

Carbon stocks and dynamics in Sub Saharan Africa



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C stocks and dynamics in Sub Saharan Africa

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Abstract

Climate change has become the most important global environmental crisis and its consideration has revealed the emergence of a new political regime that has been idealized under the hypothetical “carbon city”. The Carbon City corresponds to a political community of people who can act on the carbon cycle and enjoy its productions and services. Forests play a key role into this new city because they significantly contribute to the carbon cycle and ecosystem stability and they represent an object to meet the consensus among the different groups of interests. Physically represented by the United Nations Convention on Climate Change (UNFCCC), the climate community tends to establish an equitable repartition of the efforts to mitigate climate changes and adapt to future modifications of our environment. A fair distribution of the efforts requires the quantification of the contribution made by each country through scientific expertise. However, sub-Saharan African countries are mostly in margin of the process mostly because of the lack of knowledge about the quantitative contribution these countries can make to the global efforts. Quantification of carbon stocks has become crucial for sub-Saharan African countries to increase their participation to the climate discussions arena and develop actions to mitigate an environmental crisis they are the most vulnerable to. Better understanding the carbon cycle also allows a better comprehension of our interaction between the global climate and our activities. The aim of this thesis is to better understand the dynamics of carbon stocks in sub-Saharan Africa. The objectives were (1) to understand the most important factors influencing the estimation of carbon stocks and carbon stock changes, (2) to inventory the state of knowledge at continental scale and (3) to fulfill some of the gaps while identifying the necessary further researches. Three field experiments were implemented in Ghana to measure the variability of biomass within plots, between plots and between wet evergreen, moist evergreen and moist semi-deciduous forests. The wet evergreen forest was selected to analyze the variation of biomass within and between trees based on an original method to build tree allometric equation. The three forests were logged and the wet evergreen forest was selected to measure the impact of logging activities on carbon stocks. In parallel, an intensive data collection in various libraries of the world has allowed the development of the first tree volume and biomass allometric database and the first biomass and carbon stock database at continental scale. The data were organized and reviewed to allow the comparison between equations and carbon stocks data.

About two third of the continental carbon stock is found in the soil. Using different soil databases and soil maps may result in variation of the soil organic carbon estimates of about 30%. The choice of the tree allometric equation to estimate the tree biomass can induce variation of aboveground biomass of about 40%. Using already available biomass data, the aboveground carbon stocks ranges 10-105 Pg C. Using the data collected in this study allowed increased the number of data and its harmonization. It follows a major reduction in the variability of carbon stocks that is between 58 and 76 Pg C. Measurements in humid tropical forests in Ghana revealed variations of biomass at different scales, from trees to different types of forests. Aboveground biomass ranges 348-364 ha^{-1} between ecological zones, 218-485 Mg ha^{-1} between plots and 0 - 4681 Mg ha^{-1} within plots of 1 ha. Carbon stocks are on average 355 Mg ha^{-1} with 49, 39, 9, 1, 0.9, 0.8, and 0.2% are in the aerial part of trees, soil organic

carbon, roots, litter, dead wood, lianas and palms. The biomass of a tree was mainly influenced by the diameter of the trunk, the crown diameter and the wood density in a tropical rainforest of Ghana. However, various factors influence the ecosystem biomass variability. At plant scale, the tree biomass is influenced by the tree species, the plant functional type and the growth strategies. At ecosystem scale, the biomass is influenced by the effect of topography, plant distribution, slope, soils, history of perturbations and forest management. At biome scale, the biomass is influenced by climate, ecological zone, age, structure, and management.

When considering the impact of anthropic activities on carbon stocks, deforestation and forest exploitation emissions ranged 0.06-0.5 and 0.03 – 0.08PgC Yr⁻¹ respectively. While deforestation had already been studied in previous research, I have focused on forest degradation caused by selective logging. In Ghanaian rainforests, selective logging impact 12 Mg C ha⁻¹. Based on the relation between harvested volume and the impact of forest carbon stocks, I have estimated that 88 Tg C yr⁻¹ are being emitted at continental scale which means selective logging would contribute to 20– 25% of the continental C balance. However, the potential for decreasing GHG emissions from selective logging has been limited by the accuracy and the cost of field measurements. Forest restoration has been identified as the highest potential activity for emission reduction and C sequestration in Ghana. While this activity is not recognized by the climate convention, enhancement of forest C stock can sequester significant amount of C. It was estimated that intensification of already existing cocoa farms was the most feasible option to sequester important amount of C in Ghana while increasing the farming income by about 19%. However, carbon sequestration and financial compensation are among many other aspects to better consider when implementing developing activities. Land and forest tenure issues have to be particularly addressed in Ghana to allow effective implementation. The mis-consideration of some social entities would lead to massive forest destructions that already happened in the past.

Sub-Saharan Africa faces important gaps related to the understanding of the contribution of the African ecosystems to the C cycle. Only one percent of the necessary tree allometric equations is currently available. The impact of degradation and deforestation on the role of the decomposition of wood and carbon dynamics in soil are particularly poorly understood. The dynamics of forest regeneration after perturbations such as selective logging are poorly known. While C stocks are assumed to recover after a 40 years period, the structure of the forest and the biodiversity are still strongly affected. The use of remote sensing is often presented as a panacea and the solution to monitor natural resources such as forest biomass. However, I have pointed out that the estimation of biomass using available satellite imageries of Ghana is not an accurate option while the use of high resolution imageries are too costly for countries that have low human and technical capacities to achieve their forest inventories using these techniques. This study highlights the issue of the language used to describe the environment. The global land descriptions are often not in relation with the language used in the field to describe the vegetation in term of structure, floristic composition, position in the landscape and management. The identification of the degraded forest is strongly limited by the poor definitions and the poor previous consideration and analysis. While several attempts to harmonize the vegetation descriptors have been developed on the basis of classification systems, however, they have been facing the complexity of wording, defining and translating our perception of environment. At last, very few socio-economic

studies have considered the impact of carbon services to local farmer livelihood. However, they are considered as part of the main process of deforestation. There is an urgent need to identify the potential for improving farmer livelihood while sequestering carbon stocks and reducing emissions from deforestation and forest degradation. This would be achieved by an increasing consideration of agricultural activities in developing countries by the climate change convention. Still, the agricultural sector will be considered if a carbon quantification system can be implemented for farming.

Résumé

Les changements climatiques sont devenus la crise environnementale mondiale la plus importante et sa considération a révélé l'émergence d'un nouveau régime que l'on peut idéaliser comme une hypothétique « cité du carbone ». Il s'agirait d'une communauté politique des hommes qui peuvent agir sur le cycle du carbone et jouir de ses productions et de ses services. Les forêts y joueraient un rôle particulier parce qu'elles contribuent de manière significative au cycle du carbone et à la stabilité des écosystèmes et représentent un outil de consensus entre les différents groupes d'intérêts. Physiquement, représentée par la Convention des Nations Unies sur les Changements Climatiques, la communauté, réunie dans l'arène des négociations sur le climat, tend vers une répartition équitable des efforts visant à atténuer les changements climatiques et à s'adapter aux modifications futures de l'environnement. Une répartition équitable de l'effort nécessite une quantification de la contribution de chaque pays par le biais de l'expertise scientifique. Cependant, les pays de l'Afrique Sub-saharienne sont pour la plupart en marge du processus, principalement car la quantification de leur contribution potentielle à l'effort global est limitée par les connaissances disponibles. La quantification des stocks de carbone est devenue cruciale pour que l'Afrique sub-saharienne puisse mieux participer et développer des actions d'atténuation d'une crise environnementale à laquelle ils sont les plus vulnérables. Une meilleure connaissance des interactions entre le climat global et la mise en place d'actions nationales de réduction des émissions qui soient efficaces. Cette thèse tend vers une meilleure compréhension de la dynamique des stocks de carbone en Afrique sub-saharienne. Les objectifs sont : (1) mieux connaître les facteurs qui influencent les stocks de carbone et leurs changements, (2) faire un inventaire de l'état des connaissances à l'échelle continentale et (3) améliorer l'état des connaissances et identifier les recherches futures qui soient nécessaires.

