Climate Stewards Seal of Approval
Methodology for Estimating Carbon Sequestration Potential on Woodlots

1. Introduction

This document explores the viability of establishing simple, lightweight carbon offsetting schemes based on estimating woodlot above- and below-ground biomass (AGB and BGB) using publicly available allometric equations and data about tree species.

Such an offsetting scheme could be used by small organisations which have limited technical knowledge and access to data, but which would be capable of running the scheme to the required standard – including planting and ongoing monitoring.

The overall methodology is based on the principle that if trees are grown to a certain, defined size (measuring diameter at breast height – DBH) they will have sequestered a known amount of carbon dioxide. The quantity of CO_2 sequestered is directly proportional to the biomass of the tree, which can be derived using allometric equations for biomass. From biomass, carbon stocks and, hence, carbon sequestration potential can be calculated if wood density and carbon fraction are known.

This methodology has been applied in the making of the ***Cquestr*** woodlot carbon sequestration estimation tool as well as Climate Stewards' own internal estimation tools.[1]

1.1. Advantages and Disadvantages

This methodology turns the usual method of calculating sequestration over a period of years based on growth rates on its head and brings both advantages and disadvantages:

- The primary advantage is that the amount of data required is significantly reduced as growth rates, mean annual increment (MAI), height increments, etc. are no longer required. In addition, the data that is required is generally readily available or can be easily gathered in the field with minimal training – for example, monitoring would require measurement of DBH using either callipers or tape measures, but height would not need to be measured or calculated; this is because the allometric equations detailed below rely only on DBH.
- The primary disadvantage is that fixing a "target" DBH will only ever be able to be approximate as the estimated length of the project will depend on the target DBH, but the target DBH may (or may not) be achieved within the stated life of the project. This means that some information as to how long it takes for trees in a locality to reach the target size needs to be gathered in order to set realistic targets. There would also have to be a decision made as to whether to prioritise the length of the project or the DBH:
    - If the length of the project is prioritised then if the trees don't reach the target DBH in that time the total sequestered carbon will be lower than estimated (which could affect the sale and retirement of ex-ante carbon offsets).
    - Alternatively, if DBH is prioritised, the length of the project may need to be increased, which pushes the financial reward for the sale of timber further into the future. In the latter case, however, project participants do have a financial incentive to properly manage the project to (as far as is possible) achieve the target DBH in the stated time

[1] Available at https://climatestewards.org/cquestr.

since, if DBH is prioritised, they can only sell the timber when the trees meet the target DBH.

1.2. Commercial Planting and Permanent Forests

The methodology is primarily designed to be used for commercial woodlots where the trees will be harvested (and replanted) once they reach the defined target size. That the methodology was initially developed for commercial woodlots does not preclude it from being used for permanent forests (reforestation).

1.2.1. Commercial Planting

For commercial planting the methodology is to be used based on the following conditions:

- Trees will be grown to a defined target DBH such that the tree stems are of merchantable size and quality, and thus commercially viable for use as timber. The target DBH is more important than the time taken to reach it and should be prioritised as mentioned above – this means that if the estimated DBH is 25cm at 10 years, but the trees are only 22cm at 10 years then the project duration must be extended to allow the trees to reach the target DBH. Thorough advance research, knowledge of local conditions on behalf of the project implementer, proper project management and good husbandry will reduce the risks of project delays.
- The wood, as indicated by the merchantable stem volume, must be sold on the basis that it will be used as timber, for example as power transmissions poles, housing materials, chipboard, veneers – any application where the wood will be used long-term.[2]
- Branches, trimmings and thinnings may be sold as fuel wood – they are not included in the carbon accounting calculations.
- Harvested trees will be replanted. Those new trees won't be included in the original project's carbon accounting period but could be the basis for a new accounting period.
- Where trees are coppiced, BGB can be included in the carbon accounting.

1.2.2. Permanent Forests

If the methodology is used for permanent forests then data on annual DBH increments is required. The total AGB and BGB of the trees would be used in the carbon accounting calculation.

2. Assumptions

Use of this methodology is based on certain assumptions about the project area:

- Land to be used for tree planting is bare. If there is ground cover, grasses and scrub – the removal of which will affect current carbon stocks – then the IPCC Tier-1 Global Biomass Carbon Map For the Year 2000 from CDIAC shall be used to estimate those stocks.[3] This value is

[2] According to the IPCC in 2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol (IPCC, Hiraishi T, Krug T, Tanabe K, Srivastava N, Baasansuren J, Fukuda M and Troxler TG (eds). 2014. Available at: https://www.uncclearn.org/sites/default/files/inventory/ipcc20_0_1.pdf), as shown in Table 2.8.2, the average half-life of wood panels and sawn wood are 25 and 35 years respectively. Half-life is defined as "the number of years it takes to lose one-half of the material currently in the pool". This suggests that, compared to the anticipated duration of any project, the amount of time the harvested timber will keep carbon locked up is sufficient to justify commercial forestry for an offsetting project.

