)$	Dry forests	5cm ≤ DBH ≤ 63.4cm	Chave et al. 2005
$AGB(kg) = \text{Exp}(-2.134 + (2.530 * \text{Ln}(DBH)))$	Tropical moist forests	Not specified	Brown, 1997



Recommended open access literature compiling allometric equations

Henry, M., Picard, N., Perttunen, J., Trotta, C., Manlay, J.R., Valantine, R., Bernoux, M. & Saint-André, L. (2011). [Estimating tree biomass of sub-Saharan African forests: a review of available allometric equations](#). *Silva Fennica*, 45(3B):477-569

Ponce-Hernandez, P. (2004) [Assessing carbon stocks and modelling win-win scenarios of carbon sequestration through land-use changes](#). FAO

Brown, S. 1997. [Estimating biomass and biomass change of tropical forests: a primer](#). *FAO Forestry Paper*, 134, Food and Agriculture Organization of the United Nations, Rome, Italy. ISBN 92-5-103955-0



Recommended database for sourcing wood-specific densities

Carsan S, Orwa C, Harwood C, Kindt R, Stroebe A, Neufeldt H, and Jamnadass R. (2012). [African Wood Density Database](#). World Agroforestry Centre, Nairobi.

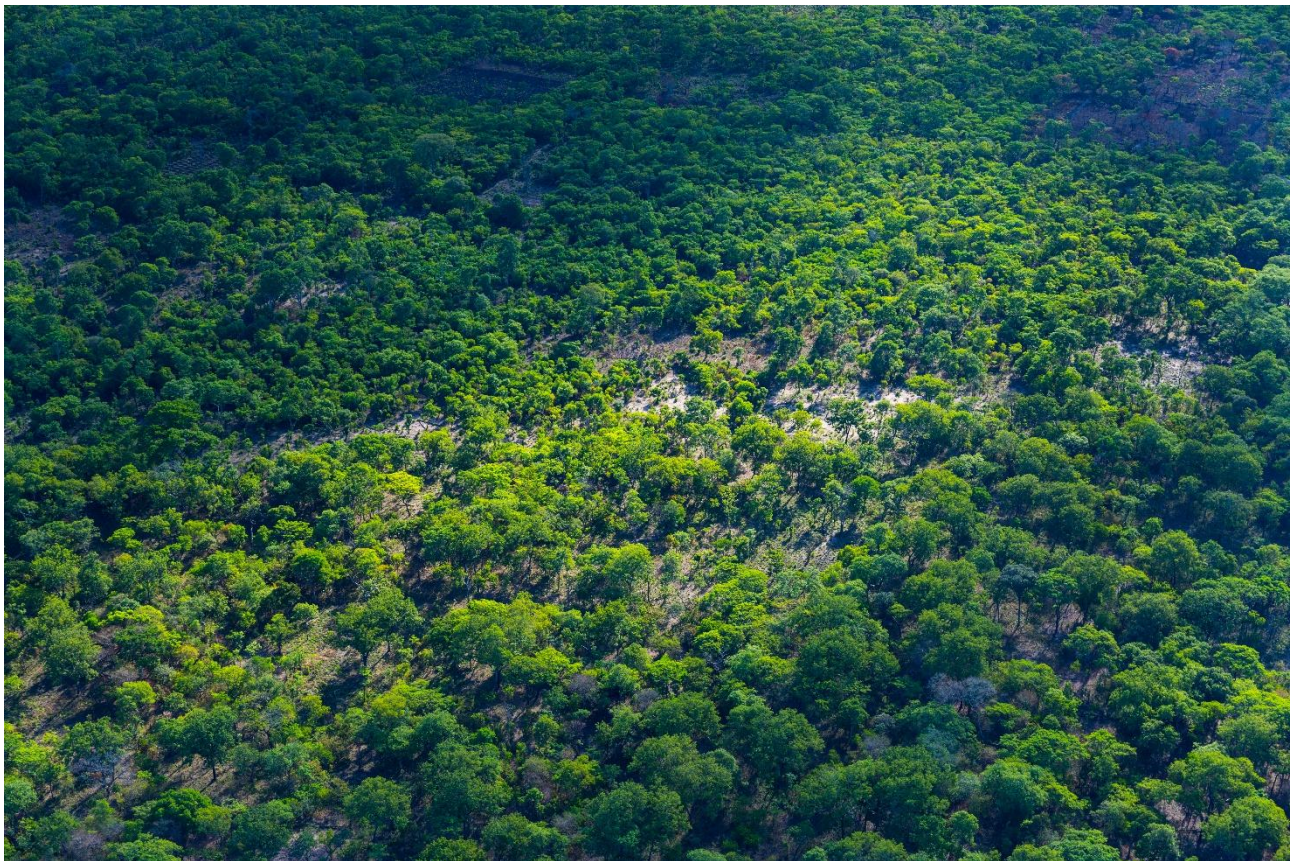


Figure. Kasanka National Park, Zambia. © Juan Carlos Munos, Adobe Stock, # 273833150. This figure is not covered by the CC BY-NC license of this publication.

2.3 Selection of allometric equation

The selection of an allometric equation for a study depends on the:

- i. study location (country, climate zone)
- ii. the land-use under study (ecosystem-type)
- iii. the species under study (mixed-species ecosystem, or monocultures, comparison of both)
- iv. the availability of equations (what equations are developed)
- v. project or initiative requirements/guidelines (projects or initiatives may have specific guidelines and/or requirements on the allometric equation and/or other methods to be used)

It is usually assumed that the more variables (tree characteristics) the equation includes, the more accurate it is. This means that an allometric equation accounting DBH, height, and wood density is likely to produce more reliable results than an equation accounting only for DBH.

! Before starting fieldwork or any tree measurements (DBH, height etc)., it's very important to familiarise with the woody species and land-uses under study, review the available allometric equations and make initial selection of the equation. This ensures that you take all the individual tree measurements needed (but do not consume your time taking measurements you do not need)