Trois sites expérimentaux furent mis en place au Ghana pour mesurer la variabilité de la biomasse au sein des parcelles, entre les parcelles, et entre les forêts pluvieuse sempervirente, humide sempervirente, et humide semi-décidue. La forêt pluvieuse fut sélectionnée pour analyser la variation de la biomasse dans les arbres et entre les arbres à partir d'une méthode originale qui permettent également la réalisation d'équations allométriques. Ensuite, les parcelles dans les trois forêts subirent un traitement par exploitation sélective et la forêt pluvieuse sempervirente fut sélectionnée pour mesurer l'impact de l'exploitation sélective sur les stocks de carbone. En parallèle, une récolte intensive des données dans diverses bibliothèques dans le monde permit le développement de la première base de données pour les équations allométriques pour le volume et la biomasse et la première base de données sur les stocks de carbone à l'échelle continentale.

Environ les deux tiers des stocks de carbone du continent se trouvent dans le sol. Leurs estimations varient d'environ 30% en fonction des cartes pédologiques et des bases de données disponibles. En ce qui concerne l'estimation de la biomasse des arbres, le choix de l'équation allométrique peut induire des variations de la biomasse aérienne de l'ordre de 40%. En utilisant les données déjà disponibles dans les bases de données internationales, l'estimation des stocks de carbone varie entre 10 et 105 Pg C. La base de données réalisée dans cette étude a permis un accroissement du nombre de données et leur harmonisation. Il résulte une réduction importante de la variabilité des stocks de carbone qui se situe

entre 58 et 76 Pg C. Les mesures effectuées dans les forêts tropicales humides au Ghana ont permis de révéler des variations de la biomasse à différentes échelles, de l'arbres aux différents types de forêts. La biomasse aérienne varie entre 348 et 364 Mg ha⁻¹ entre forêts tropicales humides, 218 – 485 Mg ha⁻¹ entre les parcelles et 0-4681 Mg ha⁻¹ dans les parcelles de 1ha. Les stocks de carbone sont en moyenne 355 Mg ha⁻¹ dont 49, 39, 9, 1, 0.9, 0.8, et 0.2% se trouvent dans la partie aérienne des arbres, le carbone organique du sol, les racines, la litière, le bois mort, les lianes et les palmiers. La biomasse d'un arbre est principalement influencée par le diamètre du tronc, le diamètre de la couronne et la densité du bois dans une forêt tropicale humide. Aussi, divers facteurs influencent la variabilité de la biomasse des écosystèmes. À l'échelle des plantes, la biomasse des arbres est principalement influencée par les espèces, le type fonctionnel et les stratégies de croissance. À l'échelle des écosystèmes, la biomasse est influencée par l'effet de la topographie, la distribution des plantes, de la pente, les sols, l'histoire des perturbations et de la gestion des forêts. À l'échelle des biomes, la biomasse est influencée par le climat, la zone écologique, l'âge, la structure et le type d'occupation du sol.

En ce qui concerne l'impact des activités anthropiques sur les stocks de carbone, la déforestation et la dégradation forestière issue de l'exploitation sélective varient entre 0.06-0.5 et 0.03-0.08 Pg C yr⁻¹ respectivement. La déforestation a déjà été largement étudiée par d'autres recherches précédentes. Aussi, je me suis essentiellement concentré sur la dégradation des forêts par l'exploitation sélective. Dans une forêt tropicale humide du Ghana, l'exploitation sélective affecte environ 12 Mg ha⁻¹. Sur la base de la relation entre le volume récolté et l'impact engendré sur les stocks de carbone, j'ai estimé que 88 Tg C an⁻¹ sont émis à l'échelle du continent. Ceci signifierait que l'exploitation sylvicole contribuerait à 20-25% du bilan C continental. Toutefois, le potentiel de réduction des émissions de GES provenant des coupes sélectives est limité par la précision et le coût des mesures de terrain. La restauration des forêts a été identifiée comme présentant le plus grand potentiel de réduction des émissions de GES et la séquestration du C au Ghana. Bien que cette activité ne soit pas reconnue par la convention climatique, l'amélioration des stocks de carbone forestiers pourrait séquestrer des quantités importantes de C. En prenant les plantations de cacao comme exemple, l'accroissement de la densité arborée représente l'option la plus faisable pour séquestrer des quantités importantes de C au Ghana, tout en augmentant le revenu d'environ 19%. Toutefois, la séquestration du C et les compensations financières sont parmi les nombreux aspects à tenir compte dans la mise en œuvre d'activités de développement. Les tenures foncière et forestière sont des questions qui doivent être particulièrement adressées pour une mise en œuvre effective des projets de développement forestier au Ghana. L'exclusion de certaines entités sociales conduirait à des destructions massives des forêts, phénomène qui s'est déjà produit par le passé.

L'Afrique Sub-saharienne fait face à d'importantes lacunes liées à la compréhension de la contribution des écosystèmes africains au cycle du C. L'inventaire des données actuellement disponibles révèle qu'un pour cent des équations allométriques sont disponibles. L'impact de la dégradation et la déforestation sur le rôle de la décomposition du bois et la dynamique du carbone dans le sol sont particulièrement peu connus. Même si les stocks de carbone sont supposés se reconstituer après une période de 40 ans après l'exploitation, la structure de la forêt et la biodiversité restent fortement touchés. L'utilisation de la télédétection est souvent présentée comme une panacée et la solution pour suivre l'évolution des

ressources naturelles telles que la biomasse forestière. Cependant, l'étude souligne que l'estimation de la biomasse en utilisant les satellites disponibles pour le Ghana est une option peu précise et l'utilisation d'images à haute résolution est une option trop coûteuse pour les pays qui ont de faibles capacités humaines, techniques et financières. Cette étude met en évidence la question du langage utilisée pour décrire l'environnement. La considération de la structure, la composition floristique, la position dans le paysage et la gestion et la dégradation des forêts est largement limitée par la pauvreté du langage, des définitions et des analyses antérieures. Plusieurs tentatives tentent d'harmoniser les descripteurs de la végétation sur la base de systèmes de classification. Ils restent fortement limités par la complexité de la formulation, la définition et la traduction de notre perception de l'environnement. Enfin, très peu d'études socio-économiques ont examiné l'impact des services lié au carbone sur les conditions de vies des agriculteurs locaux. Ils font pourtant partie du processus de déforestation. Il est urgent d'identifier le potentiel pour améliorer les conditions de vie des agriculteurs tout en séquestrant du carbone et en réduisant les émissions liées à la déforestation et la dégradation des forêts. Cet objectif peut être atteint par une croissante prise en compte des activités agricoles dans les pays en développement par la convention climat. Cependant, ce n'est que lorsqu'un système de quantification du carbone adapté aux activités agricoles, que ces dernières pourront alors être considérées.