[3] Ruesch A and Gibbs HK. 2008. New IPCC Tier-1 Global Biomass Carbon Map For the Year 2000. By the Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee. Available at: http://cdiac.ess-dive.lbl.gov/epubs/ndp/global_carbon/carbon_documentation.html

subtracted from the final estimated carbon sequestration potential. (See Section 5. for more detail.)

- There will be no displacement activity as a result of tree planting – i.e. if the land is being used for agriculture, when the trees are planted the users of the land will not cut down trees elsewhere to clear land for agriculture. See also the first point above with respect to potential clearance of land that is in use.
- The project activity area is located in the tropics such that the use of the allometric equations listed below is appropriate.
- Soil in the project area is at least 30cm deep, suitable for the species and number of trees that are proposed and the ground is not regularly waterlogged or flooded.
- No nitrogen-based fertilisers are used which would either increase growth rates, or alter soil nitrogen content so as to affect soil organic carbon.[4]

3. Calculating Biomass

3.1. Above-Ground Biomass

The calculation of above-ground biomass is based on the work of Dr Jerome Chave *et al*, 2014.[5]

Chave provides a series of allometric equations for estimating oven-dry (rather than wet weight) biomass based on a number of variables. Of the published equations the one that best suits our purposes is Model 7 which is "for estimating AGB in the absence of height measurements". Chave states that Model 7 is worse than Model 4 which includes height measurements; however, where height data is not available Model 7 is sufficient. See below for further discussion of DBH and height in relation to allometric models.

Estimated AGB in kilograms according to Model 7:

$$AGB_{est} = \exp[-1.803 - 0.976\mathbf{E} + 0.976\ln(\boldsymbol{\rho}) + 2.673\ln(\mathbf{D}) - 0.0299[\ln(\mathbf{D})]^2]$$

Where:

- **E** = Environmental Stress Factor – this is provided as a 2.5 arc minute resolution raster file from Dr Chave's website which is mapped to latitude and longitude.
- **ρ** = wood density (or specific gravity) (g/cm^3).[6]
- **D** = diameter at breast height (cm).

[4] There are different theories as to how the application of nitrogen fertilisers affects soil organic carbon – some say it increases sequestration (Aula L *et al*, 2016, Effect of Fertilizer Nitrogen (N) on Soil Organic Carbon, Total N, and Soil pH in Long-Term Continuous Winter Wheat (Triticum Aestivum L.)), some suggest it can reduce sequestration (Khan SA *et al*, 2007, The Myth of Nitrogen Fertilization for Soil Carbon Sequestration) – overall, for the purposes of this methodology fertilisers just complicate matters.

[5] Chave J, Rejou-Mechain M, Burquez A, Chidumayo E, Colgan MS, Delitti WBC, Duque A, Eid T, Fearnside PM, Goodman RC, Henry M, Martinez-Yrizar A, Mugasha WA, Muller-Landau HC, Mencuccini M, Nelson BW, Ngomanda A, Nogueira EM, Ortiz-Malavassi E, Pelissier R, Ploton P, Ryan CM, Saldarriaga JG, Vieilledent G. Improved allometric models to estimate the above ground biomass of tropical trees. 2014. Available from: http://onlinelibrary.wiley.com/doi/10.1111/gcb.12629/abstract

[6] Wood density (or specific gravity – the terms appear to be used interchangeably despite specific gravity being a dimensionless term) is generally defined as wood volume at 12% moisture content divided by oven-dry weight. There are, however, other definitions.

Unless locally available wood density information is available, the Global Wood Density Database[7] should be used to provide an average wood density for use in calculations.

Although Chave's improved allometric equation is of general use (see "Pantropical Allometries" below), species specific allometric equations can be used if they allow for the calculation of AGB based on DBH alone or in conjunction with wood density.

We have done work on modelling carbon sequestration potential for Eucalyptus based on allometric equations developed by Kuyah *et al*.[8]

This allows us to make a comparison between the results from using both Chave and Kuyah's equations at a number of tree sizes. The Environmental Stress Factor "E" used was for Rongai in Kenya which is comparable with the climate used in Kuyah's study and allowed us to use DBH data from a known project for "sanity checking".