It's also highly recommended to review previous studies in the same region and/or ecosystem to see what equations they have used. Using the same equations as previous studies also allows comparison of the results. If you are measuring the carbon stock as part of specific project/initiative/carbon market scheme, it is important to check if they have specific requirements or guidance for allometric equations or other methods.

! It is important to decide in advance if you wish to include shrubs or small trees in your carbon stock inventory. For short woody individuals, using allometric equations requiring DBH may not be suitable. Shrubs or small trees may require specific equations that can be based on e.g. basal diameter, height, or canopy diameter. However, in general, there are not many equations available for shrubs/small trees.

3 Root-to-shoot ratios and equations

Woody belowground biomass, i.e. root biomass, is often calculated from the aboveground biomass using root-to-shoot ratios or other equations. As with allometric equations, root-to-shoot ratios can vary based on species, regions and ecosystems.

Table 2. Selected root-to-shoot ratios to estimate root biomass. Table derived from Mänttinen (2020), see references to the sources within.

Formula	Region	Source
$BGB = \text{Exp}(-1.0587 + 0.8836 * \text{Ln}(AGB))$	Tropical	Cairns et al.1997
$BGB = \text{Exp}(-1.0850 + 0.9259 * \text{Ln}(AGB))$	Tropical	Cairns et al.1997
$BGB = 0.25 * AGB$	Not specified	Takimoto, et al., 2008
$BGB = 0.27 * AGB$	Tropical/sub-tropical dry forests	IPCC, 2003
$BGB = 0.275 * AGB$	Dry forest / Plantation	Mokany et al. 2006
$BGB = 0.322 * AGB$	Tropical/sub-topical/temperate dry woodland	Mokany et al. 2006
$BGB = 0.38 * AGB$	Not specified	Bille & Poupon 1972 in Woomer et al. 2004a
$BGB = 0.404 * AGB$	Dry forest / Plantation	Mokany et al. 2006
$BGB = 0.47 * AGB$	Dry deciduous forests	Brown, 1997
$BGB = 0.48 * AGB$	Woodland / Savanna	IPCC, 2003
$BGB = 0.563 * AGB$	Dry forest / Plantation	Mokany et al. 2006

4 Carbon stock calculations

The examples below provide step-by-step guidance on how to calculate carbon stocks in Excel using field data (tree DBH, height, and wood density) and allometric equations.