Contents

Acknowledgements.....	25
Foreword.....	27
Chapter 1.....	1
Forests grow well in the carbon city.....	1
1. Introduction: climate change is one environmental crisis among others	3
2. Climate change: The emergence of a global consideration.....	4
2.1 Figures on the impact of climate changes	4
2.2 Climate Change reconfigures the international policy arena.....	5
2.3 The emergence of global models to understand climate change.....	6
3. The supremacy of the climate issue	7
4. The orders of the justification.....	9
4.1 An axiomatic developed around the carbon	9
4.2 The carbon city and the other cities.....	10
5. The political forests and the biophysical forests	10
5.1 Biophysical Assessment.....	10
5.2 The political tree.....	12
5.3 Biophysical forest vs. political forest	13
5.4 On the importance of the “carbon” language	14
5.5 The Sub-Saharan Africa has something to say!	15
6. Conclusion.....	16
Organization.....	17
Objectives	17
Methodological approach.....	18

Outline of the thesis.....	21
Chapter 2.....	23
Deforestation and forest degradation: assessing for emission reductions	23
1. Introduction	25
2. The current sub-Saharan carbon budget	26
3. Deforestation and forest degradation	27
3.1 Defining forest degradation and deforestation.....	28
3.2 Deforestation	30
3.3 Forest Degradation.....	31
4. Current methods that are proposed to monitor REDD+	31
4.1 Methods to measure the change of forest cover and forest area.....	32
4.2. Emission factors	34
5. Adapting REDD+ methods to the sub-Saharan Africa context - an accounting problem	34
5.1 Estimating C stocks and emission factors in sub-Saharan Africa	34
5.2 Detecting forest area and forest cover change in SSA	36
6. Conclusion.....	39
Chapter 3.....	41
Soil carbon stocks in Africa	41
1. Introduction	43
2. Materials and methods	45
2.1 Source of data	45
2.2 Calculation of carbon stock.....	45
2.3 Computation of soil carbon stocks	46
2.4 The soil carbon map of Africa.....	46
2.5 Calculation of the carbon stocks per biomes and per country	47

3. Results and discussion	47
3.1 Map of soil C stocks of Africa	47
3.2 African SOC and the global cycle	48
3.3 Soil C stocks in ecoregions of Africa.....	50
3.4 Variation of soil C stocks of Africa estimates	51
3.5 Error of SOC estimates	54
4. Conclusion.....	56
Chapter 4.....	57
The importance of tree biomass allometric equations in assessing carbon stock and carbon stock changes	57
1. Introduction	59
2. Methods	60
3. Results	63
4. Discussion.....	65
4.1 Allometric equations are fundamental to determine forest carbon stock and stock changes.....	65
4.2 Consistent methods between GHG inventories are necessary but not enough to be conservative and avoid hot air	67
4.3 Conservativeness increases environmental integrity of reported estimates and emission reductions	67
5. Conclusion.....	68
Chapter 5.....	69
Wood density and biomass variations within and among trees in a tropical rainforest.....	69
1. Introduction	71
2. Materials and method	73
2.1 Study site.....	73
2.2 Sample Trees.....	73

2.3	Wood density	76
2.4	Analysis of the wood density	76
2.5	Estimation of Small-sized tree mass	77
2.6	Estimation of big-sized-trees mass	78
2.7	Choice of a functional form for the allometric equation	78
2.8	Validity of generalized allometric models	81
3.	Results	81
3.1	Wood density	81
3.2	Tree biomass.....	84
3.3	Tree allometric equation	84
4.	Discussion.....	87
4.1	Wood density	87
4.2	Modelling tree mass	89
4.3	Status of Generalized allometric equations.....	92
4.4	Estimating biomass and carbon stocks.....	92
5.	Conclusion.....	94
Chapter 6.....		95
Reviewing volume and biomass allometric equations at continental scale		95
1.	Introduction	97
2.	Material and methods	98
2.1	Data compilation and classification	98
2.2	Quality control assessment.....	101
2.3	Comparison of tier methods	102
2.4	Data analysis and access	103
3.	Results	103

3.1	Description of the database	103
3.2	Predictors of tree biomass.....	104
3.3	Tree species	106
3.4	Tree compartments.....	106
3.5	Data quality	111
3.6	Chronology of forest biomass research in tropical sub-Saharan Africa.....	111
3.7	Wood gravity	112
3.8	Volume and biomass allometric equations	112
4.	Discussion.....	123
4.1	Current knowledge on tree biomass allometric equations in sub-Saharan Africa	123
4.2	Variability of tree volume and biomass.....	123
4.3	Using the Tier approach provides consistent biomass estimations.....	124
4.4	Toward improvement of methods and data reporting for volume and biomass estimates 126	
5.	Conclusion.....	129
Chapter 7.....		131
Structure and functioning of rain forests ecosystems in Ghana.....		131
1.	Introduction	133
2.	Materials and method	135
2.1	Study sites	135
2.2	Sampling design.....	136
2.3	Aboveground biomass	138
2.4	Litter and belowground compartment.....	139
2.5	Carbon and biodiversity assessment	139
3.	Results.....	140
3.1	Floristic composition	140

3.2	Forest structure	143
3.3	Soil properties	145
3.4	Variation of biomass with habitat	148
3.5	Variation in biomass across the plots	149
3.6	Above and belowground carbon stocks	150
3.7	Factor influencing biodiversity and carbon stock distribution	150
4.	Discussion.....	151
4.1	Floristic composition is influenced by soil, climate, topography and anthropic factors.....	151
4.2	Variation of biomass and carbon stocks.....	153
4.3	Toward a better understanding of tropical forest ecosystem functioning.....	155
5.	Conclusion.....	156
Chapter 8.....		157
Analyzing the structure: towards harmonization of aboveground forest biomass estimates		157
1.	Introduction	159
2.	Material and methods	160
2.1	Case studies	160
2.2	Volume and biomass calculation	160
2.1	Analysis of the data	161
3.	Results.....	163
3.1	Structure of the tree vegetation forms	163
3.2	Modelling tree structure	164
3.3	Modelling volume and biomass.....	167
4.	Discussion.....	168
4.1	Ecosystems structure.....	168
4.2	Modeling ecosystem structure	169

4.3	Factor in tree structure variability.....	170
4.4	Volume and biomass conversion factors.....	170
5.	Conclusion.....	172
Chapter 9.....		173
Variability of carbon stocks at continental scale		173
1.	Introduction	175
2.	Background	176
2.1	Biome classifications.....	176
2.2	Remote sensing and Land cover classifications.....	176
2.3	Existing carbon stock estimates and their variations	178
3.	Materials and methods.....	179
3.1	Data collection	179
3.2	Data classification and harmonization	180
4.	Data integration with land cover products.....	186
4.1	Assessing average biomass and carbon stocks per land cover classes.....	186
4.2	Statistical analysis	187
5.	Variability of carbon stocks at local scale	188
5.1	Aboveground carbon stocks in agroforestry systems of western Kenya	188
5.2	Aboveground carbon stocks in agricultural systems in the Sudanian savanna	190
5.3	Carbon stocks in tropical rain forests of Ghana	192
6.	Variability of biomass at national scale	194
6.1	Biomass variability in Zambia	194
6.2	Biomass variability in Cameroon	195
6.3	Biomass variability in Mozambique.....	196
7.	Variation of C stocks at continental scale	197