Comparing Kuyah with Chave for Eucalyptus with DBH from 10 to 30cm, for total above-ground biomass (stem, branches and leaves):

DBH (cm)	Kuyah (AGB, kg)	Chave (AGB, kg)
10	25.1	24.5
15	68.5	68.1
20	139.4	139.9
25	242.0	243.7
30	379.7	382.6

It can be seen that the results for Eucalyptus are comparable; where other allometric equations for defined species become available this comparison could be repeated as it would give (over time) a good idea of the applicability of Chave's allometric equation to the type of projects that would be of interest for carbon offsetting. This would, however, depend on being able to find peer-reviewed allometric equations for different species in appropriate environments.

3.2. Below-Ground Biomass

Below-ground biomass (BGB) can be estimated by using the root:shoot ratio for a given species of tree, or by using an equation developed by Cairns *et al* in "Root biomass allocation in the world's upland forests".[9]

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[7] Chave J, Coomes DA, Jansen S, Lewis SL, Swenson NG, Zanne AE (2009) Towards a worldwide wood economics spectrum. Ecology Letters 12(4): 351–366. https://doi.org/10.1111/j.1461-0248.2009.01285.x and Zanne AE, Lopez-Gonzalez G, Coomes DA, Ilic J, Jansen S, Lewis SL, Miller RB, Swenson NG, Wiemann MC, Chave J (2009) Data from: Towards a worldwide wood economics spectrum. Dryad Digital Repository. https://doi.org/10.5061/dryad.234

[8] Kuyah S, Dietz J, Muthuri C, van Noordwijk M, Neufeldt H. (2013) Allometry and partitioning of above- and below-ground biomass in farmed eucalyptus species dominant in Western Kenyan agricultural landscapes. Available from: http://www.academia.edu/19745635/Allometry_and_partitioning_of_above-_and_below-ground_biomass_in_farmed_eucalyptus_species_dominant_in_Western_Kenyan_agricultural_landscapes

[9] Cairns MA, Brown S, Helmer EH, Baumgardner GA. (1997) Root biomass allocation in the world's upland forests. Available from: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.484.5959&rep=rep1&type=pdf

From Cairns' paper, equation 1 is for use where only above-ground biomass is known. Equations 2 and 3 extend equation 1 to include age and latitudinal zone respectively.

Cairns' equation for below-ground biomass in kilograms given above-ground biomass, also in kilograms is:

$BGB_{est} = \exp[-1.0850 + 0.9256\ln(\mathbf{AGB})]$

When compared with Kuyah's specific equations for Eucalyptus which provide estimates for BGB as well as AGB, Cairns' equation appears very conservative. For a Eucalyptus tree of 25cm DBH, Kuyah estimates BGB at 72.8kg, whilst Cairns' equations would give a figure of 54.7kg. Climate Stewards uses Cairns' equation for its calculation of below-ground biomass.

3.3. DBH and Height

Chave in his 2005 paper[10] develops allometric models for biomass calculations for three ecosystem types (based on rainfall): dry, moist and wet. For each type, two models were developed – one that used DBH data alone and one that used DBH and height data. The models that used the two variables produced consistently better results in estimating biomass.

Feldpausch *et al*[11] comments on the lack of African data and (relatively) small sample size used in Chave's 2005 allometric models suggesting that: "Such a lack of data for calibration may bias estimates of carbon stocks in tropical forests".[12]

He goes on to propose a model that relates DBH to height. If this model is used to predict height for a given DBH, the result can then be "plugged in" to Chave's 2005 DBH and height allometric models. Doing this produces better results than using the DBH models alone, and this is the case even though the height is derived from DBH. Feldpausch tested his model on a similar set of data to that used by Chave.

Chave, in his 2014 models, addresses Feldpausch's 2012 model and concludes that Model 7 of his improved allometric equations, which is based on environmental stress factor, density and diameter, produces more accurate results than Feldpausch's height from DBH model in conjunction with the earlier DBH only allometric models. Chave develops a model (Model 6a) for height based on diameter and integrates that into his model such that Model 7 takes account of height indirectly (i.e. there is never an output for height).

