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PROTOCOL

## Carbon modelling for afforestation and reforestation projects

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# 1 Introduction

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Afforestation and reforestation activities in developing countries are included in the CDM, and there are a growing number of projects seeking to secure carbon finance from voluntary offsets generated through afforestation and reforestation activities including agroforestry. For CDM projects carbon credits are purchased after the carbon offset has been generated (ex-post), while some projects in the voluntary market (for example Plan Vivo) sell carbon credits in advance of the offset being generated (ex-ante). In both situations the capacity to predict carbon sequestration through project activities is important, either for determining the potential carbon sequestration, and therefore project feasibility for projects with ex-post payments; or to predict how much carbon will be sequestered so that appropriate ex-ante payments can be made.

The IPCC has produced guidelines for estimating baselines and project monitoring<sup>1</sup>, but there are no internationally agreed guidelines for modelling the carbon sequestration potential of projects. Some Annex I countries have developed models for national level forest carbon accounting, for example FullCAM in Australia<sup>2</sup>, and CBM-CFS3 in Canada<sup>3</sup>. National models are typically parameterised for the country in which they were developed, however, and their broader application may not be appropriate. This protocol therefore describes the methods and models available for estimating carbon sequestration potential for afforestation and reforestation projects in countries without existing carbon accounting models, and in which information relating to tree growth, and environmental factors may be lacking.

## 2 Modelling carbon accumulation

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Models used to estimate carbon offset potential, or determine the likely carbon accumulation within a project, must represent the changes in carbon storage throughout the duration of the project in a robust and conservative manner. Models are used to predict the changes in carbon stocks of various components of the ecosystem that result from afforestation and reforestation activities. These carbon pools may include:

- tree biomass (stem wood, foliage, branches and roots);
- non-tree biomass (shrubs and herbs);
- necromass (dead wood, leaf litter, and soil organic matter); and
- products removed from the forest.

Modelling requires estimates of both the potential size of carbon pools and the rate of change of these stocks.

### 2.1 Carbon accounting models

Most models currently used for assessing the carbon sequestration potential of forestry activities are carbon accounting models (CAMs). CAMs account for the flux in various carbon pools due to forestry activities in a location, but do not attempt to model the processes that cause this accumulation. Instead fluxes of carbon through various pools are estimated using production or

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<sup>1</sup> methods for determining project baselines are described in a separate protocol: *Baseline survey for agroforestry projects*

<sup>2</sup> <http://www.greenhouse.gov.au/ncas/index.html>

<sup>3</sup> [http://carbon.cfs.nrcan.gc.ca/index\\_e.html](http://carbon.cfs.nrcan.gc.ca/index_e.html)

yield data, biomass coefficients and assumptions concerning the turnover and decomposition of biomass in various pools (litter, soil, products etc). The basic structure of a CAM is shown in Figure 1.

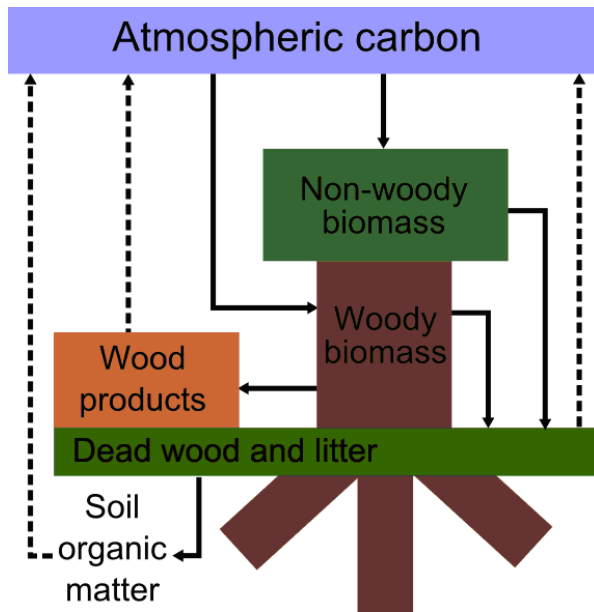


Figure 1. The main carbon stocks (boxes) and fluxes (arrows) that can be included in carbon accounting models.