7.1	Carbon stocks in African countries	197
7.2	Influence of forest definition on C stocks	197
8.	Discussion.....	198
9.	Conclusion.....	199
Chapter 10.....		201
Estimating the impact of selective logging on aboveground carbon stocks in a wet evergreen forest of Ghana		201
1.	Introduction	203
2.	Materials and methods.....	205
2.1	Study site.....	205
2.2	Mapping logging activities	206
2.3	Inventorying aboveground biomass	206
2.4	Aboveground carbon losses	207
2.5	Greenhouse gas balance of logging activities.....	209
2.6	Testing methods	210
3.	Results.....	212
3.1	Aboveground biomass	212
3.2	Ground impacts	213
3.3	Impacted biomass	213
3.4	The greenhouse gas balance.....	217
3.5	Estimating GHG emissions from selective logging.....	218
4.	Discussion.....	220
4.1	Selective logging contributes for a significant proportion of the African carbon budget 220	
4.2	Reducing impact from selective logging.....	221
4.3	Improving the GHG balance calculation	222

5. Conclusion.....	224
Chapter 11.....	225
Potential for country-level aboveground carbon sequestration and emission reductions through forestry activities– evidence from Ghana	225
1. Introduction	227
2. Calculation of C stocks and C sequestration	227
2.1 Study area	227
2.2 Map of carbon stocks.....	228
2.3 Land cover of Ghana.....	230
2.4 Carbon stocks of Ghana.....	230
3. Baseline C stocks and potential for C sequestration country wide	230
3.1 Assessing carbon sequestration and emission reduction potentials	232
3.2 C sequestration and C emission reduction potentials	233
4. Constraints to the implementation of C forestry projects.....	234
4.1 Identification of land cover.....	234
4.2 Estimation of C stocks	235
4.3 C sequestration	236
4.4 Limitations of the accounting methods	237
5. Conclusion.....	238
Chapter 12.....	239
Enhancing forest carbon stocks in agroforestry systems: the case of cocoa in Ghana	239
1. Introduction	241
1.1 The agroforestry potential.....	241
1.2 Agroforestry in the context of REDD+	242
2. Ghana and climate change.....	243
2.1 The GHG balance of Ghana.....	243

2.2	State of deforestation and forest degradation in Ghana.....	244
2.3	The proximate and underlying factors of deforestation and forest degradation.....	245
3.	Cocoa agroforestry: an alternative to mitigate deforestation and forest degradation?.....	247
3.1	Agroforestry and climate change	247
3.2	Cocoa agroforestry systems in Ghana	247
3.3	Carbon storage in cocoa agroforests	248
4.	Analysis	249
4.1	Carbon sequestration potential in cocoa agroforestry systems	249
4.2	Assumptions	250
5.	Results	250
5.1	Carbon stocks, carbon sequestration and emission reductions	250
5.2	Profitability of cocoa agroforests under REDD+	251
6	Discussion.....	252
6.1	There is a potential for C sequestration in existing cocoa farms.....	252
6.2	Integrating agroforestry into the REDD+	253
7	Conclusion.....	254
Chapter 13.....		257
General discussion and conclusions		257
References		263
List of acronyms		293
List of figures.....		295
List of Tables		299
List of Appendixes		301

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Foreword

At the core of this manuscript is the study of dynamics of carbon stocks in sub-Saharan Africa, particularly in Ghana, and the assessment of the impact of methods on carbon stocks and carbon stock change estimations. However from a chapter to another, this study is carried out in various frameworks and different aspects are dealt with. Furthermore, these chapters differ on their nature: state-of-the art, published or submitted papers, or simply the present version of some research works still in progress (Figure 1). All the chapters are the result of a personal work. In this thesis, most of the chapters can be read separately. While chapters 4, 5 and 6 are closely connected and deal with tree allometric equations, chapters 7, 8 and 9 deal with estimation of forest biomass and carbon stocks at local and continental scale, chapters 11 and 12 present predictive scenarios for emission reduction and carbon sequestration at national scale. Since almost all the chapters are already submitted or ready for submission, chapter 8 and 9 are still in preparation. The manuscript is organized as follows:

Chapter 1 introduces the conceptual framework. It explains why this thesis deals with climate change and carbon in sub-Saharan Africa, the role of forests to sequester carbon and mitigate climate change. It presents the “carbon city” concept and the different justifications that are behind the word “carbon”. It highlights the situation of sub-Saharan, the lack of scientific data to understand African ecosystems and the potential biophysical and political contribution to the climate change mitigation and adaptation. This chapter is based on various experiences in international conferences of the United Nations Framework on Climate Change, the Convention on Biodiversity, meetings at the Food and Agriculture Organization of the United Nations and the Centre Koyré in Paris (Figure 2).

Chapter 2 synthesizes the various constraints that sub-Saharan African countries meet when assessing their forest carbon stocks in the context of reducing the emissions from deforestation and forest degradation. This chapter gives first estimates on the potential emission reductions from reducing emissions from deforestation and forest degradation based on available data.

Chapter 3 deals with soil organic carbon. It presents the various databases that are available to estimate soil carbon stocks at continental scale. It explains how the choice of the classification system, the soil maps and the database can influence the soil carbon stock estimation.

Chapter 4 highlights the importance of the tree allometric equation to estimate not only tree biomass, but also forest carbon stocks, carbon stock changes and the greenhouse gas balance. While several discussions concern the use of few generalized equations, I wanted to insist on the importance of the allometric equations in order to introduce the next two chapters.

Chapter 5 presents the first biomass allometric equations in a tropical humid forest of sub-Saharan Africa. While the previous estimations were using equations that had been developed in other continents, this chapter compares the generalized and the local allometric equation. It also explains the biomass variation observed within and between the trees.

Chapter 6 corresponds to the unique review of the tree allometric equation that has been achieved in Africa at continental scale. It presents the gaps and proposes a tier method that would be used to improve volume, biomass and carbon stocks estimation.

Chapter 7 assesses the biomass and the carbon stocks in three forest types and in three ecological zones of Ghana. This study is the only one that analyzed the spatial variation of biomass within tropical humid forest of West Africa. It looks at the relation between plant ecology, plant distribution and variability of biomass, biodiversity and carbon stocks.

Chapter 8 tackles the problem of harmonization of data. Most of the data comparison on biomass and carbon stocks does not consider the fact that the forest inventory does not address the same population. While some forest inventories start at 10cm others start at 20cm of diameter. Moreover, based on several forest inventories in Western Kenya, North Cameroon, Ghana, and Congo, in agroforestry systems, agricultural land, plantation and natural forests, this study develops methods and functions to allow data harmonization.

Chapter 9 assesses the aboveground carbon stocks of Africa based on an intensive data collection from various institutes in the world, consultant and student work. The chapter presents how the data has been harmonized and integrated to land cover product in order to assess carbon stocks and analyze the variability and the impact of using different ecological land classifications. It particularly highlights the problem of the language and data description when scaling up local field measurements to global land products.

