ECOLOGICAL MANAGEMENT OF TROPICAL FORESTS: IMPLICATIONS FOR CLIMATE CHANGE AND CARBON FLUXES

Goettingen, 2010

Adrien Djomo Njepang

1. Gutachter: Prof. Dr. Gode Gravenhorst

2. Gutachter: Prof. Dr. Joachim Saborowski

Tag der mündlichen Prüfung: 12.11.2010

TABLE OF CONTENT

LIST OF FIGURES

Chapter 3

Chapter 4

Chapter 5

LIST OF TABLES

Chapter 2

Chapter 3

Chapter 4

Chapter 5

USING COMPENSATED REDUCTION INPUTS TO AVOID CONTINUOUS DEFORESTATION AND FOREST DEGRADATION

1. Kyoto protocol

The United Nations Convention on Climate Change (UNFCCC), adopted in 1992 was a major step for tackling the problem of global warming. As the levels of greenhouse gas (GHG) emissions were continued to rise around the world, it became quite evident that only a firm and binding commitment by developed countries could send a signal strong enough to convince politics, businesses, communities and individuals to act on climate change. Therefore, member countries of UNFCCC began negotiations on an international agreement. The Kyoto Protocol was adopted at the third Conference of the Parties to the UNFCCC (COP 3) in Kyoto, Japan, on 11 December 1997. The Protocol shares the objectives and institutions of the Convention. The major distinction between the two, however, is that while the Convention encouraged developed countries to stabilize GHG emissions, the Protocol commits them to do so. The detailed rules for its implementation were adopted at COP 7 in Marrakesh in 2001, and are called the "Marrakesh Accords." Most of the countries have agreed to the protocol, but some have chosen not to ratify it. The Kyoto Protocol entered into force on 16 February 2005, following the ratification by Russia.

The Protocol requires developed countries to reduce their GHG emissions below levels specified for each of them in the Treaty. These targets must be met within a five-year time frame between 2008 and 2012, and add up to a total cut in GHG emissions of at least 5% against the baseline of 1990. The developed countries have the target limits because they have historically contributed more to the problem by emitting larger amounts of GHGs per person than in developing countries. In order to give to developed countries a certain degree of flexibility in meeting their emission reduction targets, the Protocol has developed three innovative market mechanisms - known as Emissions Trading (ET), Joint Implementation (JI) and the Clean Development Mechanism (CDM). These mechanisms help identify lowest-cost opportunities for reducing emissions and attract private sector participation in emission reduction efforts. While the cost of limiting emissions varies considerably from region to region, the benefit for the atmosphere is the same, wherever the action is taken.

Emissions trading, as set out in Article 17 of the Kyoto Protocol, provides for Annex I Parties to acquire units from other Annex I Parties and use them towards meeting their emission targets under the Kyoto Protocol. Only Annex I Parties to the Kyoto Protocol with emission limitation and reduction commitments inscribed in Annex B to the Protocol may participate in such trading. Joint Implementation, as set out in article 6 of the Kyoto Protocol, provides for the purpose of meeting its commitments, to any Party included in Annex I to transfer to, or acquire from, any other such Party emission reduction units resulting from projects aimed at reducing anthropogenic emissions by sources or enhancing anthropogenic removals by sinks of greenhouse gases in any sector of the economy. As defined in Article 12 of the Kyoto Protocol, the Clean Development Mechanism provides to countries of Annex I parties to implement project activities that reduce emissions in non-Annex I Parties, in return for certified emission reductions (CERs). The CERs generated by such project activities can be used by Annex I Parties to help meet their emission targets under the Kyoto Protocol. The CDM projects aim to assist non Annex I Parties in achieving sustainable development and in contributing to the ultimate objective of the Convention. The CDM is expected to generate investment in developing countries, especially from the private sector, and promote the transfer of environmentally-friendly technologies in that direction. Definitions and modalities have been developed for including afforestation and reforestation activities (often referred to as “sinks”) in the CDM for the first commitment period. However, Annex I Parties are limited in how much they may use CERs from such activities towards their targets (up to 1% of the Party’s emissions in its base year, for each of the five years of the commitment period). CDM project activities must have the approval of all Parties involved and this may be gained from designated national authorities from Annex I and non-Annex I Parties. CDM project activities must reduce emissions below those emissions that would have occurred in the absence of the CDM project activity. The CDM is supervised by the CDM Executive Board, which itself operates under the authority of the COP/MOP (Conference of the Parties/ Meeting of the Parties). In Cameroon, on the 26 January 2006, the executive board of the CDM, which is the Designated National Authority, has been created under the authority of the Ministry of Environment and Protection of Nature.

2. Monitoring tropical deforestation through compensated reduction

A functional system providing carbon credits to tropical countries for reduced deforestation in the international carbon emission trading arena depends on accurate and timely monitoring. Santilli *et al*. (2003, 2005) suggested the concept of compensated reduction as a means of both reducing the substantial emissions of carbon from deforestation and facilitating significant developing country participation in the Kyoto Protocol framework. The concept of compensated reduction considers the entire forest area within a country to ensure overall net reduction at a national scale (DeFries et al., 2005; Santilli et al., 2005). Analysis of satellite data, combined with local expertise and field validation to assure accuracy, is the only practical way to achieve these objectives (Skole et al., 1997). A workable system for monitoring tropical deforestation for compensated reductions depends on development of international standards with clear definitions of initial forest extent, types of forest disturbance, and minimum clearing size to be monitored (DeFries et al., 2005). Developing countries that elect to reduce their national emissions from deforestation during the 5 years of the first commitment period (taking average annual deforestation over some agreed period in the past, measured with robust satellite imagery techniques, as a baseline), would be authorized to issue carbon certificates, similar to the Certified Emissions Reductions (CERs) of the CDM, which could be sold to governments or private investors. Baselines should be designed in accordance with different regional dynamics of deforestation in the tropics. Any historical average since the 1970s over a sufficient time period to compensate for anomalous yearly highs and lows would be adequate, provided that the baseline refers to a period prior to adopting compensated reductions, so that no incentive to increase deforestation in order to get credit for reductions is created (Santilli et al., 2005). The Marrakech Accords excluded deforestation avoidance projects under the CDM because of leakage, which refers to indirect effects of the mitigation project on GHG emissions outside the project or even country boundaries. To address this problem, Santilli et al. (2003, 2005) suggested that deforestation can be measured at the beginning and end of a commitment period just as can national emissions for Annex I countries. But international market leakage is potentially a much bigger issue under current Kyoto Protocol rules – forest sinks, and activities that increase carbon stocks in Annex I countries are credited, but developing country forest destruction is not debited (Niesten et al., 2002). The same risk, however, obtains for all sectors as long as only some countries have emissions caps – multinational corporations might, for example, reduce emissions in Kyoto countries and invest in high emission operations in non-Kyoto countries (Santilli et al., 2005). Another reason for excluding deforestation avoidance from CDM in non Annex I parties was non permanence. This occurs, when carbon sequestered in a forest restoration project, or carbon "protected" through deforestation avoidance, is released to the atmosphere at a future date due to natural or anthropogenic disturbance. Banked carbon credits could be used to insure offsets. Permanence of reductions is also an issue for all sectors – a country that meets commitments in the first period might opt out of the second and increase emissions. Carbon insurance mechanisms for all emissions offsets should be developed and their costs incorporated into emissions trading (Santilli et al., 2005). Compensated reductions differ from previous forest protection programs and agreements in that it promises to give governments, forest communities, and private owners access to a market for forest ecosystem services, creating the economic value to old growth forest when their essential use is forest conservation (Kremen et al., 2000; Bonnie et al., 2000; Santilli et al. 2005). With a cost given to deforestation avoidance, the participation of the various stakeholders in non Annex I parties is expected to be higher than it is now with the Kyoto Protocol. Recent studies proves that deforestation is not decreasing on its own or through actual policies including forest management, forest conservation, forest certification, etc. (DeFries et al., 2002; Curran et al., 2004). This is a proof that sustained reductions in deforestation rates would not have occurred without compensated reductions (Santilli et al., 2005). Schlamadinger et al. (2005) analyzing Santilli et al. (2003) proposal stated that "the proposal is interesting, but further refinements are needed to improve the incentive structure for countries to sign on to this voluntary approach".

3. Involving local population in REDD

Tropical deforestation contributes to 20% of the global emission of greenhouse gases. It is therefore essential to seek drivers to involve directly local population in the climate change mitigation and adaptation as well as in the REDD (Reducing Emissions from Deforestation and forest Degradation) policies. Human activities such as shifting cultivation, illegal logging, forest clearance for settlement, forest fire for agriculture cause steady net release of CO2 into the atmosphere. With the REDD mechanism, one will expect many countries to increase the conservation areas such as Forest Reserves and National Parks. This appears as an important measure to reduce the emission from forest degradation. Therefore, crop areas devastated by large protected mammals such as Elephants, Gorillas, Chimpanzees, Buffalos, etc. may increase. This could lead to more conflicts between indigenous population and animal. Without compensation to local population, poverty would continue to rise in rural areas which still represent more than 60% of the area of most developing countries.

Since 1992, community forestry has been introduced in many developing counties for poverty alleviation. After 17 years, there are very few countries which have successful experience. Among the reasons behind this poor result is the administrative procedure which is still very long and expensive for local population, the lack of capacity of local population to run a community forest as local forest enterprise, the lack of finance to comply with administrative requirements, pay for service of technicians and buy machineries necessary for forest operations. There also exists poor connection with the local population and the market. Goods can be sold easily only in the cities or abroad. With poor conditions of roads and in general without internet connection in many rural areas the potential to valorise Non Timber Forest Products (NTFP) and other forest products is decreasing. Therefore, indigenous people have agriculture and other related activities as the only opportunity for daily work. Without sustainable support this will lead in most cases to large forest clearances with its negative impact.

Community forestry represents an opportunity to reduce CO2 emission from local population. Through this process, the forest administration signs an agreement with local population for the management of the forest close to the village, and they receive as gain forest products. A management plan is supposed to be approved and controlled by the forest administration. With this agreement, indigenous people have more interest on the control of this forest and make sure that logging activities are not carried out by forest companies in this area. Therefore, the community forest becomes a permanent forest and the local population is supposed to harvest only trees or NTFP surplus to allow sustainability. The expectation is also to give to the local population additional income to increase their know how in other activities through the use of fertilizers, improved genetic materials and also intensive agriculture. The new climate treaty should involve indigenous people as drivers of emission reduction through sustainable community forestry. This achievement is necessary to bring the REDD in the right track with the local populations.

OBJECTIVES AND STUDY AREA

1. Problems statement

Five main problems have been identified concerning the forest management in Cameroon.

- **Deforestation and its negative impacts**: Forest degradation has affected almost all forests, resulting in decline of considerable forest area and production potential, as well as loss of biodiversity. Only small parts of the land surface are still covered by primary (untouched) forests. The causes of this degradation are the overexploitation by logging companies and local populations, the clearing of medium and large scale areas for agriculture and settlement for urban areas, the poor management techniques and the insufficient implementation of the existing laws.

- **Degradation of valuable timber species**: forest degradation is evaluated not only on the basis of forest cover, but also according to the biomass, volume and the proportion of valuable tree species remaining on stand after selective logging. In 1997, the distribution of timber exploited was the follow (in percentage of total volume): *Tripochliton scleroxylon* (30%), *Entandrophragma cylindricum* (7%), others (63%). The lack of silvilcultural research on enrichment planting of valuable tree species, restoration and regeneration of natural forests has been a major cause of forest degradation. Selective cutting of the largest and the most valuable tree species without enough care on natural regeneration, forest recruitment, and growth dynamics has resulted in many cases to poor secondary forests.

- **Increasing population and high timber market demand**: the increase of the world and local population has also increased significantly the need of timber for local consumption and also for exportation. This situation has lead to a pressure on natural forests.

- **Increase poverty**: one of the biggest problems threatening the lives of millions of inhabitants in SSA (Sub-Saharan Africa), especially those residing in the rural areas, is land degradation. This situation has conducted to extreme poverty and the dependence on the remaining fertile areas in the forests. The slash and burn agriculture system usually practiced and the non existence of management plan in many agro-forest areas contributes also in a high extend to this situation.

- **Community forestry:** community forestry represents an alternative for sustainable management in the community areas (non permanent forests). The lack of experts in the rural areas, the lack of finance to support the cost of establishment of a management plan and also the complexity of the procedure have conducted up to now to a low rate of attribution of the community forests in Cameroon.

As part of this the forest management policy in Cameroon, the Kudu-Zombo program has been established in the Campo-Ma'an landscape.

2. The Kudu-Zombo program

Situated within the Atlantic Equatorial Coastal Forest Eco-region (One of WWF's 200 priority ecoregions) the Campo-Ma'an landscape has an exceptionally high level of species richness and endemism. The coastal patches of the landscape are known to be an important setting for sea turtle nesting. The proximity of the CMNP to the Rio-Campo Natural Reserve in Equatorial Guinea provides a unique opportunity for species habitat connectivity and as such offering a wide home range for endangered species like the elephant. The richness of the biological resources of the landscape makes it attractive for the enhancement of conservation activities. It holds an important livelihood value for local people, estimated at 60,853 inhabitants distributed into 119 villages, 5 towns and 17 worker camps. An important part of this population (25,000) is made up of immigrant workers attracted by job opportunities in the logging and agro-industrial sector. In the rural areas, the average population density is about 16.2 inhabitants per square kilometre. Amongst the rural communities, the Bakola/Bagyeli pygmies, a group of less than 1000 people, constitute a minority marginalised by neighbouring tribes and estranged from mainstream society due to weak institutional integration policies. The Overall Objective of WWF intervention in the Campo-Ma'an is "to conserve globally significant terrestrial and marine ecosystems in the Campo-Ma'an/Rio Campo area through landscape planning and management for sustainable development". Six thematic issues and specific objectives are considered:

- Species conservation: to ensure the conservation of endangered species (elephants, great apes, marine tortoise) and their habitats;

- Protected area management: to ensure the protection of biodiversity of the Campo-Ma’an National Park;

- Community-Based and Co-management of Natural Resources: to ensure the management of natural resources through the participation of all parties in order to improve their living conditions;

- Trans-boundary collaboration: to define and implement trans-boundary conservation activities;

- Marine ecosystem management: to ensure the effective management of the marine ecosystems for biodiversity conservation and improved livelihoods;

- Climate change: to ensure long-term integrity of mangrove ecosystems around the Ntem Estuary by strengthening resistance and resilience to climate change and socio-economic activities.

3. Objectives of the study

The overall objective of this study is to provide a scientific contribution on ecological management of moist tropical forests for their adaptation and mitigation on climate change impacts. The specific objectives are to:

1. Analyze the stand development of a forest in the eastern Cameroon and discuss a methodology for estimating the potential carbon emissions or reductions from forest degradation.
2. Discuss a silvicultural system for monitoring forest management under REDD.
3. Develop allometric equations for estimating biomass in Campo-Ma’an area and to develop pan moist tropical equations including data from Africa.
4. Develop diameter tree height relationships for most important species of the Campo-Ma’an forest and general diameter tree height relationships for mixed-species.
5. Estimate the total aboveground biomass of a moist tropical forest in South-Western Cameroon based on locally developed mixed-species allometric equations and compare the result with other allometric equations.
6. Estimate carbon pools and Net Primary Productivity (NPP) and their spatial distribution on different strata and land use types of the Campo-Ma’an area.
7. Develop a map showing the spatial distribution of the carbon pool in the Campo-Ma’an forest.

The objectives 1 and 2 were developed and discussed in chapter3. The objectives 3 and 4 were studied and discussed in chapter4. The objectives 5, 6 and 7 were developed and discussed in chapter5.

4. Description of study areas

The studies for this thesis have been conducted in two different locations. The first study, which is in detail developed in chapter 3, has been conducted in the communal forest of Yokadouma. The second study, which is developed in chapter 4 and 5, was conducted in the Campo-Ma’an forest.

4.1 The communal forest of Yokadouma

The data for this study were collected in Cameroon, in the eastern province, within the district of Boumba and Ngoko, sub-district of Yokadouma. Yokadouma is a city situated 650 km east of the capital (Yaoundé), in the heart of the tropical rain forest (Fig. 3.1). The research area is located between latitude 3°17’33’’N and 3°25’9’’N and longitude 14°44’22’’E and 14°53’33’’E. The geological formations in this area are of Precambrian origin and comprise sandstones rich in quartz, schists and limestones. Ferralitic acid soils of red and red-brown colour with high clay content and a surface horizon characterized by a low concentration of organic matter are dominant in this region. In some areas, the ferralitic soils are interwoven with hydromorphic soils of brown-black colour which are rich in organic matters. The topography is in general gently undulating with valleys and ridges among flat basins, ranging in elevation from 400 m to 700 m above sea level (Gartlan, 1989). For more details see also chapter 3 or the author Master thesis (Djomo, 2006).

4.2 The Campo-ma’an forest

4.2.1 Land use planning

The Campo-Ma’an area is located between latitudes 2°10’-2°52’ N and longitudes 9°50’-10°54’ E. It is bounded to the west by the Atlantic Ocean and to the south by the border with Equatorial Guinea. The main components of the TOU are a National Park, five forest management units (FMU), two agro-industrial plantations and an agro-forestry zone (Table 2.1).

Table 2.1: Present land use planning of the Campo-Ma'an Technical Operational Unit (TOU)

Land use	Area (ha)	% of TOU
Campo-Ma'an National Park	**264 064**	**34.2**
Logging concessions (FMU 09021-25)	**241 809**	**31.3**
FMU 09021 (WIJMA)	42 410	5.5
FMU 09022, 18% in the TOU (GAU services)	14 514	1.9
FMU 09023, 19% in the TOU (Bubinga)	11 777	1.5
FMU 09024 (WIJMA)	76 806	9.9
FMU 09025 (SCIEB)	96 302	12.5
Agro-forestry zone	**196 155**	**25.4**
CF Akak	5 000	0.7
CF Biboulemam	2 157	0.3
CF Tyasono	1 649	0.2
CF Djabilobe	3379	0.4
Others	183 970	23.8
Agro-industrial plantations	**57 750**	**7.5**
HEVECAM (Rubber plantation)	41 339	5.4
SOCAPALM (Oil palm plantation)	16 411	2.1
Proposed protected area	**11 968**	**1.6**
Coastal zone	**320**	**-**
Total	**772 066**	**100**

Adapted from de Kam et al. (2002) and Tchouto (2004). HEVECAM (Hévéa du Cameroun) and SOCAPALM (Société Camerounaise des Palmeraies).

The Campo-Ma'an National Park covers about 264,064 ha. It is a permanent state forest that represents 34% of the Technical and Operational Unit (TOU) and is solely used for forest conservation and wildlife protection. The following activities are therefore forbidden: logging, hunting and fishing, mineral exploitation, pastoral industrial, agricultural and other forestry activities. The logging concessions that are also called "Forestry management unit" (FMU) represent about 31.4% of the area. There are five FMU belonging to three forest companies: WIJMA (FMU 09 021 and 09 024), SCIEB (FMU 09 025), GAU services (FMU 09 022) and Bubinga (FMU 09 023). Agro-forestry zones are part of the non-permanent forest estate that can be used for purposes other than forestry. Added to agro-industrial plantations they represent 33% of the TOU and are mainly allocated for human activities such as agro-industry, agriculture, agro-forestry, community forest, communal forest, or private forest.

The coastal zone is a narrow strip along the Atlantic Ocean from the Lobe waterfalls to the Ntem estuary in the Dipikar islands. It measures about 65 km long and extends about 2-3 km inland. The coastline is one of the most important marine turtle breeding habitats in Central Africa where four species of marine turtles come to feed or nest every year.

4.2.2 Bio-diversity of UTO Campo-Ma'an

The Campo-Ma'an area is recognized as an important site within the Guineo-Congolian Centre of Endemism (White, 1983; Gartlan, 1989; Davis *et al.*, 1994). Most of the area is covered by lowland evergreen tropical rain forests that extend from Southeast Nigeria to Gabon and the Mayombe area in Congo. Campo-Ma'an is situated at the middle of this belt and the main vegetation type is part of the domain of the dense humid evergreen forest that belongs to the Atlantic Biafran district and the Atlantic littoral district (Letouzey, 1968; 1985). The Campo area is dominated by lowland evergreen forests rich in Caesalpinioideae, with *Calpocalyx heitzii* and *Sacoglottis gabonensis*, a vegetation type that is only known from this area. The drier Ma'an area in the rain shadow, to the east of Campo, is dominated by a mixed evergreen and semi-deciduous forest. The Campo-Ma'an area also supports a great diversity of habitats from coastal vegetation on sandy shorelines at sea level to the sub-montane forest at about 1100 m.

The campo ma'an forest borders the Atlantic Ocean to the west and Equatorial Guinea to the south. The area is marked by outstanding biological diversity, with Atlantic biafran, Atlantic littoral, mixed Atlantic, semi-caducifoliated, subtropical mountain, degraded and swamp forests (Tchouto, 2004). The vegetation is comprised largely of coastal evergreen moist forest. There are, however, areas of intact and secondary mixed evergreen and semi-evergreen moist forest in the Ntem valley in the southern part of the park, which surround extensive Raphia-dominated marshes.

MODELLING STAND DYNAMICS AFTER SELECTIVE LOGGING: IMPLICATIONS FOR REDD AND ESTIMATIONS OF ABOVEGROUND CARBON POOLS FROM FOREST DEGRADATION

Adrien N. Djomo[1,*], Gode Gravenhorst[2]

[1]*Buesgen-Institute, Chair of Bioclimatology, Buesgenweg 2, D-37077 Georg-August-Universität Goettingen, Germany*

[2]*Faculty of Forest Sciences and Forest Ecology, Centre for Tropical and Subtropical Agriculture and Forestry (CeTSAF), Buesgenweg 1, D-37077 Göttingen, Georg-August-Universität Goettingen, Germany*

Abstract

Forest degradation and biomass damage resulting from logging is currently difficult to evaluate with satellite images, but contributes substantially to carbon emissions in the tropics. To address this situation, a post-logging stand development of a semi-deciduous natural forest in Cameroon was modelled for one felling cycle (30 years) after selective logging.

To simulate how different management practices influence post-logging forest dynamics, we studied how changes in the minimum felling diameter (MFD) affect stem density, basal area and the related carbon biomass at the end of the felling cycle.

With these MFDs estimated, at 7% logging damage rate, we found that the stem density of initially harvestable trees reduces from 12.3 (50.4 MgC ha^{-1}) to 6.7 (32.5 MgC ha^{-1}) trees per ha and the number of initial residual trees increases from 80 (18.9 MgC ha^{-1}) to 85.7 (36.8 MgC ha^{-1}) trees per ha. This corresponds to an avoided damage estimated at 17.9 MgC ha^{-1}. We also found that increasing mortality and damage intensity also increases the damage on carbon biomass estimated to be 8.9 MgC ha^{-1} at 10% or to be 17.4 MgC ha^{-1} at 15% logging damage.

Overall, our study shows that proper determination of MFD of logged species taking into consideration their capacity of reconstitution at the end of the felling cycle associated with Reduced Impact Logging (RIL) can avoid up to 35 MgC ha^{-1}. These estimations could be achieved if there is a combination of Policy and Measures allowing monitoring of forest development after logging.

***Keywords*:** carbon estimations, felling cycle, future prediction, logging damage, minimum felling diameter (MFD), moist tropical forest, species reconstitution

1. Introduction

In tropical forests, selective logging results in substantial impacts not only on selected trees for harvest but also on small and other trees not selected for harvest resulting in forest degradation (Uhl et al. 1997; Sist & Nguyen-Thé 2002; Asner et al. 2004). This forest degradation due to harvest directly alters the species composition, the forest biomass, and the micro-climate (Johns et al. 1996; Holdsworth & Uhl 1997; Holmes et al. 2002; Schulze & Zweede 2006). One of the consequences of this human activity is that carbon dioxide and other gases such as methane and carbon monoxide can be released into the atmosphere, immediately if the trees are burned, or more slowly as unburned organic matter decays. The part of the biomass which ends up stored in long-lasting structures (e.g. houses, wood materials) represents only a fraction of the biomass initially hold in a forest (Houghton 2005). About 30% of the land surface is covered by forests which store up to 80% of global aboveground terrestrial carbon (C) and up to 40% of global belowground terrestrial organic C (Dixon et al. 1994). Tropical forests cover less than half of the entire world forest area and store as much carbon in their below and aboveground biomass as in all the other forests outside the tropics. This is due to the fact that in tropical forests trees hold, on average, about 50% more carbon per hectare than trees in temperate and boreal forests (Dixon et al. 1994; Malhi et al. 1999). Therefore, an equivalent rate of deforestation or forest degradation will result in general in a larger amount of carbon removed from the tropical forests than in the other forests (Houghton et al. 2001). Recent estimates for the period 1990–2005 estimate net land-use change CO_2 emissions to be 1.5±0.7 PgC year^{-1} and almost all of it can be attributed to the tropics (Le Quéré et al. 2009). These estimates represent emissions equivalent to between 14% and 25% of the annual global emissions from fossil fuels in the years 1990 to 2005 (Le Quéré et al. 2009). The carbon dioxide mixing ratio in the air has increased by one third from pre-industrial 280 parts per million by volume in air (ppm) to 380 ppm today predominantly as a result of burning fossil fuels, deforestation, and other changes in land-use. Most emission scenarios predict a doubling of pre-industrial levels of greenhouse gases within the next 50 years. Model predictions indicate that these increased CO_2 mixing ratios in the atmosphere will lead to a rise of global mean temperature between 2-5 °C probably between 2030 and 2060 (Stern 2006). Reducing CO_2 emissions from deforestation and forest degradation in the tropics has been shown by recent studies as one of the cost effective options to reduce CO_2 emissions into the atmosphere (Santilli et al. 2005; Angelsen 2008).

Consequently, the concept of Reducing Emissions from Deforestation and forest Degradation (REDD) has been developed over the last few years to address this global problem.

The objective of the present study is to analyze the stand development of a typical forest area in Cameroon and to discuss a methodology for estimating the potential carbon emissions reduction from forest degradation under responsible forest management. The specific objectives are to: (i) analyze the impact of harvest on the stand dynamic and the reconstitution of the forest at the end of the felling cycle (30 years); (ii) analyze the yield of commercial species and determine the minimum felling diameter (MFD); (iii) compare growth projection for the harvestable trees and the residual stand at different logging damage intensities; and (iv) discuss a methodology for estimating carbon emissions (sink or source) from forest degradation in the tropics.

2 Material and methods

2.1 Study site

The data for this study were collected in Cameroon, in the eastern province, within the district of Boumba and Ngoko, sub-district of Yokadouma. Yokadouma is a city situated 650 km east of the capital (Yaoundé), in the heart of the tropical rain forest (Fig. 3.1). The research area is located between latitude 3°17’33’’N and 3°25’9’’N and longitude 14°44’22’’E and 14°53’33’’E. The geological formations in this area are of Precambrian origin and comprise sandstones rich in quartz, schists and limestones. Ferralitic acid soils of red and red-brown colour with high clay content and a surface horizon characterized by a low concentration of organic matter are dominant in this region. In some areas, the ferralitic soils are interwoven with hydromorphic soils of brown-black colour which are rich in organic matters. The topography is in general gently undulating with valleys and ridges among flat basins, ranging in elevation from 400 m to 700 m above sea level (Gartlan 1989). The climate is equatorial Guinean with four distinguished seasons constituted of two rainy seasons and two dry seasons. From mid-March to mid-June there is normally a shorter and less intensive rainy season; the period from mid-June to mid-August usually corresponds to a short dry season; in the period from mid-August to mid-November there is a long and heavy rainy season; during the period from mid-November to mid-March there is usually a long dry season. The mean air temperature fluctuates between 23°C and 25°C with very low variation during the year. The annual rainfall varies between 1600 mm and 2000 mm (White 1983). The river system is very dense and belongs to the Congo Basin.

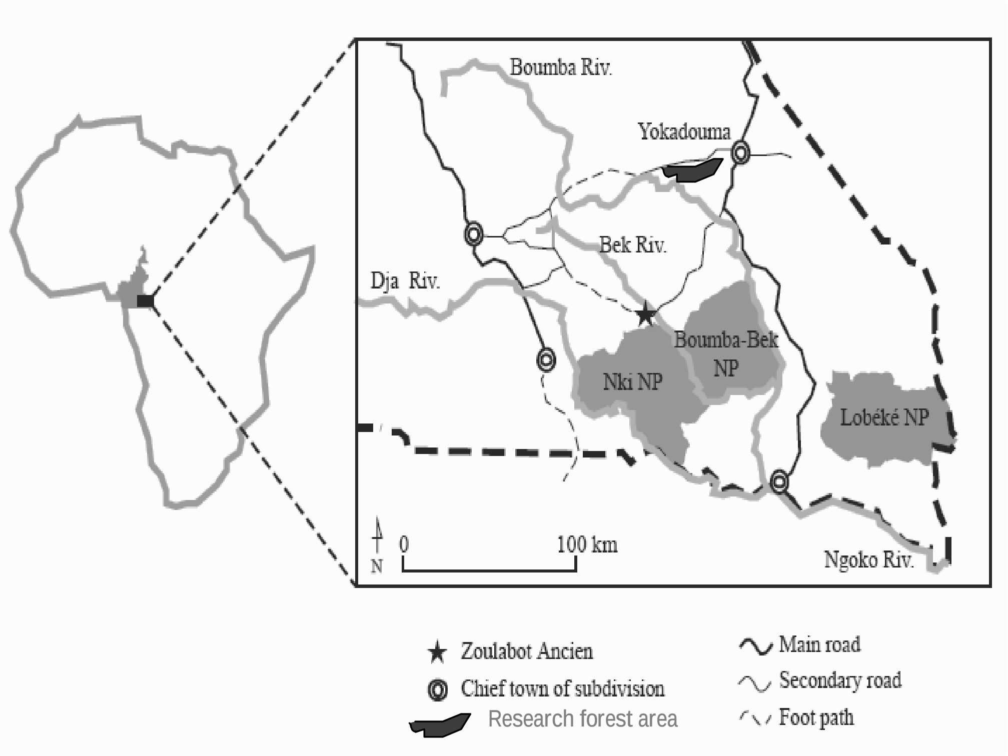


Fig. 3.1. Forest research area

2.2 Sampling design

The research forest is a semi-deciduous natural forest of 22 000 ha comprising different ecological features (one logged, two logged, unlogged, low land and moderate hills). For this research, 30 sample plots of 20 m x 50 m were spread uniformly in the different ecological features of the study area. In each plot, a subplot, of 20 m x 5 m was used additionally for seedling assessment. All trees with diameter at breast height (dbh) exceeding 20 cm were recorded in the plots. In the subplots, small trees with dbh ranging between 10 cm and 19 cm were recorded. For each tree, the species name, the dbh, the height, the stratum and the geographical coordinates x and y were assessed.

2.3 Classification system

For this study, four tree species groups were used for the classification of the occurring trees. Group 1 stands for mature merchantable trees with diameter above the minimum felling diameter (MFD). Group 2 contains immature merchantable trees with diameter under the MFD. Group 3 stands for all non commercial trees with a prescribed MFD by forest administration. Group 4 contains all non commercial trees without a prescribed MFD. The future stand projection analysis was made on 24 commercial species constituted by Group 1 and Group 2. The yield and determination of sustainable minimum felling diameter (MFD) were made for nine commercial species contained in Group 1. Trees were grouped in diameter classes. The width of a diameter class used was 10 cm. For example, a diameter class 35 contains all trees with dbh between 30 cm and 39.9 cm.

2.3 Future stand projection

The future stand projection was evaluated for 24 commercial species belonging to Group 1 and 2. The number of survival N after t years in a forest stand initially constituted of No individuals was calculated using the formula proposed by de Madron et al. (1998a):

$$N_t = [N_o(1-\Delta)]\times(1-a)^t \qquad (1)$$

where a is the mortality rate for each diameter class (% year^{-1}), No the number of individuals at time 0, Nt the number of individuals after t years, t the number of years and Δ the damage rate for each diameter class (% of logging damage year^{-1}). Based on the study of de Madron et al. (1998a) in Dimako forest in Eastern Cameroon we considered a value of 1% of all trees number for the mortality rate and 7% for damage rate due to forest exploitation in all diameter classes. For estimation of the stand development, the concept of a Diameter Class Projection Model (DCPM) was used (Alder 1995). The ingrowths into class k and outgrowths from the kth class are a result of the combination of mean increment, mortality and logging damage. Therefore 'equation 1' can be rewritten as follows:

$$N_{k,t+1} = N_{k,t} + \frac{i\cdot t}{w}\times[N_{k-1,t}(1-\Delta)]\times(1-a)^t - \frac{i\cdot t}{w}\times[N_{k,t}(1-\Delta)]\times(1-a)^t \qquad (2)$$

where $N_{k-1,t}$ is the number of trees in the k-1th class at each period t, *i* the mean annual growth (cm year^{-1}), *t* the length of period (year), *w* the width of the diameter class (cm), *a* the mortality rate for each diameter class (% year^{-1}) and Δ damage rate for each diameter class (% of logging damage year^{-1}). Many studies on tree growth of commercial species have been carried out in Cameroon using the tree ring analysis method (Detienne 1989; Worbes *et al.* 2003), successive measurements of commercial trees of the stand in Cameroon and other countries in Central Africa (Alder 1995; Dykstra *et al.* 1997; de Madron *et al.* 1998a; de Madron *et al.* 1998b; MINEF 2000; Bibani & Jonkers 2001). For this research, the mean annual diameter growths were obtained from growth analysis conducted during these studies. The stand projection was calculated for all commercial species after each period of 5 years up to 30 years. We used 30 years as a limit because it corresponds to the duration of felling cycle in Cameroon. The likely future stand was evaluated for the number of trees per hectare and also for the basal area per hectare of all commercial trees in all diameter classes. To account for the incoming natural regeneration of new trees into the smallest diameter class, a constant value of 60 trees ha^{-1} obtained from the analysis at initial year in the smallest diameter class 15 cm at all time steps was assumed.

2.4 Determination of Minimum Felling Diameter (MFD)

The specifications of rules for harvesting and associated silviculture in a mixed tropical forest are complex and many variations are possible. The most basic elements are generally felling cycle and a species-determined minimum felling breast height diameter (Alder 1995). According to Dykstra et al. (1997), the felling cycle is the period between two successive harvests in the same forest stand. The optimum felling cycle is one that ensures complete forest recovery and sufficient stem recruitment. The minimum felling diameter is the lower limit which will retain enough trees to give a second harvest after the felling cycle. It is also the legal diameter limit for harvest. For the determination of the minimum felling diameter, we used the values for different species suggested by the forest administration in Cameroon (Table 3.1) as starting point of the calculation of the percentage of reconstitution. The percentage of reconstitution is defined here as the rate of the original harvestable tree population which will likely recover through stem growth after harvest until the end of the felling cycle. For this calculation, we used the following formula:

$$\%Re = [N_o(1-\Delta)] \times (1-a)^t / N_p \qquad (3)$$

where $\%Re$ is the percentage of reconstitution of individuals initially exploitable, N_o the number of considered individuals below the MFD, N_P the number of trees initially exploitable, t the projection period (30 years), a the mortality rate for each diameter class (% $year^{-1}$) and Δ the damage rate for each diameter class (% of logging damage $year^{-1}$). The calculation was done for each commercial species. The optimum MFD was obtained by repeating many times the calculation of the percentage of reconstitution, while changing the value of the MFD. The optimum level was achieved when the new MFD was able to ensure a recovery of at least 80% of the original tree density and basal area at the end of the felling cycle (Fig. 3.2).

