CHAPTER 12
A First Look at Carbon Stocks and their Variation in Congo Basin Forests

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Introduction

The Kyoto Protocol allows for only afforestation and reforestation under its Clean Development Mechanism (CDM). The rules and modalities established under the Marrakech Accords allow developing countries to sell CDM certified emission reduction to developed countries up to a limit of 230 millions metric tons of carbon dioxide (CO_2) during the period 2008-2012 (about 45 million metric tons of CO_2 per year on average). At the same time the Intergovernmental Panel on Climate Change (IPCC) estimates that 1.7 billion metric tons of CO_2 are released annually to the atmosphere because of land use change and largely from tropical deforestation, dwarfing the possible impact of possible forest CDM projects. The magnitude of the emissions from deforestation not included in the Kyoto Protocol triggered the Conference of Parties (COP) to the UN Framework Convention on Climate Change (UNFCCC) to initiate a two-year process to address issues relating to reducing emissions from deforestation in developing countries. This process peaked during the COP13 in Bali in December 2007 with the Decision 2/CP.13 "Reducing emissions from deforestation in developing countries: approaches to stimulate action." It is interesting to note that it took more than 10 years for the international community to accept that reducing emissions from deforestation or sequestering carbon from standing forests is more effective than through planting trees and reintroduce this topic to the international climate negotiations. It will probably take another five years to have the rules and modalities in place but some countries and donors are eager to get an early start.

Put simply, without entering the innumerable arguments ongoing about baselines or financial mechanisms, the idea behind the concept of reduced emissions from deforestation and forest degradation (REDD) is to provide financial incentives to help developing countries voluntarily reduce national deforestation rates and associated carbon emissions below a baseline. Countries that demonstrate such reduced emissions would be able to sell carbon credits on the international carbon market or receive financial compensation in one way or another for their good behavior.

No matter which final REDD mechanism is chosen, we will need to know as accurately as possible how much carbon (C) is:

- stored in different standing vegetation types (especially forests) and soils;
- released through AFOLU (agriculture, forestry and other land use) activities.

In this chapter we will try to bring the best possible answers to these two questions without entering into much scientific complexity, but at the same time avoiding oversimplification. We will start with some definitions and explanation of terms. To determine the existing C stocks by vegetation type we will present the respective area and C content per hectare of each vegetation type. Then to have an estimation of past and present human activities, we will give estimates of deforestation and degradation linked to agriculture, forestry (logging) and other land uses. We will briefly expose the state of knowledge about C fluxes through ecological processes and what we can reasonably deduce for Congo Basin forests. Finally we will conclude with a note of caution describing the uncertainties in the estimations presented in this chapter.

Definitions[44]

Forest lands include all land with woody vegetation consistent with thresholds used to define forest land in the national greenhouse gas inventory. They also include vegetation types that, *in situ,* could potentially reach the threshold values used by a country to define the forest land category (like regenerating stands).

For the purpose of the Kyoto Protocol, Parties should select a single value of crown cover, tree height and area to define forests within their national boundaries. Selection must be made using the following ranges:

- minimum forest area: 0.05 to 1 ha matching the two following criteria;
- potential to reach a minimum height at maturity *in situ* of 2 to 5 m;
- minimum tree crown cover (or equivalent stocking level): 10 to 30 %.

At the time of writing the only published nationally selected minima for Congo Basin countries are the ones for the DRC, which are: minimum forest area 1 ha, minimum height at maturity 5 m and minimum tree crown cover 30 %. These values however were only agreed upon for the purpose of the Kyoto Protocol and CDM and might be revised for a future REDD mechanism.

Deforestation is the long-term or permanent conversion of forest land to other non-forest uses. The UNFCCC (Decision 11/CP.7) defines it as: "...the direct, human-induced conversion of forested land to non-forested land." Deforestation is therefore a reduction in crown cover below the nationally defined threshold (e.g., for DRC deforestation would not be recorded until the crown cover was reduced below 30 %). If forest cover passes below the threshold only temporarily due to say logging, and is expected to grow again above the threshold, then this is not considered deforestation. Based on AFOLU land use classes, there is deforestation when "forest lands are converted to crop lands, grass lands, settlements, wetlands or other lands".

Degradation is defined as a loss of carbon stocks in forests impacted by human activities but still remaining forests according to the three criteria defined above. There is no accepted quantitative definition of the term, which can seriously complicate monitoring of how much is emitted by "degrading" forests or could be kept sequestered by reducing degradations. To develop a monitoring system for degradation, it is first necessary that the major causes of degradation (extractive industries, agriculture…) are identified and the likely impact on the carbon stocks assessed. Furthermore, degradation by fire, through fuelwood harvesting or because of invasive species, all also important causes of degradation, is likely to be more complicated to monitor with remote sensing. In AFOLU terms a decrease in carbon stocks of "forest lands remaining forest lands" will be equated to degradation.

In the "climate" negotiations and for REDD purposes, deforestation and degradation are only considered in terms of carbon stocks, without proper attention to biodiversity and other forest functions. Knowledge on forest ecology (Dupuy, 1998; Zobi, 2002; Gourlet-Fleury *et al.,* 2004) shows that significantly reducing the stand basal area of a dense rainforest (e.g., from 30 m^2/ha to below 20 m^2/ha) can induce a profound change in the forest dynamics and jeopardize recovery both in term of diversity and biomass. Such a change in basal area can happen before the crown cover is reduced below 30 %. This implies that land use practices, not technically considered as immediate deforestation (leaving 30 % of crown cover), may cause straightforward deforestation in the short term. Similarly, repeated entry into the stand, accompanied by selective logging of shade intolerant timber trees, will greatly reduce forest basal area and can sequentially eliminate timber species from the forest while keeping the overall cover above the 30 % threshold, resulting in a degraded forest where no future crop trees exist.

The IPCC Guidelines refer to two **basic inputs to calculate greenhouse gas inventories**.

- "Activity data" in the case of deforestation and forest degradation refers to area change data (e.g., the area of forest land converted to other land use).
- "Emission factors" refer to emissions/removals of greenhouse gases per unit area (e.g., metric tons of CO_2 emitted per hectare of deforestation).

Among the three possible approaches (see table below) for representing the change in area of different land categories it is likely that only the third Approach, which involves tracking of land conversion between categories using spatially-explicit land conversion information, can be used for REDD implementation.