Chapter 10 constitutes the first study on the impact of selective logging in sub-Saharan Africa. While many studies have reported large potential for reducing emissions from improved logging practices, this study shows the limits and the impossibility of using carbon credits to compensate this type of actions.

Chapter 11 uses Ghana as a case study to analyze the national potential for carbon sequestration and emissions reduction under the Clean Development Mechanism (CDM) and the Reducing Emissions from Deforestation and forest Degradation (REDD+) mechanisms of the United Nations Framework on Climate Change. (UNFCCC)

Chapter 12 proposes to analyze the potential for cocoa agroforests to enhance carbon stocks in Ghana as an option within the REDD+ mechanism. This chapter uses the carbon stocks maps that have been developed in chapter 10 and proposes several scenarios for project implementation. Using an economic model integrated to the carbon stock maps, and carbon sequestration scenarios, it estimates the potential economic income for farmers and highlights the various constraints and benefits for REDD+ implementation in the context of Ghana.

At last, chapter 13 discusses the various results obtained in the thesis.

Figure 1: state of progress

Chapters

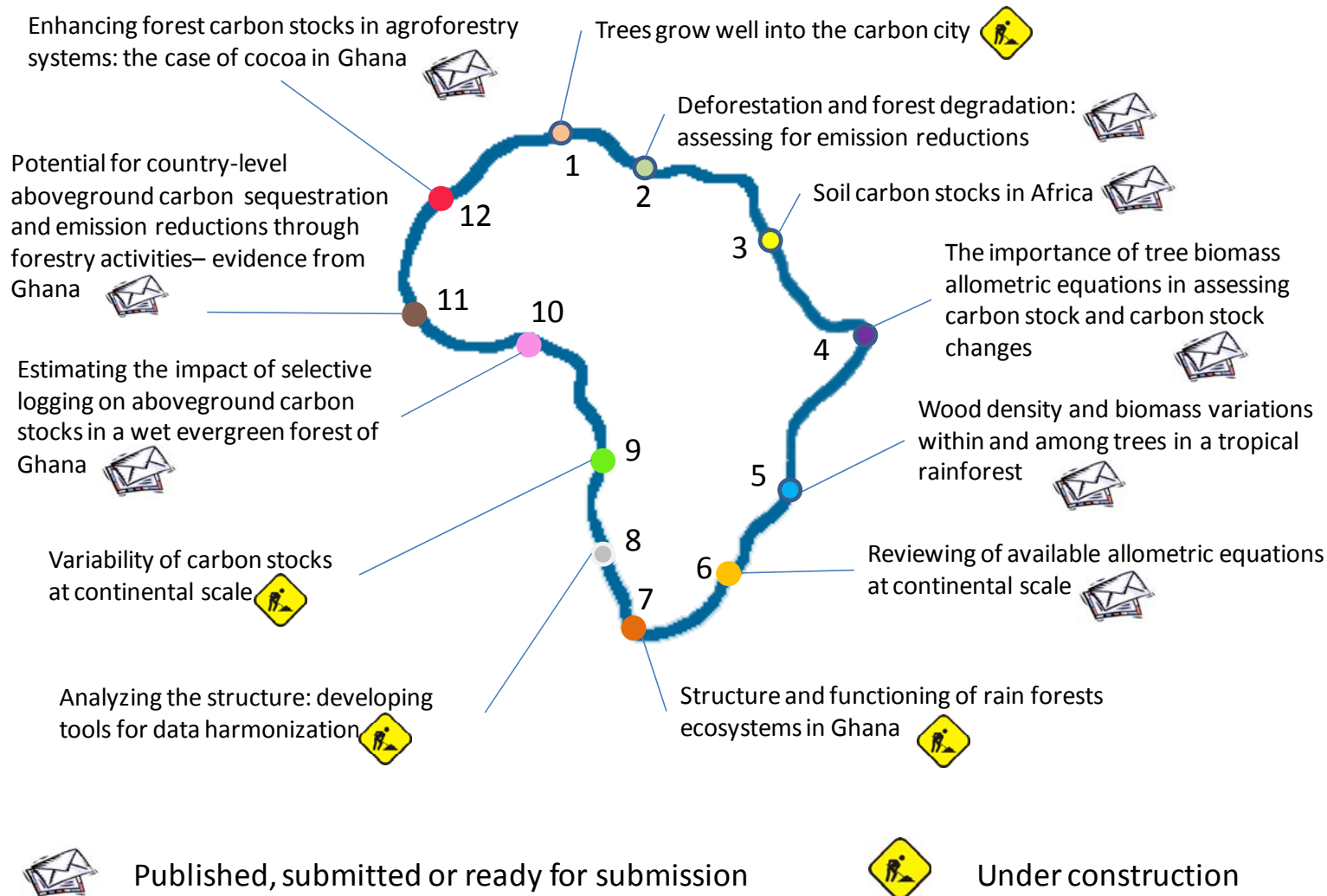




Figure 2: study sites per chapter

Copenhagen: 15th conference of the parties to the UNFCCC, Poznan: 14th conference of the parties to the UNFCCC, Nancy: Institut National de la Recherche Agronomique, Paris: Centre Koyré, United Nations Educational, Scientific and Cultural Organization,, The Convention on Biological Diversity, Montpellier: Institut de recherché pour le Développement, Centre de la recherche agronomique pour le développement, Maison de la télédétection, AgroParisTech/Engref, Viterbo : Università degli studi della Tuscia, Rome : The Food and Agriculture organization of the United Nations, Kumasi : The forest Research Institute of Ghana, Samerboi: Samartex Timber & Plywood Company Limited, Accra: University of Legon, Pointe Noire: Centre de la recherche agronomique pour le développement, Nairobi: The World Agroforestry Centre, Tropical Biology and Fertility Institute of the International Center of Tropical Agriculture, Bali: 13th conference of the parties to the UNFCCC.

Chapter 1

Forests grow well in the carbon city

Abstract

The threats of climate changes and global warming reconfigure the international political order and create new forms of justification, discourse tinted by greenhouse gas emissions and deforestation, a structured language based on technical and scientific terminologies that come from the interactions between international policy and Science. Based on the theory of the justification developed by Boltanski and Thevenot and the attempts to find the green city, this article demonstrates the importance of forests in the emergence of a new city named the Carbon City. The Carbon City corresponds to a political community of people who can act on the carbon cycle and enjoy its productions and services. Forests play a particularly important role in the fight against climate changes by contributing to the mitigation and adaptation, carbon sequestration and ecosystem stability. However, the role assigned to them in speeches has overtaken its biophysical dimension. Forests are suppliers of multiple services to Nature and humankind and are vector of consensus and conflicts within the climate arena. Between political blackmail and noble representations, forests have found a particularly fertile soil in the carbon city. These fertile grounds allowed the development of a scientific language based on the quantification of carbon which is used in politics, resulting in an almost unanimous recognition of their newly gained place in the carbon city. However, some parties and particularly the sub-Saharan African countries have difficulties in accessing the carbon city particularly as the appropriation of its specific language is difficult.

Keywords: Climate changes, climate policy, IPCC, Environmental management, sociology of organizations

1. Introduction: climate change is one environmental crisis among others

Today, climate changes are presented as the major environmental crisis of the twenty-first century. The majority of scientists stress that the changes the humanity faces will have irreversible consequences. Nonetheless, climate skeptics say environmental crises always existed and climate changes are only one amongst many others. However, the emphasis on climate change is justified by the link that this phenomenon has with the human societies on two closely related aspects. On the one hand, for the first time, the question of human responsibility to climate changes at a global scale is discussed. On the other hand, the consequences of this crisis on the human societies appears to be becoming colossal. They are expressed on all fronts - economic, social, and ecological.