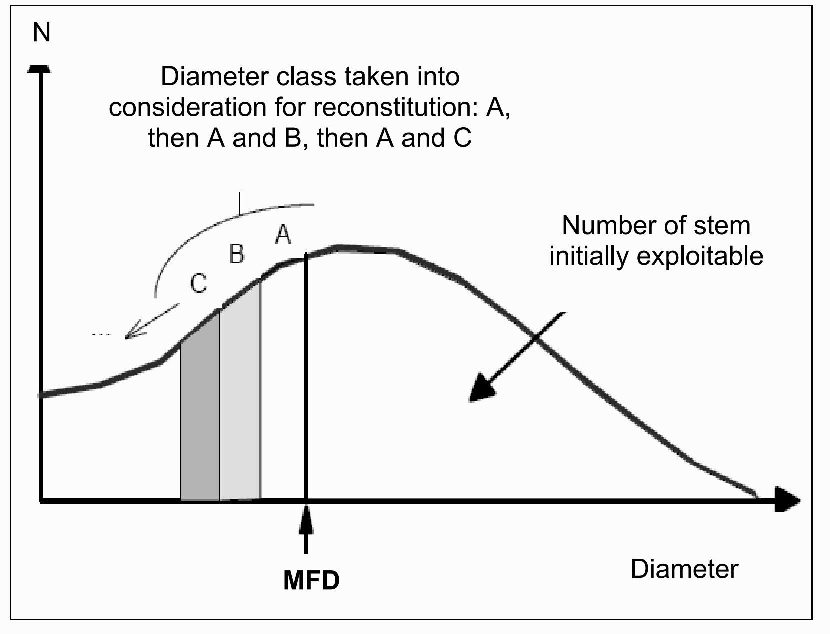


Fig. 3.2. Analysis of reconstitution of initially exploitable trees by those below the minimum felling

2.5 Sensitivity analysis

Mortality rate can be defined as the number of trees dying during a growth period due to internal or external factors. The internal factors can be the lack of nutrients, shading, pest and diseases, or age of trees. The external factors can be catastrophes such as tropical storms or logging damages. Logging damage is the damage or mortality of residual trees due to harvest of trees. In many studies and also in our case, mortality refers to damage due to internal factors. Tree mortality in undisturbed tropical rain forest falls on average between 1% and 3% of stem number per year (Phillips & Gentry 1994; Condit et al. 1995a; van der Meer & Bongers 1996) in all diameter classes. These values are almost similar to the typical values of 1-2% of stem number per year for the average tree mortality rates in primary rain forests suggested by other authors (Putz & Milton 1982; Lang & Knight 1983; Swaine et al. 1987a, b; Milton et al. 1994; Phillips & Gentry 1994; Condit 1995; Condit et al. 1995b; Köhler et al. 2001). Many studies of tropical forests in Africa and other tropical forests over the world have reported logging damage intensities exceeding 7% (Dupuy 1998; Forshed et al. 2006; Forshed et al. 2008). We considered three scenarios for stand projection of commercial species: low (7%), moderate (10%) and high (15%) logging damage rate per logging year associated with 1%, 3% and 5% mortality rate per year respectively. For each of these scenarios the stand projection was refined comparing the situation for the MFD as suggested by the forest administration to the situation of the newly estimated MFD.

2.6 Carbon estimations

For total aboveground biomass estimation of trees, we used a regression equation developed by Brown et al. (1989) for moist tropical forests, with 168 trees ranging from 10 cm - 130 cm collected across three tropical countries. This equation is as follows:

$$M = 38.4908 - 11.7883 \times (D) + 1.1926 \times (D^2) \tag{4}$$

where M represents the total dry aboveground biomass of a tree in kg and D the diameter in cm. The corresponding carbon content in biomass was estimated assuming 50% of carbon in the biomass. In this paper, the biomass stands for the carbon content in total dry aboveground biomass and is expressed in MgC ha^{-1}.

3. Results

3.1 Composition of the Forest

In species Group 1 (all mature merchantable species, dbh ≥ MFD) we found 12 trees per hectare (3% of all measured trees) with a basal area of 7 m^2 ha^{-1} (23% of total basal area) and a carbon pool of 50.4 MgC ha^{-1} (26.6% of total carbon stock). The low stem number in combination with a large basal area indicates that trees in this category are large in diameter size. In Group 2 (all immature merchantable species, dbh < MFD) we found 80 trees per hectare with a basal area of only 3.6 m^2 ha^{-1} and a carbon pool of 18.9 MgC ha^{-1} (10% of total carbon stock) (Fig. 3.3). These values show that this group generally contains small trees with dbh smaller than the minimum felling diameter. Groups 3 and 4 which are constituted of species of non commercial value, unknown or less known commercial values represent in total 80% of total stem number, 66% of total basal area and 63.4% of total carbon stock of the research area.

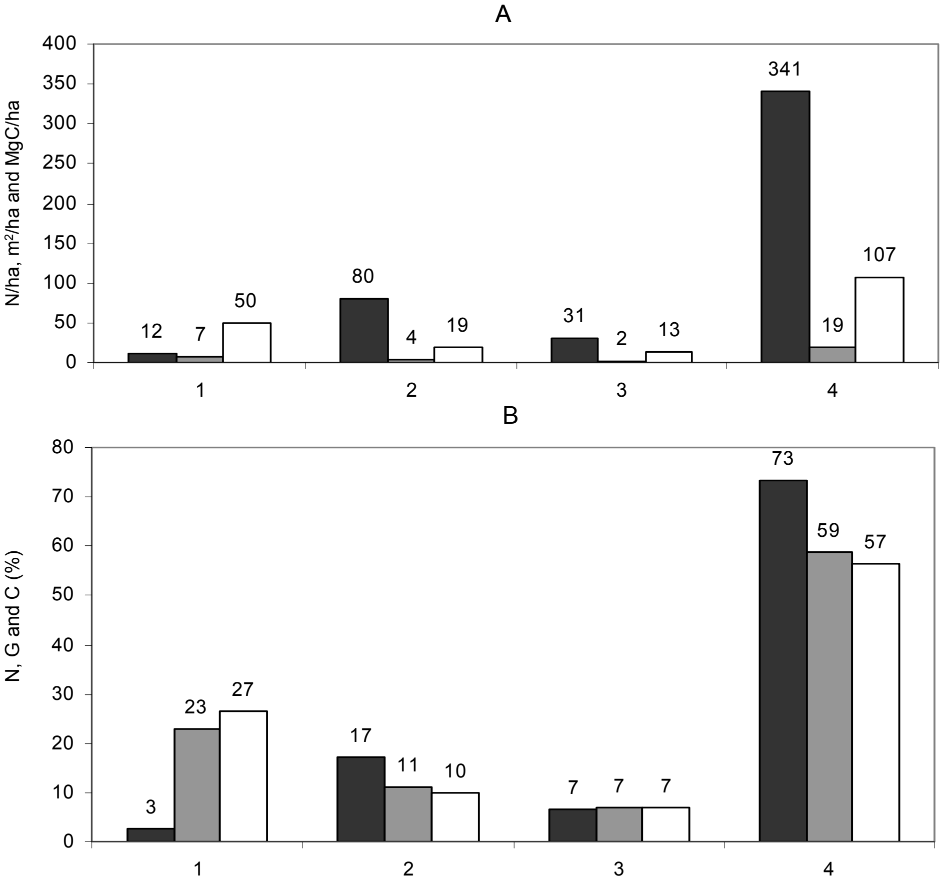


Fig. 3.3. Stem number N (black), basal area G (grey) and carbon pool C (white) in the four species groups. Group1 mature merchantable species with diameter above the minimum felling diameter (MFD). Group2 immature merchantable species with diameter smaller than the MFD. Group3 all non commercial trees species with a MFD prescribed by forest administration. Group4 all non commercial trees without a prescribed MFD. A: Number of stems per ha (N/ha), basal area per ha (m^2/ha) and carbon pool (MgC/ha). B: Stem number N, basal area G and carbon pool C in % of all tree species in stand at year 0.

3.2 Stand projection

The distribution of the stem number in year 0 varies from 60 trees ha^{-1} in diameter-class 15 to 0.3 tree ha^{-1} in diameter-class 135. A projection of the stand development over a period of 30 years shows that the shape of the distribution will change over time as a result of growth and ingrowths into the next diameter-class (Fig. 3.4). For each time step of 5 years, the stand development models maintain the J-shape frequently encountered in natural forests in the tropics: the number of trees decreases with increasing tree diameter (Lamprecht 1989). In Fig. 3.4, the logarithm scale has been used for the representation of Y scale (N/ha) to enable differentiation for bigger diameters with stem number less than 0.5 tree ha^{-1}. Because it was not possible to predict the incoming regeneration of new trees into the smallest diameter class, a constant value of 60 trees ha^{-1} in the smallest class diameter 15 cm at all time steps was assumed. The projection predicts a high number increase in smaller diameter classes to a very small increase in bigger diameter classes. The average growth rate of stem density per 5 year period moves from 5.7 trees ha^{-1} (33.9 trees ha^{-1}) in the class 25 to 2.8 trees ha^{-1} (17 trees ha^{-1}) in the class 35, 1.1 tree ha^{-1} (6.8 trees ha^{-1}) in the class 45, 0.4 tree ha^{-1} (2.2 trees ha^{-1}) in the class 55 and to between 0.1 tree ha^{-1} and 0.2 tree ha^{-1} in the other diameter classes. The values in brackets give the tree stem density after 30 years. The predicted stem density distribution did not change when the newly estimated MFD were used. The average growth rate of basal area per 5 year period moves from 0.3 m^2 ha^{-1} (1.7 m^2 ha^{-1}) in the class 25 to 0.3 m^2 ha^{-1} (1.6 m^2 ha^{-1}) in the class 35, 0.2 m^2 ha^{-1} (1.1 m^2 ha^{-1}) in the class 45, 0.1 m^2 ha^{-1} (0.5 m^2 ha^{-1}) in the class 55 and to between 0 and 0.2 m^2 ha^{-1} in the other diameter classes. The values in brackets give the basal area after 30 years. The model predicts an increase of harvestable trees on average by 0.1 tree ha^{-1} during each period of 5 years corresponding to an increase of basal area of 0.7 m^2 ha^{-1}. The density of all harvestable trees increases from 12.3 trees ha^{-1} (7.4 m^2 ha^{-1}) (50.4 MgC ha^{-1}) at initial time to 18.1 trees ha^{-1} (12 m^2 ha^{-1}) (81.3 MgC ha^{-1}) after 30 years.

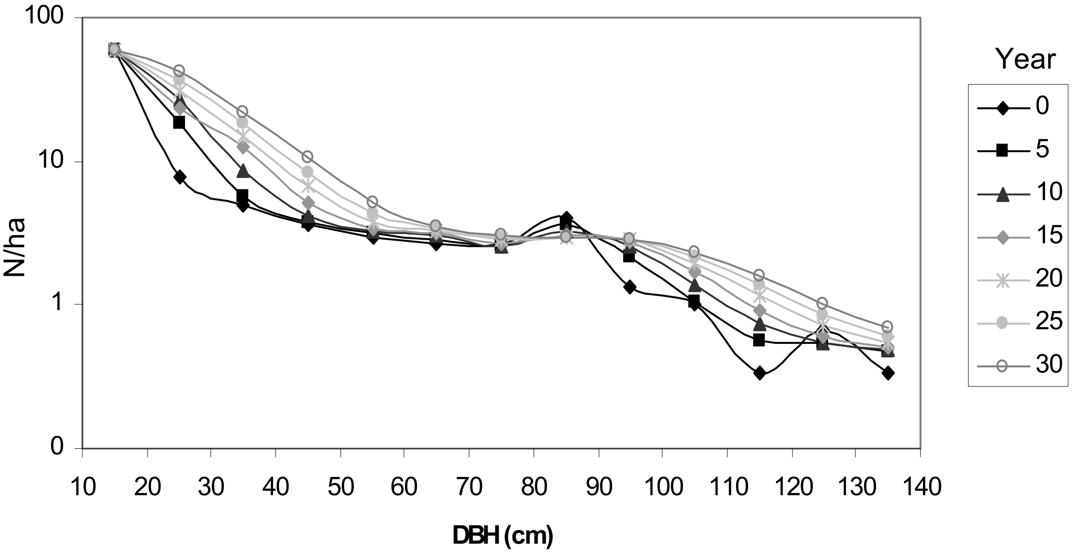


Fig. 3.4. Stand projections of number of trees per hectare (N/ha) of 24 commercial species in the research area over periods of 5 year up to 30 years (individual lines). All curves in general follow the J-shape: many trees with smaller diameters to very few with bigger diameters. Tree species have minimum felling diameter between 50 cm and 80 cm.

The model predicts an increase of residual trees (dbh > 10 cm) on average by 9.9 trees ha^{-1} at each period of 5 years corresponding to an increase of basal area of 0.8 m^2 ha^{-1}. The density of residual trees (dbh >10 cm) increases from 80 trees ha^{-1} (3.6 m^2 ha^{-1}) (18.9 MgC ha^{-1}) at initial age to 139.3 trees ha^{-1} (8.3 m^2 ha^{-1}) (45.3 MgC ha^{-1}) after 30 years. The diameter distribution shows that some species are not ecologically big enough to ensure the sustainability of tree stock in the stand (Fig. 3.5). This will lead to genetic drift in the future due to the lack of parent trees for those species. The use of the newly estimated MFDs (Table 3.1) decreases the stem density of harvestable trees and increases those of the residual trees (dbh > 10 cm) in the stand (Fig. 3.5). The stem density for harvestable trees at initial age becomes 6.7 trees ha^{-1} (4.8 m^{2} ha^{-1}) (32.5 MgC ha^{-1}). The projection suggests a constant increase of harvestable trees by on average 0.9 tree ha^{-1} (0.8 m^{2} ha^{-1}) each period of 5 years, moving from 6.7 trees ha^{-1} (4.8 m^{2} ha^{-1}) (32.5 MgC ha^{-1}) to 12.4 trees ha^{-1} (9.4 m^{2} ha^{-1}) (64.7 MgC ha^{-1}) after 30 years. With these new MFDs, the density, of residual stand (dbh > 10 cm) at initial age becomes 85.7 trees ha^{-1} (6.3 m^{2} ha^{-1}) (36.8 MgC ha^{-1}). The projection suggests a constant increase of residual stand (dbh > 10 cm) by on average 9.9 trees ha^{-1} (0.8 m^{2} ha^{-1}) each period of 5 years, moving from 85.7 trees ha^{-1} (6.3 m^{2} ha^{-1}) (36.8 MgC ha^{-1}) to 145 trees ha^{-1} (10.8 m^{2} ha^{-1}) (62 MgC ha^{-1}) after 30 years.

3.3 Yield and determination of Minimum Felling Diameter

The mature merchantable species in Group 1 contain 12.3 harvestable trees per hectare and 21.3 residual trees per hectare. For *Ceiba pentandra* and *Erythropleum ivorense* no residual trees are observed. *Triplochyton scleroxylon* has 1.3 residual trees per hectare and 3 harvestable trees per hectare. For other species more residual trees than harvestable trees are observed. The analysis of tree density reconstitution of *Alstonia boonei* shows that with a MFD of 70 cm, the percentage of reconstitution (e.g. Eq. 3) will be 74%. With a MFD of 80 cm, the percentage of reconstitution will be 93% which represents the optimum minimum diameter for this species. For *Ceiba pentandra* only 0.3 stems ha^{-1} are found in the diameter class 55. The absence of trees in smaller diameter classes suggests that in case of harvest, this species will not recover. For *Erythropleum ivorense* no reconstitution was observed by using a MFD of 50 cm which is suggested by the traditional forest management system. With a MFD of 90 cm, this species will have a percentage of reconstitution of 41% after 30 years. The distribution of stem numbers of this species shows that it was not possible to consider a higher MFD (Fig. 3.5). Therefore, 90 cm represents the optimum MFD of this

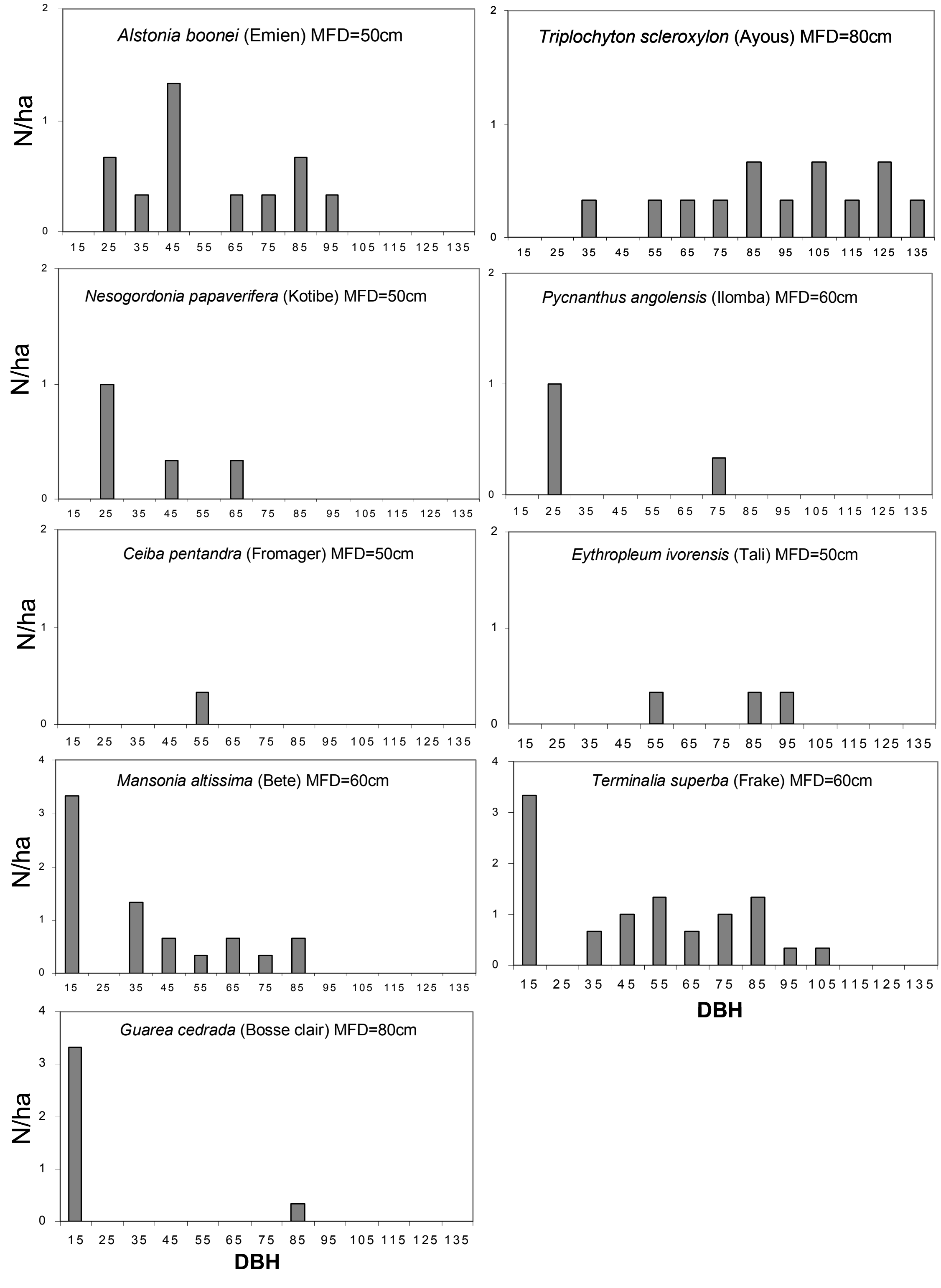


Fig. 3.5. Diameter distribution of 9 commercial species in the Yokadouma forest (3ha). The minimum felling diameter (MD) is the limit above which all trees should be cut. *Alstonia boonei, Terminalia superba, Mansonia altísima*, and *Nesogordonia papaverifera* have enough regeneration to overcome the harvestable trees. For *Triplochyton scleroxylon, Erythropleum ivorense, Pycnanthus angolensis, Guarea cedrata,* and *Ceiba pentandra,* further investigation on reconstitution needs to be carried out.

species in our case study. However, two different suggestions can be formulated for *Erythropleum ivorense* using the new MFD 90 cm: the first is that, it is totally forbidden to harvest this species during 15 years. The second is that, only half or better less than half of the harvestable trees of this species should be selected. For *Guarea cedrata* a percentage of reconstitution of 147% is estimated by using a MFD of 80 cm proposed by forest administration. Therefore, 80 cm represents the optimum MFD for this species. For *Mansonia altissima* the percentage of reconstitution is only 70% with the MFD of 60 cm specified in the traditional forest management system. This value increases to 111% with a MFD of 70 cm which represents the optimum MFD of this species. *Nesogordonia papaverifera* and Pycnanthus angolensis obtain a percentage of reconstitution of 110% respectively 108% (Table 3.1) by using the MFD 50 cm respectively 60 cm suggested by the forest administration. For Terminalia superba a percentage of reconstitution of 50% is resulted by using a MFD of 60 cm. This value increases to 64% by calculating with a MFD of 70 cm and up to 83% by using a MFD of 80 cm. This last value represents the best MFD for the reconstitution of this species. For *Triplochyton scleroxylon* the percentage of reconstitution is 17% by using a MFD of 80 cm. The percentage increases up to 52% by using a MFD of 110 cm and up to 69% by using a MFD of 120 cm. The distribution of stem number per hectare of this species shows bigger trees than smaller trees. Therefore, the optimum minimum felling diameter of this species should be 110 cm. With this MFD, only half of the harvestable stock will be present at the end of the felling cycle. Therefore, it is suit to harvest only half of this stock meaning one harvestable tree on two to allow the reconstitution of this species.

Table 3.1: Reconstitution of each harvestable commercial species. The percentage of reconstitution (%R) of each species is calculated using the Administrative Minimum Felling Diameter (Adm. MFD) as starting point. Whenever the %R is < 100%, a heigher MFD is considered and a new percentage of reconstitution (%R) recalculated. The bold values represent the optimum MFD.

Scientific Name	Ø increment (cm/year)	Adm. MFD	%R	New MFD	%R with new MFD	New MFD	%R with new MFD
Alstonia boonei	0.9	50	87	70	74	**80**	93
Ceiba pentandra	0.9	50	0	60	0	60	-
Erythropleum ivorense	0.4	50	0	**90**	41	90	-
Guarea cedrata	0.5	**80**	147	80	-	80	-
Mansonia altissima	0.5	60	70	**70**	111	70	-
Nesogordonia papaverifera	0.4	**50**	110	50	-	50	-
Pycnanthus angolensis	0.7	**60**	108	60	-	60	-
Terminalia superba	0.7	60	50	70	64	**80**	83
Triplochyton scleroxylon	0.9	80	17	**110**	52	120	69

3.4 Sensitivity analysis

Higher logging damage tested in this study affected the resulting stand structure distribution and the growth prediction (Fig. 3.6 b,d). Increasing the logging damage intensity but keeping the diameter growth rate constant resulted in a reduction of the stand density, and the stand growth distribution. In comparison to the moderate logging damage (7%), the model predicts at 10% a reduction of 8.3 trees ha^{-1} (1.4 m^{2} ha^{-1}) (8.8 MgC ha^{-1}) after 30 years. This corresponds to a loss of 0.7 tree ha^{-1} (0.6 m^{2} ha^{-1}) (4.2 MgC ha^{-1}) on harvestable trees and 7.6 trees ha^{-1} (0.8 m^{2} ha^{-1}) (4.6 MgC ha^{-1}) on residual stand. At logging damage of 15%, the model predicts a reduction of 16.8 trees ha^{-1} (2.8 m^{2} ha^{-1}) (17.3 MgC ha^{-1}) after 30 years, compare to logging of 7%. This corresponds to a loss of 1.5 trees ha^{-1} (1.2 m^{2} ha^{-1}) (8.4 MgC ha^{-1}) on harvestable trees and 15.4 trees ha^{-1} (1.6 m^{2} ha^{-1}) (8.9 MgC ha^{-1}) on residual stand. The mean annual growth found was 2.2 trees ha^{-1} (0.3 m^{2} ha^{-1}) (1.9 MgC ha^{-1}) at 7% logging damage, 1.9 trees ha^{-1} (0.3 m^{2} ha^{-1}) (1.6 MgC ha^{-1}) at 10% and 1.6 trees ha^{-1} (0.2 m^{2} ha^{-1}) (1.3 MgC ha^{-1}) at 15%.

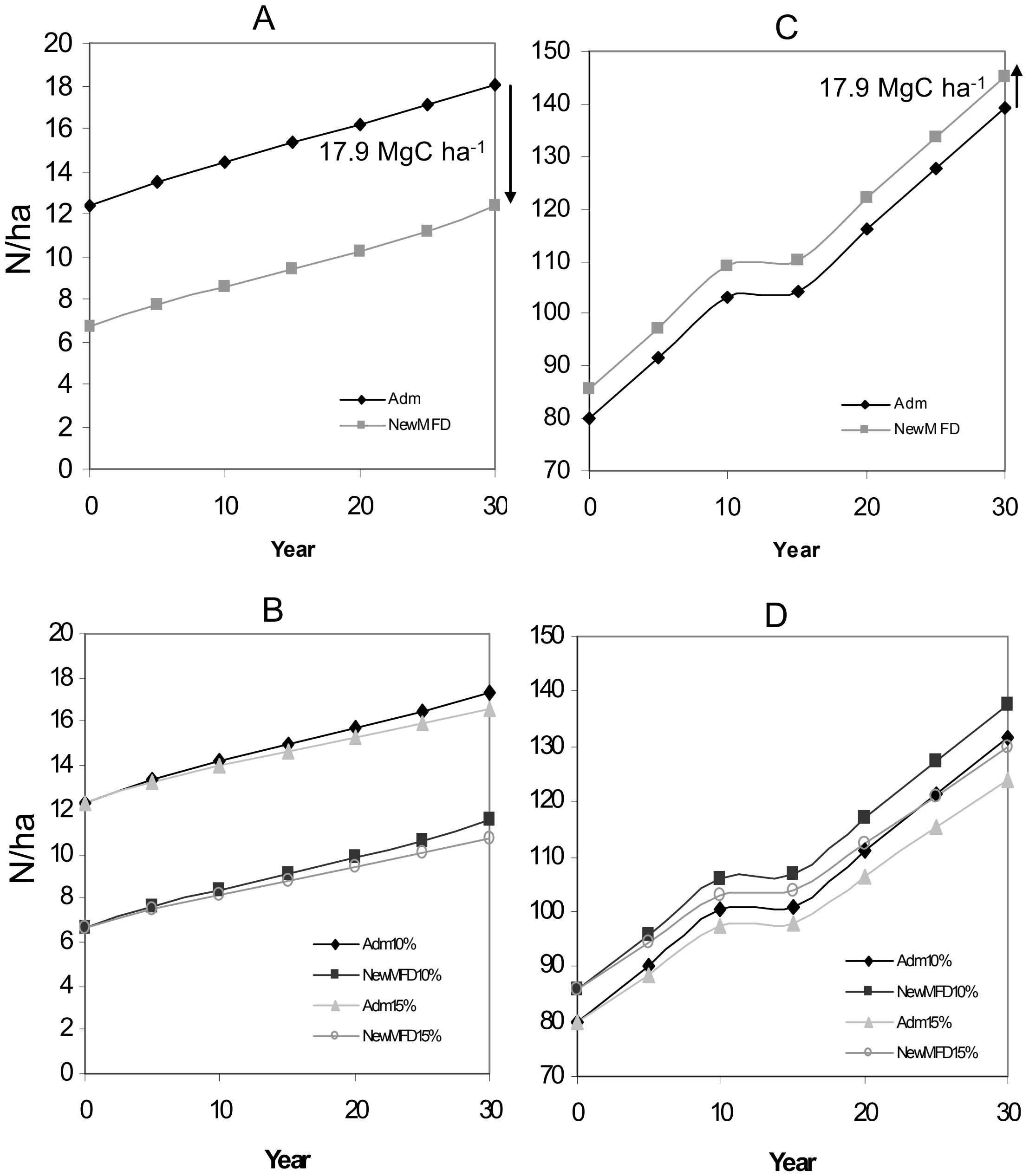


Fig. 3.6. Comparison of projections of the stem density (N/ha) for 24 commercial species calculating with the administrative MFDs and the newly estimated MFDs. A: projection of harvestable species with moderate damage (1% mortality rate and 7% logging damage intensity). Adm projection with MFDs as suggested by forest administration, NewMFD projection with the newly estimated MFDs. B: projection of commercial species with 10% logging damage intensity (3% mortality rate) and 15% (5% mortality rate). C: projection of the residual stand (dbh > 10 cm) after harvest. D: projection of the residual stands (dbh > 10 cm) with 10% logging damage intensity (3% mortality rate) and 15% (5% mortality rate). 17.9 MgC ha^{-1} in A and C represents the avoided damage when introducing the new MFD. At 10%, there was more damage on forest stand representing a biomass of 8.9 MgC ha^{-1}; the biomass damage becomes 17.4 MgC ha^{-1} at 15%.

4. Discussions

Our finding that the number of trees per hectare in a natural tropical forest is unequally distributed for the various species groups, with 80% in group 3 and 4 is in accordance with findings by Bibani & Jonkers (2001). Our findings for the basal area distribution of 56.6% for Groups 1 and 2 and 33.4% for Groups 3 and 4 was smaller than the values given by these authors. For the study reported by these authors, Group 2 contains timber species of high future potential (species which are likely to be commercial after 20-30 years) and Group 3 non-timber forest products (NTFP) species, which are used by the local population. The difference of definition in Groups 2 and 3 may be the justification of the discrepancy in basal area distribution. The high concentration of tree species in Groups 3 and 4 with actually very little or no commercial interest, suggests that research is required to increase the knowledge in wood properties which can change the status of a species from a non-commercial value to a commercial value. The valorization of secondary species can also change the status of certain species.

The estimated MFD was similar to the one of Dykstra et al. (1997) who reported typical values between 50 and 110 cm for MFD of different species in West Africa. According to these authors, enough information was not given concerning the basis of determination of these minimum felling diameters. The MFD should be estimated on the base of diameter distribution, of the probable density of residual trees which will remain after human interventions, and of the availability of parent trees. The estimation should be species and also forest specific. It cannot be generalized for a region or a country since the conditions are not the same between different forests within a region or country. Within the same forest, the value of MFD needs to be updated after human interventions, probably after 5 or 10 years. It is likely that the change of the length of the felling cycle will also affect the MFD. For species with low percentage of reconstitution like *Triplochyton scleroxylon* or *Terminalia superba*, increasing slightly or maintaining the lower administrative MFD and adopting a longer felling cycle (50 or 60 years or even more) as suggested by the study of Huth & Ditzer (2001), can also be another alternative. Alder (1995) recommended different length of felling cycles for species with different percentage of reconstitution. This can be difficult to manage especially in situations where fixed annual allowable cutting areas are preferred. A longer felling cycle can also result in smaller annual allowable cutting areas. For *Triplochyton scleroxylon*, a MFD of 110 cm has also been used in Ghana which has a high reduction of the original forest cover (Dykstra et al., 1997) with a felling cycle similar to this study. The study of Bedel et al. (1998) compared the percentage of reconstitution after logging and after logging followed by thinning. These authors showed that logging followed by thinning will enable doubling the percentage of reconstitution after 20 or 30 years for tree species with diameter between 60 cm and 80 cm. Above 80 cm, no significant changes were observed. The study presented here does not include the effect of thinning on the diameter growth rate on the residual stand. Since one cannot predict the future effect of thinning, a first approximation is to adjust the MFD so that the percentage of the modelled reconstitution is close to 100% as in this study. It is also important to analyze the diameter distribution before taking decision. For example, in the case of *Guarea cedrata* (Fig. 3.5), diameter distribution coupled with the percentage of reconstitution, shows that the MFD can be shifted backwards from 80 cm to 60 cm without degradation. Measurements of stem densities 10 or 15 years after logging are necessary to compare the modelled projection with the real reaction of the stand and adjust the MFD.

The increase in stem density by 2.2 trees ha^{-1} year^{-1} corresponds to a basal area of 0.3 m^{2} ha^{-1} year^{-1} for all commercial trees seems to be consistent with other studies. De Madron et al. (1998b) after 14 years of investigation in a natural forest in Ivory Cost estimated an increase by 3.2 trees ha^{-1} year^{-1} in an untouched forest and 5 trees ha^{-1} year^{-1} in a thinned forest. De Madron et al. (1998c) observed a lower value of 0.6 tree ha^{-1} year^{-1} in another untouched forest and 1.8 trees ha^{-1} year^{-1} in another thinned forest. The natural regeneration (all new trees below 10 cm) which was numerically estimated in this study may probably play as well an important role on the forest growth structure.

4.1 REDD and carbon estimations from forest degradation

Today, through satellite images and field surveys it is possible to estimate deforestation during a long enough reference period. One of the headaches in the REDD mechanism is how to determine credible policy and determine acceptable techniques for linking measurements of reduced damage from forest degradation to emission of greenhouse gases (Olander et al. 2006). Efforts for measuring forest degradation to date focused on the detection of selective logging and fire damage (Asner et al. 2004). Since these methods are still in the research and development phase, it is questionable whether a small forest clearance representing a harvest of 3 trees of 100 cm dbh during which 150 of small trees are damaged, can be detected by satellite imagery. In this case study we show that modelling stand dynamics of managed tropical forests can provide essential information for estimating greenhouse gas emissions from forest degradation. For example, with the new MFDs estimated in this study and with a low logging damage of 7% and moderate mortality rate of 1%, an equivalent value of 17.9 MgC ha^{-1} remained on stand (damage avoidance). This value may be probably more if there is consideration of the effect of each avoided harvestable tree on residual trees and also the impact of the incoming solar radiation due to logging. In fact, selective logging changes light and nutrient conditions, and therefore stimulates growth of tree species and most especially of light-demanding species (Nussbaum et al. 1995; Tuomela et al. 1996). Normally, when trees are taken out from a forest system, it influences the nutrients coming from the stems, branches, roots, barks and leaves as well. It has to be analyzed, whether the pool of nutrient within the forest system can be kept constant or even increasing to maintain a sustainable forest. Solar radiation reaching individual trees of the remaining tree population is increasing and thus photosynthesis and tree growth rate of the individual trees could change. Probably, most of the remaining trees will grow faster so that the diameter increment after the thinning will be larger than before. This study shows also that increasing mortality and damage intensity increases also the amount of carbon biomass destroyed (dead trees due to higher mortality or logging intensity) estimated to be 8.9 MgC ha^{-1} at 10% or to be 17.4 MgC ha^{-1} at 15% logging damage at the end of the felling cycle (30 years).