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[10] Chave J, Andalo C, Brown S, Cairns MA, Chambers JQ, Eamus D, Fölster H, Fromard F, Higuchi N, Kira T, Lescure JP, Nelson BW, Ogawa H, Puig H, Riéra B, Yamakura T. (2005). Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Available from http://chave.ups-tlse.fr/chave/chave-oecologia05.pdf

[11] Feldpausch TR, Lloyd J, Lewis SL, Brienen RJW, Gloor M, Monteagudo Mendoza A, Lopez-Gonzalez G, Banin L, Abu Salim K, Affum-Baffoe K, Alexiades M, Almeida S, Amaral I, Andrade A, Aragão LEOC, Araujo Murakami A, Arets EJMM, Arroyo L, Aymard C, GA, Baker TR, Bánki OS, Berry NJ, Cardozo N, Chave J, Comiskey JA, Alvarez E, de Oliveira A, Di Fiore A, Djagbletey G, Domingues TF, Erwin TL, Fearnside PM, França MB, Freitas MA, Higuchi N, E Honorio C, Iida, Y, Jiménez E, Kassim AR, Killeen TJ, Laurance WF, Lovett JC, Malhi Y, Marimon BS, Marimon-Junior, BH, Lenza E, Marshall AR, Mendoza C, Metcalfe DJ, Mitchard ETA, Neill DA, Nelson BW, Nilus R, Nogueira EM, Parada A, Peh KS-H, Pena Cruz A, Peñuela MC, Pitman NCA, Prieto A, Quesada CA, Ramírez F, Ramírez-Angulo H, Reitsma JM, Rudas A, Saiz G, Salomão RP, Schwarz M, Silva N, Silva-Espejo JE, Silveira M, Sonké B, Stropp J, Taedoumg HE, Tan S, ter Steege H, Terborgh J, Torello-Raventos M, van der Heijden GMF, Vásquez R, Vilanova E, Vos VA, WhiteL, Willcock S, Woell H, Phillips OL. (2012): *Tree height integrated into pantropical forest biomass estimates*, Biogeosciences, 9, 3381-3403. Available from: https://doi.org/10.5194/bg-9-3381-2012

[12] Ibid.

Although it would be possible to derive height from DBH and use it as an input to Chave's Model 4, it is unlikely that the results would be improved in the absence of locally measured height data. In fact, according to Chave, it might do worse: "We also verified that if the regional diameter–height models of Feldpausch *et al*. (2012) had been used instead of Model 6a, the bias would have been much larger (mean bias: +22.41%; Figure S6)".

On that basis, we have decided to use Chave's Model 7 as the default allometric equation in calculations unless either a peer reviewed species specific allometric model is available or we are able to derive a provably better local allometric equation for the desired species.

3.4. Pantropical Allometries

One question that arises when looking at pantropical allometric equations, such as developed by Chave (2015), is whether they are sufficiently accurate for the particular species of tree or trees that a project might wish to grow.

Chave notes that "[t]errestrial carbon stock mapping is important for the successful implementation of climate change mitigation policies. Its accuracy depends on the availability of reliable allometric models to infer oven-dry above ground biomass of trees from census data. The degree of uncertainty associated with previously published pantropical above ground biomass allometries is large".

As a result Chave and his team analysed a global database of directly harvested trees at 58 sites, spanning a wide range of climatic conditions and vegetation types. They looked at 4,004 trees with a DBH greater than 5cm. (The dataset Chave used was larger than that used to develop his 2005 equations and included African species.)

Chave found that, "[w]hen trunk diameter, total tree height, and wood specific gravity were included in the above ground biomass model as covariates, a single model was found to hold across tropical vegetation types, with no detectable effect of region or environmental factors" and "[t]his convergence of tropical tree biomass allometries across biomes and continents is striking".

This means that the pantropical allometric model is sufficient for biomass calculations. But even Chave suggests that "to minimize bias, the development of locally derived diameter–height relationships is advised whenever possible".

So, where species specific allometries are available they should be preferred, but as long as the trees conform to Chave's general criteria – i.e. DBH > 5cm and are of good form, and supposing that density data is available in the Global Wood Density Database, then Chave's Model 7 is perfectly adequate across tropical species.

3.5. Land Area and Number of Trees

Chave's allometric model is based on the analysis of large amounts of data. This means that any uncertainty in the results is largely smoothed over by the fact that a lot of trees are contributing to the model. If, however, the model is applied to small numbers of trees then uncertainty will creep back into the results.

Chave notes that, "Tree-level uncertainty in AGB estimation from our model is about 50% of the mean, thus individual tree AGB cannot be estimated precisely with any such model. However, assuming an average of 500 trees with D > 10 cm per ha, then the plot-based uncertainty in AGB can be computed... uncertainty due to the allometric equation drops to ca. 10–15% for a ¼ ha plot and ca. 5–10% for a 1 ha plot."