The importance of the phenomenon "climate changes" for our society appears under various forms: hyper-media, politicization, "scientification" of the phenomenon, and the development of a new form of language, filtering into discussions at the local pub to the G8 speakers. The increasing consideration was considerable during the large meetings held in Bali in 2007 and Copenhagen in 2009. On the other hand, the rising concerns on the climate change crisis have in parallel lead to the progressive isolation - voluntary or involuntary - of other global environmental problems that have emerged in recent decades such as biodiversity loss and desertification. It begs the question why climate changes are considered to be so important? Would tackling the issue of climate changes be more "justifiable" than the loss of biodiversity or desertification?

As part of this study the aim is to show, on the basis of work related to the theory of justification developed by Boltanski and Thevenot (1991), that climate changes are becoming the sole repository of the environmental issues as a whole. The overall consideration of environmental issues through climate changes is made possible by the role of forests in the global scientific models, simplified under the carbon cycle, and secondly, the climate changes negotiation process. Indeed, all the environmental issues are reduced to the carbon issues and all the disappointed interests from the other environmental causes look for a place within the negotiations in order to be recognized and represented. The inclusion of forests in the context of climate negotiations is a particular way of finding synergies between the other conventions such as biodiversity and desertification for example.

The first part of this chapter deals with the emergence of the global consideration of climate changes and how this issue somehow appears to have incorporated all other environmental issues. Subsequently, the emergence of a new order of justification, related to climate changes, focusing on the carbon issue and the role of scientific analysis, will be questioned. Finally, the analysis will address the place of forests in the climate change negotiations in order to question how "consensual" the consideration of forest is, the language and the scientific issues relative to the carbon measurement and more precisely in the context of sub-Saharan Africa. While the reader may get the impression that this thesis will be about social science, I would like to clarify that this chapter was developed as an introduction to lay down the conceptual framework the conceptual framework that will justify the research undertaken in this thesis.

2. Climate change: The emergence of a global consideration

2.1 Figures on the impact of climate changes

Global warming and climate changes are largely attributed to the increase of greenhouse gases concentration into the atmosphere. There now exists "more than 90% chance" that human activities play a role in global warming (IPCC, 2001). This is mainly due to the massive burning of fossil fuels and land cover change that result in increased atmospheric GHG concentrations. GHGs alter the radiative budget of the earth and tend to warm the atmosphere (Figure 3). Carbon dioxide (CO₂) is by far the main contributor to anthropogenic GHG (IPCC, 2001). Direct and indirect measurements confirm that the concentration of CO₂ of 280 ppmv in the pre-industrial era has increased by about 100 ppm (36%) over the last 250 years to reach a concentration of 379 ppm in 2005 (Forster, et al., 2007). According to the different scenarios developed by the Intergovernmental Panel on Climate Change (IPCC, 2007e), the temperature increase caused by the increase of GHG concentration should be between 1.1 and 6.4°C by 2100 compared to 1990 levels, depending on the mitigating policy that would be implemented.

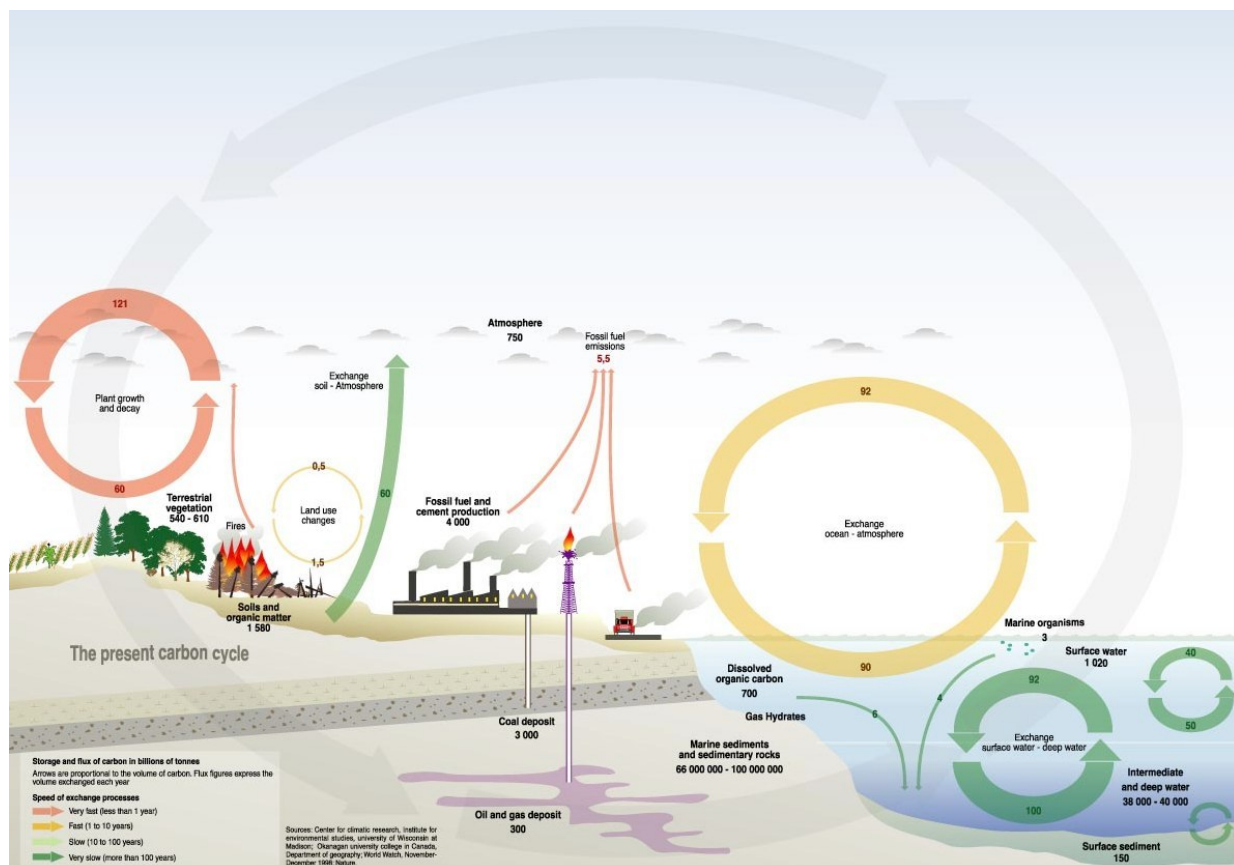


Figure 3 : The carbon cycle

Source: Centre for Climatic Research, Institute for Environmental Studies, University of Wisconsin at Madison (USA), Okanagan University College (Canada), Geography Department; World Watch, November-December 1998; Nature; Intergovernmental Panel on Climate Change, 2001 and 2007.

2.2 Climate Change reconfigures the international policy arena

Environmental issues and their relationship to the development of human societies are not a new theme in international relations. It is useful to briefly outline the evolution of these discussions at the international level to illustrate how the discourse on environmental issues, and in particular climate change, has evolved over the last two decades.