For monitoring of carbon pools in tropical forests, we feel that estimations of national equivalent baseline carbon (sink or source) and the actual level need to be split into local estimations provided by individual projects. The sum of local estimations will lead in a national estimation. Thus the quantification of national baseline estimations will avoid sub-national leakages; the local baseline estimations will enable more accurate estimations. In this study, three logging damage intensities of 7%, 10% and 15% with newly estimated MFDs (Table 3.1) taking into consideration the reconstitution of the stand and the length of the felling cycle, resulted in different growth scenarios of the stand both for harvestable trees and residual trees (Fig. 3.6). It is possible for a particular forest management project involved in REDD to assume a logging intensity with low impact, to determine new MFDs and length of felling cycle with ecological considerations and to estimate on this base a growth scenario of the forest stand. It may then be feasible to estimate the harvest intensity, the damage on the residual stand, an avoidable damage compared to the previous level and its corresponding carbon emission reduction. The estimation could be projected in a commitment period (if already defined) and compared to the local baseline issued. By this method, a carbon trade can be realized: if the emissions are lower (higher) than the baseline, an individual project can sell (buy) carbon. It may be even the case that carbon is not emitted but absorbed because of the high photosynthesis rate due to higher absorbed photosynthetic radiation, higher CO_2 concentration and due to deposition of fertilizer compounds. Then the saved carbon is larger and more carbon bonds could be sold. Policy and Measures (PAM) needs to be combined with Cap and Trade (CAT) to make the trade efficient and avoid leakage. Post harvest inventories have to be carried out to evaluate the damage on residual stand and the avoided damage compared to the previous activities. The leakage of CO2 from the soil can also increase after logging and thinning. This effect has also to be considered when assessing an overall CO2 budget. The resulted financial incentives could be invested in the reduced impact logging (RIL) and in the silvicultural techniques such as suggested in Table 3.2 to increase information on growth increment and on mortality of trees, and to reduce damage on the residual stands. Additional studies on biodiversity and on wood properties of less used or unused trees which represent in this case 80% of the total number (Fig. 3.3) could be promoted by means of these financial incentives. De Madron et al. (1998a) reported a mean coefficient of commercialization (ratio between the volume of wood effectively used and the volume harvested for a given species) of 51% for 24 commercial species with values ranging between 25% and 70%. This coefficient could be improved with financial incentive and a real implementation of a newly orientated forest policy.

5. Conclusion

Sustainable management of tropical forests for timber production requires an effective system for predicting future forest growth and yields (Alder & Silva 2000). Inventories have to be updated for optimizing stand management practices and evaluate economics of future stands (Nepal & Somers 1992). Future stand developments may be derived from current structures through stand projection, using estimated diameter increment rates, a mortality ratio, a logging damage intensity and a CO2 leakage rate from the soil under different conditions. The future stand development for commercial species of the studied stand was derived up to the end of the first felling cycle (30 years). The projection for harvestable trees suggests an increase of the stem density from 12.3 to 18.6 trees per hectare. The basal area for harvestable trees will also increase from 7.4 $m^2 ha^{-1}$ to 11.2 $m^2 ha^{-1}$ at the end of the 30 year felling cycle. This can only be achieved if the remaining trees are not seriously damaged during harvest and no unpredictable event seriously deteriorates the forest stand.

Table 3.2: Proposed silvilcultural system scenario for monitoring forest management under REDD (Reducing Emissions from Deforestation and Forest Degradation) during a felling cycle of 30 years and for example a commitment period (period during which the carbon is estimated at the beginning and evaluated at the end, with a potential carbon trade) of 10 years.

Year	Operations
L-3	Stratification of the forest according to the ecological characteristics and past logging operations; planning of activities.
L-2	Inventory of the entire forest at low intensity in transect lines. Use for example plots S of 20 m x 250 m subdivided in two subplots S_1 of 20 m x 5 m and S_2 of 5 m x 5 m. In the plots S, all trees with dbh > 10 cm are counted. In the subplot S_1, all trees with dbh between 5-10 cm are counted; in the subplot S_2 evaluate the natural regeneration with dbh < 5 cm. Diameter distribution and percentage of reconstitution analysis and estimation of MFD. Growth projection analysis and estimation of an avoidable damage reduction with the related carbon estimation.
L-2	Inventory in at least 2 to 3 permanent plots of 100 m x 100 m located on different ecological zones. The permanent plots should be subdivided in subplots S_1 and S_2. Measure trees as mentioned above.
L-1	- Inventory of 1/30 of the total forest. In this section of the forest, count all the trees ≥ MFD. Sampling intensity: 100%. - Marking of at least one future crop tree per ha and trees to be felled. Ensure that all commercial tree species to be harvested are represented in the future crop trees.
L	- Felling of marked trees on the above mentioned 1/30 of the forest. - Post felling inventory; Thinning of the future crop trees. Logging damage analysis.
L+5	2nd inventory on the permanent plots.
L+10	3rd inventory on the permanent plots. End of the first commitment period. 2nd inventory of the entire forest at low intensity. Evaluation of avoided logging damage. New carbon pools estimations.
L+15	4th inventory on the permanent plots.
L+20	5th inventory on the permanent plots. End of the second commitment period. 3rd inventory of the entire forest at low intensity. Evaluation of avoided logging damage. New carbon pools estimations.
L+25	6th inventory on the permanent plots
L+30	End of the felling cycle. Inventory on the permanent plots. End of the third commitment period. Inventory of the entire forest at low intensity. Evaluation. Start of a new cycle.

Note

L: Year of logging; L-1: one year before logging; L+5: 5 years after logging.

Logging takes place each year in a 1/30 section of the forest. Always repeat inventory before logging and post inventory after logging in each logged section of the forest.

An estimation of the MFD of commercial species should take into consideration the diameter distribution of the species in the stand, the reconstitution of the harvestable trees at the end of the felling cycle and the length of the felling cycle. The tree growth rate used to simulate the stand development after logging should take into account the different growth conditions after logging. With the MFDs estimated in this study, the stem density of initial harvestable trees decreased from 12.3 to 6.7 trees per ha and the number of initial residual trees increased from 80 to 85.7 trees per ha. These changes correspond to an estimate of 17.9 MgC ha^{-1} which was not damaged.

Financial incentives induced eventually through the REDD mechanism will probably enable forest administrations and other stakeholders to implement a reduced forest degradation policy. The expectation through this new orientation is to facilitate a voluntary option to a low logging damage intensity and to a proper estimation of MFD, which provides sustainable timbers production during the next felling cycle, reduces damage and allows reconstitution of the original and probably the historical forest. The fund from REDD should be re-invested in the implementation of a silvicultural technique which will allow reduced impact on the residual stand, provide more information on tree growth and also increase research on technical, biophysical and biochemical properties of actually non used tree which represents, for instance, in the present studied forest 80% of the overall tree wood.

ALLOMETRIC EQUATIONS FOR BIOMASS ESTIMATIONS IN CAMEROON AND PAN MOIST TROPICAL EQUATIONS INCLUDING BIOMASS DATA FROM AFRICA

Adrien N. Djomo[1,*], Adamou Ibrahima[2], Joachim Saborowski[3], Gode Gravenhorst[1]

[1]*Faculty of Forest Sciences and Forest Ecology, Buesgen-Institute, Chair of Bioclimatology, Buesgenweg 2, D-37077 Göttingen, Georg-August-Universität Goettingen, Germany*

[2]*Department of Biological Sciences, Faculty of Science, University of Ngaoundéré, Cameroon*

[3]*Faculty of Forest Sciences and Forest Ecology, Buesgen-Institute, Chair of Eco-Informatics, Biometrics and Forest Growth and Chair of Ecosystem Modelling, Buesgenweg 4, D-37077 Göttingen, Georg-August-Universität Goettingen, Germany*

Abstract

Moist tropical forests in Africa and elsewhere store large amounts of carbon and need accurate allometric regressions for their estimation. In Africa the absence of species-specific or mixed-species allometric equations has lead to broad use of pan moist tropical equations to estimate tree biomass. This lack of information has raised many discussions on the accuracy of these data, since equations were derived from biomass collected outside Africa.

Mixed-species regression equations with 71 sample trees using different input variables such as diameter, diameter and height, product of diameter and height, and wood density were developed to estimate total aboveground biomass and biomass of leaves and branches for a Cameroon forest. Our biomass data was added to 372 biomass data collected across different moist tropical forests in Asia and South America to develop new pan moist tropical allometric regressions. Species-specific and mixed-species height diameter regression models were also developed to estimate heights using 3833 trees.

Using only diameter as input variable, the mixed-species regression model estimates the aboveground biomass of the study site with an average error of 7.4%. Adding height or wood density did not improve significantly the estimations. Using the three variables together improved the precision with an average error of 3.4%. For general allometric equations tree height was a good predictor variable. The best pan moist tropical equation was obtained when the three variables were added together followed by the one which includes diameter and height. This study provides height diameter relationships and wood density of 31 species. The pan moist tropical equation developed by Chave et al. (2005), estimates total aboveground biomass across different sites with an average error of 20.3% followed by equations developed in the present study with an average error of 29.5%.

Keywords: Biomass, Cameroon, Moist tropical forests, Tree allometry

Received: 5 June 2010, Accepted: 19 August 2010, Forest Ecology and Management 260: 1873–1885.

1. Introduction

Climate change during the last decades has increased the need of information on the amount of forest biomass in different regions for climate policy definition. This requires reliable estimations of carbon pools in forest ecosystems (Brown, 2002; Wirth et al., 2003; Joosten et al., 2004). The estimation of above and below ground biomass pools is of great importance for the characterization of structure and function of ecosystems (Chave et al., 2003). The information on biomass amounts helps not only to understand energy accumulation within forest ecosystems, but also serves as an ecological indicator for sustainability (Aboal et al., 2005). Reliable information on the amount of forest biomass is also useful for implementing REDD (Reducing Emissions from Deforestation and Forest Degradation) policy recently introduced in the Kyoto Protocol. These estimates can also help to assess forest productivity, carbon pools, and carbon sequestration in biomass components including roots, trunk, branches and leaves (Návar, 2009).

One of the major sources of uncertainty in estimating the amount of biomass is the lack of reliable regression equations which can convert the parameters measured directly in the field, such as diameter and height, to aboveground biomass estimates. General and site specific allometric equations have been developed from biomass of mixed tropical species (Dawkins, 1961; Ogawa et al., 1965; Brown et al., 1989; Overman et al., 1994; Brown, 1997; Araújo et al., 1999; Nelson et al., 1999; Chambers et al., 2001; Keller et al., 2001; Ketterings et al., 2001; Chave et al., 2005; Basuki et al. 2009). No allometric equation for biomass estimations has been developed so far specifically for African tropical forests. For biomass estimations in African forests, general allometric equations derived from data collected outside Africa are often used (e.g. Brown et al., 1989; Chave et al., 2005). Even if covariance analyses show for these equations that there is no detectable effect of continents, their practical use should be restricted to large scales, global and regional comparisons. Their application to particular species on specific sites should be limited. One of the constraints of some of these equations is that they include only diameter at limited range and exclude height. Before using allometric equations, their validity within a particular area needs to be tested (Crow, 1978; Brown et al., 1989; Houghton et al., 2001; Chave et al., 2001, 2005). If regression equations take into account dbh across the entire tree species range, the tree height and the specific wood density, they can provide more accurate biomass estimates (Cole and Ewel, 2006; Litton and Kauffman, 2008).

The most accurate method to determine tree biomass is the destructive method, which requires felling of trees and measurement of tree components. This method is labour intensive and time consuming and is in most cases restricted to small trees at small scales (Ketterings et al., 2001; Li and Xiao, 2007). Harvesting trees requires in general special authorization which is not often easy to acquire. It also draws attention of local population who in many cases ask for compensation for trees harvested in their locality. Therefore, biomass studies are very costly and consequently only few datasets are available. The use of regression equations allows estimating the total aboveground biomass of trees as well as of different components (root, stem, branches, and leaves) with easily measured parameters such as diameter (Kershaw and Maguire, 1995; Monserud and Marshall, 1999; Návar et al., 2002; Porté et al., 2002; Xiao and Ceulemans, 2004; Northup et al., 2005; Bullock and Heath, 2006; Fehrmann and Kleinn, 2006). Different species on the same site may have different tree heights, wood densities, architecture resulting consequently in different allometric relationships (Chave et al., 2003). The development of regression equations for single dominant or most used species and for mixed-species is important for forest inventory data which are composed of a multitude of species (Návar, 2009).

The objectives of this paper therefore are to (1) use destructive biomass data to develop allometric equations for estimating the amount of tree biomass in Campo-Ma'an area; (2) select the most important species of our study site and develop individual diameter tree height relationships for these species, as well as general diameter tree height relationships for mixed-species; (3) develop pan moist tropical allometric equations with the Campo-Ma'an biomass data and those of Brown (1997), Araújo et al. (1999), Nelson et al. (1999) and Ketterings et al. (2001); (4) evaluate the accuracy of existing pan moist tropical allometric equations.

2. Material and methods

2.1 Study site

The study was conducted in Cameroon within the Campo-Ma'an area which is located between latitudes 2°10' - 2°52' N and longitudes 9°50' - 10°54' E. It is an area of 772 066 ha, incorporating a National Park (264 064 ha, 34%), a protected forest (11 968 ha, 1.6%), a forest management zone with five logging concessions (241 809 ha, 31.4%), an agro-forestry area where local population have controlled access for multi-purpose uses (196 155 ha, 25.5%), a rubber and an oil plantation (57 750 ha, 7.5%) and a coastal area (320 ha). The Campo Ma'an forest is bordered in the western part by the Atlantic Ocean and in the southern part by the river Ntem and Equatorial Guinea. Most of the land is covered by lowland tropical moist forests that extend from Southeast Nigeria to Gabon and the Mayombe area in Congo (Letouzey, 1968, 1985). The area is marked by outstanding biological diversity, with Atlantic biafran, Atlantic littoral, mixed Atlantic, semi-caducifoliated, subtropical mountain, degraded and swamp forests. It is situated on the Precambrian shield constituted of metamorphic and old volcanic rocks. Metamorphic rocks such as gneisses, migmatites, schists and quartzites dominate the geologic underground in the area. Sedimentary rocks of the Cretaceous can also be found in the Campo basin. The topography ranges from undulating to rolling in the lowland area and, to steeply dissect in the more mountainous areas. The western part of the park, which reaches the coast, is generally flat, with altitudes ranging between 0 m - 300 m. In the eastern part, which is quite mountainous, the altitude varies between 400 m - 1100 m and the rolling and steep terrain has more variable landscape (Tchouto, 2004). The climate is typical equatorial with two distinct dry seasons (December-February and June-August) and two wet seasons (March-May and September-November). The average annual rainfall generally ranges between 2950 mm/year in the coastal area in the western part to 1670 mm/year in the eastern part. The average annual temperature is about 25°C and there is little variation between seasons and years. The hydrography of the area shows a dense pattern with many rivers, small river basins, fast-flowing creeks and rivers in rocky beds containing many rapids and small waterfalls. The main rivers are Ntem, Lobe, Bongola, Biwome, Ndjo'o, Mvila and Nye'ete.

2.2 Sampling and measurements

2.2.1 Biomass data

Biomass data were obtained from felled trees collected in 2000 during the main dry season in three sample plots of 10 m x 10 m (Ibrahima et al., 2002). Before felling, species name of trees were identified and the diameter at breast height (dbh) and height were measured. All trees less than 50 cm in the sample plot were felled except one tree with dbh of 79 cm. Trees were felled at ground level with machete or chainsaw according to tree size and split into fractions. The branches, twigs and leaves were separated from the trunk. Sawdust was also collected, weighted and added to the value of each category. Each category was put in a tarpaulin of 2m x 2m which was folded and weighted with a weighting scale (maximum weight 100 kg). Sub samples of each category were collected, weighted fresh in the field with an electronic balance (maximum weight 3 kg). They were oven dried in the lab at 60 °C to obtain the moisture content. The moisture content (MC) of samples enables to deduce the MC in each section of the tree. Hence, it was then possible to obtain dry mass of each section of trees using the formula dry weight = fresh weight – moisture weight.

71 trees were used for development of site specific allometric equations for estimation of total aboveground biomass of mixed species and for estimation of biomass of leaves and branches (cf. appendix A).

To develop pan moist tropical equations including Cameroon (Africa) biomass data, we selected biomass data of moist tropical forests collected in different countries and continents from literature (Brown, 1997; Araújo et al., 1999; Nelson et al. 1999; Ketterings et al., 2001). Brown (1997) reported 169 tree biomass data including only diameter collected from Para Brazil, South Asia (Indonesia and Cambodia). Among this data, the location of 42 trees was not specified. Araújo et al. (1999) provided biomass data of 127 trees ranging from 10 cm - 138 cm including diameter and height collected in the state of Para, Brazil. Nelson et al. (1999) reported 27 total aboveground biomass data with trees ranging between 2- 27 cm collected from Central Amazon. Ketterings et al. (2001) reported total above ground biomass data of 29 trees with dbh ranging from 7.6 cm - 48.1 cm including tree height and wood specific density collected in a moist forest, Indonesia.

2.2.2 Height diameter data

The data was collected from 3 different land uses namely the National Park, the Managed area (concession forests) and the Agro-forest area including community forests and open access forest areas. In each land use 8 plots of 20 m x 250 m representing in total 24 plots (12 ha) were used to assess tree species in the different vegetation types present in this area. One plot of 100 m x 100 m (1 ha) was assessed in a concession forest in the eastern part of the study area. In each of the 24 plots, a subplot of 5 m x 20 m was included. In the plots, all trees with dbh ≥ 10 cm were measured. The parameters recorded were species name, dbh, total height, stem quality and the geographical coordinates x and y. In 5 m x 20 m subplot in each of the 24 plots, all trees with dbh between 5 cm and 10 cm were additionally recorded including species name, dbh, and total height.

Table 4.1: 31 tree species selected from a total of 145 species, 3738 trees (dbh≥ 10 cm) based on their ranking according to the importance value index (IVI) and commercial use.

Case N°	Rank	Name	Abundance (N/ha)	Frequency (%)	Dominance (m^2/ha)	IVI
1	1	Edip	25.38	100	1.25	17.28
2	2	Oveng meki	13.77	80	0.89	11.03
3	3	Mekimekulu	15.00	76	0.63	10.16
4	4	Kankee	16.00	88	0.41	9.85
5	5	Mbazoa Afum	13.08	68	0.59	9.12
6	6	Ebap tom	8.46	84	0.49	7.49
7	7	Abem	6.08	60	0.78	7.31
8	8	Assam	7.62	88	0.49	7.27
9	9	Mfang	5.31	52	0.73	6.59
10	10	Assas	10.62	52	0.32	6.56
11	11	Minsi	8.54	80	0.28	6.43
12	12	Asseng	6.69	48	0.56	6.19
13	13	Ekang	4.69	28	0.74	5.76
14	14	Atjek kribi	5.00	72	0.34	5.28
15	15	Ngon	3.08	72	0.47	5.21
16	16	Mvomba	5.62	64	0.28	4.97
17	18	Bidou	1.46	28	0.78	4.83
18	19	Okweng ele	6.00	56	0.26	4.82
19	21	Omang	2.92	60	0.35	4.27
20	26	Padouk	1.08	48	0.50	3.95
21	29	Moambe jaune	3.46	64	0.17	3.74
22	30	Andok	3.46	64	0.16	3.67
23	33	Niove	2.15	64	0.20	3.39
24	34	Oyang	2.62	48	0.16	2.95
25	35	Emien	1.15	40	0.31	2.92
26	36	Azobe	0.85	32	0.38	2.92
27	37	Ekaba	3.62	20	0.22	2.81
28	41	Enak	2.85	48	0.07	2.62
29	46	Tali	0.85	32	0.25	2.31
30	47	Mevini	2.00	48	0.05	2.23
31	55	Akom/Limba	0.92	12	0.21	1.63
32-145		Other	97.23		8.52	124.41
		Total	287.54		21.83	300.00

For species which could not be identified directly on the field, voucher of the species were collected for species identification in the National Herbarium. The tree diameter was measured at 1.30 m height from the soil for all trees without buttresses and at 0.30 m height from the end of the buttresses or aerial roots. The tree height was measured with the SUUNTO height meter for all open trees with good visibility of the top and was estimated when it was not possible to see the top of the tree. To avoid over or under estimation of trees with poor visibility, a measurement was firstly made on an easily measurable border tree which helped to adjust height estimates.

In total 3833 trees with diameter ranging from 5 cm – 170 cm were selected for this study. We used the Importance Value Index (IVI) developed by Curtis and McIntosh (1951), to choose species for development of species-specific tree height allometric equations. According to this index, tree species in a given ecosystem can be classified in terms of their importance in that ecosystem. IVI evaluated according to the equation *IVI = relative abundance + relative dominance + relative frequency,* where abundance is the number of individuals (N/ha), dominance the basal area (m^2/ha) and frequency the percentage of plots in which a species is represented. 31 species out of 145 belonging to 17 families were selected for the development of species-specific height ~ diameter regression equations. The selection criteria were the ranking based on IVI and the commercial value of species (Table 4.1).

To determine the specific wood density, 4 to 5 core samples were collected for each species. The fresh volume of each sample was estimated using the Archimedes principle which states that at about 4°C a solid immersed in water experiences an upward force equal to the weight of the water it displaces. The wood sample was oven-dried during 48 h at 75 °C and weighted using an electronic balance. The specific wood density was calculated as oven dry weight divided by fresh volume. Our values seem to be similar to those of Brown (1997) but lower compared to values of Gerard et al. (2009) (Table 4.2).

2.3 Data analysis and modelling

The mathematical model for biomass studies which is most commonly used has the form of a power function (Zianis and Mencuccini, 2004; Pilli et al., 2006) because it has long been noted that a growing plant maintains the weight proportion between different parts (West et al., 1997; 1999). This function assumes the form $M = aD^b$ (Niklas, 1994; Kaitaniemi, 2004; Pilli et al. 2006) where a and b are the scaling coefficients, D the diameter at breast height and M the total weight of aboveground dry biomass of a tree. In most cases the variability of D explained largely the variability of M. This correlation makes D a good predictor for M. The most comprehensive approach to describe universal allometric scaling was presented by West et al. (1997, 1999), Brown and West (2000), Enquist (2002) and Niklas (1994, 2004). Their model commonly known as WBE model derives mainly from fractal geometry. Their fractal model predicts that aboveground biomass M scales against stem diameter D a b value of 2.67 ($M \sim D^{8/3}$). Zianis and Mencuccini (2004) using a world-wide list of 279 biomass allometric equations showed that this value should rather be closed to 2.36 and varies with species, stand age, site quality, climate, and stocking of stands. The value of b is between 2 and 3 in most cases.

Table 4.2: Wood dry density (g cm^{-3}) of selected tree species. For each species, local or commercial name, scientific name and family name and its density from three different sources are reported. A: Campo – Ma'an; B: Brown, 1997; C: Gerard et al., 2009.

N°	Name	Scientific name	Family	Density (g cm^{-3})		
				A	B	C
1	Edip	Strombosia tetrandra	Olacaceae	0.76	0.63	-
2	Oveng meki	Dialium pachyphyllum Harms	Caesalpiniaceae	-	-	-
3	Mekimekulu	Sabicea capitellata	Rubiaceae	0.66	-	-
4	Kankee	Allophylus africanus	Sapindaceae	-	-	-
5	Mbazoa Afum	Strombosia pustulata	Olacaceae	0.74	-	-
6	Ebap tom	Santiria trimera	Burseraceae	0.53	0.53	-
7	Abem (Ebiara)	Berlinia bracteosa	Caesalpinioideae	0.55	0.60	0.70
8	Assam/Rikio	Uapaca guineensis	Euphorbiaceae	0.68	0.60	-
9	Mfang (Eyoum)	Dialium pachyphyllum	Caesalpinioideae	0.96	0.83	0.94
10	Assas	Macaranga hurifolia	Euphorbiaceae	0.26	0.40	-
11	Minsi	Calpocalyx dinklagei	Mimosaceae	-	0.66	-
12	Asseng (Parasolier)	Musanga cecropioides	Moraceae	-	0.23	-
13	Ekang (Miama)	Calpocalyx heitzii	Mimosaceae	0.78	0.66	-
14	Johimbe (Atjek kribi)	Pausinystalia johimbe	Rubiaceae	0.83	-	-
15	Ngon (Eveuss)	Klainedoxa gabonensis	Irvingiaceae	0.70	0.87	1.06
16	Mvomba	Xylopia quintasii	Annonaceae	0.51	0.70	-
17	Bidou (Ozouga)	Saccoglotis gabonensis	Humiriaceae	0.57	0.74	0.89
18	Okweng ele	Hymenostegia afzeli	Caesalpiniaceae	0.78	0.78	-
19	Omang (Alep)	Desbordesia glaucescens	Irvingiaceae	0.59	-	1.05
20	Padouk (Mbel)	Pterocarpus soyauxii	Papilionoideae	0.75	0.61	0.79
21	Moambe jaune (Mfo)	Enanthia chlorantha	Annonaceae	0.53	0.42	-
22	Andok	Irvingia gabonensis	Irvingiaceae	-	0.71	-
23	Niove (M'bonda)	Staudtia kamerunensis	Myristicaceae	0.80	0.75	0.88
24	Oyang	Xylopia aethiopica	Annonaceae	0.71	0.50	-
25	Emien (Ekouk)	Alstonia congensis	Apocynaceae	0.51	0.33	0.36
26	Azobe (Okoga/Bongossi)	Lophira alata	Ochnaceae	0.92	0.87	1.06
27	Ekaba (Ekop ribi)	Tetraberlinia bifoliolata	Caesalpinioideae	-	0.54	0.62
28	Enak	Anthonotha macrophylla	Cealsapiniaceae	0.70	0.78	-
29	Tali (Elon)	Erythrophleum ivorensis	Caesalpinioideae	0.82	0.72	0.91
30	Mevini (Ebene)	Diospyros crassiflora	Ebenaceae	0.84	0.82	0.90
31	Akom/Limba	Terminalia superba	Combretaceae	0.36	0.45	0.54

To account for the heteroscedasticity of data (variance increases with increasing diameter or height of trees), the standard method for estimating the coefficients a and b is through the least-square regression of log-transformed data for D and M with the value of M obtained from destructive sample trees, i.e. $\ln(M) = \ln(a) + b\ln(D)$. This transformation introduces a systematic bias on the original scale that is generally corrected with a correction factor *CF* depending on the residual standard error (*RSE*) (Finney, 1941; Baskerville, 1972; Yandle and Wiant, 1981; Sprugel, 1983; Madgwick and Satoo, 1975) according to *CF* = exp ($RSE^2/2$). Height prediction on the original scale, for example exp (ln(a) + b ln*D*) is multiplied by *CF* (> 1) to correct underestimation. The larger the RSE, the more uncertain regression models predict biomass values, and the larger the correction factor (Chave et al., 2005).

For biomass estimations, models (1) to (14) were tested. In these models, M represents the total weight of aboveground dry biomass, D the diameter at breast height, H the total height and ρ the specific wood density of a tree.

Linear models from Brown et al. 1989

$$M = a + bD + cD^2 \quad (1)$$

Transformed nonlinear models from Brown et al. 1989

$$\ln(M) = a + b\ln(D) \quad (2)$$

$$\ln(M) = a + b\ln(D^2H) \quad (3)$$

$$\ln(M) = a + b\ln(D^2H\rho) \quad (4)$$

Models from Chave et al. 2005

$$\ln(M) = a + b\ln(D) + c\ln(H) + d\ln(\rho) \quad (5)$$

$$\ln(M) = a + b\ln(D) + c(\ln D)^2 + d(\ln D)^3 + \beta\ln(\rho) \quad (6)$$

Other models

$$\ln(M) = a + b\ln(DH) \quad (7)$$

$$\ln(M) = a + b\ln(D) + c\ln(H) \quad (8)$$

$$\ln(M) = a + b\ln(D) + c\ln(\rho) \quad (9)$$

$$\ln(M) = a + b\ln(D^2H) + c\ln(\rho) \quad (10)$$

$$\ln(M) = a + b\ln(D) + c\ln(D^2H) + d\ln(\rho) \quad (11)$$

$$\ln(M) = a + b\ln(D) + c\ln(D^2H\rho) \quad (12)$$

$$\ln(M) = a + b\ln(D^2\rho) + c\ln(H) \quad (13)$$

$$\ln(M) = a + b(\ln D)^2 + c(\ln D)^3 + d\ln(D^2H) + \beta\ln(\rho) \quad (14)$$

First, we develop equations using only diameter as predictor. Then we stepwise include height and density and analyze their effects on the predictive quality of models. For each of the models tested, the following indicators of goodness of fit are reported:

- Adjusted R^2: corrects the coefficient of determination by accounting for an increasing number of independent variables.

- Residual standard error of estimate (RSE): square root of the residual variance around the regression function.

- Akaike Information Criterion (AIC): measure of goodness of fit of a regression model proposed by Akaike (1974). The regression equation with the lowest AIC value is the best estimator. $AIC = 2k - 2\ln(L)$ where k is the number of parameters in the regression model, L the likelihood of the data under the according regression model.

All the models listed above were tested. The best ones depending on the number of variables (diameter, height, wood density) included were selected based on the residual standard error, the adjusted R^2 and the AIC. To validate these best models, we compare the mean, total, minimum and maximum biomass of measured trees with estimations of the different equations and also with their average value of the relative errors $100(Mpi - Mi)/Mi$ where Mpi is the predicted dry weight of tree i, Mi its observed dry weight.

Regression equations including height may improve significantly the models. To develop relationships of height as a function of diameter, we tested three models:

$\ln(H) = a + b \ln(D)$ (Van Laar and Akça, 1997) (15)
$\ln(H) = a + b \ln(D) + c \ln(D^2)$ (Korsun, 1948) (16)
$\ln(H) = a + b/D$ (Van Laar and Akça, 1997) (17)

The best model was selected based on the residual standard error and was used to develop the species specific relationship between height and diameter.

All data were analyzed with statistical software STATISTCA 9.

3. Results

3.1 Mixed-species allometric equations of the study site

We tested model (2) with only diameter (1–79 cm) as explanatory variable (Fig. 4.1). Then we included the height and tested its effect with diameter. Finally, we tested the effect of the three variables diameter height and wood density together in the models. The mixed species allometric equations for biomass estimation are summarized in Table 4.3. The simple allometry ln (M) = -1.8967+2.1135 ln(D) (dbh range between 1-10 cm) or ln (M) = -2.1079+ 2.3278 ln(D) (dbh range 1-79 cm) seem to be good predictors of total aboveground biomass. The introduction of total height (model 3) did not improve the accuracy of the result with a RSE of 0.328 and an adjusted R^2 of 0.9561 and an AIC of 47. The wood density (model 9) provides a better fit with an adjusted R^2 of 0.9575, a RSE of 0.325 and an AIC of 48. Putting the three variables together (model 14) gives the best fit with an adjusted R^2 of 0.9659, a RSE of 0.291 and an AIC of 34.

Table 4.3: Allometric equations for estimations of total aboveground biomass (M), biomass of leaves and of branches in Campo-Ma'an. a, b and c are the model's fitted parameters; N the sample size; RSE is the residual standard error of the estimate; Adj R^2 is the coefficient of determination, D range the diameter range of the trees analyzed, AIC the Akaike Information Criterion and the average value of relative errors in percentage.

Equation type	a	b	c	N	RSE	Adj. R^2	D (cm)	AIC	%
Total biomass									
1. $\ln(M) = a + b \ln(D)$	-1.8967	2.1135		68	0.278	0.9089	1-10	46	7.8
2. $\ln(M) = a + b \ln(D)$	-2.1079	2.3278	-	71	0.330	0.9562	1-79	48	7.4
3. $\ln(M) = a + b \ln(D^2H)$	-3.0788	0.9066	-	71	0.328	0.9561	1-79	47	7.3
4. $\ln(M) = a + b \ln(D) + c \ln(\rho)$	-1.9644	2.3382	0.3579	71	0.325	0.9575	1-79	48	7.0
5. $\ln(M) = a + b (\ln D)^2 + c \ln(D^2H) + \beta \ln(\rho)^*$	-2.3325	0.1651	0.6620	71	0.291	0.9659	1-79	34	3.4
Leaves									
6. $M = a + bD + cD^2$	-0.1009	0.0626	0.0027	71	0.129	0.9976	1-79	-83	-15.8
7. $\ln(M) = a + b \ln(D)$	-4.2028	1.6144		71	0.686	0.708	1-79	156	-13.7
Branches									
8. $M = a + bD + cD^2$	7.1585	-3.0711	0.1912	71	2.874	0.9994	1-79	357	-10.2
9. $\ln(M) = a + b \ln(D)$	-4.8605	2.3754		71	0.909	0.7496	1-79	192	-58.7

(*) $\beta = 0.1309$

To test the consistency of fits, we added 20 trees which were not included in the development of the estimators and compared the values directly measured in the field for all trees (91) with estimations of our models. The result confirms simple model 2 to be a good estimator at the study site with an average error of 7.4%. Adding the three variables improved the fit with an average error of 3.4%.

To estimate the biomass of branches and leaves, we tested two models 1 and 2. Model 1 $M = -0.1009 + 0.0626\ D + 0.0027\ D^2$ seems to be a good predictor of leaves biomass with a RSE of 0.129 an adjusted R^2 of 0.9976. Model 2 seems to give a poorer estimator $\ln(M) = -4.2028 + 1.6144 \ln(D)$ for leaves with an adjusted R^2 of 0.708 and an AIC of 156. The comparison of measured biomass with estimated biomass shows that model 2 is the best estimator with an average error of -13.7%; the average error of model 1 is -15.8%. Model 1 gives a good estimator for branches $M = 7.1585 + -3.0711\ D + 0.1912\ D^2$ with a R^2 of 0.994. The comparison of measured and estimated biomass with the two estimators confirm model 1 as the best fit for branches with an average error of -10.2%.

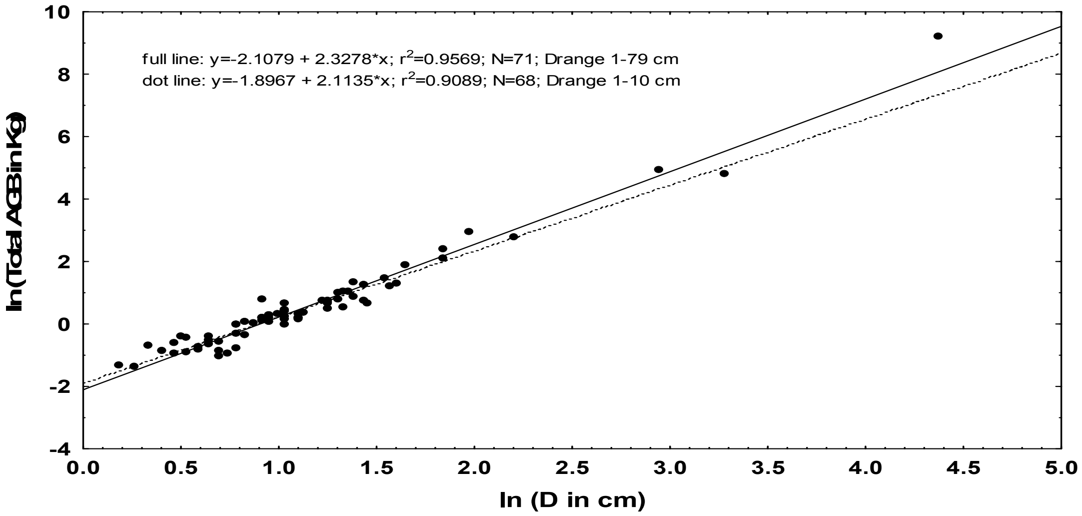


Fig. 4.1. Regression between the logarithm of total aboveground biomass in kg and the logarithm of diameter at breast height (D) in cm of 71 trees from our study site.

3.2 General allometric equations for moist tropical forests

The data used to develop general allometric equations for moist tropical forests include our data and others originating from South America and Asia (Fig. 4.2). Since inventory data do not always include diameter, height and wood density, we tested the effects of each of these variables (Fig 4.3). The best equation including only diameter $\ln(M) = -2.1801 + 2.5624 \ln(D)$ uses 443 trees with diameter ranging from 1cm - 148 cm. This equation has a RSE of 0.444 and an adjusted R^2 of 0.9671 (Table 4.4). The best allometric equation including diameter and height obtained with equation $\ln(M) = -3.2249 + 0.9885 \ln(D^2H)$ uses 274 trees with diameters ranging from 1cm - 138 cm. This equation has a RSE of 0.443

and an adjusted R^2 of 0.9710. Several models were tested to check the effect of inclusion of wood density. The equation $\ln(M) = -2.4733 + 0.2893 (\ln D)^2 - 0.0372 (\ln D)^3 + 0.7415 \ln(D^2H) + 0.2843 \ln(\rho)$ (model 14) gives the best fit with 3 variables with a RSE of 0.437, an adjusted R^2 of 0.9717 and an AIC of 334.