In terms of calculations then, particularly as this methodology is designed for use on smaller woodlots, it would be wise to build in the uncertainty that Chave talks about.

This means discounting the final carbon figures based on the plot size. So, for plots of less than a quarter of a hectare the output is reduced by 12.5% (the average of Chave's figures above) and for plots between 0.25 and 1 ha that reduction will be 7.5%. For plots above one hectare, the full output figure can be used.

4. From Biomass to Carbon Dioxide

Calculating the carbon content of any tree relies on knowing its carbon fraction – the proportion of the tree that is sequestered carbon. The IPCC default for carbon calculations is 47% but data for individual species is generally available from online sources. Given the figure for carbon fraction the carbon stock of either the individual trees or the complete cohort can be calculated by simple multiplication of the biomass by the carbon fraction.

From there, and based on molecular weights – carbon dioxide weighs 3.67 times as much as carbon – the carbon dioxide sequestered per tree to produce a known weight of carbon can be calculated, again by simple multiplication.

5. Land Use Change

As mentioned in Section 2., one of the basic assumptions given in the present methodology is that "Land to be used for tree planting is bare". This assumption is made on the basis that bare ground, prior to planting, will have soil carbon stocks that won't decrease in the project scenario, so there is no need to account for any removals in calculations. However, assumptions and reality don't always meet. The ground that is chosen for a planting project may be in use for crops, or may just be a non-forest area of land with a range of plants already in-situ. If trees are going to be planted on that land then some amount of the currently existing biomass will likely need to be cleared, with a resultant loss in carbon stocks, and also potential loss of soil carbon stocks. This loss needs to be quantified and accounted for.

It would be possible to take measurements across a representative area of the land in order to estimate above- and below-ground biomass and soil carbon stocks, but that goes against the aim of the Climate Stewards Seal of Approval which is to provide robust and easy to use methodologies for small-scale carbon offsetting projects. Many potential project implementers would not have the means or ability to carry out the necessary work required to estimate existing carbon stocks.

Therefore, where some measure of land use change is envisaged a reasonable default value for carbon stocks is required that can be applied to land being cleared prior to tree planting.

The Carbon Dioxide Information Analysis Centre (CDIAC) has published the New IPCC Tier-1 Global Biomass Carbon Map for the Year 2000 which includes tables containing average carbon stocks relating to biomass for a range of land types. There is also a dataset available with ARC/INFO grid directory structure for output GRIDS at 1km, 5 and 10 arcminute resolutions. This data is used by Climate Stewards as the basis for a "removals" figure to be deducted from the calculation of above- and below-ground tree biomass based on land use.

6. Risk Assessment and Buffers

In any tree growing project there is always a risk that trees will be lost for a variety of reasons. Building a buffer into the carbon sequestration potential calculations allows for any future losses to be accounted for. The size of the buffer is somewhat subjective, but a very conservative buffer for Seal of Approval based projects would be 10% of sequestered carbon. The buffer, is in effect, sequestered carbon that won't be sold but held in carbon offset inventory to cover any of the following losses:

- Disease;
- Pest;

- Fire;
- Damage due to animals;
- Theft of wood to be used as firewood; or
- Land loss (for example due to redevelopment).

The list is non-exhaustive.

7. Conclusion

The science and maths behind the model is simple (whilst acknowledging that the work of others to produce the allometric equations used is of a different order!). The allometric equations used produce reliable results and the papers authored by Chave *et al*, Kuyah *et al*, Cairns *et al* and Feldpausch *et al* have been published in peer-reviewed journals and, as such, are suitable for the application in which we are using them.

The idea to use target DBH as the basis of the calculation is novel but if the target DBH and estimated time to reach that DBH are considered carefully then there is no reason that the estimates should not be used in a carbon offsetting project.

As with all forestry related carbon offsetting, the devil is in the details – project management. If the trees are well planted and tended; if proper boundaries are constructed and maintained to prevent livestock incursion; if watering and weeding are carried out; proper firebreaks are kept and land tenure is secure, then from the point of view of carbon sequestration the project is likely to meet its stated goals. It would be wise to keep in mind, however, that issues of training and land ownership should not be minimised. In addition, the results from either the ***Cquestr*** model or Climate Stewards' internal estimation tools are contingent on the initial survey questionnaire being completed correctly with reasonable data being provided[13] by the project implementer.

[13] GIGO: Garbage in – Garbage Out.