By 1972, at the request of the Club of Rome, the researchers from the Massachusetts Institute of Technology highlighted the incompatibility between a terrestrial ecosystem and an infinite economic and population growth (The Limits to Growth, Report Meadows, 1972). Other studies come at that time to confirm this hypothesis, questioning the development and the economic growth as an end in itself. It is also in this period that most of the NGOs dedicated to the protection of Nature were created (Greenpeace, 1971, Friends of the Earth, 1970, FRAPNA, 1971). Alongside the political level, the first UN Conference on the Human Environment in Stockholm (Sweden) was held in 1972. The discussions focused on the possibility of moving towards models of economic development compatible with ecological and social equity, leading to the creation of the United Nations Program for Environment (UNEP).

The International Union for Conservation of Nature (IUCN) first coined the concept of "sustainable development" in 1980. The concept became very popular after it was takeover in 1987 in the report of the World Commission for the Environment and Development, commonly known as "The Brundtland report". Sustainable development is defined as the development that meets the needs of the present without compromising the ability of future generations to meet their own needs. As a result, the concept gained major importance in dialogue and development of climate policy . In 1988, the World Weather Organization and UNEP took the initiative for further research on climate change and established the Intergovernmental Panel on Climate Change (IPCC) to gather additional information. In 1990, the IPCC published its first assessment report that confirms that climate change is a real danger and suggests a global agreement. Following this important scientific assessment, the United Nations officially launched negotiations to establish a Framework Convention on Climate Change. In 1992, the United Nations Conference on Environment and Development (UNCED) was held in Rio de Janeiro, known as the "Earth Summit". This summit attempted to integrate the economic, social and environmental issues by establishing a sectoral approach and the integration of environment into development processes And discussed a wide range of environmental issues . It gave birth to three major conventions concerning: the atmosphere (United Nations Framework Convention on Climate Change, UNFCCC, 1992), biodiversity (Convention on Biological Diversity, CBD, 1992) and desertification (United Nations Convention to Combat Desertification, UNCCD, 1994). The first gained much more importance than the other two conventions and included the majority of environmental advocacies. Moreover, while one of the key points of the environmental movements during the Rio conference was the fight against deforestation in the tropics, no binding commitment was made on forestry. A non-legally binding statement regarding forests was signed which was supposed to become the "authority for a global consensus on the management, conservation and sustainable development of all types of forests". Since then, attempts to regulate binding commitments on GHG emissions at the multilateral

level within the framework of the CBD failed. A United Nations Forum on Forests (UNFFF) is still in place in order to develop international forest policy but failed to catalyze the provision of new technical and financial resources to developing countries and some developing countries believe that there are more opportunities for realizing financial gains from the UNFCCC compared to the UNFFF (Humphreys, 2008).

However, nearly 20 years after Rio, the effective implementation of the conventions faces several challenges and natural resources continue to deteriorate (Millenium Ecosystem Assessment, 2005). The conventions have ambitious goals and they do not have the mean to implement appropriate measures and no system of sanctions. It must however be noted that many secretariats act with limited capacities, in an uncoordinated manner, and even in competition. Copping the incapacity of the conventions to solve the global environmental problems, the Climate Convention gained a place that became more and more important, leading to the monopolization of a major part of discussions on the Environment.

2.3 The emergence of global models to understand climate change

The vision of a global world has different roots, which, even if it has different origins, criticizes the segmentation of the environment into sectors. The concept is one of a "world view" in which Nature is considered as a living good in which all parts are connected and that humans are a part of it. This vision is present for example in the Andean or the Siberian cultures (Haverkort and Millar, 1992, Descola, 2001). The anthropological analysis of the relationship between humans and non-humans suggests that the differentiation between human and nonhuman corresponds to a certain stage of world history that the most developed cultures appropriated (Latour, 1991). Yet, in some cultures such as the Indian and Japanese civilizations, there is no distinction between the individuals and the environment. This is the superiority of the occident that would have led to the distinction between an order of human realities and natural realities.

In occidental countries, two major developments will challenge the separation between men and the environment. The first concerns the consideration of the status of Nature and the desire to establish a contract with her. It was conceptualized by Michel Serre (1990). The second is the integration of the human in a global Environment by the scientists. The concept of geophisiology was already developed in ancient Greece and was defined during the twentieth century by Vernadsky (1929). In 1975, Robert Garrels, F. T. Mackenzie C. Hunt ("Chemical Cycles and the Global Environment: Assessing Human Influences") set out the general principles of chemical circulation systems on Earth. It is Lovelock (Lovelock, 1972), under the auspices of Gaia, which popularized the concept of geophisiology. Other models such as World 3¹ and the general circulation models used by the IPCC (2007) were further developed. Today, global biogeochemical models are numerous and can integrate plant cells to a global dimension (E.g. Krinner, et al., 2005). Climate models clearly show the impossibility of dealing separately the environmental processes and the human activities when the global scale is considered.

¹ The model of J. Forrester proposed a formal model of interactions between population, capital, and three factors that affect growth (food, resources and pollution)

3. The supremacy of the climate issue

During the last decade, and particularly since the conference of Bali in 2007, climate change has taken the lead on all the other environmental issues, which are also considered as of major concern (extinction of biodiversity, desertification, deforestation ...). In light of the theory of justification developed by Boltanski and Thévenot (1991), this study presents that the arguments in favor of the environment but not related to the climate change issue suffer a significant deficit of legitimacy. They developed a theoretical framework designed to describe people's capacity to legitimize their view of a situation. In other words, this capacity refers to their ability to justify the meaning they give to their acts. Boltanski and Thévenot (1991) named "justifications" the associations of people and objects which can lead to an agreement and a judgment on the cogency of a discourse. They point out a plurality of forms of investment and of generality in which the actors seem to use different logical classification, expression and action. According to us the generalization of the justifications is attached to a higher common principle which supports the actors involved. The theory built an agreement by creating equity between persons and objects and giving a order of hierarchy.

Each of these principles is the central element of a "city" which can be defined as a logical rationale based on a conception of a common good. Various authors sought to find the place of Nature in other "cities" even if all the arguments in favor of the environmental causes could not constitute in itself an independent system of legitimacy (Godard, 1990, Lafaye and Thévenot, 1993, Latour, 1995, Godard, 2004, Mermet, 2007). A "city" is emerging in which Green would be greatest status and pollution the smallest status. Lafaye and Thévenot (1993) show that the introduction of a new order of justification is possible only if it criticizes the other levels of justification and agreement between the parties. On the one hand, it is possible to address the criticism on other "cities". On the other hand, the authors argue that the magnitude of greenness still seems insufficiently equipped to be used in the general justifications. Two major constraints of the establishment of the ecological city emerge from their analysis:

- The future generations can't be present at the negotiating table;
- The ecological city involves humans and non-humans, which do not meet the principle of common humanity.

However, Latour (Latour, 1995) seeks to overcome these contradictions and to highlight the existence of a green city. He considers that it sufficient to extend the Kantian moral, in which the subject does not have to be considered as a mean but always as an end. Finally, according to Mermet (2007), the city discovered by Latour cannot be considered an ecological city. On the one hand, the green city does not meet the axiomatic method defined by Boltanski and Thevenot. On the other hand, the green city rejects both the environmentalist and Nature; virtually neither one nor the other has access to the city. Mermet proposes to start from new basis where the environmental activists and the Nature are the common superior principles. He elaborates an ecological city where the greatest is the one who invest in Nature and has consciousness about the services provided.