For validation of the models we compared the results of directly measured biomass with estimates of selected models in different locations across countries and continents (Table 4.5). General allometric equation with 3 variables (Model 14) confirms to be the best estimator with an average error of 29.5% reaching an average error of only 1.2% at Para Amazone. It is followed by model 3 containing two variables (diameter and height) with an average error of 30.3%. The model 2 with only one variable (diameter) gives a poor estimator for general allometric equation with an average error of 35.3%.

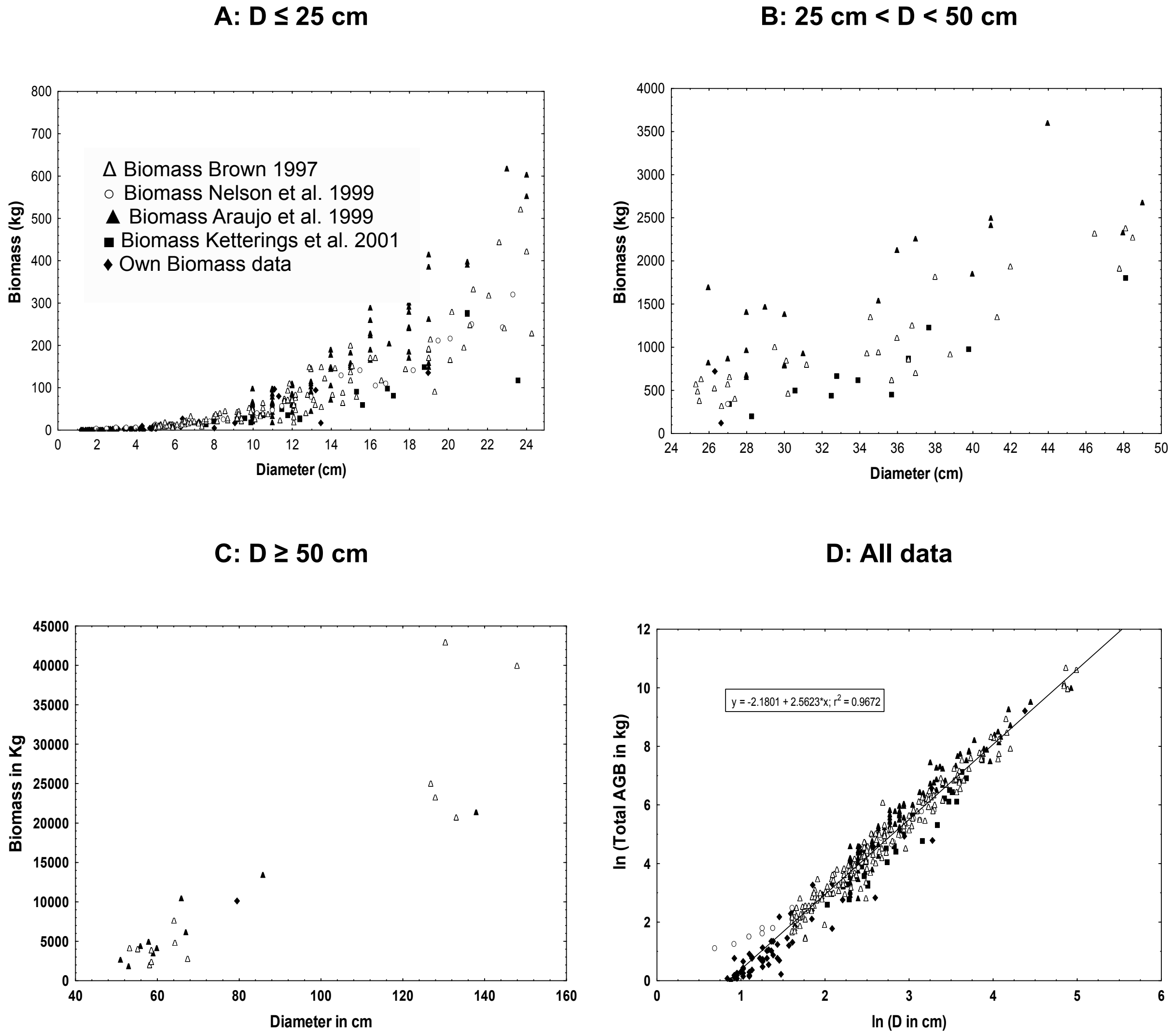
Table 4.4: General or pan tropical allometric equations for estimations of total aboveground biomass in moist tropical forests. a, b, c and d are the model's fitted parameters; N the sample size; RSE is the residual standard error of the model; Adj R^2 is the coefficient of determination, D range the diameter range of the trees used and AIC the Akaike Information Criterion. Data are from Araújo et al., 1999, Nelson et al. 1999, Ketterings et al. 2001 and this paper input. Equation 2 included these data and also data from Brown 1997.

Equation type	a	b	c	d	N	RSE	Adj. R^2	D range	AIC
1. $\ln(M) = a + b \ln(D)$									
	-2.2057	2.5841	-	-	274	0.483	0.9653	1-138	383
2. $\ln(M) = a + b \ln(D)$									
	-2.1801	2.5624	-	-	443	0.444	0.9671	1-148	542
3. $\ln(M) = a + b \ln(D^2H)$									
	-3.2249	0.9885	-	-	274	0.443	0.9710	1-138	335
4. $\ln(M) = a + b \ln(D) + c (\ln D)^2 + d (\ln D)^3 + \beta^* \ln(\rho)$									
	-1.3774	1.3919	0.5477	-0.0725	274	0.471	0.9670	1-138	375
5. $\ln(M) = a + b (\ln D)^2 + c (\ln D)^3 + d \ln(D^2H) + \beta^* \ln(\rho)$									
	-2.4733	0.2893	-0.0372	0.7415	274	0.437	0.9717	1-138	334

(*) 4. β is 0.3529; 5. β is 0.2843

Table 4.5: Average errors in percentage (%) of published pan moist tropical equations and this paper input general equations. Published regressions are from Brown et al. (1989), (Brown 2, 3), Brown (1997), (Brown 1) and Chave et al (2005). D, H and ρ are the input parameters for regressions, which stands for diameter, height and wood density.

Site	Brown1 (D)	Brown2 (D, H)	Brown3 (D, H, ρ)	Chave. (D, H, ρ)	General1 (D)	General2 (D, H)	General3 (D, H, ρ)
Para Amazone	-17.2	-10.9	5.0	-12.3	-4.3	1.3	1.2
Asia	65.5	54.2	54.9	28.7	91.7	75.5	76.5
Central Amazone	-10.3	-6.4	-9.9	-29.6	2.4	4.5	-1.9
Africa	29.5	31.3	60.8	10.7	42.8	39.9	38.4


A: D ≤ 25 cm

B: 25 cm < D < 50 cm

C: D ≥ 50 cm

D: All data

Fig. 4.2. Scatter plot showing the biomass from Brown 1997, Nelson et al. 1999, Araújo et al. 1999, Ketterings et al. 2001 and our own biomass data. Graph A shows biomass data for D ≤ 25 cm. Graph B shows biomass data diameter at breast height between 25 and 50 cm. Graph C shows biomass data with D ≥ 50 cm. Graph D shows the regression between the logarithm of total aboveground biomass in kg and the logarithm of diameter at breast height (D) in cm for all trees.

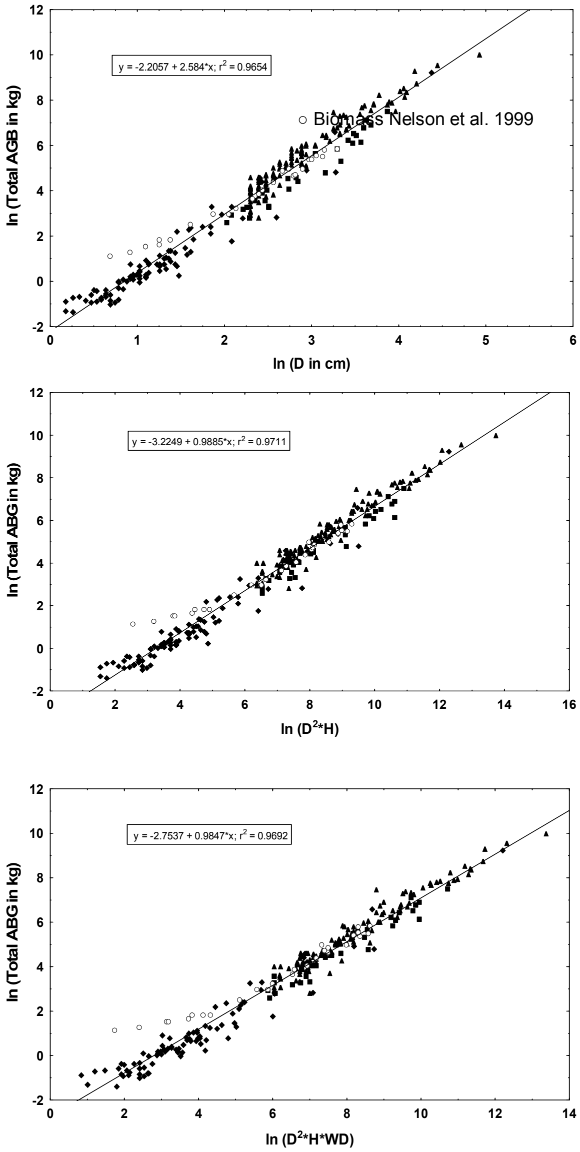


Fig. 4.3. Regression between the logarithm of total aboveground biomass and the logarithm of diameter at breast height in cm (upper graph); the logarithm of product of diameter and height in m (middle graph); the logarithm of product of square diameter, height and wood density (g cm^{-3}). Biomass data do not include data from Brown 1997.

Brown et al. (1989), Brown (1997) and Chave et al. (2005) studied pan moist tropical allometric equations for large scale biomass estimations. Their equations have been widely used in moist tropical forests in areas where no specific equations for biomass estimations was developed. We selected two equations from Brown et al. (1989), one from Brown (1997) and one from Chave et al. (2005). The first equation of Brown et al. (1989) $M = \exp(-3.1141 + 0.9719 \ln(D^2H))$ was developed with 168 trees with dbh ranging from 5 cm - 130 cm with destructive biomass data collected in Cambodia, Brazil and Indonesia. The second equation $M = \exp(-2.4090 + 0.9522 \ln(D^2H\rho))$ was developed with 94 trees with dbh ranging from 5 cm - 130 cm. The equation of Brown (1997) $M = \exp(-2.134 + 2.530\times \ln(D))$ was developed for moist forests with 170 trees ranging from 5 – 148 cm. The equation of Chave et al. (2005) $M = \exp(-2.977 + \ln(D^2H\rho))$ was developed from 1505 trees with dbh ranging from 5 cm - 156 cm collected from moist tropical forests in Brazil, French Guiana, India, Indonesia, Venezuela and Malaysia. To compare published equations with the one developed in this study, we estimated the average error made by each equation at different locations and continents. The result is summarized in Table 4.5. The equation of Chave et al. (2005) is the best estimator across continent and site with an average error of 20.3% and was directly followed by our general equation 3 of this study with 29.5%. Equation with only 2 variables (diameter and height) of Brown et al. (1989) estimates much better biomass across site than equation with three variables (Table 4.5). The dataset used (168 trees for equation with 2 variables and only 94 trees for equation with 3 variables) for the development of these equations should be a reason of this difference.

3.3 Height regression equations

The results of our biomass allometric equations study shows that the introduction of height in the allometric equation ameliorates the precision. To determine the relationship between height and diameter for our selected trees species, we tested 3 models 15-17 which have been reported by different authors to give good fit of height diameter relationship. The results are summarized in Table 4.6. The simple equation from model 15 $\ln(H) = 1.05 + 0.63 \ln(D)$ estimates better the relationship between the two variables with a correlation coefficient of 0.79 and a RSE of 0.294. For the development of specific allometric relationship between height and diameter for selected species, we used therefore model 15 as model estimator. The results of estimators for selected 31 species are summarized in Table 4.7. b values of allometric equations have a mean of 0.66 with 95% of values ranging between 0.56 and 0.83. a values of the allometric equations have a mean of 1.01 with 95% of values ranging between 0.72 and 1.51. *Xylopia aethiopica* (Oyang) has extreme values, b above 1 (1.04) and a 0.13 the lowest. Analysis of scatter plot shows a linear regression of negative slope between b and a, $b = 1.0053 - 0.3348\ a$, with adjusted R^2 of 0.88 and RSE of 0.494 (Fig. 4.4a).

Table 4.6: Result of regression analysis for the different models tested for estimation of the relationship between tree height and diameter. a, b and c are the model's fitted parameters, S.E a, S.E b, S.E c the standard error for a, b and c; R.S.E is the residual standard error of the estimate, R the correlation coefficient and N the sample size.

Equation type	a	b	c	N	R.S.E	R	D-range	AIC
$\ln(H)=a+b\ln(D)$	1.0506	0.6347	-	3833	0.294	0.7895	5-170	1497
$\ln(H)=a+b\ln(D)+c\ln(D^2)$	1.0082	0.4931	0.2163	3833	0.294	0.7898	5-170	1499
$\ln(H)=a+b/D$	3.6100	-11.2056	-	3833	0.321	0.7426	5-170	2171

4. Discussions

4.1 Site specific mixed-species regressions

Several studies have attempted to study site specific allometric regressions for different species. The study of Nelson et al. (1999) with 132 trees in Central Amazon showed that simple model with only diameter as input is a good estimator which estimates biomass of mixed-species only with an average error of 19.8%. Including the height ameliorates just very little the precision with an average error of 17.7%. Including diameter, height and wood density has resulted in their study to much better precision with an average error of 14%. The study of Overman et al. (1994) with 54 mixed tree species in an Amazon rain forest found a relative higher average error of 25.6% for biomass estimations with only diameter as input. Adding height had just little effect with an average error of 24.3%. The three variables diameter, height and wood density dropped the precision of the measurement to 11.2%.

In this study, considering only diameter as input variable estimates the biomass of the study site with an average error of only 7.4%. Adding height to diameter has not improved the regression precision. Diameter and wood density together have improved slightly the accuracy with an average error of 7%. The three input variables together have improved significantly the accuracy with an average error of 3.4%. This study provides species-specific allometric relationship for height (Table 4.7) and also data of wood density (Table 4.2) for 31 species. This can be used to improve the estimations of biomass. Knowing that larger dataset provides best fit, we added the 20 trees used to test consistency and it increases trees above 10 cm from 3 to 8 trees. The best fit was based on these 91 trees. When only diameter is the input variable, the allometric equation recommended is $M = \exp(-1.9967 + 2.3924 \ln(D))$. When diameter and height are available the regression recommended is $M = \exp(-2.9946 + 0.9317 \ln(D^2H))$. In case diameter and wood density are available, the regression equation suggested is $M = \exp(-1.8623 + 2.4023 \ln(D) - 0.3414 \ln(\rho))$. In case diameter, height and wood density are all available the equation suggested is $M = \exp(-2.4360 + 0.1399 (\ln D)^2 + 0.7373 \ln(D^2H) + 0.2790 \ln(\rho))$. In case heights and wood densities are not available in our site or similar, height diameter relationships summarized in Tables 4.6 and 4.7 and densities in Table 4.2 can be used. The mean value of densities was 0.64 g cm^{-3} and can be used in our site or similar site when there are no data available.

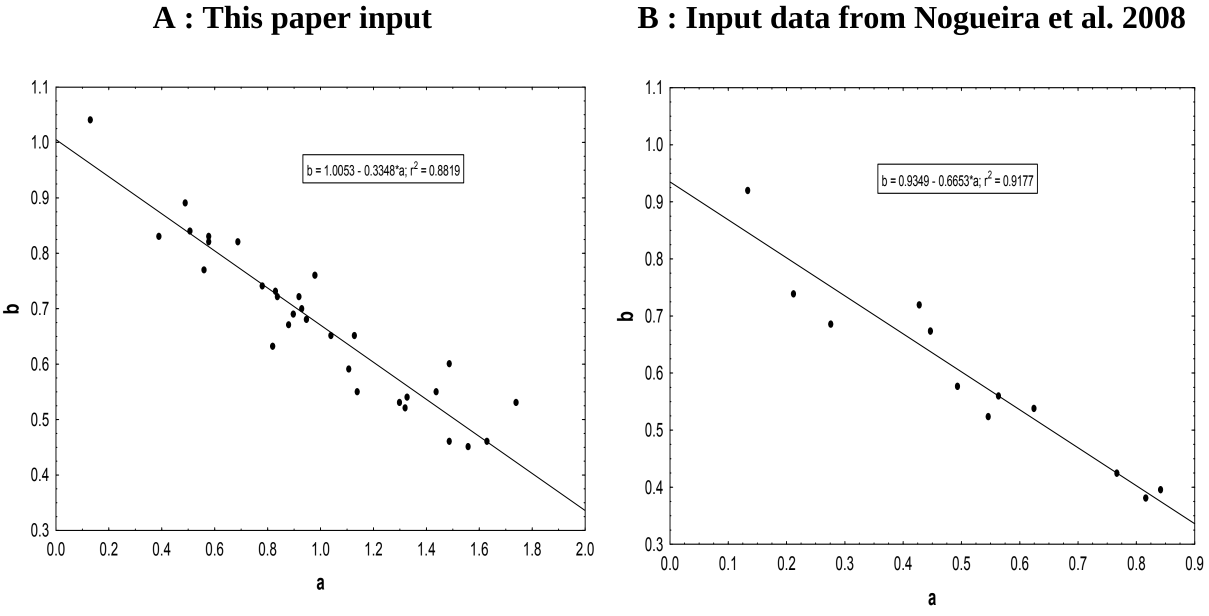
Table 4.7: Height regression model ln(*H*) = a + b ln(*D*) for selected species of our study site. a, and b are the model's fitted parameters, S.E a, S.E b the standard error for a, and b; R.S.E is the residual standard error of the estimate, R the correlation coefficient and N the sample size.

Species name	a	b	S.E a	S.E b	R.S.E	R	N	D range
Edip	1.49	0.46	0.072	0.024	0.199	0.74	312	5-75
Oveng meki	1.04	0.65	0.097	0.032	0.236	0.84	174	5-125
Mekimekulu	1.11	0.59	0.088	0.031	0.213	0.81	198	5-63
Kankee	0.58	0.83	0.118	0.044	0.191	0.82	179	5-50
Mbazoa Afum	0.92	0.72	0.078	0.027	0.165	0.91	163	5-67
Ebap tom	0.78	0.74	0.108	0.036	0.184	0.90	98	5-50
Abem	0.39	0.83	0.207	0.059	0.291	0.85	77	10-78
Assam	0.58	0.82	0.114	0.038	0.205	0.92	87	5-80
Mfang	0.51	0.84	0.145	0.043	0.225	0.93	63	10-100
Assas	0.93	0.70	0.102	0.036	0.159	0.87	127	5-45
Minsi	1.32	0.52	0.138	0.050	0.237	0.71	110	5-54
Asseng	1.33	0.54	0.196	0.059	0.229	0.71	83	9-80
Ekang	1.63	0.46	0.152	0.043	0.182	0.83	54	12-89
Atjek kribi	0.49	0.89	0.156	0.051	0.207	0.92	55	5-70
Ngon	0.84	0.72	0.235	0.066	0.236	0.88	36	11-110
Mvomba	0.98	0.76	0.216	0.071	0.275	0.80	67	10-52
Bidou	1.74	0.53	0.483	0.115	0.289	0.74	19	18-170
Okweng Ele	1.30	0.53	0.156	0.053	0.220	0.76	75	5-48
Omang	1.44	0.55	0.236	0.071	0.298	0.78	39	5-83
Padouk	0.83	0.73	0.506	0.125	0.365	0.85	15	8-140
Moambe jaune	0.69	0.82	0.235	0.079	0.235	0.86	39	10-46
Andok	0.56	0.77	0.322	0.104	0.248	0.76	43	12-45
Niove	0.95	0.68	0.228	0.072	0.249	0.88	29	5-100
Oyang	0.13	1.04	0.204	0.066	0.163	0.96	24	10-47
Emien	0.82	0.63	0.380	0.102	0.322	0.88	13	11-95
Azobe	1.49	0.60	0.364	0.094	0.329	0.90	12	5-110
Ekaba	1.13	0.65	0.248	0.081	0.285	0.77	47	10-83
Enak	1.14	0.55	0.244	0.088	0.186	0.76	30	5-52
Tali	0.90	0.69	0.337	0.094	0.328	0.91	13	6-105
Mevini	0.88	0.67	0.269	0.101	0.229	0.79	29	5-43
Akom/Limba	1.56	0.45	0.314	0.088	0.269	0.85	12	10-90

In the dataset of 71 trees, only three trees were above 10 cm. With the log transformation, the distance between biggest and small trees is remarkably reduced as one can see in Fig. 4.1. Therefore, the three biggest trees in diameter are less extreme after transformation. The few big trees help to calibrate the relationship at upper range. This can be viewed also in the scatter plot in Fig. 4.1. This argument has been supported by Chave et al. (2001) who stated that the biomass values of the smallest trees strongly affect the coefficients in the allometric between M and D. This argument was strongly discussed by Zianis and Mencuccini (2004) who showed that "valid estimates for the scaling coefficients in relationship between M and D can be obtained from only two values of D and the corresponding M". Nevertheless, more data at upper diameter range are needed for consistency of the allometry for bigger trees.

The regression equations of branches and leaves elaborated in this study constitute an additional improvement for estimations of biomass when inventory data provide information on trunk volume as it is in many cases. The relation $M = \rho \times V$ can enable to derive the biomass of trunk and the regression equations of branches and leaves to estimate their biomass. The sum of the three assortments gives the total aboveground of a tree. The expansion factor ratio of total biomass to biomass of the trunk was also estimated for each tree (Appendix A). The mean expansion factor for all trees is 1.22. It can also be used as alternative to convert bole volume from inventory data to total aboveground biomass. In this case the diameter range should be between 1–79 cm.

This study also confirms the value of *b* to be between 2 and 3 in the relationship $M = aD^b$ as predicted in many studies (West et al., 1997, 1999; Brown and West, 2000; Enquist, 2002; Niklas, 1994, 2004; Zianis and Mencuccini, 2004). In the relationship $H = aD^b$, this study found the value of *b* to be between 0.10 and 1 with a mean value close to 0.66. *b* and *a* are linked with a linear relationship with negative slope which is –0.3348 in the present study. The study of Nogueira et al. (2008) publishes 12 regression equations between height and diameter $H = aD^b$. The analysis of values between *b* and *a* confirms the tendency of linear relationship of negative slope with a value -0.6653 in their case (Fig. 4.4b). The mean value of *b* in the study of Nogueira et al. (2008) is 0.59 with a range between 0.38 and 0.92 which is similar to the results found in this study.



A : This paper input **B : Input data from Nogueira et al. 2008**

Fig. 4.4. Scatter plot showing the relationship between b and a in the height diameter allometric equation with the model ln (H) = a + b ln (D).

4.2 Pan moist tropical regressions

Different authors have attempted to develop general allometric equations which can be used irrespective of site, regions or continent. In practise, when there are species specific regression equations at a given location, it is always advisable to use them. In case of absence of species-specific regressions at a site, mixed-species regressions are the most suitable. General allometric equations are recommended only in case of lack of these equations. Since existing allometric equations developed so far have not included data from Africa, many discussions have been raised concerning their validity in Africa.

We gathered biomass data from different locations (Asia, South America and our own data) and use them to develop general allometric regressions which include data from Africa. We tested many models and selected the best one for different input variables. The analysis of average errors (Table 4.5) shows that the equation of Chave et al. (2005) is the best estimator at different locations. This should be attributed to the large input data set used for the development of this equation. It was difficult to make a general conclusion or classification of general allometric equations. The scatter plot showing errors made by general equations in estimating biomass data at different locations (Fig. 4.5) suggests using these equations at a specific site only on special conditions with care. Before using these allometry regressions, it is necessary to calibrate the relation with at least 5 to 20 biomass tree data from real measurement at the specific site. With these additional site specific data, it can be checked which of the published allometric relationship is suitable for the study site. General allometric regressions developed in this paper with three variables diameter, height and wood density reduces the errors of the estimator. Therefore, we recommend using equation of Chave et al. (2005) or the one developed in this study with 3 variables in case there is no biomass data to test consistency of different estimators.

If diameter, height and wood density are available in forest inventory data, the best general allometry developed in this research is $M = \exp(-2.3778 + 0.2893 (\ln D)^2 - 0.0372 (\ln D)^3 + 0.7415 \ln(D^2H) + 0.2843 \ln(\rho))$. If diameter and height are available in forest inventory data, the best general allometry proposed by this work is $M = \exp(-3.1268 + 0.9885 \ln(D^2H))$. If diameter and wood density are available in forest inventory data, the best general allometry developed here is $M = \exp(-1.2665 + 1.3919 \ln(D) + 0.5477 (\ln D)^2 - 0.0725 (\ln D)^3 + 0.3529 \ln(\rho))$. If only diameter is available in forest inventory data, the best general allometry is M = exp (-2.0815 + 2.5624 ln(D)). Height has shown to be a good explanatory variable across site; therefore general allometric incorporating at least diameter and tree height should be preferred.

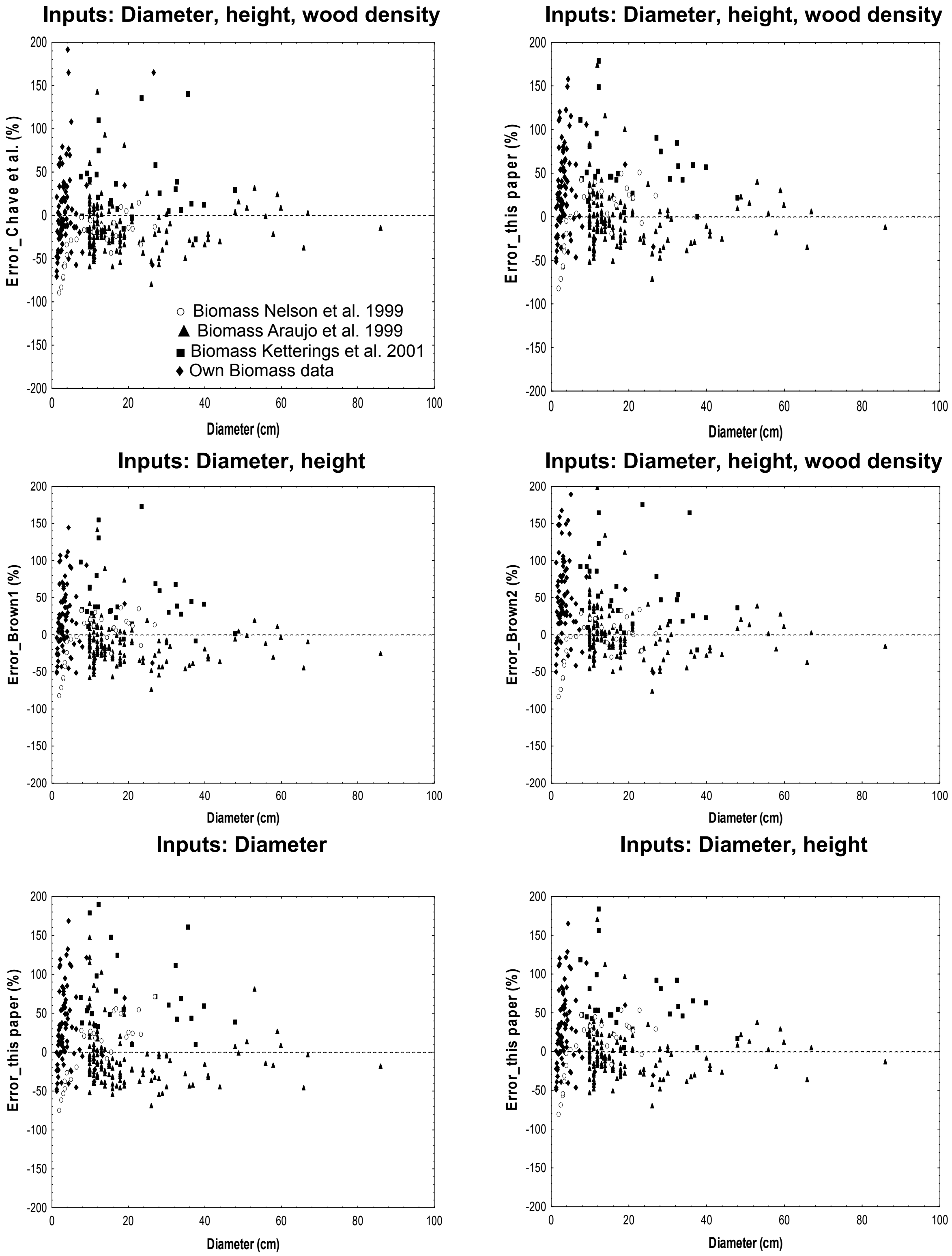


Fig. 4.5. Error of 3 published pan moist tropical equations and 3 equations of this paper to predict total aboveground biomass from different data source. Tendency to underestimate or overestimate is indicated by the distance above or below 0% line.

5. Conclusions

Mixed-species regression equations provide good estimates of total aboveground biomass of the Campo Ma'an forest with an average error of only 7.4% when using only diameter as input variable. Including height in the model has not improved the precision of the model and having the three variable diameter, height and wood density has improved the precision to 3.4%. This study has provided wood density (Table 4.2) and species-specific allometric relationship between height and diameter (Table 4.7) for 31 tree species. They can be used to improve estimations of total aboveground biomass. The regression equations of branches and leaves developed in this study can also be used to estimate total aboveground biomass when inventory data provide estimates of volumes or biomass of trunk of trees.

It should be kept in mind when using allometric equations that many sources of errors are possible. The sources of bias which can create additional errors are the range of observations, the bias of logarithm transformation and data source. The regressions should not be applied beyond the range of observations used to develop the model. Because the distance between for instance 0.1, 1, 10, 100, 1000, 10000 are the same in the logarithm scale, the transformation stretches the smaller trees and compresses the bigger ones. Using logarithm units rather than observation units minimizes the distance of observed values (Nelson et al., 1999). This can be viewed comparing Fig. 4.2,abc with Fig. 4.2d. Many authors state that this bias can be corrected by using the correction factor $CF = \exp(RSE^2/2)$ (Saldarriaga et al., 1988; Chave et al., 2005; Stow et al., 2006). The correction factor of regression equations should be introduced to minimize this bias when back transforming to the normal value for biomass (kg) or heights (m). In many cases of forest inventories, tree diameters and heights are obtained through eye estimations of skilled workers. This can be a source of errors which needs to be considered when applying regression equations.

In the absence of species-specific allometric equations or mixed-species allometric equations at a given site, general allometric equations for moist forests are an appropriate alternative. Although an allometric equation developed by Chave et al. (2005) seems to estimate more precise aboveground biomass at various sites with an average error of 20.3%, followed by the best one developed in this study, it was difficult to draw a general conclusion for the best pan moist tropical allometric equations. It is necessary to have some true biomass values to test and select the general allometric equation which fits much better on the study site. This study provides different pan moist tropical allometric equations which can be used depending on the type of data available.

ESTIMATIONS OF FOREST BIOMASS, CARBON POOLS DISTRIBUTION AND NET PRIMARY PRODUCTION OF A MOIST TROPICAL FOREST

Adrien N. Djomo[1,*], Alexander Knohl[1], Gode Gravenhorst[2]

[1]*Faculty of Forest Sciences and Forest Ecology, Buesgen-Institute, Chair of Bioclimatology, Buesgenweg 2, D-37077 Göttingen, Georg-August-Universität Goettingen, Germany*

[2]*Faculty of Forest Sciences and Forest Ecology, Centre for Tropical and Subtropical Agriculture and Forestry (CeTSAF), Buesgenweg 1, D-37077 Göttingen, Georg-August-Universität Goettingen, Germany*

Abstract

With increasing CO2 in the atmosphere, there is an urgent need of reliable biomass estimates and carbon pools in tropical forests, most especially in Africa where there is a serious lack of data. Information on net primary production (NPP) resulting from direct biomass field measurements is crucial in this context, to know how forest ecosystems will be affected by climate change and also to calibrate eddy covariance measurements. Biomass data were collected from 25 plots of 13 ha spread over the different vegetation types and land uses of a moist evergreen forest of 772 066 ha in Cameroon. With site-specific allometric equations, we estimated biomass and aboveground and belowground carbon pools. We used GIS technology to develop a carbon biomass map of our study area. The NPP was estimated using the growth rates obtained from tree ring analysis. The carbon biomass was on average 264 Mg ha^{-1}. This estimate includes aboveground carbon, root carbon and soil organic carbon up to 30 cm depth. This value varied from 231 Mg ha^{-1} of carbon in Agro-Forests to 283 Mg ha^{-1} of carbon in Managed Forests and to 278 Mg ha^{-1} of carbon in National Park. The carbon NPP varied from 2542 kg ha^{-1} year^{-1} in Agro-Forests to 2787 kg ha^{-1} year^{-1} in Managed Forests and to 2849 kg ha^{-1} year^{-1} in National Park. Our NPP values do not include fine litterfall, carbon losses to consumers and emission of volatile organic compounds. We believe that our study provides not only appropriate estimate of biomass, carbon pools and NPP, but also an appropriate methodology to estimate these components and the related uncertainty.

Keywords: Biomass increment; Carbon pools; Moist tropical forest; Net primary production; Tree rings analysis

1. Introduction

One of the most important environmental threats since the beginning of the industrial era is the increasing mixing ratio of the greenhouse gas carbon dioxide (CO2) in the atmosphere and its effects on climate (Brown et al., 1989; Malhi et al., 1999). The main sources of the accumulation of CO2 in the atmosphere are human induced fossil fuel combustion and land use changes (Le Quéré et al., 2009). Terrestrial ecosystems play an important role in the global carbon cycle and hence modify the atmospheric CO2 mixing ratio as they can act as carbon sink due to net carbon uptake during vegetation growth and as carbon source through deforestation or forest degradation (Schulze, 2006).Forests in the tropics are particularly in focus due to the potential high plant productivity on the one hand and a high level of deforestation and forest degradation as a consequence of land use intensification and population pressure on the other hand. The true level of tropical deforestation and forest degradation and its geographical extend is, however, subject to many debates. The amount of carbon accumulated or released from forest ecosystems in the tropics is poorly quantified (Achard et al., 2004).

The quantity of biomass in a forest ecosystem or a single tree is the result of the production process through photosynthesis and the consumption process through autotrophic and heterotrophic respiration and human activities such as harvest, wildfire and forest clearance for agriculture or settlements (Brown, 1997; Malhi et al., 1999). Because the forest biomass is constituted of about 50 weight % by carbon, information on biomass stocks helps to understand the quantity of carbon that can be released in the atmosphere, when the forest is cleared and/or burned (Brown et al., 1989; Brown, 1997). Quantifying the change of biomass over time can help to understand the amount of carbon fluxes between atmosphere and forests through different processes such as afforestation, reforestation, forest growth and mineralization of organic carbon in the soil.

Net primary production (NPP) of trees which includes photosynthesis and autotrophic respiration and thus represents aboveground and belowground (fine and coarse roots) biomass growth is one of the important components of the carbon budget in tropical forests (Malhi et al., 1999; Clark et al., 2001). The comparison of different biomes of the world (Malhi et al., 1999) shows that the highest NPP occurs in the tropics (Clark et al., 2001). Accurate estimates of NPP from tropical forests are necessary in order to reduce uncertainties in net carbon budgets of the tropics and to provide constraints on global biogeochemical models with data sets from typically underrepresented tropical sites.