[44] Definitions used in this chapter are extracted from the GOFC-GOLD Sourcebook (GOFC-GOLD, 2008).

Photo 12.1: Light availability in the forest is often a limiting factor for the growth of seedlings.

Approach for activity data: area change
1. total area for each land use category, but no information on conversion (only net changes)
2. tracking of conversion between land use categories
3. spatially explicit tracking of land use conversion

Emission factors are derived from assessments of the changes in carbon stocks. This information can be obtained at different "Tier" levels (see table below) independently of the "Approach" selected. Tier 1 uses IPCC default values, Tier 2 requires some country-specific estimates (i.e. inventories, permanent plots) while Tier 3 requires inventory-type data of carbon stocks in different pools and assessment of any change through repeated measurements or modeling. Accuracy, complexity and cost of monitoring increase from Tier 1 to Tier 3.

Tiers for emission factors: change in C stocks
1. IPCC default factors
2. Country specific data for key factors
3. Detailed national inventory of key C stocks, repeated measurements of key stocks through time or modeling

Estimation of Land Use and Land Cover Change

Vegetation and Land Cover Types

In the IPCC "Forest" category, different ecological types correspond to different carbon stocks. In order to provide the most accurate figures of carbon stock and change for Central Africa, we will detail the areas and the carbon associated with the main forest types using the GLC2000 map[45]. For each GLC2000 class, we analyzed the tree cover (from MODIS data) and the floristic domain (White, 1983). Results are summarized in table 12.1 and are given with the "ecological" equivalents of land cover classes.

Table 12.1: Major landcover classes and equivalent vegetation types in the Congo Basin

Land cover class derived from low resolution satellite imagery (% tree cover)	Equivalent vegetation types and ecology	Floristic domain
Dense humid forests		
Swamp and riparian forests (>70 %)	Evergreen inundated forests, fresh water swamps characterized by *Uapaca, Guibourtia, Hallea, Raphia*	Gu-Co
Closed evergreen lowland forests (>70 %)	Evergreen and semi-deciduous forests below 900 m a.s.l.; high floristic diversity	Gu-Co
Sub-montane forests (>70 %)	Transition forests between lowland and true montane forests (900 and 1500 m a.s.l.)	AfMo
Montane forests (>70 % - variable)	Evergreen montane forests (1500-2400 m a.s.l.) and alpine vegetation (>2400 m a.s.l.) characterized by *Alangium, Linoceira, Olea, Prunus*	AfMo
Mangroves (10-60 %)	Coastal evergreen forests on marine alluvium, brackish waters; little tree species diversity, dominated by *Rhizophora, Avicennia, Brugueria*	Azonal
Closed deciduous forest (>40 %)	Open forests, wet Miombo characterized by *Brachystegia* (Zam), *Julbernardia* (Zam) and *Isoberlinia* (Zam/Sud)	Zam/Sud
Mosaic forest/croplands (20-60 %)	Correspond quite closely to shifting cultivation areas (mix of crop lands, fallows, plantations, young secondary forests) located around transportation axes and human settlements; tree layer is often dominated by pioneer species (*Musanga*, *Macaranga*)	Gu-Co
Mosaic forest/savanna (30-60 %)	Humid savannas and gallery-forests; the savannas correspond to the "derived savannas" (*sensu* Keay, 1959) or Guinean savannas; they constitute fire climax savannas; the palm *Borassus aethiopium* is often common; the forests are similar to closed evergreen forest class	Gu-Co
Deciduous woodland (10-40 %)	Woodland, dry Miombo characterized by a perennial grass cover and open tree layer; Combretaceae and Leguminosae families are very common	Zam/Sud
Shrubland and grassland (<10 %)	Herbaceous dominated vegetation with scattered treelets, included in the dense forest mass. Grasslands correspond to the Plateau Batéké and Adamaoua regions; shrublands are found in the Niari-Nyanga-Ngounié region (Gabon-Congo) and in DRC	Zam/Sud

Gu-Co: Guineo-Congolian; AfMo: Afromontane; Zam: Zambezian; Sud: Sudanian. Modified from Mayaux et al., 2004

The two principal land uses in the Congo Basin sub-region are logging concessions (595,380 km²) and protected areas (444,970 km²). The third largest land use, shifting cultivation, is not easily detected using low resolution satellite imagery, but could be estimated as a first approximation at 438,801 km² (sum of the two land cover classes Croplands (embedded in "other") and Mosaic forest/croplands of table 12.2).[46]

[45] A full description of the land use/land cover types described in this chapter is available in Mayaux *et al.*, 2004.

[46] That number is probably an underestimation as some cultivated areas are located inside logging concessions or protected areas and have not been included in the figure listed here.

Table 12.2: Area estimates by land cover classes and allocation (protection, logging) in 2006

Land cover class (LCC)	Total area (km²)	% sub-region	Protected area (km²)	% land cover class protected	Area allocated for logging (km²)	% land cover class allocated for logging
Closed evergreen lowland forest	1,421,834	35	187,880	13	481,680	34
Sub-montane forest (900-1,500 m)	63,100	2	23,290	37	1,530	2
Montane forest (>1,500 m)	9,754	0.2	7,870	81	20	0
Swamp forest	123,264	3	10,280	8	28,570	23
Mangrove	1,926	0	240	12	20	1
Total humid forests	**1,619,879**	**40**	**229,580**	**14**	**511,830**	**32**
Mosaic forest/croplands	370,123	9	13,000	4	45,860	12
Mosaic forest/savanna	588,011	15	49,870	8	16,280	3
Closed deciduous forest	304,808	8	16,220	5	4,720	2
Deciduous woodland	630,890	16	64,350	10	1,680	0
Open deciduous shrubland, sparse trees	301,220	7	46,070	15	10,780	4
Other	233,540	6	25,910	11	4,220	2
Sub-region total (Congo Basin)	**4,048,470**	**100**	**444,970**	**11**	**595,380**	**15**

Source: GLC 2000, FORAF.