4.1 Example 1 – Carbon stock of an individual tree

SET-UP

Woody individual

Let's assume we have one *Faidherbia albida* tree, with the following characteristics:

- DBH: 34.3 cm
- Height: 18.5 m
- Wood Density: 0.515 g/cm³ (average from the 0.46-0.57 g/cm³ for the species, derived from [African Wood Density Database](#))
- Land-use: Malian parkland agroforestry

Allometric equation for aboveground biomass

We will use the pantropical, multispecies, allometric equation by Chave et. al, 2014, to calculate the aboveground biomass (AGB) of this individual. The equation is:

$$AGB(kg) = 0.0673 * (WD * DBH^2 * H)^{0.976}$$

where,

AGB = aboveground biomass

WD = wood density (g/cm³)

DBH = diameter at breast height (cm)

H = height (m)

Root-to-shoot ratio for belowground biomass

We will use the multispecies, dry forest/plantation root-to-shoot ratio by Mokany, et al. (2006):

$$BGB(trees) = 0.275 * AGB(trees)$$

where,

BGB= Belowground biomass

AGB = Aboveground biomass

Biomass to carbon fraction rate

47 – 50 % of dry biomass consists of carbon. Let's set the biomass-to-carbon fraction rate to 0.5. The equation is:

$$C(kg) = B(kg) * 0.5$$

where,

C = carbon

B = biomass

STEP-BY-STEP CALCULATION

When you have the tree measurements/characteristics (DHB, height, wood density) taken and the allometric equation and root-to-shoot ratio selected, the carbon stock of a tree (or plot or a land-use) is easily calculated in a spreadsheet.

The below screenshot shows the:

- tree measurements/characteristics (surrounded by red ellipse)
- calculation the results – marked with numbers and explained step-by-step and in detail below

	A	B	C	D	E	F	G	H	I	J
1	Species	Height (m)	DBH (cm)	WD (g/cm ³)	AGB (kg)	BGB (kg)	AGC (kg)	BGC (kg)	Total C (kg)	Total C (MgC)
2	Faidherbia albida	18,5	34,3	0,515	603,10	165,85	301,55	82,93	384,48	0,38

- 1 Step 1.** Insert the tree characteristics (WD, DBH, and H) into the allometric equation for aboveground biomass and calculate

$$603.10 \text{ (kg)} = 0.0673 * (0.515 * 34.3^2 * 18.5)^{0.976}$$

➔ The result shows that the **aboveground biomass (AGB)** of the *F. albida* tree is **603.10 kg**

The formula on the spreadsheet looks like

E
AGB(kg)
=0,0673*(D2*C2^2*B2)^0,976

- 2 Step 2.** Calculate the belowground, i.e. root biomass of the tree

$$165.85 \text{ (kg)} = 0.275 * 603.10 \text{ (kg)}$$

➔ The result shows that the **belowground biomass (BGB)** of the *F. albida* tree is **165.85 kg**

The formula on the spreadsheet looks like

F
BGB (kg)
=E2*0,275

- 3 Step 3.** Convert the biomass to carbon using the biomass-to-carbon fraction rate of 0.5

Aboveground carbon $301.55 \text{ (kg)} = 603.10 \text{ (kg)} * 0.5$

Belowground carbon $82.93 \text{ (kg)} = 165.85 \text{ (kg)} * 0.5$

➔ The result shows that the **aboveground carbon stock** of the *F. albida* tree is **301.55 kgC**

➔ The result shows that the **belowground carbon stock** of the *F. albida* tree is **82.93 kgC**

The formulas on the spreadsheet looks like

G	H
AGC (kg)	BGC (kg)
=E2*0,5	=F2*0,5

4 Step 4. Calculate the total carbon stock by summing aboveground and belowground stocks

$$\text{Total carbon} = \text{AGC} + \text{BGC} \quad 384.48 \text{ (kg)} = 301.55 \text{ (kg)} + 82.93 \text{ (kg)}$$

➔ The result shows that the **total carbon stock** of the of the *F. albida tree* is **348.48 kgC**

The formula on the spreadsheet looks like

I
Total C (kg)
=G2+H2

5 Step 5. Carbon stocks are often presented as megagrams rather than kilograms, especially when talking about carbon stocks per hectare. Convert kilograms to megagrams.

$$1 \text{ kg} = 0.001 \text{ megagrams} \quad 0.38 \text{ (Mg)} = 384.48 \text{ (kg)} * 0.001$$

➔ The results shows that the **total carbon stock** of the *F. albida tree* is **0.38 MgC**

The formula on the spreadsheet looks like

J
Total C (MgC)
=I2*0,001

4.2 Example 2 - Plot level carbon stock

SET-UP

Let's assume we have established a circular plot of 1500 m² in an agroforestry land-use.