One of the difficulties for ecologists is to provide a true estimate of forest biomass and hence of NPP. For instance Fang et al. (1998) state that there is a significant discrepancy between early and recent studies concerning estimations of forest biomass and of carbon emissions and absorptions from forest ecosystems. This difference may be attributed to uncertain data and different methodologies for estimating forest biomass and carbon fluxes (Brown and Lugo, 1982; 1984; Brown et al., 1989; Dixon et al., 1994; Cohen et al., 1996; Brown, 1997; Chave et al., 2004). Early studies derived from direct field measurements on small plots resulted in overestimations of biomass density and pools (Whittaker and Likens, 1973; Lieth and Whittaker, 1975; Busing et al., 1992; Birdsey et al., 1993; Dixon et al., 1994; Siccama et al., 1994). Recent studies derived from forest inventory data provide biomass data at national and regional level (Brown, 1997; Malhi et al., 1999; Nasi et al., 2009). An appropriate methodology for estimating forest biomass is required to reduce uncertainties on carbon estimates. The use of allometric equations to estimate biomass density of large plot inventories is gaining the favour of many ecologists (Brown, 1997; Fang et al., 1998; Houghton et al., 2001; Chave et al., 2004). Allometric equations are relationships between biomass and parameters such as diameter at breast height (dbh), height and wood density of trees, derived from destructive method (harvest and weight different parts of a tree) of representative trees.

Knowing how tropical forests have grown in the past is very important for ecologists. When trees form annual rings, the growth patterns can be used on many ways to assess the past environmental changes (Fichtler et al., 2003). Tree rings, which are physiological responses of trees on seasonal variations of atmospheric parameters, can be used to evaluate tree growth and therefore to estimate the production of individual trees in the forest. Several authors have studied and proved the existence of tree annual rings in the tropics (Worbes, 1999; Dünisch et al., 2002; Fichtler et al., 2003; Worbes et al., 2003; Brienen and Zuidema, 2006) and also in Cameroon (Détienne et al., 1989; Worbes et al., 2003).

Very few studies have attempted to estimate carbon biomass in tropical forests in Africa and particular in Central Africa, even though substantial rates of deforestation and forest degradation were reported. Nasi et al. (2009) estimated between 1990 and 2005 annual deforestation rate of 0.16% corresponding to a total area of 43 000 km2 of forest lost in tropical forests in Central Africa during this period. For the same time, these authors estimated annual forest degradation areas to be 0.09%. In Cameroon, Nasi et al. (2009) estimated annual deforestation areas to be 0.12% and annual forest degradation to be 0.02%. In Africa, most studies estimated biomass from pan allometric equations, i.e. relationships between biomass and stem diameter at breast height, based on biomass data collected outside Africa (e.g Brown et al., 1989; Brown, 1997; Chave et al., 2005). From inventory data collected by the Forest Tropical Technical Centre (CTFT) in 1969, Brown (1997) estimated a total aboveground biomass of 310 Mg ha^{-1} in primary moist forests in Africa. Nasi et al. (2009) estimated an aboveground carbon pool of lowland moist forests in Central Africa of 216 Mg ha–1 from sample plot field data, 126 Mg ha^{-1} from forest inventory data. The total carbon pool of Cameroon is estimated to 5 043 millions tonnes with more than half (3 162 millions tonnes) in lowland moist forests (Nasi et al., 2009).

Geographical Information System (GIS) technology coupled with field information offers a possibility to improve accuracy in estimating biomass and carbon densities and pools in large areas (Roy and Ravan, 1996; Brown, 1997; Magcale-Macandog et al., 2006). GIS allows incorporating different vegetations and other heterogeneity of the landscape such as topography in estimates of carbon pools. It offers therefore a possibility to produce biomass pool maps at local or regional level (Magcale-Macandog et al., 2006). Through this process, the result of ecological features can be extended with more confidence to areas for which there is lack of data.

This study aims (a) to estimate the total aboveground biomass of a moist tropical forest in South-Western Cameroon based on locally developed mixed-species allometric equations (Djomo et al., 2010) and compare the result with other allometric equations (e.g. Brown et al., 1989; Brown, 1997; Chave et al., 2005), (b) to estimate carbon pools and their spatial distribution at the study site, (c) to allocate carbon pools to different land uses and strata using GIS and (d) to estimate the NPP at the study site and compare the values with other investigations.

2. Material and Methods

2.1 Study site

The study was conducted within the Campo-Ma’an area in South Western Cameroon located between latitudes 2°08’33”–2°53’59” N and longitudes 9°49’09”–10°57’17” E. It is an area of 772 066 ha, incorporating a National Park (264 064 ha, 34%), a protected forest (11 968 ha, 1.6%), a forest management zone with five logging concessions (241 809 ha, 31.4%), an agro-forestry area where local population have controlled access for multi-purpose uses (196 155 ha, 25.5%), a rubber and an oil plantation (57 750 ha, 7.5%) and a coastal area (320 ha). The Campo-Ma'an forest is bordered in the western part by the Atlantic Ocean and in the southern part by the river Ntem and Equatorial Guinea. Most of the land is covered by lowland tropical moist forests that extend from Southeast Nigeria to Gabon and the Mayombe area in Congo (Letouzey, 1968; 1985). The area is subdivided in different vegetations types which have been recently described by Tchouto et al. (2009). According to this description, the coastal area (Cosaga, Cosaca, Cosas) is dominated by coastal species. Cosaga is the lowland evergreen forest rich in Caesalpinioideae with Sacoglottis gabonensis, with many more coastal indicator species and less Caesalpinioideae. Cosaca is the evergreen forest rich in Caesalpinioideae, Calpocalyx heitzii and Sacoglottis gabonensis mixes with the coastal forest. Cosas is the vegetation on sandy shorelines. In this study we use only Cosaca for coastal vegetation. Caesalp are lowland evergreen forests rich in Caesalpinioideae. Caesalpcasa are lowland evergreen forest rich in Caesalpinioideae in association with Calpocalyx heitzii and Sacoglottis gabonensis. Mixevergreen is the vegetation dominated by mixed evergreen species. Mixsemideci is the vegetation type dominated by semi-deciduous species. Swamp forest is found along rivers or river basins and is permanently or seasonally inundated (Fig. 5.1).

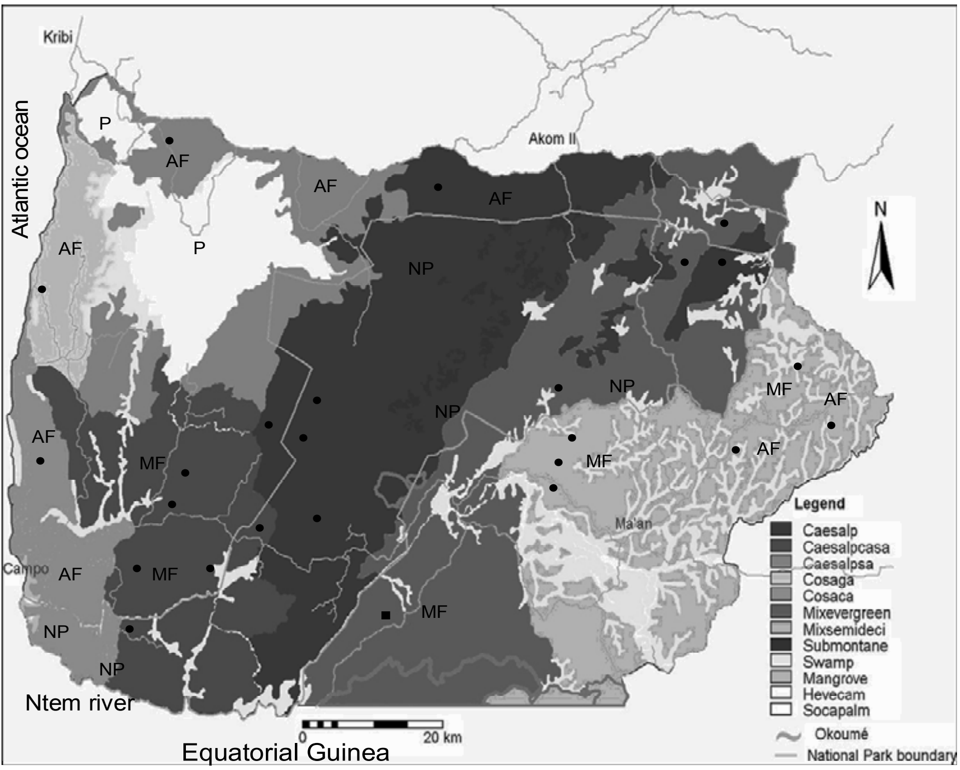


Fig. 5.1. Vegetation map of Campo-ma'an, 24 nested plots of 20 m × 250 m (●), one 100 m × 100 m plot (■) and different land uses (NP, MF, AF, P). NP: National Park; MF: Managed Forests; AF: Agro-Forests, P: Industrial Plantations. For description of the different vegetation units, confer to text. (Source: Adapted Tchouto et al. 2009).

Campo-Ma'an area is situated on the Precambrian shield constituted of metamorphic and volcanic rocks. Metamorphic rocks such as gneisses, migmatites, schists and quartzites dominate the geologic underground in the area. Sedimentary rocks of the Cretaceous can also be found in the Campo basin. The topography ranges from undulating to rolling in the lowland area and to steeply dissect in the more mountainous areas. The western part of the park, which reaches the coast, is generally flat, with altitudes ranging between 0 m and 300 m. In the eastern part, which is quite mountainous, the altitude varies between 400 m and 1100 m and the rolling and steep terrain has more variable landscape (Tchouto, 2009). The climate is typical equatorial with two distinct dry seasons (December-February and June-August) and two wet seasons (March-May and September-November). The average annual rainfall generally ranges between 2950 mm year^{-1} in the coastal area in the western part to 1670 mm year^{-1} in the eastern part. The average annual temperature is about 25°C and there is little variation between seasons and years. The hydrography of the area shows a dense pattern with many rivers, small river basins, fast-flowing creeks and rivers in rocky beds containing many rapids and small waterfalls. The main rivers are Ntem, Lobe, Bongola, Biwome, Ndjo'o, Mvila and Nye'ete. The soil parameters are shown in Table 5.1.

Table 5. 1: Soil parameters of Campo-Ma'an.

	Unit	Agro-Forests		Managed Forests		National Park	
		N	Quantity	N	Quantity	N	Quantity
Ca^{2+}	cmol/kg	6	0.07	4	0.29	1	0.06
Mg^{2+}	cmol/kg	6	0.05	4	0.16	3	0.02
K^+	cmol/kg	6	0.06	4	0.09	3	0.05
Na^+	cmol/kg	6	0.03	4	0.03	3	0.04
S	cmol/kg	6	0.21	4	0.57	3	0.13
T(CEC)	cmol/kg	6	4.15	4	6.71	3	4.20
$Al^{3+}+H^+$	cmol/kg	6	2.00	4	3.16	4	1.46
Bulk density	g cm^{-3}	7	1.21	7	1.31	7	1.23
T. org Matter	%	2	3.65	3	4.43	2	4.56
Org. C.	%	7	1.83	7	2.94	7	1.77
Humidity	%	7	1.41	7	7.34	7	4.10
PH (H_2O)		6	4.22	4	4.43	1	4.10
PH (Kcl)		6	3.65	4	3.98	1	3.90

% in the table refers to weight percentage.

2.2 Biomass data and allometric equations

Biomass data were obtained from felled trees collected in the year 2000 during the main dry season (Ibrahima et al., 2002). Before felling, species were identified and the diameter at breast height (dbh) and height were measured. Trees were felled at ground level with machete or chainsaw according to tree size and split into fractions. The branches, twigs and leaves were separated from the trunk. Sawdust was also collected, weighted and added to the value of each category. Each category was put in a tarpaulin of 2m × 2m which was folded and weighted with a weighting scale (maximum weight 100 kg). Sub samples of each part were collected, weighted fresh in the field with an electronic balance (maximum weight 3 kg). They were oven dried in the lab at 60 °C to obtain the moisture content. The knowledge of moisture content (MC) values of samples enables to deduce the MC in each section of the tree. It was then possible to obtain dry mass of each section of trees using the formula dry weight = fresh weight – moisture weight.

The biomass data was used to develop mixed-species allometric equations for the study site (Table 5.2). These biomass data were also added to 203 tree biomass collected from Asia and South America to develop pan moist tropical regression equations (Djomo et al., 2010). For aboveground biomass estimations and sensitivity analysis, we also selected from literature allometric equations which have been widely used in the past in Central Africa (Brown et al., 1989; Brown, 1997; Chave et al., 2005). These equations known as pan moist tropical allometric equations were derived from biomass collected outside Africa (Djomo et al., 2010). The allometric regressions used for this study are summarized in Table 5.2.

Table 5.2: Allometric regression equations used for aboveground biomass estimations. CF represents the correction factor of each allometric equation, N the number of sample trees.

N°	Allometric equation	Type	N	dbh range	CF
1	$M = \exp(-2.05 + 2.33 \ln(dbh))$.	Site specific	71	1 – 79	1.056
2	$M = \exp(-3.03 + 0.91 \ln(dbh^2H))$	Site specific	71	1 – 79	1.055
3	$M = \exp(-2.29+ 0.17 (\ln dbh)^2 + 0.66 \ln(dbh^2H) + 0.13 \ln(\rho))$	Site specific	71	1 – 79	1.043
4	$M = \exp(-2.36 + 0.29 (\ln dbh)^2 - 0.04 (\ln dbh)^3 + 0.74 \ln(dbh^2H) + 0.28 \ln(\rho))$	Pan moist tropical	274	1 – 138	1.100
5	$M = \exp(-3.11 + 0.97 \ln(dbh^2H))$	Pan moist tropical	168	10 – 130	1.007
6	$M = \exp(-2.41 + 0.95 \ln(dbh^2H\rho))$	Pan moist tropical	168	10 – 130	1.002
7	$M = \exp(-2.98 + \ln(dbh^2H\rho))$	Pan moist tropical	1505	5 – 156	1.051

Sources: Equation : 1 – 4 Djomo et al., 2010; Equation 5 – 6: Brown et al., 1989; Equation 7 : Chave et al., 2005.

2.3 Measurements and calculations

2.3.1 Aboveground carbon pools

The data were collected from 3 different land use types namely the National Park (NP), the Managed Forests (MF) or concession forests and the Agro-forests (AF) including community forests and open access forest areas. In each land use type 8 plots of 20 m × 250 m representing in total 24 plots (12 ha) were used to assess tree species in the different vegetation types present in this area (Fig. 5.1). One plot of 100 m × 100 m (1 ha) was assessed in a concession forest in the eastern part of the study area. In each of the 24 plots, two subplots of 5 m × 20 m and 5 m × 5 m were included (Fig. 5.2). In the plots, all trees with dbh $\geq$ 10 cm were measured. The parameters recorded were species name, dbh, total height, stem quality and the geographical coordinates x and y. In 5 m × 20 m subplot in each of the 24 plots, all trees with dbh between 5 cm and 10 cm were additionally recorded including species name, dbh, and total height. In 5 m × 5 m subplots, all small trees with dbh $<$ 5 cm were counted. For each species found in this subplot, a representative sample was collected, dried, weighted and the root system extracted from the soil and its dry weight measured when it was possible.

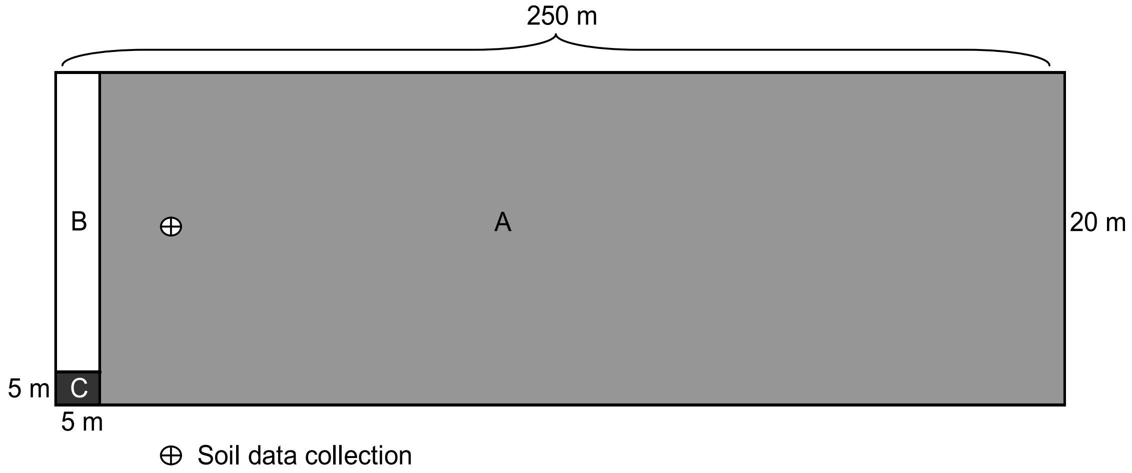


Fig. 5.2. Nested plot design. Compartment A is the entire plot of 20 m × 250 m. Compartment B is a sub-plot of 5 m × 20 m. Compartment C is the sub-plot of 5 m × 5 m. The soil samples are collected at 25 m from the beginning of each plot.

To avoid over or under-estimation of the height of trees which could be hardly seen, a measurement was firstly made on an easily measurable border tree which helped to adjust height estimates.

Visible damage on the stem bole was evaluated using quality classes. Class 1 was used for trees without visible damage or deformation on the stem. Class 2 was used for trees with light damage on the upper part of the stem. Class 3 represents all trees with heavy damage on the stem which reduced its usability. Class 4 stands for very heavy damage making the stem unsuitable for technical use. Class 5 and 5* represent standing dead and fallen dead trees respectively.

To determine the specific wood density, 4 or 5 core samples were collected for each species at breast height. The fresh volume of each sample was estimated using the Archimedes principle which states that at about 4°C a solid immersed in water experiences an upward force equal to the weight of the water it displaces. The wood sample was oven-dried during 48 hours at 75 °C and weighted using an electronic balance. The specific wood density was the arithmetic average value of all samples of a species and was calculated as oven dry weight divided by fresh volume of each sample.

Trees were grouped in diameter classes of width 10 cm except the first and last classes. For example class 2 was constituted by trees of 10 cm ≤ dbh < 20 cm. The first class (1) was constituted by trees of diameter at breast height (dbh) between 5 cm ≤ dbh < 10 cm. The last class (11) was constituted by trees of dbh ≥ 100 cm. The total aboveground biomass (TAGB) was estimated using Eq. 1:

$$TAGB = \sum_{i=1}^{3}\sum_{j=1}^{6}\sum_{k=1}^{11} f(dbh, H, \rho)n_k \qquad (1)$$

where $f(dbh, H, \rho)$ is the allometric regression equation (Table 5.2) relating *dbh*, tree height (*H*), wood density (ρ) to total aboveground biomass (*TAGB*) for each land use class (i = 1, 2, 3), stratum class (j = 1, 2, …., 6), diameter class (k = 1, 2, …., 11) and n_k the number of trees in the class *k*. The biomass density (biomass per ha) (*AGB*) for each forest type was estimated using Eq. 2:

$$AGB = \frac{1}{A}\sum_{i=1}^{3}\sum_{j=1}^{6}\sum_{k=1}^{11} f(dbh, H, \rho)n_k \qquad (2)$$

where *A* is the reference area in hectare. We included in living biomass estimation only trees of quality between 1 and 4. Class 5 and 5* which correspond to stand and fallen dead trees were excluded. For under storey, all trees with dbh < 5 cm, a sample tree was collected oven dried and its biomass weighted. The total biomass of a species in each subplot was therefore obtained by multiplying the weighted biomass by the number of small trees counted in the field for this species in the corresponding subplot.

To estimate carbon content in tree biomass, we collected with stem borer 4 to 5 core samples from each species. Each sample was oven dried at 75 °C during 24 h, ground with a graining mill type MM2 (Retsch GmbH & Co. KG., Haan, Germany), and sub samples were analysed for C-concentration using a CNS Elemental Analyzer (Elementar Vario EL, Hanau, Germany) (Miegriet et al., 2007).

2.3.2 Belowground carbon pools

Soil samples were collected at depth layers of 0 cm to 15 cm and 15 cm to 30 cm, 25 m from the centre of each of the 24 plots. To evaluate bulk density and soil organic carbon (SOC), 3 soil samples were collected at each layer (0 cm to 15 cm and 15 cm to 30 cm) with a cylinder of 5 cm of diameter and 5 cm of length. The parameters PH, bulk density (g cm^{-3}), cation exchange capacity (CEC), weatherable elements (Ca, Mg, P, Fe, Al, Na, etc.), carbon content were analyzed at the soil laboratory of IRAD (Research Institute for Agriculture and Development). Soil samples were oven dried and analyzed for C-concentration using a CNS Elemental Analyzer (Elementar Vario EL, Hanau, Germany). The soil basic parameters of Campo-Ma'an forests are summarized in Table 5.1. The soil organic carbon pool (SOC) in each layer was estimated using Equation SOC = %C × ρ × V where %C is the weight percentage of carbon in this layer, ρ the bulk density of the soil in Mg m^{-3} and V the volume (m^3) of soil per hectare.

To estimate the underground biomass of trees we applied the root to shoot ratio directly measured in the field (dbh ≤ 5 cm). For trees with dbh > 5 cm, we used the root to shoot weight ratio of 0.235 (Mokany et al., 2006; Nasi et al., 2009). The carbon content on root biomass was estimated for each species based on the C concentration obtained with CNS Elemental Analyzer (Elementar Vario EL, Hanau, Germany).

2.3.3 Net Primary production

To evaluate the net primary production (NPP), the equation of Law et al. (2003) was simplified:

$$NPP = NAGC + NBGC \qquad (3)$$

where *NPP* is the net primary production or the net carbon uptake of ecosystem per year, *NAGC* the net aboveground C stock increase rate per year (aboveground sequestration) and *NBGC* the net belowground C stock increase rate per year (belowground sequestration).

NAGC: Net rate of C storage in overstory is a result of net C increment in aboveground parts of living trees. Mean annual biomass growth was estimated from mean annual increment in diameter using tree rings analysis in species (e.g. Fig. 5.3) which have been reported by previous studies to have tree rings in Cameroon (Détienne et al., 1998; Worbes et al., 2003). To estimate the mean annual increment in the forest, 39 sample trees (32 core woods and 7 stem disks) of 9 species were collected in the field. The growth rings were analyzed at the laboratory of North-West German Forest Research Centre in Göttingen Germany. We used an optical lens coupled with a movable table and a desktop to measure the growth rings and register directly the results in the computer. This analysis enables to estimate the mean annual increment in diameter of trees with dbh between 5 cm and 10 cm to be 2.2 mm $year^{-1}$. For trees with dbh ≥ 10 cm we use these mean annual increment in diameter Terminalia Superba (9.5 mm $year^{-1}$), Erythrophleum ivorense (4.4 mm $year^{-1}$), Chlorophora excelsa (6.5 mm $year^{-1}$), Distemonanthus benthamianus (8.9 mm $year^{-1}$), Ceiba pentandra (9.0 mm $year^{-1}$). We also used mean annual increment reported by Détienne et al. (1998) p.30, by De Madron et al. (1998), p.89 and by Worbes et al. (2003). For other tree

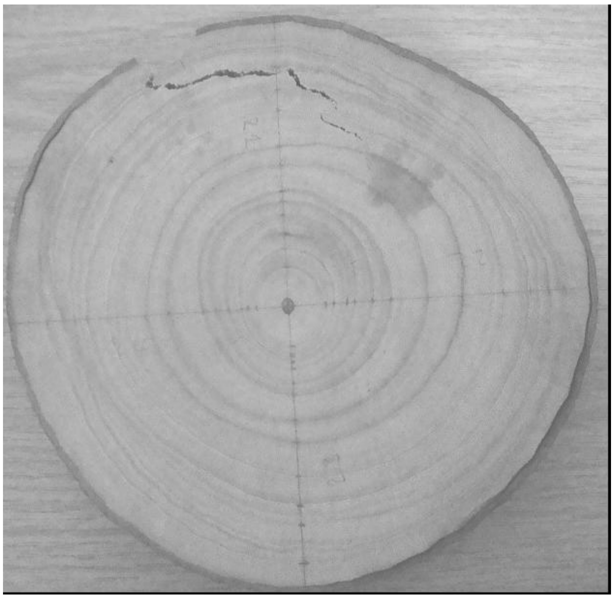


Fig. 5.3. Picture of *Terminalia Superba* showing annual growth rings.

species, which were not studied or reported by previous studies in Cameroon, we used the average mean annual increment in diameter of 5.6 mm year^{-1}. To estimate the total aboveground biomass after one year in each forest category, we used the site-specific allometric equation with only diameter ($D + \Delta D$) as input variable. The yearly biomass change per forest category is therefore obtained through the difference between the biomass estimate after one year and the original biomass. The percentage of carbon content in wood biomass per species was used to obtain the carbon pool and therefore the net carbon increment in the forest. We exclude from analysis class 5 and 5* which are constituted of standing dead and fallen dead trees.

NBGC: The net belowground carbon increment represents the net increase in fine and coarse roots. Since the relationship between roots and shoots biomass is highly explained by a ratio (Mokany et al., 2006), we assumed that the net belowground carbon production also maintains the same ratio with the net aboveground primary production (Nye, 1961; Clark et al., 2001). To estimate the NBGC, we applied the root to shoot ratio measured during this study (c.f. appendix B) to the net aboveground primary production. When there was lack of data, we applied the ratio 0.235 suggested by the study of Mokany et al. (2006).

2.4 Data analysis

All data were analyzed with STATISTICA 9.0 (StatSoft Inc., 1984 – 2009). To account for error associated at different levels (regression equations, nested plots, different land uses and strata) we used the propagation error method which have been proved by several studies to be appropriate for estimating uncertainties of a parameter resulting from different variables associated each with different errors (Winzer, 2000; Chave et al., 2001; Chave et al., 2004). The model used is:

$$s_{\bar{z}} = \sqrt{(a.s_{\bar{x}})^2 + (b.s_{\bar{y}})^2 + (c.s_{\bar{q}})^2 + ...} \tag{4}$$

where $s_{\bar{z}}$, $s_{\bar{x}}$, $s_{\bar{y}}$, $s_{\bar{q}}$… are standard errors associated to variables z, x, y, q and a, b, c coefficients representing the number associated to each variable. The uncertainty of biomass estimate was measured by $s = B \times \sqrt{CF^2 - 1}$ where CF is the correction factor of the regression equation and B the biomass weight (Chave et al., 2004).

The effects of land use and vegetation types on carbon pools and carbon fluxes (NPP) were analyzed using one-way ANOVA. If the effects were significant, means were further analyzed by post hoc comparisons with a confidence level of $p < 0.05$.

2.5 GIS and carbon pools map

The vegetation map (Fig. 5.1) and description of strata of the area were developed by Tchouto (2004) based on phytosociological parameters directly measured in the field such as basal area, relative density, relative dominance, relative frequency, importance value index, forest structure and composition and the canopy position (ground layer, understorey, midstorey, emergent), using the ESRI ArcGIS software package. The vegetation map was used to select sampling investigation plots which were directly assessed in the field for biomass estimations (Fig. 5.1).

The carbon pools map was designed with ESRI ArcGIS 9.3.1 by overlaying the vegetation, topographic maps and other thematic maps (land uses, disturbances, physical features). The carbon pools in various strata of different land uses (National Park, Managed Forest, Agro-Forest) allowed to classify the carbon biomass in 7 classes (1-7) ranging from low to high biomass. Industrial plantations (Hevecam, Socapalm) were first digitized and given the last class value 7 because biomass estimations were not measured in this area. The carbon pools distribution was digitized as polygons using carbon pools classes, topographic features (water, slope), vegetation and land use types to delineate each biomass boundary. For validation of carbon pools distribution, the resulting map and satellite image 2010 Google Earth (Image 2010 Terrametrics, Data SIO NOAA, US. Navy, NGA GEBCO) were overlaid and adjustments were made where it was necessary.

3. Results

3.1 Biomass estimations

The number of stem per hectare decreases considerably from low diameter classes to high diameter classes in the three forest types National Park (NP), Managed Forest (MF) and Agro-Forests (AF) (Table 5.3), confirming inverse J shape frequently encountered in natural forests in the tropics. The number of stem per hectare varies from 323 trees ha^{-1} (AF), 324 trees ha^{-1} (MF) to 330 trees ha^{-1} (NP), showing no significant difference ($p = 0.47$) between the three forest types. We used two regression models $f_1(D) = a \exp(-k D)$ and $f_2(D) = \exp(a \exp(-k D))$ to test the prediction of stem density (trees ha^{-1}) in each forest type. The coefficients a and k for each forest type are shown in Table 5.3.

Table 5.3: Observed and estimated (f_l and f_2) stem number (trees ha^{-1}) per diameter class in Agro-Forests (AF), Managed Forests (MF) and National Park (NP). $f_l(dbh) = a \exp(-k\ dbh)$; $f_2(dbh) = \exp(a \exp(-k\ dbh))$. Values of (a, k) for AF f_l (77.82, 0.101); f_2 (5.26, 0.043). Values of (a, k) for MF f_l (36.53, 0.063); f_2 (4.18, 0.031). Values of (a, k) for NP f_l (45.72, 0.732); f_2 (4.52, 0.034).

DBH	**Agro-Forests**			**Managed Forests**			**National Park**		
[cm]	**Obs.**	**f_1(dbh)**	**f_2(dbh)**	**Obs.**	**f_1(dbh)**	**f_2(dbh)**	**Obs.**	**f_1(dbh)**	**f_2(dbh)**
10-19	184	162	160	156	149	150	166	188	190
20-29	54	78	70	52	79	72	58	68	68
30-39	47	38	39	56	42	43	52	25	35
40-49	16	17	24	31	23	29	27	9	23
50-59	6	5	12	10	10	18	6	3	14
60-69	4	1.7	7	8	5	14	6	0.9	10
70-79	5	0.5	3	4	1.8	8	5	0.3	8
80-89	5	0.2	3	5	0.7	5	4	0.1	6
90-99	3	0.1	2	1	0.1	1.3	2	0.0	5
≥100	2	0.1	5	2	0.1	4	4	0.0	9
Total	**323**	**303**	**324**	**324**	**311**	**344**	**330**	**294**	**367**

Pairwise comparison between measured (observed) stem density (trees ha^{-1}) and estimates f_l and f_2 show no significant difference ($p > 0.09$). f_l underestimates (AF –6%, MF –4%, NP –11%) whereas f_2 overestimates (AF +0.3%, MF +6%, NP +11%). Therefore, the average $f = (f_l+f_2)/2$ of the two estimators is an approximately unbiased estimator of the stem density (trees ha^{-1}).

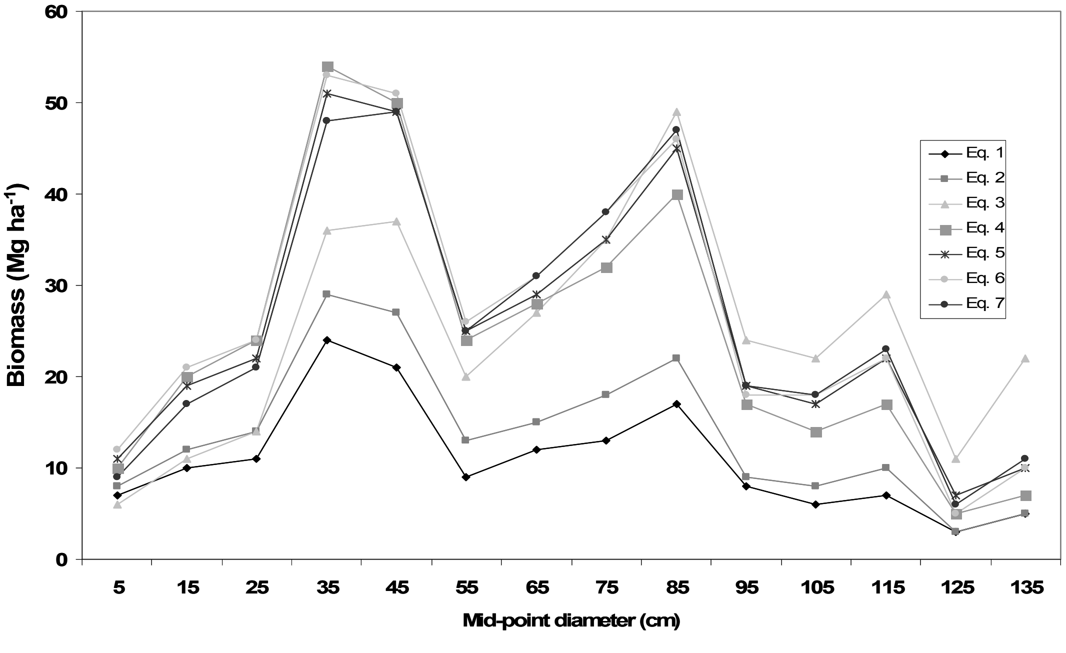


Fig. 5.4. Biomass distribution (Mg ha^{-1}) per diameter class using 7 allometric equations (See Table 5.2). Equations 1-3 are site specific and Equations 4-7 pan moist tropical equations. Equation1 has only diameter as input; Equation2 has diameter and height. For some trees species having same diameter, there was sometimes significant difference in height and wood density.

We used 7 allometric regression equations (Table 5.2) to estimate aboveground biomass for trees with dbh above 5 cm. The 3 first regression equations were obtained through destructive biomass collected from the study site. The other four equations were pan moist tropical equations derived from biomass data coming from different locations in the tropics outside Africa, except equation 4 (Table 5.2). Figure 5.4 shows the distribution of the biomass in each diameter class with each of the 7 allometric regression equations. Equation 1 with only diameter as input parameter gave lowest estimate of the biomass in all diameter classes followed by equation 2 with input parameters diameter and height. Pan moist tropical equations (Equation 4-7) gave higher estimate of the biomass at diameter class less than 80 cm. Above dbh ≥ 80 cm, allometric equation 3 gave highest estimate of the biomass. For some trees species having same diameter, there was sometimes significant difference in height and wood density; this explains high difference in biomass estimations with different allometric equations including different input parameters. Site specific equation 3 integrates diameter height and specific tree density; it estimates more precise biomass up to dbh 80 cm. We used this allometric equation 3 for estimation of biomass of all trees with dbh above 5 cm.

Total aboveground biomass density ranged from 154 Mg ha^{-1} to 375 Mg ha^{-1} (Table 5.4). Equation 3 and 4 predict more or less similar total aboveground biomass with little variations among diameter classes (e.g. dbh between 10 cm and 50 cm and dbh above 80 cm). Trees with dbh above 50 cm (8% of stem density of all trees with dbh above 5 cm) represented more than 51 % of aboveground total biomass regardless of the allometric equation selected, reaching 69 % with equation 3. Except equations 1 and 2 and equations 4 and 5, there was significant difference in biomass estimation between other equations ($p < 0.01$) for trees with dbh between 5 cm and 10 cm. For trees with dbh above 10 cm, there was no significant difference in aboveground biomass estimation between equations 3 and 4 ($p = 0.57$), equations 3 and 5 ($p = 0.06$) equations 5 and 7 ($p = 0.57$). All other pairwise comparison of equations showed significant difference ($p < 0.02$).

Table 5.4: Aboveground biomass density (Mg ha^{-1}) estimated with 7 separate allometric equations.

dbh (cm)	**Eq. 1**	**Eq. 2**	**Eq. 3**	**Eq. 4**	**Eq. 5**	**Eq. 6**	**Eq. 7**
dbh>130	5	4	20	6	9	10	11
80≤ dbh ≤130	42	54	137	92	111	109	113
50≤ dbh <80	34	46	82	85	89	95	95
10≤ dbh <50	67	82	98	147	142	149	135
5≤ dbh <10	7	8	6	10	11	12	9
Total	**154**	**194**	**343**	**340**	**362**	**375**	**363**

The carbon weight content in wood biomass was on average 46.53% with 95% of carbon content varying between 46.49% and 46.57% (Fig. 5.5). The range was between 43.75% and 49.12%.