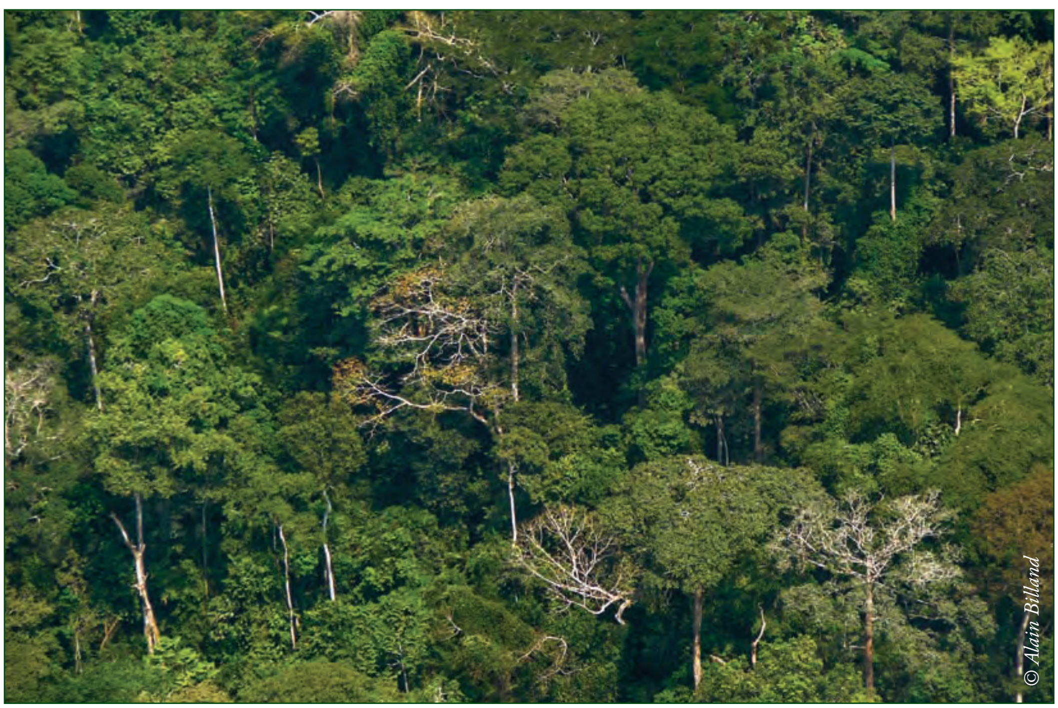


Photo 12.2: The canopy is a complex structure of various species.

While forest areas are derived from coarse resolution satellite images with high observation frequency, changes in area are better measured by the analysis of fine spatial resolution satellite images taken at two dates. Two recent studies (Duveiller *et al.*, 2008; Hansen *et al.*, 2008a), based on different methods, have produced reliable and consistent estimates on the deforestation in the humid domain between 1990 and 2005.

Table 12.3[47]: Basin-wide and national figures for annual deforestation (humid forests) and degradation rates between 1990 and 2000

Country	Net deforestation (%)	Net Degradation (%)
Cameroon	0.14	0.02
Gabon	0.09	0.07
Congo	0.02	0.01
CAR	0.06	0.02
DRC	0.20	0.12
Central Africa	**0.16**	**0.09**

Source: figures adapted from Duveiller et al., 2008 and Hansen et al., 2008a.

For the 1990-2000 period the annual gross deforestation rate for Central Africa's tropical forest is estimated at 0.21 % per year, with an annual reforestation rate corresponding to 0.05 % and net degradation rate estimated at 0.09 %. The net deforestation rate for the 10-year period is therefore 1.6 %, which means that the humid forests of the Congo Basin lost about 29,000 km^2 from 1990 to 2000. National estimates are also provided in table 12.3, with less reliable figures for Cameroon and Gabon given the paucity of available data due to quasi-permanent cloud coverage over these two countries.

The first estimates of forest change between 2000 and 2005 are derived from a combination of multi-temporal and multi-resolution satellite data (Hansen *et al.*, 2008b). The authors report a forest loss rate of 0.76 % for 5 years (0.15 %/yr), which is very close to the 0.16 %/yr reported for 1990-2000 and represents an area of about 14,000 km^2.

In summary, from 1990 to 2005, around 43,000 km^2 of humid forests have been deforested in the Congo Basin.

These observed forest-cover change rates are by far the lowest of the pan-tropical belt, with a net deforestation rate two times higher in South America and four times higher in South-east Asia. It is important to note however that deforestation is not a uniform process. Some areas (figure 12.1) show a dramatic increase of deforestation due to agricultural encroachments, particularly in regions affected by human conflicts (e.g., Kivu) and at the fringes of the Basin (Northern Equateur, Kasaï), whereas others remain almost untouched.

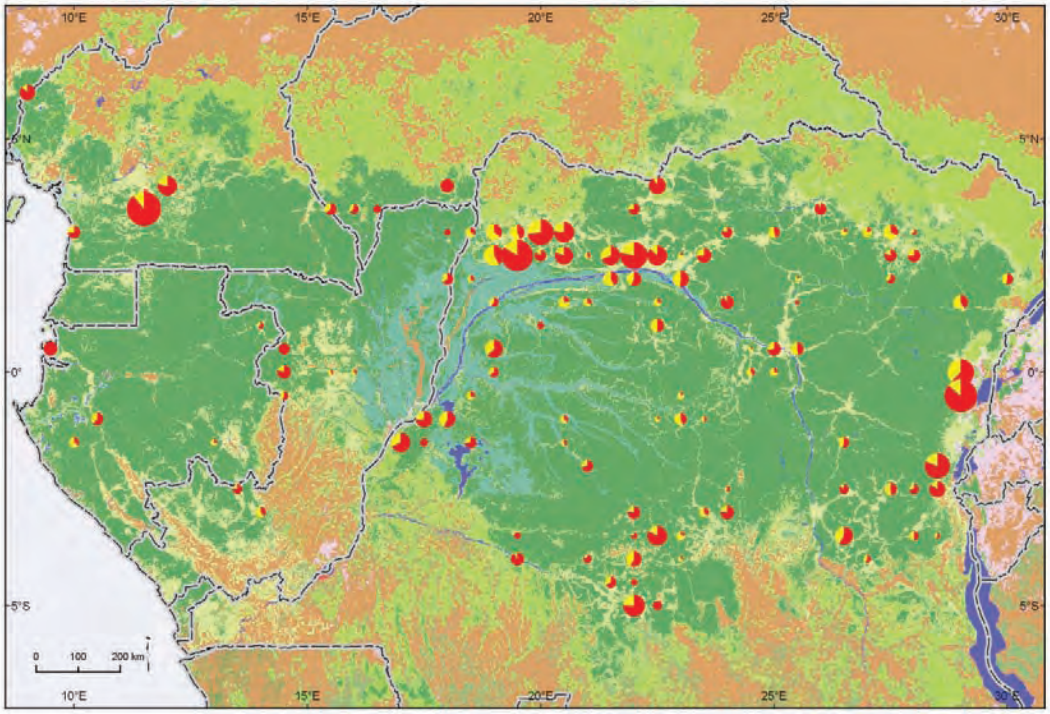
[47] Three land use classes are considered in the Duveiller *et al.*, study: dense forest, degraded forest and non-forest. The class "degraded forest" is composed of dense forest perforated by mid-size (2-5 ha) clearings or crop fields, while the GLC2000 mosaic forest-croplands class belongs to the non-forest class. The degradation produced by selective logging cannot be detected by satellite imagery at the 30-m spatial resolution currently used in regional studies of forest-cover change, and current degradation figures do not account for this.