Within the plot, there have been seven tree individuals of three different species.

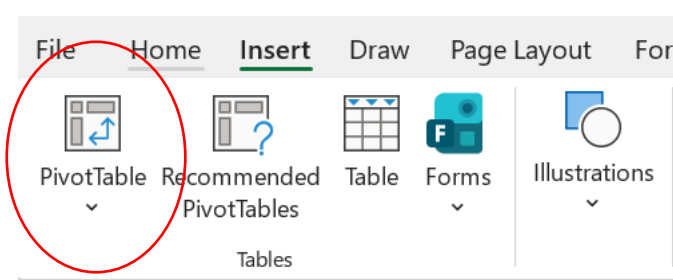
As the allometric equation is multispecies, we can use the same equation for all tree individuals regardless of their species.

- 1 However, wood-specific density varies based on the tree species, and we must acquire the specific one for each species.
- 2 We have calculated the carbon stock (MgC) of each of these tree individuals using the steps of Example 1.

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Land-use	Plot no	Plot size (m2)	Species	Height (m)	DBH (cm)	WD (g/cm3)	AGB (kg)	BGB (kg)	AGC (kg)	BGC (kg)	Total C (kg)	Total C (MgC)
2	Parkland	1	1500	Faidherbia albida	18,5	34,3	0,515	603,10	165,85	301,55	82,93	384,48	0,38
3	Parkland	1	1500	Faidherbia albida	11,75	44	0,515	629,67	173,16	314,84	86,58	401,42	0,40
4	Parkland	1	1500	Parkia biglobosa	17,5	67,5	0,61	2526,41	694,76	1263,20	347,38	1610,58	1,61
5	Parkland	1	1500	Faidherbia albida	13,8	46,2	0,515	810,29	222,83	405,15	111,42	516,56	0,52
6	Parkland	1	1500	Faidherbia albida	7,5	36,4	0,515	280,59	77,16	140,29	38,58	178,87	0,18
7	Parkland	1	1500	Azadirachta indica	9	48	0,775	857,23	235,74	428,61	117,87	546,48	0,55
8	Parkland	1	1500	Faidherbia albida	9,25	36,2	0,515	340,64	93,68	170,32	46,84	217,16	0,22

STEP-BY-STEP CALCULATION

- 1 **Step 1.** To get the plot-level carbon stock, we sum the carbon stock of the individual trees. We do this using the pivot table in excel.



The pivot table below shows the sum of the aboveground carbon (AGC) in kg, belowground carbon (BGC) in kg, and the total carbon (AGC+BGC) in kg and in Mg, within the plot no 1.

Row Labels	Sum of AGC (kg)	Sum of BGC (kg)	Sum of Total C (kg)	Sum of Total C (MgC)
1	3023,97	831,59	3855,56	3,86
Grand Total	3023,97	831,59	3855,56	3,86

➔ The result shows that the **total plot level carbon stock** is **3.86 MgC**

- 2 We know now the total carbon stock (3.86 MgC) and the plot size (1500 m², i.e. 0.15 ha)

We can convert the carbon stock per plot to carbon per hectare.

$$25.70 \text{ MgC ha}^{-1} = \frac{3.86 \text{ MgC}}{0.15 \text{ ha}}$$

Row Labels	Sum of AGC (kg)	Sum of BGC (kg)	Sum of Total C (kg)	Sum of Total C (MgC)	MgC / ha
1	3023,97	831,59	3855,56	3,86	25,70
Grand Total	3023,97	831,59	3855,56	3,86	2

- ➔ The result shows that plot no 1 contains a **total woody carbon stock** (including both above- and belowground carbon) equivalent of **25.7 MgC ha⁻¹**

4.3 Example 3 - Land-use level carbon stock

SET-UP

Let's assume that we have established a total of seven plots of the same size (1500 m²) in an agroforestry land-use.