## 2.2 Process-response models

Process-response models (PRMs) predict changes in biomass (and therefore the size of carbon pools) driven by the physiological responses of ecosystems to their environment. PRMs require detailed data for environmental parameters such as nutrient concentration or water and light availability as well as measurement of fluxes between ecosystem components. If appropriately parameterised PRMs should provide a more accurate estimate of carbon accumulation than CAMs, but in practice the broad assumptions that need to be made to parameterise them mean there is considerable uncertainty in the estimates they produce. For process-response models carbon accumulation is estimated from variables describing:

- the physical environment
- land use system;
- initial soil conditions;
- initial rates of plant growth; and
- the rates of operation of soil-plant interactions.

### 3 Recommended models

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When selecting a model it is important to consider the level of accuracy required for model outputs; and the information available to parameterise the model. Complex models may provide more accurate predictions (providing of course that the theoretical basis for the model is correct) but where data is limited increased complexity may not confer any additional accuracy. The ecosystem components included, and the detail with which these components are modelled also vary between models.

The models described in Table 1 were selected as they are transparent in their assumptions, applicable to a wide range of forest types, and are widely used for estimating carbon sequestration potential at the project level. They include a carbon accounting model CO2FIX, and a process-response model Soil Changes Under Agroforestry (SCUAF). CO2FIX requires information regarding the growth and yield of tree species that are being modelled, but many other parameters can be estimated from existing literature. In contrast SCUAF requires detailed site specific information regarding environmental conditions, but relatively little information regarding tree growth.

Table 1. Comparison of two widely used carbon models

Carbon stocks included	Inputs				Outputs	Additional features	Source
	Growth information	Biological variables	Management information	Processes			
<b>CO2FIX V3.1</b> - Woody biomass - Non-wood biomass - Dead wood and litter - Soil organic matter - Wood products	Stem volume increment	- Wood density - Carbon content - Residency time of carbon in products - Turnover period of leaves branches and roots - Decomposition and humification coefficients - Humus content of soil	- Initial biomass of foliage, roots, litter, branches, stems, and dead wood. - Rotation length - Recycle option - Self thinning/ mortality rate - Thinning/ harvest age - Fraction of stand removed - Allocation of stem wood to products	N/A	- Graphical and tabular results showing annual flux for the various carbon stocks. - Times steps of 1 year, simulations over 1 ha	- Can include interaction between cohorts of different age and/or species. - Allocation of net primary productivity to leaves, branches and roots can be changed over the life of the tree and adjusted to account for varied site conditions. - Bioenergy module - Financial module - Carbon accounting module	- Free download <sup>4</sup> - Sale of written reports associated with the Software requires a license
<b>SCUAF V5.0</b> - Woody biomass - Non-wood biomass - Dead wood and litter - Soil organic matter	Initial net primary productivity in kg/ha (excluding roots), and proportion attributed to leaves, fruit and wood	- Net primary productivity of roots as a percentage of initial NPP - % of C,N, and P in each of the plant parts - Initial soil conditions	- Changes in % cover over time in response to management - Removals of leaf, wood, fruit and trees products	- C, N, and P cycles - Soil-plant feedback - Erosion	- Graphical and tabular results showing annual flux for the various carbon and nutrient stocks. - Times steps of 1 year, simulations over 1 ha	- Can include tree and crop species - Can include additions of organic and inorganic fertilizers, and transfer of prunings - Possible to integrate a livestock component	- Free download <sup>5</sup>

4 <http://www.efi.int/projects/casfor/>

5 <http://www.une.edu.au/carbon/software.php>

## 4 Application of carbon models

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### 4.1 Determining carbon pools to include

The most important carbon pool in afforestation and reforestation projects is woody biomass, which is predicted from forest growth models or growth in response to ecosystem processes. Additional carbon pools, such as soil organic matter, and wood products, can also be included. These additional carbon pools should only be included if they are expected to make a significant contribution to total carbon stocks, and if reasonable estimates for the parameters used to estimate their carbon stock can be determined from published sources, or site specific information. To ensure a conservative estimate of carbon accumulation, carbon pools should only be excluded if they would increase or remain unchanged under project activities.