Estimation of Carbon Stocks

The estimation of C stocked in forest ecosystems requires estimates of the following C pools:

- aboveground (AG): trees, lianas, understory vegetation, litter and dead wood;
- belowground (BG): roots and soil carbon.

Carbon stocked in woody plants (C_w) is linked to the biomass (B_w) expressed in dry matter by unit of area Mg/ha or t/ha). It is estimated by a simple relation: $C_w = k.B_w$ with $k \approx 0.47$. Estimating carbon stock or biomass is therefore equivalent.



Each circle represents a 10 x 10 km sample. The size is proportional to the total area affected by deforestation and degradation, while the two colors provide information on the relative importance of the two processes.
Source: Duveiller et al., 2008.

Figure 12.1: Spatial distribution of deforestation (red) and forest degradation (yellow) in the humid forests of the Congo Basin

Aboveground Carbon Pools

To estimate the aboveground biomass (AGB) of a given forest stand, one needs first a biomass equation (allometric relation between the biomass of the vegetation –with or without the roots - and some easily measured parameters like diameter at breast height or total height). Such an allometry is built using destructive methods: an area or a sample of individuals is measured then clear-cut and all the components (stumps, stems, branches, leaves, logs…) are oven-dried and weighed; the resulting data is then used to build a biomass equation model: AGB = f(diameter, height, wood density) for the given tree of the stand. This is the most precise solution if the sample is adequate but this method is very time-consuming and labor intensive. It should be noted that this allometry is only valid for the location where it was designed and for a given range of diameter or height. The only local aboveground biomass (AGB) equation for the Congo Basin seems to be the one developed by Ibrahima *et al.*, (2002) for an evergreen forest based on 93 trees spanning 1 to 79 cm in diameter at breast height (D) but with only one tree over 50 cm.

Global biomass models based on extensive samples spanning several topical regions (Brown *et al.*, 1989; Brown, 1997; Chave *et al.,* 2005) have also been developed. The best available global models (Chave *et al.*, 2005) so far are based on 27 sites and 2,410 trees (none from African forests) using diameter and specific wood density (ρ):

- 1500-3500 mm annual rainfall, 1-4 months dry season:

$$AGB_{trees} = \rho e\ (-1.499+2.148\ ln(D)+0.207(ln(D))^2-0.0281(ln(D))^3$$

- >3500 mm, no seasonality:

$$AGB_{trees} = \rho e\ (-1.239+1.980\ ln(D)+0.207(ln(D))^2-0.0281(ln(D))^3$$

AGB_{trees} *in kg; D in cm;* ρ *in g/cm*^{3}

The other aboveground carbon pools have received less attention because in tropical forests it is generally estimated that trees above 10 cm diameter represent more than 75 % of the biomass.

The available biomass equations are then applied to census data (from permanent sample plots or using data from forest inventories) to estimate the biomass of a stand or a forest type. A review of the existing literature on plot-based biomass estimates using equations and/or destructive sampling is summarized in annex 1 and from inventory-based estimates in annex 2. Some authors (annex 3) have used GIS modeling techniques to extrapolate stand values of biomass to entire regions or entire biomes and to build biomass maps using reasonable but largely unchecked assumptions. The most recent of these biome-wide estimates provides carbon stocks for the whole of Sub-Saharan Africa (Gibbs and Brown, 2007) accounting for anthropogenic disturbances and using a rule-based GIS analysis to spatially extrapolated forest inventory data.

From the overall literature review and using the best available data both from plot, inventory and GIS approaches (annexes 1, 2 and 3), we obtain the following C stock estimates by land cover classes (table 12.4) using 0.47 as the 'biomass to carbon' conversion factor.[48]

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Photo 12.3: Forest measurements and inventories are essential for the quantification of forest carbon.

Table 12.4: Aboveground carbon (Mg/ha) in vegetation by land cover classes

Land cover classes	Aboveground carbon		
	Plot-based (annex 1)	Inventory-based (annex 2)	GIS-based (annex 3)
Deciduous woodland	**21** (2-43; 20)	-	-
Closed deciduous forest	**42** (22-68; 6)	-	36
Closed evergreen lowland forest	216 (146-275;15)	**126** (63-174;55)	178 - 211
Swamp forest	-	**85** (-; 1)	-
Sub-montane forest	-	-	**68**
Montane (moist) forest	-	-	**68**
Mosaic forest – cropland	**54** (3-141;29)	-	-
Mosaic forest – savanna	**14** (4-22;2)	-	-

Values in table: average (range; number of observations).
Sources: see annexes 7,8 and 9.

[48] All figures have to be taken with all the caveats and possible sources of errors listed in the section "A note of caution…" at the end of this chapter.

In the case of inventory-based estimates, an observation is a group of inventory plots located in the same forest strata. The total number of inventory plots is bigger than the given figures.

For closed evergreen lowland forest, inventory-based figures are slightly lower than FAO estimations (2006), FAO gives an average of 155 tC/ha (from 30-35 cm dbh, depending on the countries). These differences may be explained by:

- Different sample representativity at the sub-regional scale: for example, the opened forests of DRC and northern Congo are overrepresented in the inventory-based estimations.
- Uncertainities linked to some of the assumptions made in the calculations.

Bold values indicate values selected for the present document (even though C stocks estimated from inventories appear lower than from plot-based or GIS estimates, we believe that they are a better estimate of the reality because they are based on much larger samples).