- 1 We have calculated the carbon stock of each tree individual in each of the plot, as in the example 1.
- 2 We have calculated the plot level carbon for each plot and converted it into megagrams of carbon in hectare (MgC ha⁻¹), as in the example 2.

3	Row Labels	Sum of AGC (kg)	Sum of BGC (kg)	Sum of Total C (kg)	Sum of Total C (MgC)	MgC/ha
4	1	3023,97	831,59	3855,56	3,86	25,70
5	2	1508,07	414,72	1922,79	1,92	12,82
6	3	975,03	268,13	1243,16	1,24	8,29
7	4	2989,74	822,18	3811,92	3,81	25,41
8	5	2268,31	623,79	2892,10	2,89	19,28
9	6	806,53	221,79	1028,32	1,03	6,86
10	7	3657,06	1005,69	4662,75	4,66	31,08
11	Grand Total	15228,70	4187,89	19416,59	19,42	

STEP-BY-STEP CALCULATION

- 1 Now we just calculate the mean and standard deviation of from the plot-level carbon stocks, using the excel functions. The excel formulas of the mean and standard deviation are shown below.

2								
3	Row Labels	Sum of AGC	Sum of BGC	Sum of Total C	Sum of Total C (MgC)	MgC/ha	Avg.	Std.
4	1	3023,97	831,59	3855,56	3,86	25,70	18,49	9,04
5	2	1508,07	414,72	1922,79	1,92	12,82	=AVERAGE(F4:F10)	=STDEV(F4:F10)
6	3	975,03	268,13	1243,16	1,24	8,29		
7	4	2989,74	822,18	3811,92	3,81	25,41		
8	5	2268,31	623,79	2892,10	2,89	19,28		
9	6	806,53	221,79	1028,32	1,03	6,86		
10	7	3657,06	1005,69	4662,75	4,66	31,08		
11	Grand Total	15228,70	4187,89	19416,59	19,42			
12								

➔ The result shows that **mean carbon stock** of the **land-use** is **18.49 ± 9.04 MgC ha⁻¹**

5 Estimating carbon sequestration

Carbon sequestration refers to carbon captured and stored over time, i.e. megagrams of carbon per hectare per year ($\text{MgC ha}^{-1} \text{y}^{-1}$).

Carbon sequestration can be estimated from carbon stocks that are measured in different time periods. This approach in measuring carbon sequestration is called the carbon stock-based approach.

This approach is based on measuring the carbon stock in at least two different time periods and then calculating the difference, which tells how much carbon has been sequestered (or released) in that time period.

✓ **Advantages:** The method is simple and does not require specific, high-tech equipment

⚠ **Disadvantages:** Results differ based on the time-periods the carbon stocks are measured and does not account for the change in carbon sequestration rate over time.

Carbon sequestration rate and carbon stocks in tree-based ecosystems, such as forests change over time. In the establishment phase carbon emissions likely occur due to soil disturbance that leads to soil carbon losses and due to emissions on harvested vegetation. While trees mature, the carbon sequestration is high, and the carbon stocks grow fast. When tree growth slows down, so does the carbon sequestration rate. When trees reach their maturity and maximum size, the carbon sequestration slows down markedly, eventually reaching zero, the carbon stocks are at their highest level, and the carbon stock saturation is reached. At the end of the rotation (harvesting, fire land-use change etc.), carbon is released from the system, the carbon sequestration turns to negative and carbon stock decreases.

5.1 Example 4 – estimating carbon sequestration rate with carbon stock-based approach

SET-UP

The figure below showcased the woody carbon stock in time in a given land-use.

After the establishment, the carbon stocks grow fast due to tree growth.