### 4.2 Assumptions and limitations

The major limitation of CAMs, such as CO2FIX, is the extent of the available data and the associated assumptions that must be made. Gaps in the data exist for:

- growth rates of certain species;
- mixed species plantings and non-standard planting density and thinning regimes;
- carbon storage in forest products;
- soil carbon accumulation;
- interactions among species;
- climate change and risk assessment.

Most models require information on growth characteristics of trees. For some commercial species, established yield tables provide robust and well documented data from which estimates of total stand biomass can be obtained and fluxes over time represented. This information is lacking for many species however, particularly for agroforestry projects that aim to use local tree species. In the absence of yield tables, it may be necessary to estimate tree growth characteristics from measurements of tree in the local area<sup>6</sup>.

The carbon sequestration potential of activities that aim to create a semi-natural habitat though mixed species plantings, agroforestry, and non-standard thinning regimes is not well documented. Assumptions are therefore made based on the best existing information.

Carbon storage in forest products will be, in most cases, a small component of the overall carbon sequestration potential. CO2FIX includes a module for simulation of the fate of forest products. However, tracking the fate of forest products can be problematic and the assumptions behind these simulations are likely to be generalised.

Soil carbon can be a significant component of the total carbon stock in forest ecosystems and management practices that affect forest soils could significantly alter carbon stocks. However, in most cases management aims to reduce soil carbon loss and will generally increase soil carbon storage. For most projects, the resources required to accurately measure and represent the

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<sup>6</sup> methods for estimating tree growth from tree measurements are described in a separate protocol: *Estimating growth from tree measurements*

heterogeneity of soil properties over the entire project area mean its measurement is not practical.

The effects of climate change itself and the risks of catastrophic disturbances such as wind blow, forest pathogens, or fire are not generally represented in yield tables and growth models. The inclusion of environmental stochasticity could therefore seriously affect the long-term carbon storage of a forest. Since it is not possible to integrate these factors with the carbon accumulation models described here, their potential effect should be estimated separately, and incorporated into risk avoidance mechanisms such as the use of buffer zones.

As PRMs, such as SCUAF simulate the processes that cause changes in carbon stocks, they are less reliant on secondary data, and instead require parameterisation with data on environmental variables. The volume of data, and effort required to accurately parameterise PRMs may limit their application in small-scale afforestation and reforestation projects.

It is always important to note that the results of any model are only be as good as the data used to run it, and the assumptions used within the model should be stated when using the results of that model. A list of the necessary input parameters for CO2FIX and SCUAF are listed in Appendix A, with example of values, and/or information about how and where the necessary information can be found.

## 5 Conclusion

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The model applied in each situation should be determined by the availability of data for that site. For areas where data are severely lacking, CO2FIX can be used with locally derived species growth information, and conservative estimates for other parameters derived from the literature.

## 6 Bibliography

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## 7 Appendix A - CO2FIX example input parameters

### General

	value	description
Simulation length	100 yr	e.g. period of Plan Vivo project
Growth as a function of:	Age	
Competition relative to:	The total biomass in the stand	
Management mortality	Depends only on the total volume harvested	
Cohort start age	0 yr	For afforestation or reforestation project
Cohort type	Broadleaf	

### Biomass

	value	description
Stems carbon content	0.5 MgC/MgDM	
Stems wood density	0.52 MgDM/m <sup>3</sup>	From database e.g. Brown (1997)
Stems initial carbon	0 MgC/ha	For afforestation or reforestation project
Cohort age	yr	Defined for each cohort e.g. 5, 10, ..., 50
Cohort CAI	m <sup>3</sup> /ha/yr	Derived from yield tables or increment curves
Foliage carbon content	0.5 MgC/MgDM	
Foliage initial carbon	0 MgC/ha	For afforestation or reforestation project
Foliage growth correction factor	1	Adjustment to account for non-optimal site conditions
Foliage turnover rate	1 /yr	For deciduous trees
Cohort foliage relative growth	0.7	
Branch carbon content	0.5 MgC/MgDM	
Branch initial carbon	0 MgC/ha	For afforestation or reforestation project
Branch growth correction factor	1	Adjustment to account for non-optimal site conditions
Branch turnover rate	0.05 /yr	
Cohort branch relative growth	0.2	
Root carbon content	0.5 MgC/MgDM	
Roots initial carbon	0 MgC/ha	For afforestation or reforestation project
Root growth correction factor	1	Adjustment to account for non-optimal site conditions