Belowground Carbon Pools

Belowground biomass (BGB) consists in roots. It is considered the most difficult pool to assess and the very few data available in the literature for Central Africa (see Annex 1) have to be used with extreme caution as they come from limited, small size, samples. For this reason using a root/shoot ratio (R/S) has become a core method for estimating root biomass from the more easily measured shoot biomass: BGB= AGB * R/S

Mokany *et al.*, (2006) provide a very useful critical review of the literature on root/shoot (R/S) ratios and derived values for various vegetation types (table 12.5) recommended in IPCC (2006). No data are available for Africa and all the samples used in this table have been measured in other regions.

Photo 12.4: The transportation of logs can be disrupted by the poor quality of the road network.

Table 12.5: Root/shoot ratio values

Vegetation type	Shoot biomass(t/ha)	R/S median	Min.	Max.	Sample size
Tropical moist forest	<125	0.205	0.092	0.253	4
	>125	0.235	0.220	0.327	10
Tropical dry forest	<20	0.563	0.281	0.684	4
	>20	0.275	0.271	0.278	2
Tropical moist woodland		0.420	0.292	0.548	7
Tropical dry woodland		0.322	0.259	0.710	6
Tropical grassland		1.887	0.380	4.917	15

Modified from Mokany et al., 2006.

For the "average" tropical forest (with a tree biomass generally higher than 125 t/ha), it is estimated that the roots represent 23.5 % of the aboveground biomass. This value however increases for more arid ecosystems and the roots represent 42 % of the aboveground biomass of woodlands. It is important to note that these values are derived from a very limited number of cases (e.g.,14 for tropical moist forests and 6 for tropical dry forests) and that they need, consequently, to be treated and used with caution.

The other pool of belowground carbon is found in soils. Soil organic carbon (SOC) plays an important role in the ecology of terrestrial ecosystems through the moderation of cation exchange capacity (CEC)[49], water holding capacity, soil structure, resistance against erosion, etc. The assessment of SOC and its dynamic is the subject of many studies, largely out of the scope of this paper. Lal (2005) considers that all other soil parameters being equal, SOC is similar in tropical and temperate soils but that tropical SOC is subject to faster rates of decomposition. Some local estimates of SOC (annex 4) exist for Central Africa[50], or for similar ecosystems in West Africa, but are subject to the same caveats as root carbon estimates. Based on annex 9 and additional literature datasets we obtain the SOC values (tC/ha) summarized in table 12.6. From this table it appears that there are no significant differences between the various land use types, which means that we can use the overall weighted average (38 tC/ha) as a first approximation for the sub-region.

Table 12.6: Soil organic carbon (SOC) in metric tons/ha

Land use	Avg	StD	Median	Min.	Max.	N	Sources
Dry miombo fallow	45	14	45	20	74	28	Williams *et al.*, 2008
Chromolaena fallow	39	14	37	21	58	6	Palm *et al.*, 2000
Cocoa agroforest	42	8	41	33	53	6	Palm *et al.*, 2000; Sonwa, 2004
Humid forest crop	35	15	38	18	56	5	Palm *et al.*, 2000
Forest	52	14	49	37	75	7	Palm *et al.*, 2000; Jaffré *et al.*, 1983
Humid forest fallow	53	20	47	30	89	18	Palm *et al.*, 2000; Jaffré *et al.*, 1983
Wet miombo	83	23	NA	NA	NA	5	Walker and Desanker, 2004
Wet miombo fallow	52	17	NA	NA	NA	6	Walker and Desanker, 2004
Wet miombo crop	49	11	NA	NA	NA	11	Walker and Desanker, 2004
Dry miombo	NA	NA	58	18	140	28	Williams *et al.*, 2008
Overall weighted average	38			18	140	120	

Avg: average; StD: standard deviation; N: number of observations

An Estimate of the Carbon Stored in Congo Basin Ecosystems

Based on the abovementioned data on land cover classes and carbon stocks, table 12.7a gives an estimate of 46 billion metric tons for the C stored in the Congo Basin. Closed evergreen lowland forests represent 60 % of the carbon stored in the sub-region, while only covering 35 % of the area.

Table 12.7b gives the estimation at country level and compares our estimates with some published values from the literature.

[49] In soil science, cation exchange capacity is used as a measure of fertility, nutrient retention capacity and the capacity to protect groundwater from cation contamination (Wikipedia).

[50] An interesting new development is the use of SOTER (Batjes, 2008) to map the soil carbon stocks of Burundi, Rwanda and the Democratic Republic of Congo.

Table 12.7a: Total carbon stock estimates for the Congo Basin

Land cover classes (LCC)	Area (km²)	Carbon pools (t/ha)				Total C
		AG C	R/S	SOC	C	(million metric tons)
1. Closed evergreen lowland forests	1,421,834	125	0.235	38	192	27,299
2. Swamp forests	123,264	85	0.235	38	143	1,761
3. Sub-montane forests (900-1,500 m)	63,100	68	0.235	38	122	770
4. Montane forests (>1,500 m)	9,754	68	0.235	38	122	119
Dense humid forests (1-4)	**1,617,952**	**147**			**185**	**29,949**
Closed deciduous forests	304,808	42	0.275	38	92	2,791
Mosaic forest/croplands	370,123	54	0.275	38	107	3,955
Mosaic forest/savannas	588,011	14	0.42	38	58	3,403
Deciduous woodland	630,890	21	0.322	38	66	4,149
Grassland, shrub land, sparse trees		5	0.42	38	45	1,770
Congo Basin sub-region	4,048,470					46,016

AG C: aboveground carbon; SOC: soil organic carbon: R/S: root/shoot ratio

Table 12.7b: Total carbon stock (million metric tons) estimates for the Congo Basin by country