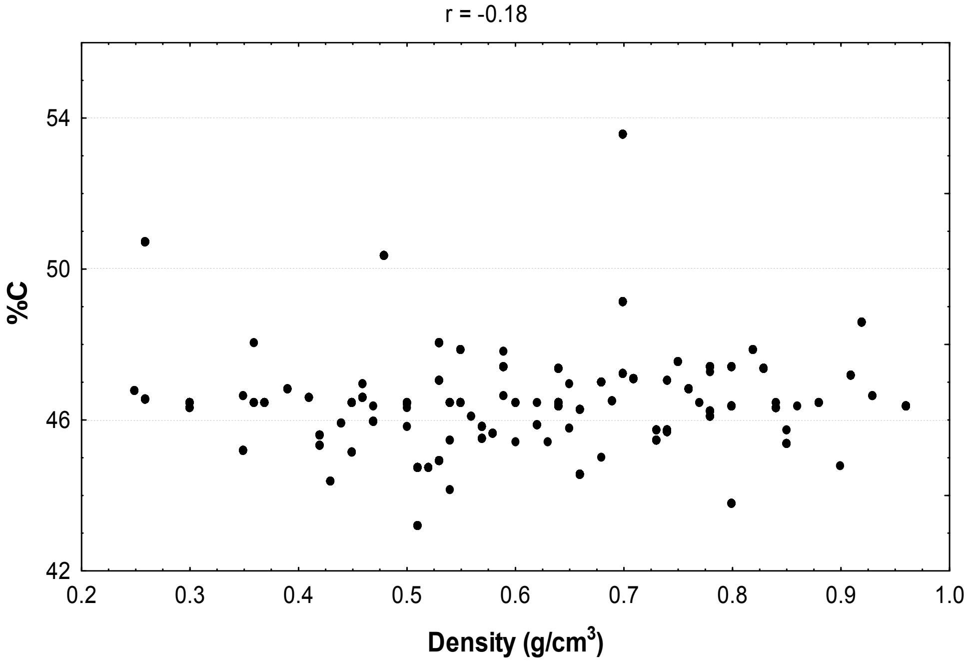


Fig. 5.5. Scatter plot showing the relation between percentage of carbon content in wood biomass and the wood specific density.

3.2 Carbon pools

The total carbon pool in Campo-Ma'an forest was on average 264 Mg ha^{-1}. This estimate includes aboveground carbon, carbon in roots and soil organic carbon up to 30 cm depth. The carbon pool varied from 231 Mg ha^{-1} in AF to 283 Mg ha^{-1} in MF and 278 Mg ha^{-1} in NP. More than 35% of that C was stored in belowground organic soil up to 30 cm depth and fine and coarse roots (Table 5.5). The average carbon pool in live aboveground biomass represented 60% of total carbon biomass, varying from 55% in MF to 62% in AF and 63% in NP. The highest carbon biomass in dead wood was found in MF, 2.6% of total carbon

Table 5.5: Carbon pools (Mg ha^{-1}) distribution in the various land uses and strata of Campo Ma'an forest (2009). N ha^{-1} represents the number of trees per hectare.

Location	Agro-Forests		Managed Forests		National Park		Average ecosystem	
	N ha^{-1}	**Mg ha^{-1}**	**N ha^{-1}**	**Mg ha^{-1}**	**N ha^{-1}**	**Mg ha^{-1}**	**N ha^{-1}**	**Mg ha^{-1}**
1. Overstorey (dbh ≥ 10 cm)								
Caesalpeasa	374	95±32	343	204±88	355	250±86	357	183±61
Cosaca	398	250±84	-	-	-	-	398	250±84
Caesalp	314	148±53	268	86±32	356	131±42	327	126±39
Mixevegreen	268	102±48	-	-	258	172±65	261	149±53
Swamp forest	236	88±39	320	155±51	-	-	292	133±43
Mixsemidec	216	99±48	309	137±42	-	-	286	127±41
All overstorey	**322**	**141±44**	**315**	**152±49**	**326**	**171±54**	**321**	**154±47**
2. Understorey (5≤ dbh <10 cm)								
Caesalpeasa	800	3.2±1.1	300	1.5±0.6	750	3.4±1.3	617	2.7±0.9
Cosaca	450	1.8±0.6	-	-	-	-	450	1.8±0.6
Caesalp	700	2.4±0.8	400	2.4±1.1	725	3.0±1.0	667	2.8±0.9
Mixevegreen	400	2.4±0.8	-	-	800	2.7±0.9	667	2.6±0.8
Swamp forest	400	1.9±0.7	800	5.9±2.4	-	-	667	4.6±1.8
Mixsemidec	500	1.3±0.4	400	1.9±0.7	-	-	425	1.7±0.6
All understorey	**563**	**2.3±0.7**	**475**	**2.9±1.0**	**750**	**3.1±1.0**	**596**	**2.7±0.8**
3. Herbaceous								
Caesalpeasa	4600	1.1±0.45	5800	1.2±0.32	8400	1.6±0.33	6267	1.3±0.21
Cosaca	5600	0.2±0.06	-	-	-	-	5600	0.2±0.06
Caesalp	3200	0.1±0.05	4400	4.0±2.48	5900	0.4±0.06	5400	0.9±0.44
Mixevegreen	3200	0.1±0.03	-	-	4400	0.3±0.05	4000	0.2±0.03
Swamp forest	3200	0.1±0.05	4200	0.5±0.25	-	-	3867	0.4±0.17
Mixsemidec	2000	0.0±0.01	3867	0.2±0.04	-	-	3400	0.1±0.03
All herbaceous	**4000**	**0.4±0.12**	**4500**	**1.0±0.34**	**6150**	**0.7±0.09**	**4883**	**0.7±0.12**
4. Dead trees								
Standing dead	8.5	2.2±0.94	10.1	3.5±1.73	3.5	0.4±0.18	7.4	2.1±0.94
Fallen dead	4.3	1.1±0.37	2.3	3.7±2.48	1.1	2.1±0.84	2.5	3.0±1.44
All dead	**12.8**	**2.2±0.94**	**12.4**	**7.2±3.46**	**4.6**	**2.5±1.38**	**9.9**	**5.2±2.14**
5 Belowground								
roots	4898	34±10	5311	37±12	7230	41±13	5813	37±11
Soil (0-15 cm)		34±3		56±5		34±7		41±4
Soil (15-30 cm)		17±2		27±5		26±6		23±3
Belowground*		**85±11**		**120±14**		**101±16**		**101±12**
Ecosystem		**231±45**		**283±51**		**278±56**		**264±48**

(*) Soil organic carbon is considered up to 30 cm depth.

biomass or 4.6% of total carbon pool in aboveground live biomass. The lowest was found in NP, 0.9% of total carbon biomass or 1.5% of total pool in aboveground live biomass. The carbon pool in trees with dbh < 5 cm represented on average 0.25% of total carbon biomass and 0.43% of total aboveground carbon pool in live biomass.

The soil organic carbon (SOC) decreases top down, from level 0–15 cm to level 15–30 cm in the three land use types and all vegetation types (Table 5.6). The SOC in level 0–15 cm represented 64% and level 15–30 cm represented 36% of total SOC (0–30 cm) which corresponded respectively to 15.5% (0–15 cm) and 8.7% (15–30 cm) of the total carbon pool. The highest SOC was encountered in MF 56 Mg ha^{-1} (0–15 cm) and 27 Mg ha^{-1} (15–30 cm). Table 2 also shows that the highest cation exchange capacity was found in MF followed by NF and AF. The carbon pool in fine and coarse roots represented on average 37% of the total belowground carbon allocation (0–30 cm SOC). It varies from 34 Mg ha^{-1} in AF to 37 Mg ha^{-1} in MF and 41 Mg ha^{-1} in NP.

Table 5.6: Variation of soil organic carbon (SOC) in the various strata of the forest (Mg ha^{-1}).

Location	Agro-Forests	Managed Forests	National Park
Soil (0 – 15 cm)			
Caesalpeasa	36	64	41
Cosaca	32	-	-
Caesalp	33	81	24
Mixevegreen	37	-	46
Swamp forest	27	52	-
Mixsemidec	36	46	-
Soil (15 – 30 cm)			
Caesalpeasa	17	19	21
Cosaca	11	-	-
Caesalp	17	19	20
Mixevegreen	27	-	43
Swamp forest	18	22	-
Mixsemidec	16	38	-

The 2010 Google Earth map (Image, 2010 Terrametrics; Data SIO NOAA; US. Navy; NGA GEBCO) allowed to do corrections on the biomass distribution. The satellite image enabled to see the extent of human disturbance most especially around the settlements. Excluding industrial plantations (Socapalm, Hevecam), the total above and belowground (SOC 0–30 cm) carbon biomass in Campo-Ma'an forest was estimated to be 121 million tonnes C. The carbon distribution of the Campo-Ma'an forest is presented in Figure 5.6. The highest carbon biomass was found in NP and in south eastern part. The lowest carbon biomass was found around the human settlements and also in Managed Forest where there was intensive logging.

3.3 Net primary production

The carbon NPP in overstorey (dbh ≥10 cm) was on average 1977 kg ha^{-1} $year^{-1}$ (Table 5.7). LSD (least significant difference) test shows significant difference in overstorey (dbh ≥10 cm) NPP between AF and MF and between AF and NP ($p < 0.04$). There was no significant difference in overstorey (dbh ≥10 cm) NPP between MF and NP ($p = 0.43$). The highest carbon NPP in overstorey (dbh ≥10 cm) was found in NP, (2041 kg ha^{-1} $year^{-1}$) and the lowest in AF (1852 kg ha^{-1} $year^{-1}$). In understorey, trees with dbh between 5 cm and 10 cm, LSD test shows significant difference in NPP between MF and AF and between MF and NP ($p < 0.001$).

Table 5.7: Carbon Net Primary Productivity (carbon uptake, kg ha^{-1} year^{-1}) distribution in the various land uses and strata of Campo Ma'an forest.

Location	Agro-Forests	Managed Forests	National Park	Average ecosystem
1. Overstorey C uptake (dbh ≥ 10 cm)				
Caesalpeasa	2127±727	2232±771	2521±870	2293±782
Cosaca	2429±835	-	-	2429±835
Caesalp	2065±719	1556±540	2032±694	1958±667
Mixevegreen	1267±452	-	1581±546	1476±508
Swamp forest	1216±429	2386±821	-	1996±685
Mixsemidec	1159±414	1838±628	-	1668±570
Average C uptake	**1852±631**	**2038±694**	**2041±695**	**1977±672**
2. Understorey C uptake (5 ≤ dbh < 10 cm)				
	206±71	**219±75**	**266±91**	**231±78**
3. Belowground C uptake (fine and coarse roots)				
Caesalpeasa	568±172	554±181	649±205	590±185
Cosaca	608±197	-	-	608±197
Caesalp	544±170	411±128	542±165	521±158
Mixevegreen	346±108	-	435±130	406±121
Swamp forest	322±102	657±196	-	545±163
Mixsemidec	307±98	470±148	-	429±135
Average Belowground C uptake				
	484±149	**530±164**	**542±165**	**519±159**
NPP	**2542±652**	**2787±717**	**2849±720**	**2727±695**

There was no significant difference in understorey (dbh between 5 cm and 10 cm) NPP between AF and NP ($p = 0.58$). This is explained by the relation $TOT_{AF} / N_{AF} = TOT_{NP} / N_{NP} \approx \bar{x}_{AF} \approx \bar{x}_{NP}$ where TOT_{AF}, TOT_{NP} (17 kg, 21 kg) are the sum of the yearly carbon uptake of trees in AF and NP, N_{AF}, N_{NP} (45, 60) the absolute number of trees in AF and in NP and $\bar{x}_{AF}$, $\bar{x}_{NP}$ (≈0.4 kg) the mean carbon tree uptake in understorey (dbh between 5 cm and 10 cm) in AF and NP. Interesting was to notice the difference in carbon NPP between AF and NP; the lowest understorey NPP (dbh between 5 cm and 10 cm) was 206 kg ha^{-1} year^{-1} in AF and the highest 266 kg ha^{-1} year^{-1} in NP. On average the aboveground carbon NPP in understorey (dbh 5–10 cm) represented 8% and the belowground NPP of all roots 19% of total NPP.

The total carbon NPP was on average 2727 kg ha^{-1} year^{-1}, varying from 2542 kg ha^{-1} year^{-1} in AF to 2787 kg ha^{-1} year^{-1} in MF and to 2849 kg ha^{-1} year^{-1} in NP (Table 5.7).

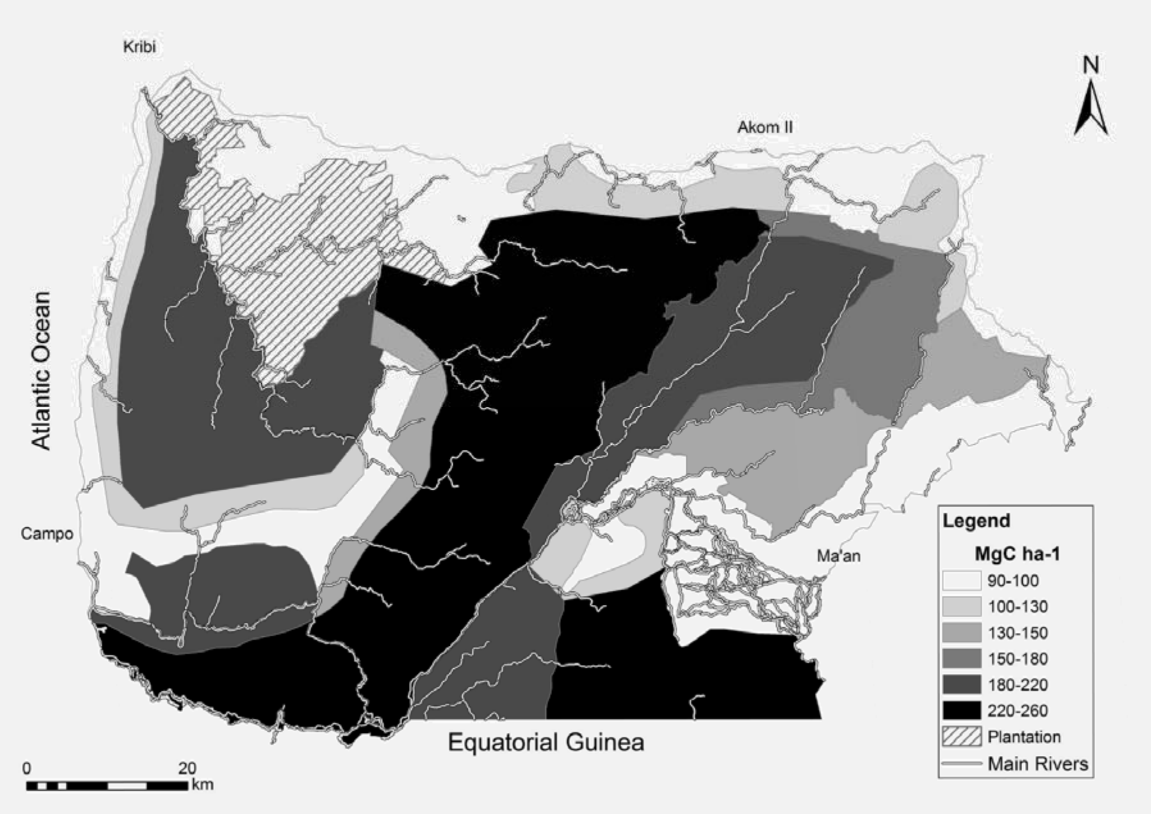


Fig. 5.6. Above and belowground carbon pools distribution in Campo-Ma'an (2009). The soil organic carbon (SOC) is measured up to 30 cm.

4. Discussions

4.1 Measurements, allometry and errors

Biomass, carbon and NPP estimations are always linked with uncertainties and it is important to consider and minimize them as much as possible. One of the potential sources of errors are the uncertainties of field measurements of individual trees (diameter, height and wood density) and tree architecture (Clark et al., 2001), which are later used with the allometric relationships (Chave et al., 2001; Keller et al., 2001; Ketterings et al., 2001; Chave et al., 2004; Chave et al., 2005; Djomo et al., 2010). The measurements of tree diameter, tree height and wood densities are associated with errors σ_D, σ_H and σ_ρ which can be termed in one single error σ_M called measurement error (Chave et al., 2001; Ketterings et al., 2001). For this study, we measured 4342 trees; this large number of trees leads to measurement errors which are normally distributed and have minimal effect on the final biomass determination (Keller et al., 2001).

Another source of errors is plot design and methodology related to establishment. Keller et al. (2001) used the Monte Carlo re-sampling to show that the coefficient of variation decreases with increasing plot size. Chave et al. (2004) stated that the size of one quarter of a hectare is the minimal size for biomass estimations; with this size, AGB can be estimated with an error of about 10%. Our plots, 0.5 ha each, were large enough to minimize plot size error. Small plots, spread across forest are consistent to assess bio-diversity, but should over or underestimate stem density and biomass. For instance Tchouto et al. (2009) with a total sampling area of 14.5 ha (0.1 ha per plot) found in the same forest stem density varying between 489 and 741 trees ha^{-1}. This range is larger than our estimates which vary between 216 and 398 trees ha^{-1}.

Environmental and physical factors such as land topography, vegetation types, climatic gradients can create serious bias on biomass estimates, its carbon content and their extrapolation to the landscape scale (Chave et al., 2004). Several authors (e.g. Clark & Clark, 2000; Keller et al., 2001; Chave et al., 2004) suggest that a total sampling size of roughly 5 ha or 20 plots of 0.25 ha can allow estimation of the AGB with an error of ±10% within 95% confidence. Our study considered 24 plots of 0.5 ha each randomly distributed uniformly along the three land use types. In addition, one other plot of 1 ha making a total of 13 ha was investigated. This sampling enabled to obtain an error of ±6% at the landscape scale.

Allometric equations selected for this study were obtained from the regression of log-transformation. These allometric relations are on the form $\ln(AGB) = \ln(f(D,H,\rho)) + \psi$ where ψ represents the residuals and are normally distributed. Using allometric equations to estimate biomass of trees is always associated with an error $\sigma_A = \sqrt{CF^2 - 1} \times AGB$ derived from the departure between the true biomass and estimation with allometry term as ψ (Brown et al., 1989; Chave et al., 2004; Chave et al., 2005; Djomo et al., 2010). Allometric equation3 used to estimate the biomass and the related carbon pools contributed in the propagated error by about 30%.

For estimation of root biomass of trees (dbh < 5 cm), we used direct method consisting of extracting roots from the soil. Since only sample trees were measured and their root to shoot ratio used to estimate the root biomass of other trees, this method is therefore associated with an error termed σ_r. This error should contribute little on the propagated error because the biomass of this category represented only 0.45% of total root biomass. Above dbh ≥ 5 cm, it was difficult to extract roots from the soil. We used therefore the root to shoot ratio suggested by Mokani et al. (2006) and Nasi et al. (2009). Keller et al. (2001) stated in their study that belowground biomass may contribute to about 20% of total uncertainty of their biomass estimation. We expect that estimation of root biomass from a constant root-shoot ratio will introduce an error which was estimated at 20%.

One of the uncertainties in biomass estimations is the development or selection of the allometric equation which estimates best the biomass of the study area. To choose the best fit for our biomass estimation, we investigated 3 site specific allometric equations and 4 pan-tropical allometric equations (Table 5.2). Chave et al. (2004) studied model selection error for tropical forest biomass and recommended selection of equation which integrates the three parameters diameter, height and wood density. In our case, there was twofold difference in biomass estimate between equation1 with only diameter and Equation 3 which integrates diameter, height and wood density. For this study Equation 3 which integrates diameter, height and wood density, and gives more precise values was choosen for biomass (carbon) estimations. The diameter range for calibration of our allometric equations was between 1 cm and 79 cm. Above this diameter it was difficult to decide which equation to use. Chave et al. (2004) recommended in such situation to choose pan-tropical allometric equation. There were two problems: first, in pan tropical Equation 4 the trees coming from our study site which contributed for calibration of this equation have diameter ranging between 1 cm and 79 cm only. Second, the other three pan-tropical Equations (5–7) were derived with trees all coming outside Africa. We expect that since Equation 3 integrates diameter, height and wood density from the study site, it should be the best fit of dbh above 80 cm. We choose this equation and recommend further study to investigate biomass of larger trees in our study site.

Many studies estimate carbon content in biomass by using a carbon proportion of 50% of dry weight (e.g. Brown and Lugo, 1982; Houghton et al., 2001; Achard et al., 2004), 48% (Malhi et al., 1999) or 47% (Nasi et al., 2009), without giving any specification on how this value was derived. We analysed the carbon content in wood with a CNS analyzer and we found a mean value of 46.53% with 95% of carbon content varying between 46.49% and 46.57%. Van Miegroet et al. (2007) reported in their study the Master thesis of Rose (2000) who estimated the carbon content of 47% in downed coarse wood debris in a spruce-fir forest in USA. Our results was consistent with the ones of Zabek and Prescott (2006) who found in their study a carbon content of 46% (n = 67, sd = 0.2%) in woody material. Ragland and Aerts (1991) studies 11 properties values of hardwood species and found carbon of wood varying between 47% and 50% of dry weight. This range was close to the one of this study (44% – 49%). Using 50% as wood density would have created an overestimation of about 3.5% in our result.

4.2 Biomass and Carbon pools

The aboveground dry biomass of 343 Mg ha^{-1} estimated with equation3 was within the range (245–513 Mg ha^{-1}) of AGB found in moist tropical forests (Malhi et al., 1999; Brown and Lugo, 1982; Brown et al., 1989; Brown, 1997; Chave et al., 2001; Keller et al., 2001; Chave et al., 2004; Nasi et al., 2009). Brown et al. (1989) reported in Cameroon the total aboveground biomass range between 238–314 Mg ha^{-1}. The difference between these values and our result could be due to the minimum size of trees included and the method used for data collection and data analysis. The minimum dbh in their study was 15 cm (5 cm in our case) and they used forest inventory data with commercial biomass and expansion factor to extrapolate the results of total forest biomass.

Estimated aboveground carbon pool for our study site (163 Mg ha^{-1}) was consistent with the range (146–275 Mg ha^{-1}) reported by Nasi et al. (2009) for expected aboveground carbon in lowland moist tropical forests in the Congo basin (Central Africa). Our result was smaller than the value 217 Mg ha^{-1} reported for tropical forests by Malhi et al. (1999) from a study in an evergreen forest in Manaus, Brazil. Achard et al. (2004) coupled remote sensing techniques and biomass densities (Brown, 1997) to estimate carbon pools and fluxes in different biomes in the world. They found in Africa (moist tropical forests) a mean carbon biomass of 143 Mg ha^{-1} with the values ranging between 115–171 Mg ha^{-1} which were consistent with our results.

A linear relationship was found between basal area and aboveground biomass (Fig. 5.7, left). Miguel (2008) found a similar relationship in his study. Introducing individual carbon concentration in biomass maintains the same feature relationship between basal area and aboveground carbon (Fig. 5.7, right), suggesting that a fixed value of carbon concentration 46.5% can be used for all trees. This same feature is also explained by Figure 5.5 which shows that 95% of values vary around the mean carbon content 46.53% of dry biomass, between 46.49% and 46.57%. The relationships found (Fig. 5.7) can be useful for quick estimation of biomass and carbon pools from forest inventories given only basal area as it is often the case in the tropics.

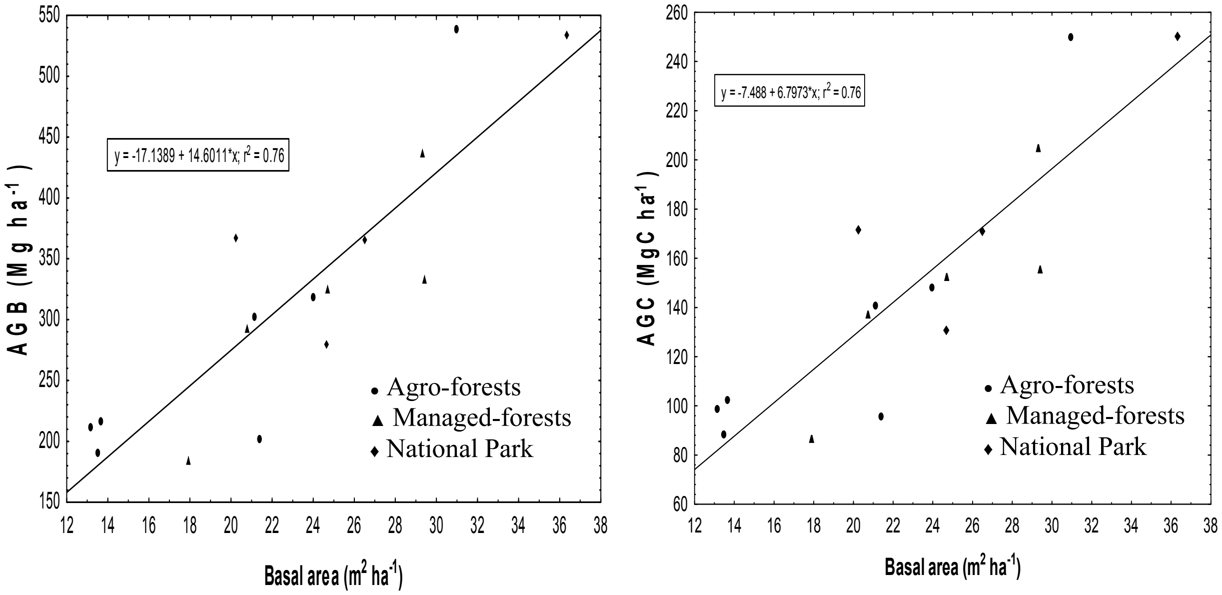


Fig. 5.7. (Left): Linear relationship between basal area (m^2 ha^{-1}) of trees with dbh ≥ 10 cm and total aboveground biomass (Mg ha^{-1}). (Right): Linear relationship between basal area (m^2 ha^{-1}) of trees with dbh ≥ 10 cm and total aboveground carbon (Mg ha^{-1}).

Belowground carbon pool (101 Mg ha^{-1}) for our study site was lower than the value of 120 Mg ha^{-1} reported by the study of Dixon et al. (1994) for belowground carbon in Africa tropical forests during the period 1987–1990. Their study considered the soil organic carbon down to 1m depth (down to 30 cm depth in our study). They also included in their results fine litter which was not considered in our study. Nasi et al. (2009) compiled soil organic carbon from various sources and ecosystems in Congo basin and found a mean value of 38 Mg ha^{-1} (range 35–82 Mg ha^{-1}) which is consistent with our results (Table 5.6). In MF, where the highest SOC was found, there were also higher humidity and cation exchange capacity found. High humidity and cation exchange capacity might explain this high SOC found since moisture and cation exchange capacity play an important role in the determination of organic matter in the soils.

The carbon biomass map resulting from this study (Fig. 5.6) was coherent with the pattern of vegetation types and land uses of the study area. For example, higher carbon biomass classes (4: 150-180 Mg ha^{-1}, 5: 180-220 Mg ha^{-1} and 6: 220-260 Mg ha^{-1}) were mostly found in National Park and Managed Forests and the lowest carbon biomass classes (1: 90-100 Mg ha^{-1}, 2: 100-130 Mg ha^{-1}) were mostly found in Agro-Forests. In Agro-Forest areas far from human settlements, we found also higher carbon biomass e.g class 5 (180-220 Mg ha^{-1}), and it was also coherent with the vegetation types found in the area. No investigation was done within industrial plantations, therefore, there was no value reported for this area. The total carbon stock of 121 million tonnes C found in Campo-Ma'an forests was in accordance with the total carbon stock estimation (3162 million tonnes C) in lowland moist tropical forests in Cameroon by the study of Nasi et al. (2009), considering the Campo-Ma'an area representing about 4% of moist forest in Cameroon.

4.3 Net primary production

The net primary production of forest ecosystems in different biomes across the world are needed for calibration and comparison of NPP estimates obtained from modelling, remote sensing and global inversions (Waring et al., 1998; Fang et al., 1998; Malhi et al., 1999; Clark et al., 2001). For estimating NPP reliable information on tree growth are required, which can be obtained by comparing successive inventories (Lieberman et al., 1985; Lang and Knight, 1983) or by tree rings analysis (Détienne et al., 1989; Worbes et al., 2003). We used in this study the tree growth rings analysis method.

For growth rings measurements, we compared the results of direct binocular (magnification factor between 7 and 10 X) measurements with the ones of indirect measurements trough projection of images of wood samples in the computer screen. Though the two methods gave almost the same results, it was easier to rotate the images on the screen and to follow the ring contour lines which is necessary to detect false rings often found in tropical woods and thus avoid errors. Our growth rates were similar to those found by Détienne et al. (1998) and Worbes et al (2003) in Cameroon. To estimate the growth rate of trees with dbh between 5 cm and10 cm, we counted the number of rings falling into this diameter range. The growth rate at this range was in general smaller than in wider diameter range. The mean growth rate of 2.2 mm year^{-1} was in accordance with the result of successive inventories carried out by Lieberman et al. (1985) (1.8 mm year^{-1}) and by Lang and Knight (1983) (1.7 mm year^{-1}). Similar to our study, their studies show the same trend between smaller and larger diameter tree growth rates.

Estimated aboveground carbon NPP of our study (2208 kg ha^{-1} year^{-1}) was within the range of 300–3800 kg ha^{-1} year^{-1} in other tropical forests (Clark et al., 2001). Our carbon NPP was consistent with the mean 1 900 kg ha^{-1} year^{-1} found within the 39 old growth tropical forests reported by Clark et al. (2001). Malhi et al. (1999) used eddy covariance techniques and biomass inventories to estimate carbon fluxes in forest biomes. They estimated carbon NPP$_a$ (net aboveground carbon biomass increment) to be 1700 kg ha^{-1} year^{-1} and NPP$_b$ (net belowground carbon biomass increment) to be 600 kg ha^{-1} year^{-1} at a tropical forest site (Brazil). Our results do not contradict their findings (Table 5.7). Recent study (Zhao and Running, 2010) has estimated the carbon NPP in our study area to be between 8000 kg ha^{-1} year^{-1} and 10000 kg ha^{-1} year^{-1}. These values are rather high compared to our results. Their method based on NPP algorithm includes in addition leaf production. Our study did not estimate some components of NPP such as fine litterfall, losses to consumers and volatile organic compounds. We did not also consider ingrowths and carbon uptake of trees with dbh below 5 cm.

5. Conclusion

Aboveground carbon pool and NPP were in general higher in the National Park followed by Managed Forests and Agro-Forests. These trends reflect the current management practice (Fig. 5.8).

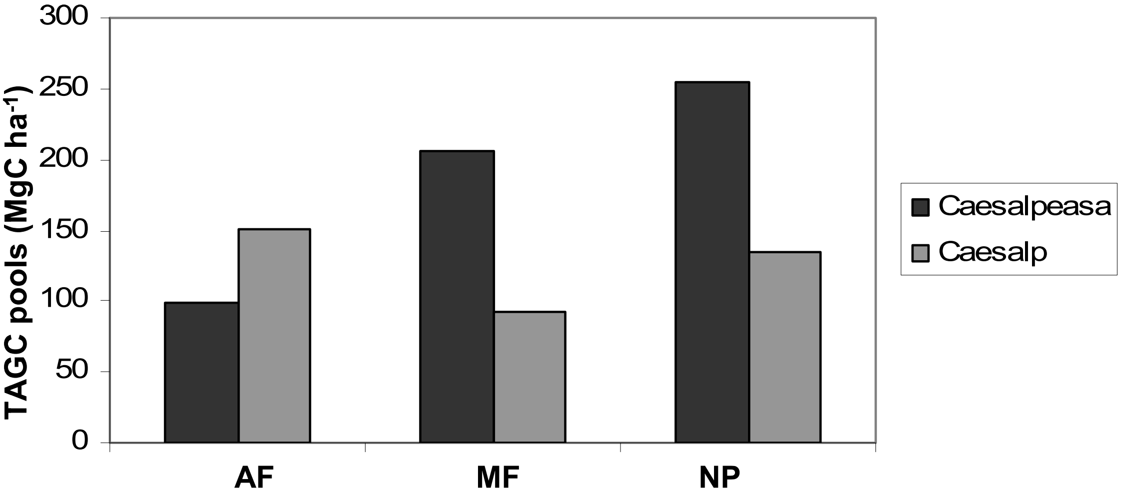


Fig. 5.8. Total aboveground carbon pools (Mg ha^{-1}) in the three land uses (AF: Agro-Forest, MF: Managed Forest, NP: National Park). Caesalpeasa and Caesalp are two vegetation types occurring in Campo-Ma'an forest.

National Park is protected by forest guards who enforce law by preventing human activities and illegal cuttings, even though there are some signs of human activities in the past in some areas. The management practise in Managed Forests is selective logging considering only trees above the minimum felling diameter. The area logged yearly is restricted to a 30th of the concession forests. In Agro-Forests, which are currently an open access area, the uses vary from illegal cutting to clear cutting for agriculture and also community forest management known as community forestry. The low population at some areas and the proximity to ocean where the main activity of most population is fishery, imposes only a low human pressure on the forest thus resulting in high carbon pool in Cosaca. In some places in Managed Forests e.g. Caesalp, where logging activity is particularly high, the aboveground carbon pool was lowest compared to this vegetation type in Agro-Forests and National Park. Overall, our study indicates the strong impact that human activities have on carbon pools and NPP in managed and unmanaged forests in Cameroon.

Summary

Tropical deforestation and forest degradation contributes to more than 20% of the global greenhouse gases emitted. Deforestation and its impacts can be more easily estimated with satellite images. Concerning forest degradation, it is difficult with the actual satellite image resolutions to evaluate accurately logging and biomass damage resulting from this activity though it contributes substantially to carbon emissions in the tropics. With increasing CO2 in the atmosphere, there is an urgent need of reliable biomass estimates and carbon pools in tropical forests, most especially in Africa where there is a serious lack of data.

Moist tropical forests store large amounts of carbon and need accurate allometric regressions for their estimation. In Africa the absence of species-specific or mixed-species allometric equations has lead to a broad use of pan moist tropical equations to estimate tree biomass. This lack of information has raised many discussions on the accuracy of these data, since equations were derived from biomass collected outside Africa. Developing site-specific equations and pan-moist tropical equations including data from Africa is becoming very important for most ecologists for accurate estimations of this contribution extend, necessary for adaptation and mitigation strategies on climate change impacts. Allometric equations are key tools for climate change scenarios since they are used for estimating biomass and carbon pool at local, regional and world level. Information on net primary production (NPP) resulting from direct biomass field measurements of annual tree ring width is crucial in this context, to know how forest ecosystems will grow in the future with their possible impacts on carbon pools and fluxes and also to calibrate eddy covariance measurements.

The overall objective of this study was to provide a scientific contribution for adaptation or mitigation of moist tropical forests on climate change impacts. The specific objectives were to (1) analyze the stand development of a forest in the eastern Cameroon and discuss a methodology for estimating the potential carbon emissions or reductions from forest degradation, (2) develop allometric equations for accurate estimations of biomass and carbon pools in moist forests in Cameroon and also in Africa, (3) estimate carbon pools and Net Primary Productivity (NPP) and their spatial distribution on different strata and land use types of the Campo-Ma'an area forest in Cameroon.