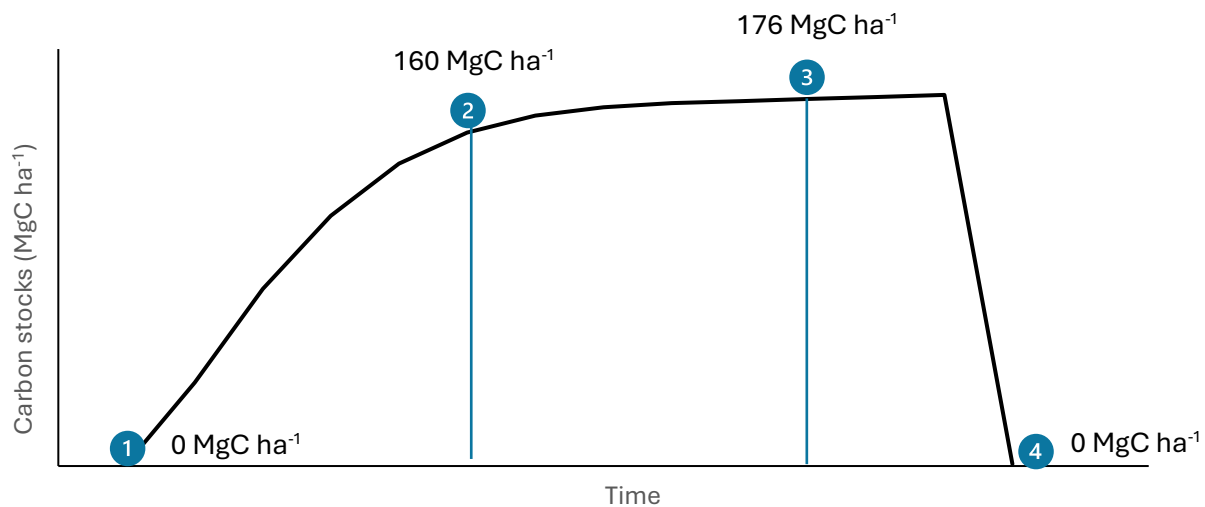
At a given stage the carbon sequestration slows down as trees reach their maturity, and carbon stocks remain rather stable.

Finally, during harvesting the carbon stock are lost.

Let's think of four time period of carbon stock assessment in the land-use.

The carbon stocks of these time periods are (please note that these are just example numbers):

- 1 Establishment phase: 0 MgC ha⁻¹ (Year 1)
- 2 End of the growth phase 160 MgC ha⁻¹ (Year 25)
- 3 Maturation phase: 176 MgC ha⁻¹ (year 50)
- 4 After harvest: 0 MgC ha⁻¹ (Year 65)



Carbon sequestration rate (MgC ha⁻¹ y⁻¹), can be calculated by calculating the difference between the carbon stocks and dividing by the number of the years:

$$\text{Avg carbon sequestration rate} = \frac{\text{MgC ha}^1_{\text{time2}} - \text{MgC ha}^1_{\text{time1}}}{N \text{ (years)}}$$

STEP-BY-STEP CALCULATION

- 1 Let's assume that the carbon stocks were measured during the time period 1 and 2, there were 25 years between the carbon stock measurement.

We insert the figures into the equation presented above.

$$6.40 \text{ MgC ha}^{-1} \text{ y}^{-1} \frac{160 \text{ MgC ha}^{-1} - 0 \text{ MgC ha}^{-1}}{25 \text{ years}}$$

- The result show that the **average carbon sequestration rate** between the time period 1 and 2 is **6.40 MgC ha⁻¹ y⁻¹**

- 2 Now let-s assume that the carbon stocks were measured during the time periods 2 and 3

We insert the figures into the equation.

$$0.64 \text{ MgC ha}^{-1} \text{ y}^{-1} \frac{176 \text{ MgC ha}^{-1} - 160 \text{ MgC ha}^{-1}}{25 \text{ years}}$$

- The result show that the **average carbon sequestration rate** between the time period 2 and 3 is **0.64 MgC ha⁻¹ y⁻¹**

Here you can see that based on the time periods used the carbon sequestration rates vary a lot.

- 3 Let's now assume that the carbon stocks were measured during the time periods 3 and 4

$$- 11.73 \text{ MgC ha}^{-1} \text{ y}^{-1} \frac{0 \text{ MgC ha}^{-1} - 176 \text{ MgC ha}^{-1}}{15 \text{ years}}$$

- The result shows that the **average carbon sequestration rate** between the time period 3 and 4 is negative: **- 11.73 MgC ha⁻¹ y⁻¹**, indicating carbon loss

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