	Cameroon	Congo	Gabon	Eq. Guinea	CAR	DRC
1. Closed evergreen lowland forests	3,162	2,762	4,029	379	886	16,082
2. Swamp forests	0	501	2	0	0	1,000
3. Sub-montane forests (900-1,500 m)	39	0	2	4	0	857
4. Montane forests (>1,500 m)	2	0	0	0	0	117
Total humid forests (1-4)	**3,203**	**3,263**	**4,033**	**383**	**886**	**18,056**
Mosaic forest/croplands	414	534	287	57	167	1,945
Mosaic forest/savanna	628	145	20	3	2,437	3,059
Closed deciduous forest	6	73	10	0	54	1,625
Deciduous woodland	684	6	2	1	1,658	1,812
Open deciduous shrubland, sparse trees	108	199	31	0	258	760
Total per country (this chapter)	**5,043**	**4,219**	**4,383**	**445**	**5,460**	**27,258**
Total per country (Gaston *et al.*, 1998)	**3,131**	**2,822**	**3,892**	**349**	**3,740**	**16,316**
Total per country (Gibbs *et al.*, 2007)	**3,454-6,138**	**3,458-5,472**	**3,063-4,742**	**268-474**	**3,176-7,405**	**20,416-36,672**

Emissions from Deforestation and Degradation

A First Estimate for the Basin

Based on the estimation of deforestation between 1990 and 2005 (about 43,000 km^2) and on the average C stock of dense humid forests derived from table 12.7a (147 tC/ha without considering the fate of the SOC), we can estimate that the region has released approximately 0.63 billion metric tons of C in 15 years.

This is of course a crude estimate that does not take into account the exact life cycle of wood carbon.

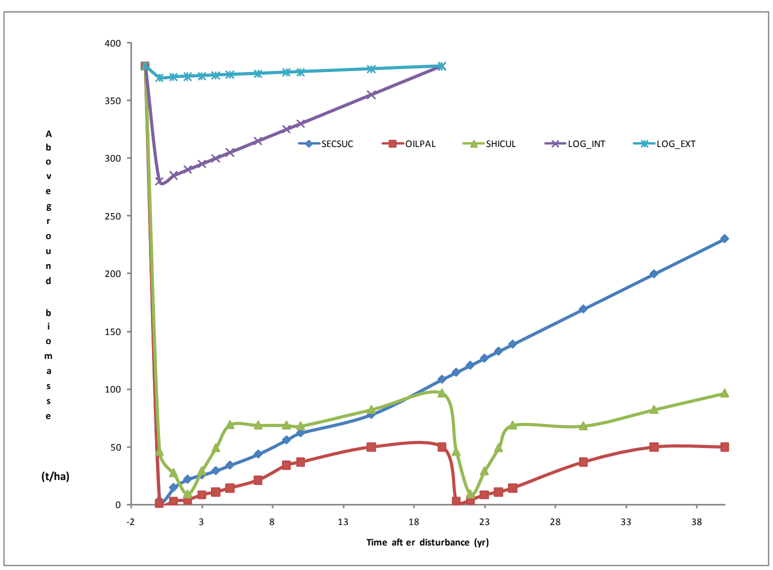
Some Specific AFOLU Examples

Photo 12.5: Sawn timber ready for export.

No matter which REDD mechanism is adopted we will need to be able to assess carbon changes linked to specific AFOLU classes. This is still largely impossible in the Congo Basin due to the lack of comprehensive studies on the effects of land use changes on carbon stock pools. Some preliminary and pioneer studies, however, do exist that provide us an idea of the relative magnitude of the primary potential cases. Using published (Jaffré *et al.,* 1983; Palm *et al.,* 2000; Ibrahima *et al.,* 2002; Kanmegne, 2004; Brown *et al.,* n.d.) and unpublished data (Gourlet-Fleury) we have been able to plot variations of C from aboveground living biomass pools for five land use systems:

- LOG_EXT: high-grade selective logging (one species, *Entandrophragma cylindricum*, constituting 95 % of the logged individuals) in a semi-deciduous rainforest managed with a 30-year rotation.
- LOG_INT: intensive selective logging in a large-scale permanent sample plot, same forest type as in LOG_EXT but with a higher logging intensity.
- SECSUC: secondary succession in an area that was slashed and burned to plant dry rice, abandoned and reverted to 40-year old secondary forest (South of Ivory Coast).
- OILPAL: oil palm plantation (130 plants/ha), with re-planting every 20 years.
- SHICUL: complete 20-year shifting cultivation cycle in Southern Cameroon (slash-and-burn; *Cucumeropsis melo* – plantain field; pure plantain field; short *Chromolaena odorata fallow*; mixed crop field, groundnut – cassava; long fallow).

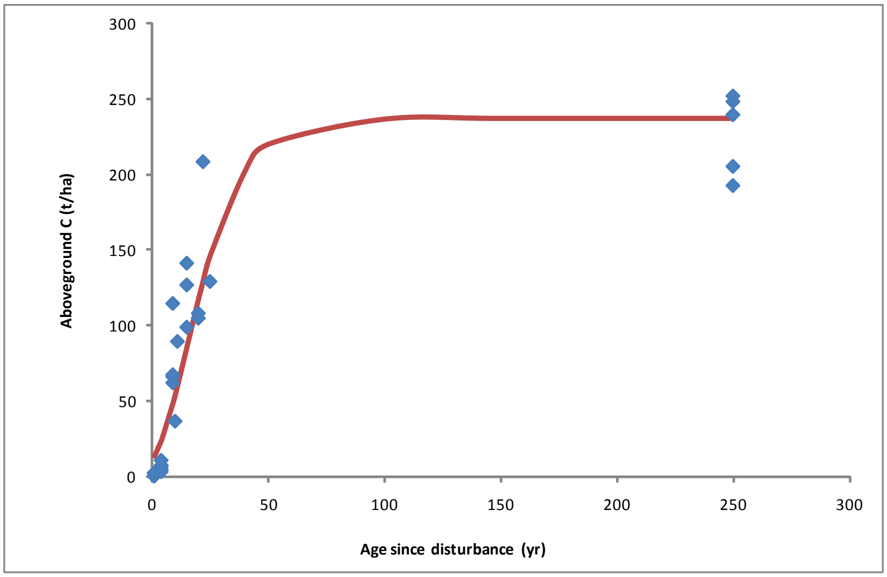
Figure 12.2 clearly shows that except for selective logging and secondary succession after 20 years, the overall aboveground living biomass following disturbance remains below 100 Mg/ha. This does not take into account the dead wood and litter carbon pools but these are small (except for the *Cucumeropsis melo* field where many unburned logs remain on the forest floor) and come essentially from the aboveground tree C pools. Oil palm plantations and shifting cultivation, unless abandoned and left to revert to forest, represent a loss of about 70-90 % of the original forest C stock.



Sources: Jaffré et al., 1983, Palm et al., 2000; Ibrahima et al., 2002; Kanmegne, 2004; Brown et al., n.d.; Gourlet-Fleury, unpub. data.