This dissertation presents results from two field studies conducted at the neighbourhood of Yokadouma in the eastern Cameroon and also in the Campo-Ma'an forest

in the southern Cameroon. The study conducted at Yokadouma resulted in a paper addressing forest degradation after selective logging and its implications for REDD and carbon pools and flux estimations. To address this situation, a post-logging stand development of a semi-deciduous natural forest in Cameroon was modelled for one felling cycle (30 years) after selective logging. To simulate how different management practices influence post-logging forest dynamics, we modelled how changes in the minimum felling diameter (MFD) affect stem density, basal area and the related carbon biomass at the end of the felling cycle.

The study conducted in Campo-Ma'an resulted in two other projected articles. The first article addressed site-specific allometric equations and also pan-moist tropical equations which can be used at other locations in moist tropical forests where there are no specific allometric equations. We used for this study 91 destructive sample trees to develop mixed-species allometric equations applying different input variables such as diameter, diameter and height, product of diameter and height, and wood density. Our biomass data were added to 372 biomass data collected across different moist tropical forests in Asia and South America to develop new pan moist tropical allometric regressions. Species-specific and mixed-species height diameter regression equations were also developed to estimate heights using 3833 trees. The second projected article used our site-specific allometric equations to estimate aboveground and belowground biomass and carbon pools. The NPP was estimated using the growth rates obtained from tree ring analysis. A carbon biomass map was also developed in this last paper using GIS technology to show the distribution in the different land uses and vegetation types.

The main findings were the following:

Forest degradation studies:

- With these MFDs estimated, at 7% logging damage rate, we found that the stem density of harvestable trees reduces from 12.3 (50.4 MgC ha^{-1}) to 6.7 (32.5 MgC ha^{-1}) trees per ha and the number of residual trees increases from 80 (18.9 MgC ha^{-1}) to 85.7 (36.8 MgC ha^{-1}) trees per ha. This corresponds to an avoided damage estimated at 17.9 MgC ha^{-1}. We also found that increasing mortality and damage intensity also increases the damage on carbon biomass estimated after a felling cycle of 30 years to be 8.9 MgC ha^{-1} at 10% or to be 17.4 MgC ha^{-1} at 15% logging damage.
- This study shows that proper determination of MFD of logged species taking into consideration their capacity of reconstitution at the end of the felling cycle associated

with Reduced Impact Logging (RIL) can avoid up to 35 MgC ha^{-1}. These estimations could be achieved if there is a combination of Policy and Measures allowing monitoring of forest development after logging.

Allomeric equations

- Using only tree diameter as input variable, the mixed-species regression equation estimates the aboveground biomass of the study site with an average error of ±7.4%. Adding height or wood density did not improve significantly the estimations. Using the three variables together improved the precision with an average error of ±3.4%. For general allometric equations tree height was a good predictor variable. The best pan moist tropical equation was obtained when the three variables were added together followed by the one which includes diameter and height. This study provides height-diameter relationships and wood density of 31 species. The pan moist tropical equation developed by Chave et al. (2005), estimates total aboveground biomass across different sites with an average error of ±20.3% followed by equations developed in the present study with an average error of ±29.5%.

Biomass, carbon, NPP

- The carbon biomass of Campo-Ma'an forest was on average 264 Mg ha^{-1}. This estimate includes aboveground carbon, root carbon and soil organic carbon down to 30 cm depth. This value varied from 231 Mg ha^{-1} of carbon in Agro-Forests to 283 Mg ha^{-1} of carbon in Managed Forests and to 278 Mg ha^{-1} of carbon in National Park. The carbon NPP varied from 2542 kg ha^{-1} $year^{-1}$ in Agro-Forests to 2787 kg ha^{-1} $year^{-1}$ in Managed Forests and to 2849 kg ha^{-1} $year^{-1}$ in National Park. Our NPP values do not include fine litterfall, carbon losses to consumers and emission of volatile organic compounds.

We believe that our study provides not only appropriate estimate of biomass, carbon pools and NPP, but also an appropriate methodology to estimate these components and the related uncertainty.

Résumé

La déforestation et la dégradation des forêts tropicales contribuent à plus de 20% des émissions des gaz à effet de serre. La déforestation et ses impacts peuvent être plus faciles à estimer avec des images satellites. En ce qui concerne la dégradation des forêts, il est difficile avec les résolutions des images satellites actuelles d'évaluer avec précision l'impact de l'exploitation forestière et des dommages résultant de cette activité sur la biomasse bien qu'elle contribue de façon significative aux émissions de carbone sous les tropiques. Avec l'augmentation de CO2 dans l'atmosphère, il y a un besoin urgent d'estimations fiables de la biomasse et de carbone issus des forêts tropicales, surtout en Afrique où il y a un manque crucial de données.

Les forêts tropicales humides stockent de grandes quantités de carbone et nécessitent par conséquent des régressions allométriques précises pour leur estimation. En Afrique, l'absence des équations allométriques spécifiques par essences forestières ou pour des multitudes d'espèces forestières a conduit à une large utilisation des équations générales pour estimer la biomasse des arbres. Ce manque d'information a soulevé de nombreuses discussions sur l'exactitude de ces données, puisque les équations ont été développées à partir des données de biomasses collectées en dehors de l'Afrique. Développer des équations propres à chaque site et des équations générales avec des données en provenance de l'Afrique est devenu très important pour la plupart des écologistes pour obtenir des estimations précises de cette contribution nécessaire pour établir les stratégies d'adaptation et d'atténuation aux impacts des changements climatiques. Les équations allométriques sont des outils essentiels pour établir les scénarios de changement climatique, car elles sont utilisées pour estimer la biomasse et le stock de carbone au niveau local, régional et mondial. Les informations sur la production primaire nette (PPN) résultant de mesures directes de la biomasse à partir des cernes de croissance, sont cruciales dans ce contexte, pour savoir la dynamique de croissance des écosystèmes forestiers dans le futur et leur possible impacts sur les stocks de carbone et aussi pour calibrer les mesures de covariance des turbulences.

L'objectif global de cette étude était de fournir une contribution scientifique pour l'adaptation ou l'atténuation des forêts tropicales humides sur les impacts du changement climatique. Les objectifs spécifiques étaient de : (1) analyser l'évolution du peuplement d'une forêt au Cameroun et de discuter une méthodologie pour estimer les émissions ou les

réductions potentielles de carbone issues de la dégradation des forêts tropicales, (2) développer des équations allométriques pour obtenir des estimations précises de la biomasse et des stocks de carbone des forêts tropicales humides du Cameroun et aussi d'Afrique, (3) estimer les stocks de carbone et la productivité primaire nette (PPN) et leur répartition spatiale sur les différentes strates et les types d'utilisation des terres de la forêt de Campo-Ma'an au Cameroun.

Cette thèse présente les résultats de deux études de terrain menées au voisinage de Yokadouma à l'est du Cameroun et aussi dans la forêt de Campo-Ma'an dans le sud du Cameroun. L'étude menée à Yokadouma a conduit à une dissertation sur la dégradation des forêts tropicales après la coupe sélective et de ses impacts sur les estimations de carbone et du REDD (Réduction des Emissions issues de la Déforestation et la Dégradation Forestière). Pour mener cette étude, la dynamique de croissance après la coupe d'une forêt semi-décidue naturelle au Cameroun a été modélisée pendant un cycle d'abattage (30 ans). Afin de simuler la façon dont différentes pratiques de gestion post-exploitation influencent la dynamique des forêts, nous avons modélisé comment les changements dans le diamètre minimum d'exploitabilité (DME) affectent la densité des tiges, la surface terrière et la biomasse de carbone résultante à la fin du cycle d'abattage.

L'étude réalisée à Campo-Ma'an a abouti à deux autres articles. Le premier article traite les équations allométriques spécifiques au site d'étude et aussi des équations allométriques générales qui peuvent dans d'autres forêts tropicales humides où il n'y a pas d'équations allométriques spécifiques. Cette étude a utilisé 91 échantillons d'arbres abattus pour développer des équations allométriques mixtes en appliquant différentes variables d'entrée telles que le diamètre, le diamètre et la hauteur, le produit du diamètre et de hauteur, et la densité du bois. Nos données sur la biomasse ont été ajoutées à 372 autres données de biomasse recueillies dans différentes forêts tropicales humides en Asie et en Amérique du Sud pour développer de nouvelles équations allométriques générales. Les modèles de régression hauteur - diamètre spécifiques aux espèces et aussi pour des espèces mixtes ont été développés pour estimer la hauteur en utilisant 3833 arbres. Pour le deuxième article nous avons utilisé nos équations allométriques spécifique au site pour estimer la biomasse aérienne et souterraine ainsi que les stocks de carbone. La PPN a été estimée au moyen du taux de croissance obtenus à partir de l'analyse des cernes. Une carte de la biomasse de carbone a également été développée dans ce dernier document en utilisant la technologie du SIG pour visualiser la distribution dans les différentes utilisations des terres et des types de végétation.

Les principales conclusions étaient les suivants:

Dégradation des forêts tropicales:

- Avec les DME estimés dans cette étude, à 7% de dégât d'abattage sur le peuplement, nous avons trouvé que la densité de tiges d'arbres exploitables a été réduite de 12,3 (50,4 MgC ha^{-1}) à 6,7 (32,5 MgC ha^{-1}) arbres à l'ha et le nombre d'arbres résiduels a augmenté de 80 (18,9 MgC ha^{-1}) à 85,7 (36,8 MgC ha^{-1}) arbres par ha. Cela correspond à des dégâts évités estimés à 17,9 MgC ha^{-1}. Nous avons également trouvé qu'en augmentant le taux de mortalité et de dégâts d'abattage sur le peuplement, on augmente également les dégâts sur le stock de carbone à la fin d'un cycle d'abattage de 30 ans estimée à 8,9 MgC ha^{-1} à 10% ou à 17,4 MgC ha^{-1} à 15% de dégâts d'abattage.

- Cette étude montre qu'une bonne détermination de DME des essences exploitées en tenant compte de leur capacité de reconstitution à la fin du cycle d'abattage associée à une exploitation à faible impact (EFI) permet d'éviter jusqu'à 35 MgC ha^{-1}. Ces estimations pourraient être réalisées s'il y a une combinaison de politiques et de mesures permettant un suivi de la dynamique de croissance des forêts après abattage.

Equations Allométriques

- En utilisant seulement le diamètre comme variable d'entrée, l'équation de régression d'espèces mixtes a permis d'estimer la biomasse aérienne du site d'étude avec une erreur moyenne de ±7,4%. L'ajout de la hauteur ou de la densité du bois n'a pas permis d'améliorer de façon significative les estimations. En utilisant les trois variables ensemble (diamètre, hauteur, densité du bois) la précision a été améliorée avec une erreur moyenne de ±3,4%. Pour les équations allométriques générales, la hauteur des arbres a été une bonne variable prédictive. La meilleure équation allométrique générale a été obtenue lorsque les trois variables ont été ajoutées suivie par celles qui utilisent le diamètre et la hauteur. Cette étude a aussi développé des relations hauteur - diamètre spécifiques de 31 espèces et présente aussi la densité du bois de ces espèces. L'équation allométrique générale développée par Chave et al. (2005), estime la biomasse aérienne totale à travers différents sites avec une erreur moyenne de ±20,3%, suivi par les équations développées dans la présente étude avec une erreur moyenne de ±29,5%.

Biomasse, carbone, PPN

- Le stock de carbone dans la forêt de Campo-Ma'an était en moyenne de 264 Mg ha^{-1}. Cette estimation comprend le stock du carbone aérien, des racines et du carbone organique du sol jusqu'à 30 cm de profondeur. Ce stock varie de 231 Mg ha^{-1} de carbone dans les zones Agro-Forestières à 283 Mg ha^{-1} de carbone dans les forêts aménagées et à 278 Mg ha^{-1} de carbone dans le parc national. Le carbone PPN a varié de 2542 kg ha^{-1} an^{-1} dans les zones Agro-Forestières, de 2787 kg ha^{-1} an^{-1} dans les Forêts Aménagées et de 2849 kg ha^{-1} an^{-1} dans le Parc National. Nos valeurs PPN ne comprennent pas la litière forestière fine, les pertes de carbone pour les consommateurs et les émissions de composés organiques volatils.

Nous croyons que notre étude ne fournit pas seulement une estimation appropriée de la biomasse, des stocks de carbone et de PPN, mais aussi une méthodologie appropriée pour l'estimation de ces composantes et des incertitudes relatives.

Zusammenfassung

Tropische Entwaldung und Waldschädigung (Degradation) trägt zu mehr als 20% zu den global emittierten Treibhausgasen bei. Entwaldung und ihre Auswirkungen können leichter mit Satellitenbildern abgeschätzt werden. Was Waldschädigung anbelangt, ist es schwierig, mit den aktuellen Satellitenbild-Auflösungen Abholzung und Biomasse-Schäden, die daraus resultieren, genau zu evaluieren, obwohl Waldschädigung wesentlich zu den Kohlenstoff-Emissionen in den Tropen beiträgt. Mit zunehmendem CO_2-Gehalt in der Atmosphäre besteht ein dringender Bedarf an zuverlässigen Schätzungen von Biomasse und Kohlenstoff-vorräten in den tropischen Wäldern, ganz besonders in Afrika, wo der Datenmangel erheblich ist.

Feuchte Tropenwälder speichern große Mengen an Kohlenstoff und benötigen genaue allometrischen Regressionen für deren Schätzungen. In Afrika hat die Abwesenheit von artspezifischen oder artübergreifenden allometrischen Gleichungen zum breiten Einsatz der pan-feucht-tropischen Gleichungen zur Baum-Biomasse Abschätzung geführt. Dieser Mangel an Informationen hat viele Diskussionen über die Richtigkeit dieser Daten angestoßen, da die Gleichungen aus Biomasse, die außerhalb Afrikas gesammelt wurde, abgeleitet wurden. Die Entwicklung von ortsspezifischen Gleichungen und pan-feucht-tropischen Gleichungen, unter Einschluß von Daten aus Afrika, wird für die meisten Ökologen immer wichtiger, um die genaue Schätzung dieses Beitrags zu erweitern, der für Anpassung und Klimaschutz-Strategien notwendig ist. Allometrische Gleichungen sind Schlüssel-Werkzeuge für die Szenarien des Klimawandels, da sie für die Abschätzung von Biomasse und Kohlenstoff-Pool auf lokaler, regionaler und globaler Ebene verwendet werden. Informationen zur Netto-Primärproduktion (NPP), die sich aus direkten Biomasse Feldmessungen ergeben, sind in diesem Zusammenhang von entscheidender Bedeutung, um zu wissen, wie die Waldökosysteme durch den Klimawandel betroffen sein werden und auch um Eddy-Kovarianz-Messungen zu kalibrieren.

Das übergeordnete Ziel dieser Studie war es, einen wissenschaftlichen Beitrag zur Anpassung oder Schadenseindämmung von feuchten tropischen Wäldern auf die Auswirkungen des Klimawandels zu erstellen. Die spezifischen Ziele waren: (1) Analyse der Bestandesentwicklung eines Waldes im östlichen Kamerun und Diskussion einer Methodik zur Schätzung der potenziellen Kohlendioxidemissionen oder zur Eindämmung von

Waldschäden. (2) Entwicklung allometrischer Gleichungen für die genaue Schätzung der Biomassen und Kohlenstoffvorräte in feuchten Wäldern in Kamerun und auch in Afrika. (3) Schätzung der Kohlenstoffspeicher und der Netto-Primärproduktion (NPP) und ihre räumliche Verteilung auf verschiedene Schichten und Landnutzungstypen des Campo-Ma'an Bereichwaldes in Kamerun.

Diese Dissertation präsentiert Ergebnisse aus zwei Feldstudien, durchgeführt in der Nachbarschaft von Yokadouma im östlichen Kamerun und auch in der Campo-Ma'an Wald im südlichen Kamerun. Die vorliegende, in Yokadouma durchgeführte Studie resultierte in einer Veröffentlichung, die Waldschädigung nach selektivem Holzeinschlag und deren Implikationen für REDD und die Kohlenstoff-Schätzungen ansprach. Um diese Situation anzugehen wurde die Post-logging-Bestandsentwicklung eines semi-natürlichen Laubwaldes in Kamerun für einen Einschlagszyklus (30 Jahre) nach selektivem Holzeinschlag modelliert. Um zu simulieren wie verschiedene Management-Praktiken Einfluss auf die Post-logging-Bestandsdynamik haben, modelliert man, wie Änderungen des Mindest-Einschlagsdurchmessers (MFD) Stammzahlen, Dichte, Grundfläche und die damit verbundene Kohlenstoff-Biomasse am Ende des Einschlagszyklus beeinflussen.

Die in Campo-Ma'an durchgeführte Studie resultierte in zwei weiteren Artikeln. Der erste Artikel behandelt ortsspezifische und auch pan-feucht-tropische allometrische Gleichungen, die auch an anderen Standorten in feuchten tropischen Wäldern, wo es keine spezifischen allometrischen Gleichungen gibt, benutzt werden können. Diese Studie verwendet 91 destruktive Probebäume, um damit artübergreifende allometrische Gleichungen zu entwickeln, und zwar unter Anwendung verschiedener Eingangsgrößen wie Durchmesser, Durchmesser und Höhe, ein Produkt von Durchmesser und Höhe, und Holzdichte. Unsere Biomassedaten wurden zu 372 Biomassedaten aus verschiedenen feuchten tropischen Wälder in Asien und Südamerika hinzugefügt, um damit neue pan-feucht-tropische allometrische Regressionen zu entwickeln. Artspezifische- und artübergreifende Höhen-Durchmesser-Regressionsmodelle wurden auch entwickelt, um Höhen von 3833 Bäumen abzuschätzen. Der zweite Aufsatz verwendet unsere ortsspezifischen allometrischen Gleichungen, um oberirdische und unterirdische Biomasse- und Kohlenstoffvorräte zu schätzen. Die NPP wurde anhand der Wachstumsraten aus Baumringanalysen ermittelt. Eine Kohlenstoff-Biomasse-Karte wurde auch in dieser letzten Arbeit mit GIS-Technologie entwickelt, um Verteilungen der verschiedenen Nutzungen und Vegetationstypen darzustellen.

Die wichtigsten Ergebnisse waren folgende:

Waldschädigungs-Studien:

- Mit diesen geschätzten MFDs ermittelten wir bei 7% Fällungsschadensraten, dass sich die Stamm-Dichte von erntereifen Bäume von 12,3 (50,4 MgC ha^{-1}) auf 6,7 (32,5 MgC ha^{-1}) Bäume pro Hektar reduziert und sich die Zahl der bleibenden Bäume von 80 (18,9 MgC ha^{-1}) auf 85,7 (36,8 MgC ha^{-1}) Bäume pro Hektar erhöht. Dies entspricht einem vermiedenen Schaden von geschätzten 17,9 MgC ha-1. Wir fanden auch heraus, dass eine Erhöhung der Mortalität und Schadensintensität auch die Schädigung der Kohlenstoff-Biomasse erhöht in 30 Jahre, und zwar schätzungsweise auf 8,9 MgC ha^{-1} bei 10% oder auf 17,4 MgC ha^{-1} bei 15% Fällschaden.

- Diese Studie zeigt, dass die korrekte Bestimmung des MFD der gefällten Arten (unter Berücksichtigung ihrer Fähigkeit zur Rekonstitution am Ende des Fällungszyklus im Zusammenhang mit Reduced Impact Logging (RIL)) die Freisetzung von bis zu 35 MgC ha^{-1} vermeiden kann. Diese Schätzungen könnten erreicht werden, wenn eine Kombination von Politik und Maßnahmen erfolgt, die die Überwachung der Waldentwicklung nach dem Einschlag beinhaltet.

Allometrische Gleichungen

- Mit nur dem Durchmesser als Eingangsgröße schätzt das artenübergreifende Regressionsmodell die oberirdische Biomasse des untersuchten Ortes mit einem mittleren Fehler von 7,4%. Hinzufügung von Höhe oder Holzdichte trug nicht wesentlich zur Verbesserung der Schätzungen bei. Mit den drei Variablen zusammen verbesserte sich die Genauigkeit auf einen mittleren Fehler von 3,4%. Für allgemeine allometrische Gleichungen war die Baumhöhe eine gute Prädiktor-Variable. Die beste pan-feucht-tropische Gleichung erhielt man, wenn die drei Variablen hinzugefügt wurden, gefolgt durch jene, die Durchmesser und Höhe umfasste. Diese Studie liefert Höhen-Durchmesser-Beziehungen und Holz dichten von 31 Arten. Die pan-feucht-tropische Gleichung durch Chave et al. (2005) schätzt die gesamte oberirdische Biomasse von verschiedenen Standorte mit einem mittleren Fehler von 20,3%, gefolgt von den in der vorliegenden Studie entwickelten Gleichungen mit einem mittleren Fehler von 29,5%.

Biomasse, Kohle, NPP

- Die Kohlenstoff-Biomasse betrug im Durchschnitt 264 Mg ha^{-1}. Diese Schätzung beinhaltet oberirdischen Kohlenstoff und wurzel-organischen Kohlenstoff des Bodens bis zu 30 cm Tiefe. Dieser Wert variiert von 231 Mg ha^{-1} an Kohlenstoff in Agroforstwäldern bis zu 283 Mg ha-1 an Kohlenstoff in bewirtschafteten Wäldern und bis zu 278 Mg ha^{-1} an Kohlenstoff in einem Nationalpark. Die Kohlenstoff-NPP variierte pro Jahr von 2542 kg ha^{-1} in Agroforstwäldern bis zu 2787 kg ha^{-1} in bewirtschafteten Wäldern und bis zu 2849 kg ha^{-1} Jahr^{-1} im Nationalpark. Unsere NPP Werte beinhalten keine Fein-Streu, Kohlenstoffverluste durch Verbraucher und Emissionen von flüchtigen organischen Verbindungen.

Wir glauben, dass unsere Studie nicht nur die entsprechenden Schätzungen von Biomasse, Kohlenstoff-Pools und NPP liefert, sondern auch eine geeignete Methode darstellt, um für diese Komponenten und die damit verbundenen Unsicherheiten generell Schätzungen zu liefern.

Appendix A: Biomass data of Campo-Ma'an.

For each tree, the local name, the dry wood density, the diameter, the height and the corresponding value of biomass for leaves, branches, trunk, total and expansion factor are reported. The expansion factor is the ratio total biomass to trunk biomass.

N°	Local name	Density g cm^{-3}	Diameter (cm)	Height (m)	Leaves (Kg)	Branches (kg)	Trunk (kg)	Total (kg)	Expansion factor
1	akendeng	0.64	4	6.4	0.13	0.22	3.49	3.85	1.10
2	ako ele	0.65	1.6	3.8	0.07	0.03	0.44	0.55	1.24
3	ako ele	0.65	3	5.4	0.16	0.07	1.12	1.35	1.20
4	awonog	0.5	3.1	5.5	0.11	0.06	1.27	1.44	1.13
5	awonog	0.5	6.3	8.3	0.36	0.43	7.40	8.19	1.11
6	awonog	0.5	2.8	5.2	0.16	0.17	1.24	1.57	1.27
7	awonog	0.5	3.9	6.3	0.28	0.32	2.16	2.75	1.28
8	awonog	0.5	3.5	5.9	0.08	0.10	1.42	1.60	1.13
9	awonog	0.5	2.2	4.6	0.02	0.05	0.66	0.72	1.09
10	awonog	0.5	2.3	4.7	0.06	0.10	0.92	1.08	1.18
11	awonog	0.5	3.7	6.1	0.09	0.13	2.53	2.74	1.08
12	azobe	1.08	2.8	5.2	0.06	0.06	1.80	1.93	1.07
13	dabema	0.73	1.7	3.9	0.01	0.07	0.32	0.41	1.26
14	ebene	1.05	1.3	3.4	0.01	0.01	0.23	0.25	1.08
15	ebene	1.05	1.8	4.1	0.05	0.06	0.33	0.44	1.34
16	ebene	1.05	4.2	6.6	0.06	0.04	2.04	2.14	1.05
17	edon	0.64	2	4.3	0.02	0.02	0.52	0.56	1.08
18	ekong	0.59	2.5	4.9	0.08	0.03	1.11	1.22	1.10
19	ekong	0.59	3.5	5.9	0.05	0.02	2.02	2.09	1.04
20	ekong	0.59	2.6	5	0.05	0.02	0.99	1.07	1.08
21	ekong	0.59	1.2	3.2	0.01	0.00	0.25	0.27	1.05
22	ekong	0.59	3.8	6.2	0.19	0.07	2.57	2.83	1.10
23	ekong	0.59	2.5	4.9	0.07	0.10	0.94	1.11	1.17
24	ekop naga	0.68	5.2	7.4	0.37	0.99	5.11	6.48	1.27
25	endon	0.64	2.2	4.6	0.08	0.11	0.78	0.97	1.24
26	endon	0.64	1.7	3.9	0.04	0.04	0.58	0.65	1.13
27	endon	0.64	4.2	6.6	0.19	0.18	3.10	3.47	1.12
28	essang afan	0.64	2.2	4.6	0.09	0.14	0.73	0.96	1.31
29	etup ngon	0.64	3	5.4	0.02	0.07	1.10	1.18	1.08
30	etup ngon	0.64	2.6	5	0.20	0.23	0.88	1.31	1.49
31	etup ngon	0.64	2.8	5.2	0.29	0.22	0.99	1.50	1.52
32	eveus	0.87	2.8	5.2	0.09	0.08	0.97	1.14	1.17
33	ewolet	0.47	26.7	18.8	3.18	58.00	59.73	120.92	2.02
34	ilomba	0.5	9.1	10.2	0.60	0.99	14.39	15.98	1.11
35	kanda	0.7	3.5	5.9	0.04	0.01	1.87	1.91	1.02
36	keka afan	0.64	2	4.3	0.12	0.05	0.20	0.36	1.84
37	keka afan	0.64	2	4.3	0.05	0.04	0.33	0.42	1.28
38	keka afan	0.64	1.8	4.1	0.04	0.09	0.34	0.47	1.39
39	keka afan	0.64	2.6	5	0.07	0.16	1.07	1.30	1.21
40	keka afan	0.64	2.7	5.1	0.15	0.18	1.02	1.35	1.32
41	keka afan	0.64	1.9	4.2	0.02	0.04	0.62	0.68	1.11
42	keka afan	0.64	2.3	4.7	0.07	0.06	0.57	0.70	1.22
43	keka afan	0.64	3.8	6.2	0.13	0.21	1.37	1.71	1.25
44	keka afan	0.64	3.4	5.8	0.10	0.22	1.79	2.11	1.18

45	keka afan	0.64	2.4	4.8	0.13	0.16	0.71	1.00	1.41
46	keka afan	0.64	3.7	6.1	0.15	0.17	1.83	2.15	1.18
47	keka afan	0.64	2.5	4.9	0.11	0.14	0.95	1.21	1.27
48	keka afan	0.64	3.0	5.4	0.10	0.11	0.95	1.16	1.22
49	Koffi afan	0.64	1.7	3.9	0.11	0.07	0.50	0.68	1.36
50	mbe mvaa	0.64	3.0	5.4	0.02	0.14	1.05	1.21	1.15
51	mfang mvanda	0.52	1.9	4.2	0.07	0.04	0.40	0.51	1.26
52	mfo	0.55	3.5	5.9	0.49	0.35	1.13	1.98	1.74
53	mfo	0.55	4.3	6.7	0.06	0.05	1.85	1.96	1.06
54	miasmigomo	0.64	2.1	4.4	0.03	0.04	0.33	0.39	1.19
55	minsii	0.83	1.9	4.2	0.04	0.05	0.48	0.58	1.20
56	minsii	0.83	2.5	4.9	0.15	0.06	1.95	2.16	1.11
57	minsii	0.83	1.5	3.7	0.03	0.02	0.38	0.43	1.12
58	minsii	0.83	2.8	5.2	0.05	0.02	0.90	0.96	1.07
59	minsii	0.83	5.0	7.3	0.08	0.39	3.20	3.67	1.15
60	niove	0.93	4.7	7.0	0.17	0.21	3.93	4.31	1.10
61	nom ovoe	0.64	1.4	3.5	0.04	0.11	0.36	0.51	1.40
62	nom sikong	0.64	2.2	4.6	0.09	0.07	0.30	0.45	1.53
63	okekela	0.64	7.2	9.0	0.29	0.84	17.86	18.99	1.06
64	ossang mevini	0.73	1.6	3.8	0.03	0.05	0.30	0.39	1.28
65	ossang mevini	0.73	2.8	5.2	0.05	0.08	1.15	1.28	1.12
66	Owoe	0.55	6.3	8.3	0.34	2.66	7.81	10.81	1.38
67	Owoe	0.55	4.0	6.4	0.18	0.26	1.93	2.37	1.23
68	Owoe	0.55	4.8	7.1	0.03	0.03	3.22	3.28	1.02
69	rikio	0.65	2.6	5.0	0.07	0.02	1.13	1.22	1.08
70	sangomo	0.65	19.0	15.5	2.78	4.68	129	136	1.06
71	tali	0.90	79.4	35.0	22.03	969	9054	10045	1.11

Appendix B: Root to shoot ratio (R/S) of shrub, seedlings and grass (Diameter < 5 cm).

N°	Name	Scientific name	Family	Type of plant	N	R/S
1	Asep	*Sphenocentrum jollyanum*	*Menispermaceae*	Shrub	1	0.33
2	Johimbe	*Pausinystalia johimbe*	*Rubiaceae*	Tree	1	0.36
3	Azobe	*Lophira alata*	*Ochnaceae*	Tree	2	0.29
4	*Bidong dong bimo*			Grass	1	0.14
5	Bidou	*Saccoglotis gabonensis*	*Humiriaceae*	Tree	1	0.19
6	Bongo	*Fagara heitzii*	*Rutaceae*	Shrub	1	0.17
7	Ebah			Tree	1	0.31
8	Ebap	*Santiria trimera*	*Burseraceae*	Tree	1	0.47
9	Ebaye	*Pentaclethra macrophylla*	*Mimosoideae*	Tree	1	0.40
10	Ebene sp	*Diospyros sp*	*Ebenaceae*	Tree	5	0.28
11	Ebiara	*Berlinia bracteosa*	*Caesalpinioideae*	Tree	1	0.34
12	Ebom	*Anonidium mannii*	*Annonaceae*	Shrub	1	0.50
13	Eborok			Vine	1	0.40
14	Edip Mbazoa	*Strombosia tetrandra*	*Olacaceae*	Tree	1	0.64
15	Efofoe	*Palisota barteri*	*Commelinaceae*	Grass	2	0.15
16	Ekess	*Acridocarpus Sp.*	*Malpighiaceae*	Shrub	2	0.33
17	Enak	*Anthonotha macrophylla*	*Cealsapiniaceae*	Tree	1	0.54
18	Essoun	*Scorodophloeus zenkeri*	*Caesalpinioideae*	Shrub	2	0.28
19	Eyabe	*Cola ballayi*	*Sterculiaceae*		1	0.35
20	Koltcha			Grass	3	0.56
21	Lomo-Des	*Rhektophyllum kamerunense*	*Araceae*	Grass	3	0.33
22	Mbazoa	*Strombosia scheffleri*	*Olacaceae*	Tree	3	0.31
23	Mbazoa Afum	*Strombosia pustulata*	*Olacaceae*	Tree	2	0.39
24	Mbazoa avie	*Strombosia grandifolia*	*Olacaceae*	Tree	2	0.78
25	Meki mekulu	*Sabicea capitellata*	*Rubiaceae*	Tree	4	0.37
26	Minsi	*Calpocalyx dinklagei*	*Mimosaceae*	Tree	1	0.24
27	Zo'o	*Massularia accuminata*	*Rubiaceae*	Grass	2	0.42
28	Zeng	*Ctenitis Sp.*	*Dryopteridaceae*	Grass	1	0.60
29	Set	*Memecylon afzelii*	*Melastomataceae*	Shrub	1	0.22
30	Seh	*Haumania danckelmaniana*	*Marantaceae*	Grass	6	0.18
31	Otoan	*Polyalthia suavelens*	*Annonaceae*	Tree	3	0.27
32	Mvomba	*Xylopia quintasii*	*Annonaceae*	Tree	2	0.25
33	Nditip	*Lasianthera africana*	*Icacinaceae*	Shrub	2	0.23
34	Ngnia Mvini			Grass	1	0.44
35	Ngollon			Tree	1	0.33
36	Ntom			Tree	1	0.13
37	Okekara lenga	*Palisota Sp.*	*Commelinaceae*	Grass	2	0.19
38	Okwamp			Vine	2	0.25
39	Ole esun	*Afrostyrax kamerunensis*	*Huaceae*	Shrub	1	0.30
40	Onon	*Carpolobia alba*		Shrub	1	0.30
41	Otobessong			Shrub	1	0.30
42	Oveng nkol	*Guirboutia ehie*	*Cealsapiniaceae*	Tree	1	0.43
43	Owe	*Hexalobus crispiflorus*	*Annonaceae*	Tree	1	0.24
	All				75	0.32

References

Aboal, J. R., Arévalo, J.R., Fernández, Å., 2005. Allometric relationships of different tree species and stand above ground biomass in the Gomera laurel forest (Canary Islands). Flora. 200, 264-274.

Achard, F., Hugh, D.E., Mayaux, P., Stibig, H.J., Belward, A., 2004. Improved estimates of net carbon emissions from land cover change in the tropics for the 1990s. Global Biogeochemical Cycles 18, doi:10.1029/2003GB002142.

Akaike, H., 1974. A new look at the statistical model identification. IEEE Transactions on Automatic Control 19 (6), 716-723.

Alder, D. & Silva, J.N.M., 2000. An empirical cohort model for management of Terra Firme forests in the Brazilian Amazon. Forest Ecology and Management 130, 141-157.

Alder, D., 1995. Growth Modelling for Mixed Tropical Forests. Tropical Forestry papers 23. Oxford Forestry Institute, Department of Plant sciences, University of Oxford.

Angelsen, A., 2008. REDD models and baselines. International Forestry Review 10(3), 465-475.

Araújo, T.M., Higuchi, N., Andrade de Carvalho Júnior, J., 1999. Comparison of formulae for biomass content determination in a tropical rain forest site in the state of Para´, Brazil. Forest Ecology and Management 117, 43-52.

Asner, G.P., Keller, M., Pereira, R., Zweede, J.C. & Silva, J.N.M., 2004. Canopy damage and recovery after selective logging in Amazonia: field and satellite studies. Ecological Applications 14, S280-S298.

Baskerville, G.L., 1972. Use of logarithmic regression in the estimation of plant biomass. Canadian Journal of Forest Research 2, 49-53.

Basuki, T.M., van Laake, P.E., Skidmore, A.K., Hussin, Y.A. 2009. Allometric equations for estimating the above-ground biomass in tropical lowland Dipterocarp forests. Forest Ecology and Management 257, 1684-1694.

Bedel, F., de Madron, L.D., Dupuy, B., Favrichon, V., Maitre, H.F., Bar Hen, A., Narboni, P., 1998. Growth dynamics in logged and thinned stands of Africa tropical forest. The case study of M'Baiki in Central African Republic (1982 to 1995). CIRAD Forêt.

Bibani, M.R., Jonkers, W.B.J., 2001. Silvicultural monitoring in permanent sample plots in Ebom forest, southern Cameroon. Seminar proceedings 'Sustainable management of African rain forest', part II: Symposium (eds W.B.J. Jonkers, B. Foahom, & P. Schmidt), pp. 102-111. Tropenbos International, Wageningen, the Netherlands.

Birdsey, R.A., Plantinga, A.J., Heath, L.S., 1993. Past and prospective carbon storage in United States forests. Forest Ecology and Management 58, 33-40.

Bonnie, R., Schwartzman, S., Oppenheimer, M., Bloomfield. J., 2000. Counting the cost of deforestation. Science 288, 1763-1764.