Root turnover rate	0.07 /yr	
Cohort root relative growth	0.25	

### Mortality

	value	description
Mortality rate	0.01 /yr	Annual mortality as a fraction of standing biomass

### Management

	value	description
Age	yr	e.g. 60, 70, ..., 100
Fraction removed	0.25	Proportion of total biomass
Stems logwood	0.25	Proportion of removed stems
Stems pulpwood	0	Proportion of removed stems
Branches logwood	0	Proportion of removed branches
Branches pulpwood	0	Proportion of removed branches
Slash firewood	0	Proportion of slash used as firewood

### Soil

	value	description
Degree days (above zero)	9757 °C	Calculated from monthly mean temperatures; <a href="http://www.worldclimate.com">http://www.worldclimate.com</a>
Potential evapo-transpiration in growing season	1152.48 mm	Calculated from monthly mean temperatures; <a href="http://www.worldclimate.com">http://www.worldclimate.com</a>
Precipitation in growing season	1200 mm	
Annual input from foliage	MgC/ha/yr	
Annual input from branches	MgC/ha/yr	
Annual input from roots	MgC/ha/yr	
Annual input from stems	MgC/ha/yr	

### Products

	value	description
Raw material allocation		Default model parameters
Process losses		Default model parameters
Products allocation		Default model parameters

End of life		Default model parameters
Recycling classification		Default model parameters
Half life		Default model parameters

## 8 Appendix B - SCUAF example input parameters

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### Physical environment

	value	description
Climate	Lowland humid	Select a description from list
Slope	Flat	Select a description from list
Drainage	Free	Select a description from list
Soil texture	Sandy	Select a description from list
Soil reaction	Acid	Select a description from list
Soil parent material	Felsic	Select a description from list

### Land-use system

Number of periods	2	Define periods with different growth or management characteristics
Length	10	For each period
Fraction of land under trees	0.5	For each period
Fraction of land under crop	0.5	For each period (crop could also be another tree species)
Is it a cut year?	0	Binary choice for each period
Standing biomass harvested		Proportion of Leaf; Fruit; Wood; Root (in a cut year), harvested in each period
Standing biomass burnt/lost		Proportion of Leaf; Fruit; Wood; Root (in a cut year), burnt in each period
Standing biomass retained		Proportion of Leaf; Fruit; Wood; Root (in a cut year), retained in each period
Is it a burn year?	0	Binary choice for each period (only valid in a cut year)

### Additions

Organic additions	0 kg/ha/yr	e.g. grass, leaf mulch, farmyard manure
Organic crop fraction	1	Proportion applied to the crop only, the remainder goes to trees
Inorganic additions	0 kg/ha/yr	e.g. fertilisers
Inorganic crop fraction	1	Proportion applied to the crop only, the remainder goes to trees
C fraction of organic additions	0.5	
C:N ratio of organic additions	25	
C:P ratio of organic additions	250	

N fraction of inorganic additions	0.2	
P fraction of inorganic additions	0.2	

#### Removals and transfers

Fraction of leaf NPP harvested		for trees and crops in each period (e.g. removal of crop residues)
Fraction of fruit NPP harvested	1	for trees and crops in each period (e.g. removal of crop fruit)
Fraction of wood NPP harvested		for trees and crops in each period (includes prunings that are harvested; typically all or most of the tree wood in cut years)
Fraction of leaf NPP lost		For tree and crop in each period
Fraction of fruit NPP lost		For tree and crop in each period
Fraction of wood NPP lost		For tree and crop in each period
Fraction of N in ash	0.1	
Fraction of P in ash	0.75	
Fraction of leaf NPP pruned and transferred		
Fraction of fruit NPP pruned and transferred		
Fraction of wood NPP pruned and transferred		Only include prunings left on the soil
Fraction of prunings transferred from tree to crop area	0	i.e. by hand
Fraction of litter transferred from tree to crop area	0	e.g. by wind
Fraction of leaf NPP retained		
Fraction of fruit NPP retained		
Fraction of wood NPP retained		