Figure 12.2: Temporal evolution in aboveground living biomass of different land use systems

To better understand the time needed for these systems once abandoned to recover the original C stocks we used the dataset collected by the ASB (Alternatives to Slash-and-Burn) initiative in Cameroon (Palm *et al.*, 2000a) and fitted (r^2= 0.95) a Gompertz sigmoid (S-shaped) growth curve to the data (figure 12.3). The data shows that the original aboveground biomass could be recovered in less than 50 years after abandonment. The two logging examples show a full biomass recovery in about 20 years. This does not mean however that the C stock will have reconstituted to the same level, as some of the growth could be composed of fast growing light-demanding trees with lower specific densities or of smaller-size shade-tolerant species. It also does not imply that forest quality will have fully recovered after 30 years, as forest composition, structure and functioning will still be recovering after such a time period. Moreover, these two examples do not take into account the fact that in some places the forest is totally and permanently destroyed during the first logging operation (e.g., for permanent roads or camp infrastructure).



Source: Palm et al., 2000a.
Figure 12.3: Carbon accumulation curve (slash-and-burn clearing of intact forest)

These examples demonstrate the magnitude of C-pool variations to be expected for the most frequently encountered land use systems in the Congo Basin region. Agriculture, traditional or modern, seems to be by far the biggest potential emitter of C as opposed to selective logging as practiced in the region.

These limited datasets are not only the only ones available for the sub-region but they are also not the most pertinent as they are not concerned with the main zones where carbon fluxes are likely to occur (e.g., forest margins). If the region is to embark seriously in REDD, then there is a pressing need to carry out more studies of this type to enable the use of higher IPCC tiers and approaches for C stock accounting. Without this work, it will be impossible to know whether emissions are truly being reduced because of less deforestation and degradation or if it is simply a case of generating "hot air."

A Note of Caution: Data, Errors and Uncertainties

Now that we have shown the importance of the Congo Basin forests (and of other tropical forests) in the global C cycle, and their unique potential to offset some of the CO_2 released in the atmosphere by human activities, a word of caution is warranted regarding data errors and uncertainties; there is still an immense amount of work to be carried out to really accurately assess the C stored, sequestered and released annually by the Congo Basin forests.

Estimates of Biomass Based on Field Studies

Most of the estimates of C stocks in living vegetation are calculated on an unacceptably small area of permanent sample plots (probably less than 300 ha for the whole region) or calculated by allometric equations derived from an even smaller sample of destructive biomass studies and extrapolated to use extensive forest inventories, which were never designed to assess biomass but instead commercial volume. The stocks and exchanges in the soil both from roots or soil biology are even less well known.

Photo 12.6: Access to forests is facilitated with the creation of permanent trails.

The uncertainties in building a biomass equation from destructive sampling of trees and other vegetation components are:

- errors in the measurement of tree parameters (diameter, height, specific density) necessary to build the model;
- sampling uncertainty, related to the number and diameter range of measured trees;
- error due to the construction of the allometry.

To develop an allometric model to predict the biomass of a tree from other easily measured parameters like diameter or height, each species or group of species should have its own equation, based on a destructive study of a large sample size. This is still largely unrealistic for tropical forests. The existing allometric models for tropical trees are constructed from limited samples, applied beyond their valid diameter range and seldom include wood-specific gravity. They are also generally based on harvests from a single forest. We should add that none of the existing models, even the most recent ones, use data from African tropical forests.

The uncertainties in deriving biomass using a set of permanent sample plots are:

- error in the estimation of individual tree aboveground biomass because of measurement errors and construction of allometry;
- error due to the choice of allometric models to derive biomass from other parameters;
- sampling uncertainty, related to the size of the plot(s);
- landscape scale representativity of the plot(s).

The uncertainties in deriving biomass estimates from classical forest inventories are the same as those using permanent sample plots plus:

- sampling uncertainty, related to inventory design (intensity of sampling, size of the plots, *a priori*/*a posteriori* stratification…);
- error linked to the minimum diameter limit for the inventory (30 or 40 cm dbh in past inventories, now 10-20 cm dbh);
- errors linked to the use of expansion factors to convert volumes above the minimum diameter limit to volumes above 10 cm dbh, and to convert stand volume in biomass.

It is even more complicated to estimate the propagation of these errors from one stage of the biomass evaluation process to another and to the final result. One thing is sure, this is not a simple relation and it is likely that most errors are additive or multiplicative and that, even though some of these errors might be compensated without generating biases, the confidence interval of any biomass estimation is very likely to be disturbingly large. It is largely out of the scope of the present chapter to provide a detailed review of these errors and uncertainties. Instead we are simply providing a table that gives an idea of the relative scale of the possible errors based on existing literature (table 12.8).

Photo 12.7: The mobile saw "Mighty Might" is used to cut logs on site (Gabon).

Table 12.8: Some biases, errors and uncertainties in biomass estimation

	Source of error/uncertainty	Error (of mean, in %)	Parameter
Building a biomass equation	irregularly shaped and hollow trees		
	if dbh >50 cm	+30	BA stand
	if dbh <5 cm	+11	BA stand
	measure of trees (dbh, H, density)		
	if dbh >10 cm	±17	AGB tree
	if dbh <10 cm	±23	AGB tree
	sampling error (5, 100, 300 trees)	±10, 5, 3	AGB stand
	allometry error		
	if dbh >10 cm	±31	AGB tree
	if dbh <10 cm	±55	AGB tree
Estimating biomass using a set of permanent sample plots	tree-level AGB estimate		
	if dbh >10 cm	±47	AGB PSP
	if dbh <10 cm	±78	AGB PSP
	allometric model (with/without corrections)	±22 to 11	AGB PSP
	PSP size (0.1, 0.25, 1 ha)	±16, 10, 5	AGB PSP
	landscape representativity of set of PSP	±11	AGB landscape
Estimating biomass using an existing forest management inventory	minimum diameter limits for census		
	30 cm	-30	VOB FMU
	45 cm	-55	VOB FMU

PSP: permanent sample plot, BA: basal area, AGB: aboveground biomass, VOB: volume over bark, FMU: forest management unit

Source: modified from Chave et al., 2004; Feldpausch et al., 2006; Nogueira et al., 2006.