Brienen, R.J.W., Zuidema, P.A., 2006. The use of tree rings in tropical forest management: Projecting timber yields of four Bolivian tree species. Forest Ecology and Management 226, 256-267.

Brown, J.H., West, G.B., 2000. Scaling in Biology. Oxford University Press, New York.

Brown, S., 1997. Estimating biomass and biomass change of tropical forests: A primer. FAO Forestry Paper 134, Rome, p 55.

Brown, S., 2002. Measuring carbon in forests: current status and future challenges. Env. Pollut. 116 (3), 363-372.

Brown, S., Gillespie, A., Lugo, A.E., 1989. Biomass estimation methods for tropical forests with applications to forest inventory data. For Sci. 35, 881-902.

Brown, S., Lugo, A.E., 1982. The storage and production of organic matter in tropical forests and their role in the global carbon cycle. Biotropica 14, 161-187.

Brown, S., Lugo, A.E., 1984. Biomass of tropical forests: a new estimate based on forest volumes. Science 223, 1290-1293.

Bullock, S.H., Heath, D., 2006. Growth rates and age of native palms in the Baja California desert. Journal of Arid Environments 67, 391-402.

Busing, R.T., Clebsch, E.E.C., White, P.S., 1992. Biomass and production of southern Appalachian cove forests reexamined. Canadian Journal of Forest Research 23, 760-765.

Chambers, J.Q., dos Santos, J., Ribeiro, R.J., Higuchi, N., 2001. Tree damage, allometric relationships, and above-ground net primary production in central Amazon forest. Forest Ecology and Management 152, 73-84.

Chave, J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., Fölster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J.-P., Nelson, B.W., Ogawa, H., Puig, H., Riéra, B., Yamakura, T., 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 145, 87-99.

Chave, J., Condit, R., Aguilar, S., Hernandez, A., Lao, S., Perez, R., 2004. Error propagation and scaling for tropical forest biomass estimates. The royal society 359, 409-420.

Chave, J., Condit, R., Lao, S., Caspersen, J.P., Foster, R.B., Hubbell, S.P., 2003. Spatial and temporal variation in biomass of a tropical forest: results from a large census plot in Panama. Journal of Ecology 91, 240-252.

Chave, J., Riéra, B., Dubois, M., 2001. Estimation of biomass in a Neotropical Forest of French Guiana: spatial and temporal variability. Journal of Tropical Ecology 17, 79-96.

Clark, D.A., Brown, S., Kicklighter, D.W., Chambers, J.Q., Thomlinson, J.R., Ni, J., 2001. Measuring net primary production in forests: concepts and field methods. Ecological Applications 11, 356-370.

Clark, D.B., Clark, D.A., 2000. Landscape-scale variation in forest structure and biomass in a tropical rain forest. Forest Ecology and Management 137, 185-198.

Cohen, W.B., Harmon, M.E., Wallin, D.O., Fiorella, M., 1996. Two decades of carbon flux from forests of the Pacific Northwest: estimates from a new modeling strategy. Bio-Science 46, 836-844.

Cole, T., Ewel, J.J. 2006. Allometric equations for four valuable tropical tree species. Forest Ecology and Management 229, 351-360.

Condit, R., 1995. Research in large long-term tropical forest plots. Trends in Ecology and Evolution 10, 18-21.

Condit, R., Hubbell, S.P., Foster, R.B., 1995a. Mortality rate of 205 neotropical tree and shrub species and the impact of a severe drought. Ecological monographs 65, 419-439.

Condit, R., Hubbell, S.P., Foster, R.B., 1995b. Demography and harvest potential of Latin American timber species: data from a large permanent plot in Panama. Journal of Tropical Forest Science 7, 599-622.

Crow, T.R., 1978. Common regressions to estimate tree biomass in tropical stands. Forest Science 24:110-114.

Curran, L.M., Trigg, S.N., McDonald, A.K., Astiani, D., Hardiono, M., Siregar, P., Caniago, I., Kasischke., I., 2004. Lowland forest loss in protected areas of Indonesian Borneo. Science 303, 1000-1003.

Curtis, J.T., McIntosh, R.P., 1951. An upland forest continuum in the prairie-forest border region of Wisconsin. Ecology 32 (3), 476-496.

Davis, S.D., Heywood, V.H., Hamilton, A.C., 1994. Centres of Plant Diversity. A guide and strategy for their conservation. Vol. 1.

Dawkins, H.C., 1961. Estimating total volume of some Caribbean trees. Caribbean Forester 22, 62-63.

de Kam, M., Fines, J.P., Akogo, G., 2002. Schéma Directeur pour le developpement de l'Unité Technique Opérationnelle de Campo-Ma'an, Cameroun. Campo-Ma'an Series 1.

de Madron, L.D., Karsenty, A., Loffeier, E., Pierre, J.M., 1998a. Le Projet d'Aménagement Pilote Intégré de Dimako (Cameroun) (1992-1996). CIRAD-Forêt.

de Madron, L.D., Favrichon, V., Dupuy, B., Bar Hen, A., Houde, L., Maître, H.F., 1998b. Growth and productivity in humid tropical forest: results of experiments in Mopri - Ivory Cost. CIRAD-Forêt.

de Madron, L.D., Favrichon, V., Dupuy, B., Bar Hen, A., Maître, H.F., 1998c. Growth and productivity in humid tropical forest: results of experiments in Irobo - Ivory Cost. CIRAD-Forêt.

DeFries, R., Asner, G., Achard, F., Justice, C., Laporte, N., Price, K., Small, C., Townshend, J., 2005. Monitoring tropical deforestation for emerging carbon markets. In: Moutinho, P. and Schwartzman, S. (Eds): Tropical Deforestation and Climate Change. Amazon Institute for Environmental Research. Ford Foundation. pp. 35-44.

DeFries, R.S., Houghton, R.A., Hansen, M.C., Field, C.B., Skole, D., Townshend, J., 2002. Carbon emissions from tropical deforestation and regrowth based on satellite observations for the 1980s and 90s. Proceedings of the National Academy of Sciences 99, 14256-14261.

Detienne, P., 1989. Appearance and periodicity of growth rings in tropical woods. IAWA Bull. 10, 123-132.

Détienne, P., Oyono, F., de Madron, L.D., Demarquez, B., Nasi, R., 1998. L'analyse de cernes : applications aux études de croissance de quelques essences en peuplements naturels de forêt dense africaine. CIRAD-Forêt, Campus International de Baillarguet. Montpellier, France.

Dixon, R.K., Brown, S., Houghton, R.A., Solomon, A.M., Trexler, M.C., Wisniewski, J., 1994. Carbon pools and flux of global forest ecosystems. Science 263, 185-190.

Djomo, A.N., 2006. Structure and Stand Dynamics of a Moist Evergreen Forest in East Cameroon. Msc. Thesis. Georg-August-University Goettingen.

Djomo, A.N., Ibrahima, A., Saborowski, J., Gravenhorst, G., 2010. Allometric equations for biomass estimations in Cameroon and pan moist tropical equations including biomass data from Africa. Forest Ecology and Management 260, 1873-1885.

Dünisch, O., Bauch, J., Gasparotto, L., 2002. Formation of increment zones and intraannual growth dynamics in the xylem of Swietenia macrophylla, Carapa guianensis and Cedrela odorata (Meliaceae). Iawa Journal 23, 101-119.

Dupuy, B., 1998. Basis for silviculture in humid tropical rainforest of Africa. Project FORAFRI. CIRAD.

Dykstra, D.P., Kowero, G.S., Ofosu-Asiedu, A., Kio, P., 1997. Promotion de l'aménagement forestier dans la zone de forêt tropicale humide d'Afrique occidentale et centrale anglophone. PNUE and CIFOR.

Enquist, B.J., 2002. Universal scaling in tree and vascular plant allometry: toward a general quantitative theory linking plant form and function from cells to ecosystems. Tree Physiology 22, 1045-1064.

Fang, J.Y., Wang, G.G., Liu, G.H., Xu, S.L., 1998. Forest biomass of china: an estimate based on the biomass–volume relationship. Ecological Applications, 8(4), 1084-1091.

Fehrmann, L., Kleinn, C. 2006. General considerations about the use of allometric equations for biomass estimation on the example of Norway spruce in central Europe. Forest Ecology and Management 236, 412-421.

Fichtler, E., Clark, D.A., Worbes, M., 2003. Age and Long-term Growth of Trees in an Old-growth Tropical Rain Forest, Based on Analyses of Tree Rings and $^{14}C^1$. Biotropica 35(3), 306-317.

Finney, D.J., 1941. On the distribution of a variate whose logarithm is normally distributed. Journal of Royal Statistical Society S. 7 (2), 155-161.

Forshed, O., Karlsson, A., Falck, J., Cedergren, J., 2008. Stand development after two modes of selective logging and pre-felling climber cutting in a dipterocarp rainforest in Sabah, Malaysia. Forest Ecology and Management 255, 993-1001.

Forshed, O., Udarbe, T., Karlsson, A., Falck, J., 2006. Initial impact of supervised logging and pre-logging climber cutting compared with conventional logging in a dipterocarp rainforest in Sabah, Malaysia. Forest Ecology and Management 221, 233-240.

Gartlan, J. S., 1989. La conservation des ecosystemes forestiers du Cameroun. IUCN, Gland, Switzeland.

Gerard, J., Guibal, D., Beauchêne, J., Fouquet, D., Langbour, P., Thévenon, M.F., Thibaut, A., Vernay, M., 2009. Technogical characteristics of 245 species. Tropix 6.0 update March 2009. CIRAD.

Goulden, M.L., Munger, J.W., Fan, S.M., Daube, B.C., Wofsy, S.C., 1996. Exchange of carbon dioxide by a deciduous forest: response to interannual climate variability. Science 271, 1576-1579.

Holdsworth, A.R., Uhl, C., 1997. Fire in Amazonian selectively logged rain forest and the potential for fire reduction. Ecological Applications 7, 713-725.

Holmes, T.P., Blate, G.M., Zweede, J.C., Pereira, R.J., Barreto, P., Boltz, F., Bauch, R., 2002. Financial and ecological indicators of reduced impact logging performance in the eastern Amazon. Forest Ecology and Management 163, 93-110.

Houghton, R.A., 2005. Tropical deforestation as a source of greenhouse gas emissions. Tropical Deforestation and Climate Change (eds P. Moutinho & S.Schwartzman), pp. 13-21. Amazon Institute for Environmental Research, Ford Foundation.

Houghton, R.A., Lawrence, K.L., Hackler, J.L., Brown, S. 2001. The spatial distribution of forest biomass in the Brazilian Amazon: a comparison of estimates. Glob Change Biol. 7, 731-746.

Huth, A., Ditzer, T., 2001. Long-term impacts of logging in a tropical rain forest-a simulation study. Forest Ecology and Management 142, 33-51.

Ibrahima, A., Schmidt, P., Ketner, P., Mohren, G.J.M., 2002. Phytomasse et cycle des nutriments dans la foret tropicale dense humide du Sud Cameroun. Tropenbos-Cameroon Documents 9. The Tropenbos Cameroon Programme.

Johns, J.S., Barreto, P., Uhl, C., 1996. Logging damage during planned and unplanned logging operations in the eastern Amazon. Forest Ecology and Management 89, 59-77.

Joosten, R., Schumacher, J.,Wirth, C., Schulte, A., 2004. Evaluating tree carbon predictions for beech (Fagus sylvatica L.) in western Germany. Forest Ecology and Management 189, 87-96.

Kaitaniemi, P., 2004. Testing allometric scaling laws. Journal of Theoretical Biology 228, 149-153.

Keller, M., Palace, M., Hurtt, G., 2001. Biomass estimation in Tapajos National Forest, Brazil examination of sampling and allometric uncertainties. Forest Ecology and Management 154, 371-382.

Kershaw, J.A., Maguire, D.A., 1995. Crown structure in western hemlock, Douglas-fir, and grand fir in western Washington: trends in branch-level mass and leaf area. Canadian Journal of Forest Research 25, 1897-1912.

Ketterings, Q.M., Coe, R., van Noordwijk, M., Ambagu, Y., Palm, C.A., 2001. Reducing uncertainty in use of allometric biomass equations for predicting above-ground tree biomass in mixed secondary forests. Forest Ecology and Management 146, 199-202.

Köhler, P., Ditzer, T., Ong, R.C., Huth, A., 2001. Comparison of measured and simulated growth on permanent plots in Sabah's rain forests. Forest ecology and management 144, 101-111.

Korsun, F., 1948. The height curve. Leśne Prace Badawcze 27 (10/12), 326-337.

Kremen, C., Niles, J.O., Dalton, M.G., Daily, G.C., Ehrlich, P.R., Fay, J.P., Grewal, D., Guillery, R.P., 2000. Economic incentives for rain forest conservation across scales Science 288, 1828-1832.

Lamprecht, H., 1989. Silviculture in the Tropics. Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ), Eschborn, Germany.

Lang, G.E., Knight, D.H., 1983. Tree growth mortality, recruitment and canopy gap formation during a 10 year period in a tropical forest. Ecology 64, 1075-1080.

Law, B.E., Sun, O.J., Campbell, J., Van Tuyl, S., Thornton, P.E., 2003. Changes in carbon storage and fluxes in a chronosequence of ponderosa pine. Global Change Biology 9, 510-524.

Le Quere, C., Raupach, M.R., Canadell, J.G., Marland, G., Bopp, L., Ciais, P., Conway, T.J., Doney, S.C., Feely, R.A., Foster, P., Friedlingstein, P., Gurney, K., Houghton, R.A., House, J.I., Huntingford, C., Levy, P.E., Lomas, M.R., Majkut, J., Metzl, N., Ometto, J.P., Peters, G.P., Prentice, I.C., Randerson, J.T., Running, S.W., Sarmiento, J.L., Schuster, U., Sitch, S., Takahashi, T., Viovy, N., van der Werf, G.R., Woodward, F.I., 2009. Trends in the sources and sinks of carbon dioxide. Nature Geoscience 2(12), 831-836.

Letouzey, R., 1968. Etude phytogeographique du Cameroun. Le Chevalier, Paris.

Letouzey, R., 1985. Notice de la carte phytogéographique du Cameroun, vol. 1-5. Institut de la Carte Internationale de la Végétation, Toulouse.

Li, C.P., Xiao, C.W., 2007. Above- and belowground biomass of Artemisia ordosica communities in three contrasting habitats of the Mu Us desert, northern China. Journal of Arid Environments. 70, 195-207.

Lieberman, D., Lieberman, M., Hartshorn, G., Peralta, R., 1985. Growth rates and age-size relationships of tropical wet forest trees in Costa Rica. Journal of Tropical Ecology 1, 97-109.

Litton, C.M., Kauffman, J.B., 2008. Allometric models for predicting aboveground biomass in two widespread woody plants in Hawaii. Biotropica 40, 313-320.

Madgwick, H.A.I., Satoo, T., 1975. On estimating the aboveground weights of tree stands. Ecology 56, 1446-1450.

Magcale-Macandog, D.B., Delgado, M.E.M., Ty, E., Villarin, J.R.T., 2006. A GIS-based model to improve estimation of aboveground biomass of secondary forests in the Philippines. Journal of Tropical Forest Science 18(1), 8-21.

Malhi, Y., Baldocchi, D.D., Jarvis, P.G., 1999. The balance of tropical, temperate and boreal forests. Plant, Cell and Environment 22, 715-740.

Miguel, C.J., 2008. Aboveground biomass and ecosystem carbon pools in tropical secondary forest growing in six life zones of Costa Rica. PhD thesis dissertation. Oregon State University. USA.

Milton, K., Laca, E.A., Demment, M.W., 1994. Successional patterns of mortality and growth of large trees in a Panamanian lowland forest. Journal of Ecology 82, 79-87.

MINEF., 2000. Procedures of preparation, approval, monitoring and control of management plans for production forest. Ministry of Environment and Forests. Cameroon.

Mokany, K., Raison, J., Prokushkin, A.S., 2006. Critical analysis of root: shoot ratios in terrestrial biomes, Global Change Biology 12, 84-96.

Monserud, R.A., Marshall, J.D., 1999. Allometric crown relations in three northern Idaho conifer species. Canadian Journal of Forest Research 29, 521-535.

Nasi, R., Mayaux, P., Devers, D., Bayol, N., Eba'a Atyi, R., Mugnier, A., Cassagne, B., Billand, A., Sonwa, D.J., 2009. Un aperçu des stocks de carbone et leurs variations dans les forêts du Bassin du Congo. Office des publications de l'Union européenne, Luxembourg 199-216.

Návar, J., 2009. Allometric equations for tree species and carbon stocks for forests of northwestern Mexico. Forest Ecology and Management 257, 427-434.

Návar, J., Nájera, J., Jurado, E., 2002. Biomass estimation equations in the Tamaulipan thornscrub of northeastern Mexico. Journal of Arid Environments 52, 167-179.

Nelson, B.W., Mesquita, R., Pereira, J.L.G., de Souza, S.G.A., Batista, G.T., Couta, L.B., 1999. Allometric regressions for improved estimate of secondary forest biomass in the Central Amazon. Forest Ecology and Management 117, 149-167.

Nepal, S.K., Somers, G.L., 1992. A generalized approach to stand table projection. Forest Science 38, 120-133.

Niesten, E., Frumhoff, P.C., Manion, M., Hardner., J.J., 2002. Designing a carbon market that protects forests in developing countries. Philosophical Transactions: Mathematical, Physical and Engineering Sciences 360, 1875-1888.

Niklas, K.J., 1994. Plant Allometry. In: The Scaling of Form and Process, The University of Chicago Press, Chicago and London.

Niklas, K.J., 2004. Plant allometry: is there a grand unifying theorem? Biological Review 79, 871-889.

Nogueira, E.M., Nelson, B.W., Fearnside, P.M., França, M.B., de Oliveira, A.C.A., 2008. Tree height in Brazil's 'arc of deforestation': Shorter trees in south and southwest Amazonia imply lower biomass. Forest Ecology and Management 155, 2963-2972.

Northup, B.K., Zitzer, S.F., Archer, S., McMurtry, C.R., Boutton, T.W., 2005. Above-ground biomass and carbon and nitrogen content of woody species in a subtropical thornscrub parkland. Journal of Arid Environments 62, 23-43.

Nussbaum, R., Anderson, J., Spencer, T., 1995. Factors limiting the growth of indigenous tree seedlings planted on degraded rainforest soils in Sabah, Malaysia. Forest ecology and management 74, 149-159.

Nye, P.H., 1961. Organic matter and nutrient cycles under moist tropical forest. Plant and Soil 13, 333-346.

Ogawa, H., Yoda, K., Ogino, K., Kira, T., 1965. Comparative ecological studies on three main types of forest vegetation in Thailand. II. Plant Biomass. Nature Life Southeast Asia 4, 49-80.

Olander, L.P., Murray, B.C., Steininger, M. & Gibbs, H. (2006) Establishing credible baselines for quantifying avoided carbon emissions from reduced deforestation and forest degradation. Coalition for Rainforest Nations. NI WP 06-01.

Overman, J.P.M., Witte, H.J.L., Saldarriaga, J.G., 1994. Evaluation of regression models for above-ground biomass determination in Amazon rainforest. Journal of Tropical Ecology 10, 207-218.

Phillips, O.L., Gentry, A.H., 1994. Increasing turnover through time in tropical forests. Science 263, 954-958.

Pilli, R., Anfodillo, T., Carrer, M., 2006. Towards a functional and simplified allometry for estimating forest biomass. Forest Ecology and Management 237, 583-593.

Porté, A., Trichet, P., Bert, D., Loustau, D., 2002. Allometric relationships for branch and tree woody biomass of Maritime pine (Pinus pinaster Ait.). Forest Ecology and Management 158, 71-83.

Putz, F.E., Milton, K., 1982. Tree mortality rate on Barro Colorado Island. The ecology of a tropical forest (eds E.G. Leigh, A.S. Rands, D.M. Windsor), pp. 95-100. Smithsonian Institution Press, Washington, DC.

Ragland, K.W., Aerts, D.J., 1991. Properties of wood for combustion analysis. Bioresource Technology 37, 161-168.

Rose, A.K., 2000. Coarse woody debris and nutrient dynamics in a Southern Appalachian Spruce-fir forest. Msc thesis. University of Tennessee, Knoxville, Tennessee.

Roy, P.S., Ravan, S.A., 1996. Biomass estimation using satellite remote sensing data - An investigation on possible approaches for natural forest. Journal of Biological Sciences 21, 535-561.

Saldarriaga, J.G., West, D.C., Tharp, M.L., Uhl, C. 1988., Long-term chronosequence of forest succession in the upper Rio Negro of Colombia and Venezuela. Journal of Ecology 76, 938–958.

Santilli, M., Moutinho, P., Schwartzman, S., Nepstad, D.C., Curran, L.M., Nobre., C.A., 2005. Tropical deforestation and the Kyoto Protocol: an editorial essay. Climatic Change 71, 267-276.

Santilli, M., Moutinho, P., Schwartzman, S., Nepstad, D.C., Curran, L.M., Nobre., C.A., 2003. Tropical Deforestation and the Kyoto Protocol: a new proposal. Paper presented at COP-9, Milan, Italy.

Schlamadinger, B., Ciccarese, L., Dutschke, M., Fearnside, P.M., Brown, S., Murdiyarso, D., 2005. Should we include avoidance of deforestation in the international response to climate change? In: Moutinho, P. and Schwartzman, S. (Eds): Tropical Deforestation and Climate Change. Amazon Institute for Environmental Research. Ford Foundation. pp. 53-62.

Schulze, E.D., 2006. Biological control of the terrestrial carbon sink. Biogeosciences 3, 147-166.

Schulze, M., Zweede, J., 2006. Canopy dynamics in unlogged and logged forest stands in the eastern Amazon. Forest ecology and management 236, 56-64.

Siccama, T.G., Hamburg, S.P., Arthur, M.A., Yanai, R.D., Bormann, F.H., Likens, G.E., 1994. Corrections to allometric equations and plant tissue chemistry for Hubbard Brook Experimental Forest. Ecology 75, 246-248.

Sist, P., Nguyen-Thé, N., 2002. Logging damage and the subsequent dynamics of a dipterocarp forest in East Kalimantan (1990–1996). Forest ecology and management 165, 85-103.

Skole, D., Justice, C.O., Janetos, A.C., Townshend., J., 1997. A land cover change monitoring program: a strategy for international effort. Mitigation and Adaptation Stategies for Global Change 2, 157-175.

Sprugel, D.G., 1983. Correcting for bias in log-transformed allometric equations. Ecology 64, 209–210.

Stern, N.H., 2006. The economics of climate change: the Stern review. Cambridge: Cambridge University Press.

Stow, C.A., Reckhow, K.H., Qian, S.S., 2006. A bayesian approach to retransformation bias In transformed regression. Ecology 87(6), 1472–1477.

Swaine, M.D., Hall, J.B., Alexander, I.J., 1987a. Tree population dynamics at Kade Ghana (1982-1986). Journal of tropical ecology 3, 331-345.

Swaine, M.D., Liebermann, D., Putz, F.E., 1987b. The dynamics of tree populations in tropical forest: a review. Journal of tropical ecology 3, 359-366.

Tchouto, M.G.P., 2004. Plant diversity in a Central African rain forest: implications for biodiversity conservation in Cameroon. PhD thesis, Wageningen University, Wageningen.

Tchouto, M.G.P., de Wilde, J.J.F.E., de Boer, W.F., van der Maesen, L.J.G., Cleef, A.M., 2009. Bio-indicator species and Central African rain forest refuges in the Campo-Ma'an area, Cameroon. Systematics and Biodiversity 7 (1), 21-31.

Tuomela, K., Kuusipalo, J., Vesa, L., Nuryanto, K., Sagala, A., Ådjers, G., 1996. Growth of dipterocarp seedlings in artificial gaps: an experiment in a logged-over rainforest in South Kalimantan, Indonesia. Forest ecology and management 81, 95-100.

Uhl, C., Barreto, P., Veríssimo, A., Vidal, E., Amaral, P., Barros, A.C., Souza Jr., C., Johns, J., Gerwing, J., 1997. Natural resource management in the Brazilian Amazon. Bioscience 47, 160-168.

Van der Meer, P.J., Bongers, F., 1996. Patterns of trees-fall and branch-fall in a tropical rain forest in french Guiana. Journal of ecology 84, 19-29.

van Laar, A., Akça, A. 1997. Forest Mensuration. Goettingen.

Van Miegroet, H., Moore, P.T., Tewksbury, C.E., Nicholas, N.S., 2007. Carbon sources and sinks in high-elevation spruce–fir forests of the Southeastern US. Forest Ecology and Management 238, 249-260.

Waring, R.H., Landsberg, J.J., Williams, M., 1998. Net primary production of forests: a constant fraction of gross primary production? Tree Physiology 18, 129-134.

West, G.B., Brown, J.H., Enquist, B.J., 1997. A general model for the origin of allometry scaling laws in biology. Science 276, 122-126.

West, G.B., Brown, J.H., Enquist, B.J., 1999. A general model for the structure and allometry of plant vascular systems. Nature 400, 664-667.

White, F., 1983. The vegetation of Africa. A descriptive memoir to accompany the Unesco/AETFAT/ UNSCO vegetation map of Africa. UNESCO.

Winzer, P.J., 2000. Accuracy of error propagation exemplified with ratios of random variables. Review of scientific instruments 71 (3), 1446-1454.

Wirth, C., Schumacher, J., Schulze, E.-D., 2003. Generic biomass functions for Norway spruce in central Europe-a meta-analysis approach toward prediction and uncertainty estimation. Tree Physiology 24, 12-139.

Worbes, M., 1999. Annual growth rings, rainfall-dependent growth and long-term growth patterns of tropical trees from the Caparo Forest Reserve in Venezuela. Journal of Ecology 87, 391-403.

Worbes, M., Staschel, R., Roloff, A., Junk, W.J., 2003. Tree ring analysis reveals age structure, dynamics and wood production of a natural forest stand in Cameroon. Forest Ecology and Management 173, 105-123.

Xiao, C.W., Ceulemans, R., 2004. Allometric relationships for below- and aboveground biomass of young Scots pines. Forest Ecology and Management 3, 177-186.

Yandle, D.O., Wiant, H.V., 1981. Estimation of plant biomass based on the allometric equation. Canadian Journal of Forest Research 11, 833-834.

Zabek, L.M., Prescott, C.E., 2006. Biomass equations and carbon content of aboveground leafless biomass of hybrid poplar in Coastal British Columbia. Forest Ecology and Management 223, 291-302.

Zhao, M., Running, S.W., 2010. Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. Science 329, doi:10.1126/science.1192666.

Zianis, D., Mencuccini, M. 2004. On simplifying allometric analyses of forest biomass. Forest Ecology and Management. 187, 311-332.

Acknowledgement

My PhD studies have been made with a lot of difficulties. I took these as a personal challenge and it has been a long battle to go up to the end. The presented work would not have been possible without numerous supports…

Alexander Knohl. I was without scholarship when he arrived at the institute. With his struggle, I finally obtained the financial support of the Ulrich Stiftung foundation. I am also particularly grateful to his scientific guidance, comments, the encouragements and the possibilities he gave me to present my work at international conferences.

Uschi Seele. Uschi has been wonderful not only for assisting me on myriad of administrative challenges, but also and mostly because she was always there during my difficult periods seeking to provide me with all the necessary support.

Simone Saure. At the time I was scholar with KAAD, Mme Saure was considered as my mother. She put at my disposal all what was necessary for the success of my work. I am grateful for all what she did for me.

Financial support. This work would not have been possible without the financial support of these institutions: WWF Kudu Zombo supported my field work with the grant WWFCCPO/KZ/GRANT/FY09/020/TNM/GAN/nep. Katholisher Akademischer Ausländer Dienst (KAAD) has supported my PhD study for two years. Ulrich Stiftung foundation supported the last part of my thesis with a special grant for all my submitted manuscripts.

Gode Gravenhorst. He has been very helpful for his scientific guidance, critical and engaged discussions which help to improve the quality of this work.

Joachim Saborowski. I am particularly grateful for the brilliant remark he gave me which help to improve this work on allometric equations.

Katherine Korus. She was very helpful when I had an accident. She also helped for GIS design of biomass map. I'm grateful for all the time she devoted for me.

Putz Francis E. Since we met at a conference in the Netherlands he has been helping me with many positives information for the success of my study. He puts me in contact with one of his student Vincent Medjibe whom I consider now as a brother.

Ralph Mitlöhner. Thanks to the scientific contribution he gave at the beginning of this study.

Research groups. My thanks are extended to the research group of Tropical Silviculture and Forest Ecology for their valuable comments on sampling design and methodology. The atmosphere has been very nice in Bioclimatology and was helpful for the work. I am particularly grateful to my office mate Mr. Heiner for his easy understanding.

My field assistant. The work was done in most cases on remote areas and difficult conditions. They have been able to the challenge. I am grateful for their courage and engagement.

Field study. We also thank the forest companies SCIEB and WIJMA who accepted studies at their site. Our thanks are extended to the staff of the forest conservation. They provide to me the administration facilities needed for field study.

My thanks are extended to the Cameroon community of Göttingen for their support especially during the death of my father. My special thanks are extended to Suzanne Bünte for all her support throughout this study. Special thanks to my close friend Lawrence Fu.

My special thanks are extended to my close family (my wife Djouakep Sylvie and my children) who understand that I could stay away for this study. My thanks are extended to my brothers who have been very supportive during this study.

This work is dedicated to my late father.

DECLARATION OF HONOR

I hereby declare that I am the sole author of this dissertation entitled “Ecological management of tropical forests: Implications on climate change and carbon fluxes”. All references and data sources that were used in the dissertation have been appropriately acknowledged. I furthermore declare that this work has not been submitted elsewhere in any form as part of another dissertation procedure.

Goettingen, November, 2010 ______________________________

(Adrien Djomo Njepang)

CURRICULUM VITAE

Adrien Djomo Njepang

adriendjomo@yahoo.com

Education

- 04. 2009 – 11. 2010	PhD study, Institute of Bioclimatologie.
- April 2007- April 2009	PhD study, Institute of Silviculture, Dept. of Tropical Silviculture, University of Göttingen
- 2004 - 2006	MSc in Tropical and International Forestry, University of Göttingen, Germany
- 1999 - 2002	Certificate in Organization Development, GTZ,SAAP
- 1989 - 1992	BSc Forest sciences and Forest exploitation, ENSET, University of Douala, Cameroon

Working Experience

1992-2004	Lecturer of forest sciences and forest management in Government Technical High School in Cameroon
1995-2004	Director of CEDEFE (Centre for Forest Development and Environment)
2004	One month coordination of survey operation in the forest operation unit belonging to TAGETIO & SONs.
	Two months coordination of delimitation and elaboration of management plan for the Forest Unit 10 022 (35 000 ha) belonging to the forest company "Ingénierie Forestière".
	Four months project leader of socio - economic studies in the villages surrounding the Forest Unit 10 062 (160 000 ha) belonging to forest company PANAGIOTIS MARELIS in Eastern Cameroon
2003	Four months project leader of forest inventory and socio-economic studies in the Forest Unit 10 022 (35 000 ha) belonging to the forest company "HAZIM" in Eastern Cameroon
	Two months project leader of forest inventory in the forest exploitation unit N°3 of the Forest Unit 10 057 belonging to the forest company "Ingénierie Forestière" in Eastern Cameroon
	Follow up the activities of community forestry in the villages EBODJE, LOLABE, NLENDE-DIBE in Southern Cameroon
2002	One month project leader (on behalf AES-SONEL) of forest inventory of trees disturbing the high tension cables 90 kv Bekoko - Nkongsamba in Loum forest reserve in Cameroon
	Two months principal animator of the seminar entitled "Reinforcement of organization capacities for the rational management of natural resources" organized in three different areas Campo, Akom II and Ma'an by SNV in Southern Cameroon

	One week coordinator and animator of a training seminar "The setting and management of micro-projects in community forestry" organized at Kribi by SNV in Cameroon
	Three months project leader for workshops and participative elaboration of the community forest management plan for the village NKOKON (financial support of LIVING EARTH) in the Littoral province Cameroon
2001	Six months project leader of forest inventories in two forest exploitation units belonging to the forest company R. PALLISCO and in one forest exploitation units belonging to the forest company KIEFFER&Cie in Eastern Cameroon
	Two weeks Coordinator and animator of a training seminar "Reinforcement of capacities of local communities for the management of natural resources" organised by ECOFAC.
2000	Two months project leader of the survey of MINEF (Ministry of Environment and Forest) approved offices for forest inventories in Cameroon (financial support of WWF and European Union).
	Two months pedagogic director and animator of the training seminar "Appropriate strategies for forest management and inventories techniques for communities forests" organized in the forest school EEF in Mbalmayo (Central Cameroon)
1999	Six months drafting for CARPE the project "Corridors problematic in the management of protected areas in Central Africa"
	One week participation in the first training on forest certification organized by SMARTWOOD, WWF Belgium, and European Union.
1998	Two months Consultant CAID (Canadian Agency for International Development) to comment the Norms for inventory of exploitation.
	Two months Pedagogic director of a workshop “Training of prospectors for forest inventory and management of Forest Units”.

Other experience

- 03.2010 - 11.2010	Principal Mayor at Rosenbachweg (residence of 400 inhabitants), in Goettingen, Germany.
- 06.2010 – 11. 2010	Helping as field research assistant in bioclimatology research group of University of Goettingen. Task: calibration of Eddy covariance and other biophysical instruments, control of parameters, change of filters and deteriorated parts, dendrometrical measurements.

Distinction

Since 1999	Admitted as forest expert in of Cameroon.
Since 1996	Certify forest professional approved in the domain of forest inventory and forest management for MINEF (Ministry of Environment and Forestry).

Publications

Peer reviewed

Djomo, A.N., Ibrahima, A., Saborowski, J., Gravenhorst, G., 2010. Allometric equations for biomass estimations in Cameroon and pan moist tropical equations including biomass data from Africa. Forest Ecology and Management 260, 1873-1885.

Other articles on reviewed

Djomo, A.N., Knohl, A., Gravenhorst, G., accepted. Estimations of forest biomass, carbon pools distribution and net primary production of a moist tropical forest. Forest Ecology and Management.

Book contributions

1) DJOMO, N.A. (1996): Techniques de mesures des arbres et des peuplements forestiers. Tome1. CEDEF. 193p.

2) DJOMO, N.A. (1996): Techniques de mesures des arbres et des peuplements forestiers. Tome2. CEDEF. 198p.

3) DJOMO, N.A. (1996): Notions de cartographie. CEDEF. 138p.

4) DJOMO, N.A. (1996): Barème de cubage. Vol1. CEDEF. 108p.

5) DJOMO, N.A. (1996): Barème de cubage. Vol2. CEDEF. 108p.

Adrien Djomo

Ecological management of tropical forests in Africa and elsewhere can contribute for mitigation of greenhouse gas emissions impacts. This can also provide social benefit and long term income to alleviate the livelihood of people living in rural areas.

This study provides a scientific contribution for accurate estimations of carbon fluxes in moist tropical forests, and a methodology to monitor future forest degradation impacts without using satellite images and to enhance growth of tropical forests.

Compensated reduction if introduced with clear policy and measures in REDD under Kyoto protocol, can enhance sustainable contribution of tropical forests on mitigation of greenhouse gases emissions.

GEORG-AUGUST-UNIVERSITÄT
GÖTTINGEN

Bioklimatologie
Göttingen

WWF for a living planet

KAAD
Katholischer Akademischer
Ausländer-Dienst • KAAD

gtz

Göttingen, 2010 ECOLOGICAL MANAGEMENT OF TROPICAL FORESTS: IMPLICATIONS FOR CLIMATE *CHANGE* AND CARBON FLUXES Adrien Djomo Njepang