#### Initial plant growth aboveground

NPP	10000 kg/ha/yr	EITHER observed plant growth OR plant growth expected with no nutrient constraints; for a hectare completely covered by the plant; in each period
Initial biomass	0 kg/ha	for leaf; fruit; wood; root

#### Roots

Fraction of AGB	0.24	
Fraction of roots that are coarse	0.77	fine roots are those roots that die back annually, coarse roots only die after a cut year
Fraction of tree-roots growing	0.33	

into deep soil		
Fraction of tree-roots growing into crop soil	0.1	

### Plant composition

Apportionment of NPP to leaf	0.32	
Apportionment of NPP to fruit	0.02	
Apportionment of NPP to wood	0.66	
Fraction of dry matter which is carbon	0.5	
Percentage N in leaf	2.5%	
Percentage of N in fruit	2.5%	
Percentage of N in wood	0.5%	
Percentage of N in root	1.5%	
Percentage P in leaf	1.5%	
Percentage of P in fruit	0.25%	
Percentage of P in wood	0.05%	
Percentage of P in root	0.05%	

### Soil-plant feedback

Change in topsoil C causes change in plant growth of x percent	2%	
Change in soil depth of 1cm causes change in plant growth of x percent	1%	

### Soil

Depth	100 cm	lower boundary of the plant-soil system taken as the basis for modelling (approx depth reached by crop roots; rock/soil boundary; lower boundary of topsoil; arbitrary depth e.g. 1m)
Number of soil horizons	2	Maximum of 5
Depth of horizon	20 cm	For each horizon
Percentage carbon	2%	For each horizon
Percentage total N	0.2%	For each horizon
Percentage organic P	0.02%	For each horizon
Available P	8 mg/kg	For each horizon
Total P	200 mg/kg	For each horizon

Bulk density	1.3 g/cc	For each horizon
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### Erosion

Climate factor	1000	
Soil erodibility factor	0.3	
Slope	0.1	
Tree cover factor	0.006	
Crop cover factor	0.3	
Tree Proportionality Factor	0.8	
Conservation practice factor	1	
Erosion adjustment factor for measured erosion	1	
C enrichment factor for eroded sediments	2	
N enrichment factor for eroded sediments	2	
P enrichment factor for eroded sediments	2	

### Carbon cycle

Fraction C lost as oxidation of litter	0.85	
Fraction C lost as oxidation of roots	0.67	
Fraction C lost as oxidation of organic additions	0.67	
Fraction of initial humus in stable form	0.67	
Proportion transformed from stable to labile	0.005	
Decomposition constant for labile humus	0.03	
Decomposition constant for stable humus	0.002	

### Nitrogen cycle

Fraction of plants that are N fixing	1	usually 0 or 1
Fraction of requirement obtained from symbiotic fixation	0.5	

Throughfall and stemflow of nutrients	10 kg/ha/yr	
Non-symbiotic fixation of nitrogen	8 kg/ha/yr	
Fraction of nitrogen mineralisation from previous years litter becoming available this year	0.25 kg/ha/yr	
Atmospheric inputs (rain, dust)	12 kg/ha/yr	
Root density modifier	1	
Fraction of mineral N of organic origin (after mineralisation) that is leached	0.05	
Fraction of N from fertiliser (after mineralisation) that is leached	0.1	
Fraction of mineral N lost by gaseous losses (denitrification, volatilisation)	0.05	
Fraction of N lost by fixation on to clay minerals (net)	0	

#### Phosphorus cycle

Throughfall and stemflow of nutrients	1 kg/ha/yr	
Weathering of rock minerals	4 kg/ha/yr	
Atmospheric inputs (rain, dust)	1 kg/ha/yr	
Fraction of mineral P of organic origin (after mineralisation) that is leached	0.01	
Fraction of P from fertiliser (after mineralisation) that is leached	0.02	
Fraction of P lost by fixation on to clay minerals (net)	0.1	