From the above table, the minimum adequate samples or values appear to be:

- 100 – 150 weighted trees spanning a wide diameter range to build a biomass equation;
- 0.25 ha individual plot area for dendrometric parameters estimates;
- 10 cm minimum diameter for censuses.

Estimates of Forest Biomass and Forested Areas Using Remote Sensing Technologies

The use of satellite data has undoubtedly increased the accuracy of forest maps and of forest-cover change estimates. However, some uncertainties remain in the current datasets and affect the overall accuracy of estimations of carbon stocks and fluxes. These uncertainties in estimating forest areas from maps derived from remote sensing are:

- errors due to the coarse spatial resolution (1 km) of forest-cover maps;
- approximations in the legend adapted to the spectral signature of vegetation types, which are not necessarily directly related to carbon content, and inconsistency in the forest land definition with the definitions used in the Kyoto protocol;
- uncertainties due to the lack of data in regions under nearly-permanent cloud coverage, such as the coastal part of Gabon, Cameroon and Equatorial Guinea.

New techniques and datasets have been used to reduce these errors but these techniques are still in the research domain. Regional forest maps are currently based on an accumulation of Landsat images (30-m spatial resolution), but the resulting forest typology is less detailed than the ones computed by using daily images. Radar sensors present the advantage of being independent of cloud coverage, but their sensitivity to the terrain at a meso-scale, to the soil and vegetation moisture conditions, to the roughness of the surface (canopy, soil), and to the structure of the leaves preclude their use for any reliable assessment of forest types and carbon stocks.

Forest cover changes occur at a very fine scale and requires the use of time-series of fine spatial resolution images. Two main information extraction techniques are available:

- the spectral difference between images on wall-to-wall datasets, which produces a simple deforestation map of the entire area;
- the delineation of many transition types based on image segmentation techniques on a sampling of sites, which produces a more complete change matrix but on a limited number of sites.

Both methods can be affected by several sources of errors:

- the lack of satellite images at the right year or the right season;
- the underestimation of subtle changes (degradation, forest recovery…) by purely spectral techniques;
- the sampling density that affects the precision and the confidence interval of the estimates.

Underestimation of subtle changes by spectral techniques is difficult to evaluate but sampling uncertainty has been already assessed in the Congo Basin. A minimum of 30 samples of 10x10 km is necessary for estimating the deforestation rate at a regional level (country, province), with an optimum of 50 samples. Increasing the sample size or of the number of samples can reduce this sampling uncertainty, as is the case for the OFAC estimates (20x20 km squares every half-degree (+/-55 km), with a sampling intensity of 16 %). For assessing the degradation area induced by selective logging, indirect techniques combining forest management documents and reports and the detection of logging roads could be applied, but with huge uncertainties.

The direct assessment from remote sensing of carbon stocks of dense humid forests currently suffers from major errors due to the absence of clear and understandable relationships between parameters influencing the carbon amount and the spectral and backscattering properties in the optical and radar domains. Although these relationships have been demonstrated in the savanna domain with low to medium biomass, the radar signal saturates at high biomass levels and the other parameters influencing the spectral properties of the vegetation (moisture, slope, leave structure…) lead to significant instability in carbon estimates. New techniques such as LIDAR can improve the quantification of carbon stock changes during logging operations, but there is still a need for more investigation before that technology may provide reliable figures.

Box 12.1: Are Congo Basin Mature Forests Absorbing or Releasing C?

About 8 billion metric tons of C are produced annually by human activity (6.3 from fossil-fuel emissions, 1.7 from land use changes - mainly deforestation in the tropics). Studies of the global C cycle show that about 3.2 billion metric tons remain in the atmosphere and 2.1 and 2.6 billion metric tons are sequestered by marine and terrestrial (forests) carbon sinks respectively. It was estimated that as much as 2.4 billion metric tons of this carbon was sequestered in boreal and temperate forests and marginally in tropical vegetation (Clark, 2004; Lewis *et al.*, 2005). However, in 2001, assessments of C exchanges in northern regions were only able to account for about 0.7 billion metric tons (Myneni *et al.*, 2001). There was therefore what was called a "missing sink" of about 1.9 billion metric tons sequestered in terrestrial ecosystems.

Two options are possible for the role of land use changes in the tropics in releasing C in the atmosphere:

- a large release of C through land use changes (especially deforestation and forest degradation) compensated by a large sink in undisturbed tropical vegetation;
- a smaller release through land use change with little or no sink in undisturbed vegetation.

The first option seems the most probable as sequestration of C by undisturbed tropical forests seems to be confirmed by the results of recent analyses of sets of permanent sample plots throughout the tropics showing an estimated net C sink of about 1 billion metric tons. As forester's conventional wisdom says that a mature undisturbed forest is at equilibrium, what would explain such a large accumulation of C (equivalent to growth) in undisturbed tropical forests?

Two main hypotheses are currently in favor:

- there is an increase of net primary productivity very likely to be caused by the rising CO_2 concentration in the atmosphere. Tropical forest dynamic is changing with faster growth and turnover (recruitment, mortality), and replacement of shade-tolerant slow-growing species by light-demanding fast-growing ones. The current environment with higher CO_2 is, for the time being, favorable to tropical vegetation (Lewis *et al.,* 2005);
- there is no real increase of net primary productivity. Tropical forests are recovering from disturbance hence a significant increase in aboveground biomass and a shift towards slow-growing species at the expense of fast-growing species. The global occurrence of natural disturbances in untouched forests suggests that they are growing in an increasingly hostile environment (Chave *et al.,* 2008).

In 2007 (Stephens *et al.*), a comprehensive study of atmospheric samples apparently confirmed that tropical forests absorbed about 1 billion metric tons more C than previously estimated (with respectively northern mid-latitude forests absorbing 0.9 billion metric tons less than assumed in 2001).This would weigh in favor of the first hypothesis but as of today it is yet not possible to reach a definite conclusion on this matter. Both hypotheses might be true, but only locally. Forests of eastern or western Amazon, coastal or inland Central Africa, continental or insular South-East Asia, Australia … are most likely following one or the other hypothesis, or a mix of both, depending on local conditions and short-term climate variations. The resolution of this issue is important in modeling scenarios for the future. Tropical forests sequester C but for how long? Will they become net sources if the temperature continues to increase? What will be the impact of more frequent global disturbances (El Niño, drought, floods…)?

R. Nasi 2008