Despite these efforts, and in light of the current situation where natural resources continue to deteriorate and where environmental issues are largely left to the margins of the political agenda (except climate change), the commitment in favour of the environment suffers from a lack of legitimacy (Godard, 1990). I want to raise the hypothesis of the emergence of an "other" city in which all those concerned by environmental issues are concerned and considered - or are forced to be included - structured around climate change and especially carbon fluxes. I will call it the "carbon city". This city replaces the stillborn ecological city claimed by Mermet (Mermet, 2007) and Latour (1995).

Before considering the characteristics of what could be the basis of a new order of justification, it seems important to present some indicators of the important weight that climate change has taken in environmental debates during the in recent years.

- (1) First, the issue of climate change affects everyone, through the question "how is the weather today". Who has never started a discussion with his baker by saying "it's sunny today" or "the winter is cold this year"? On the contrary to the biodiversity issues, the hole in the ozone, the disappearance of fish in the ocean, such as highlighting Latour (Latour, 1995) and Lafaye and Thévenot (Lafaye and Thévenot, 1993), are not able concern all the men, all the parties. On the other hand, climate changes posses a global dimension that is immediately accessible for everyone, and everyone is able to appropriate it in its way;
- (2) Next, financial support given to scientific research made of climate changes THE topic of research of the late twentieth century and early twenty-first, in almost all the relevant disciplines. The theoretical knowledge that justifies the actions in the name of climate changes exceeds by far the knowledge produced by other environmental issues;
- (3) The environmental risk posed by climate change is regarded by many as more urgent than the extinction of species and desertification; these problems are even now climate change's subordinates. However, climate change directly concerns industrialized countries which are also major donors to the instruments of the environmental conventions, while the countries which are generally affected by desertification have limited capacity and their presence in the international sphere is small or insignificant.

Thus, the climate convention has evolved considerably and now occupies a central place in the management of the environment. The Convention on Desertification and the Convention on Biodiversity are now trying to find ways of synergy and build on the momentum of the Convention on climate, as climate change is as indirect and direct effects on the extinction of biodiversity and desertification. For example, the FAO report (2001b) on the role of soil in the mitigation of climate change calls for cooperation between the UN and other organizations and agencies in charge of the implementation of UN conventions on climate change, desertification and biodiversity (CBD, 2003, Secretariat of the Convention on Biological Diversity, 2006).

Which are the justifications used by the different actors when they refer to climate changes? How is the consideration of climate change by the other environmental issues expressed in speeches? These are the questions that will be presented in the next session, focusing our discussion on the role of carbon in all the references made on climate change.

4. The orders of the justification

4.1 An axiomatic developed around the carbon

Today the issue of climate change has taken precedence over all other environmental concerns at many levels of discussion. This hegemony of the issue of climate change is caused by two major phenomena of justification:

- 1) At many levels, we justify the ecological character of our acts because they are low carbon emitters, and because it is urgent to act against the threat of climate change;
- 2) The issue of climate change has gained such authority that activists and environmentalists are using the climate changes issues to be heard, considered and funded.

The first phenomenon can be considered as the starting point of the emergence of an environmental justification, while the second corresponds to the movement imposed by the first phenomenon of environmentalists and other activists from the ecological city to the carbon city which is progressively growing. This is an assumption that I make in order to see the foundations of this hypothetical city and the possible consequences. Which are the elements that shape the emergence of this new order of justification?

The first significant factor is the emergence of a new language whose lexical field is influenced by the reference made to carbon. Carbon gained a place that neither the struggle for the conservation of butterflies or the elephants, nor the struggle for the preservation of Lake Chapala and Lake Victoria has managed to achieve. The "environmental" and "climate change" issues gained importance through the carbon. It can be explained by: (1) the message is carried by other actors than the previous environmental activists (mostly scientists), and secondly because (2) environmental activists were considered as fanatics or people who are not serious, and were thus rejected by the various cities (Godard, 1990), including the designers of the environmental city (Mermet, 2007). But above all, a new set of axioms around carbon is emerging and creates a framework for definition and representation of a "common good" or desirable social status, and a mode of coordination (Godard, 1990). It is defined by the following axioms:

- (1) A common humanity: all are concerned with carbon dioxide emissions;
- (2) The principle of dissimilarity, which increased with the economic disparities, as the economic development of industrialized countries is significantly correlated with emissions of carbon dioxide (Bengochea-Morancho, et al., 2001);

- (3) A common dignity, everyone has an opportunity to "grow" in the carbon city;
- (4) Disagreements end on a shared awareness and assumed the new environmental status;
- (5) A link between higher status and sacrifice, in which the access to modernity is the main issue, and the subjects must relinquish to some goods;
- (6) Actors who recognize the effects on the common GHG emission reductions even if there is still a cloud of ignorance from the technocrats in this regard.

4.2 The carbon city and the other cities

The Carbon City is increasingly recognized in the other cities: (1) The Market Logic - the monetization of emissions reductions through carbon sequestration gives a monetary value to an environmental service. Indirectly, carbon allows a re-evaluation of some market goods according to their "ecological footprint". The market may however be used to reduce the emissions reduction efforts by creating hot air² and inadequately address equity (Liverman, 2008). (2) The Industrial Logic - the greatest status can be considered as the sustainable production that takes into account a business in the long term and its impact on natural resources. (3) The Civic Logic - there is a global form of collective agreement to maintain the global environment. The perceptions are obviously different, but global warming has become a common argument³. (4) The Fame Logic - The attribution of the Nobel prize to the Al Gore and the IPCC is a significant historical event. (5) The Domestic Logic - Climate change is represented by the transmission of the environmental footprint.

5. The political forests and the biophysical forests

Why do forests occupy an important place in the Carbon City? Why are forests different from other terrestrial ecosystems?

5.1 Biophysical Assessment

Carbon stocks management is a key issue in the fight against climate changes. This section presents how the role of forests in the carbon cycle in order to understand why they did gain so much importance. Carbon is the object of various exchanges between the various terrestrial, atmospheric and ocean

² "Hot air" means the production of fictive emission reductions

³ Jean Giono expresses it very well in *The Man Who Planted Trees* "When I consider that a single man, using his own simple physical and moral resources, was able to transform the desert land of Canaan, I think, nevertheless, the human condition is admirable. But when I take into account all the necessary constancy in the greatness of the soul and the selfless dedication to achieve this result, I feel an immense respect for this old uncultured peasant, who was able to complete this work worthy of God. "

reservoirs⁴ (Houghton, 1997) that make up the global carbon cycle (Figure 3). On land, forests play a major role in carbon cycling. The process of photosynthesis is the starting point for the synthesis of biomass⁵; plants fix carbon dioxide from the atmosphere which is then allocated and stored in plant "reservoirs". Forests represent significant reservoirs of carbon and trees contain more carbon per unit area than all other types of ecosystems (Fearnside, 2000). At the forest level, the carbon content in the biomass and soil organic matter. The terrestrial biosphere is considered a "carbon sink" that absorbs about 2.3 Gt C per year (Houghton 1997), almost 0.7 Gt C in vegetation. The vegetation is about $550 \pm 100 \text{ Pg}^6$ nearly 30% of fossil fuel emissions (Valentini, et al., 2000) and approximately one third of the carbon in the soil (Jobbagy and Jackson, 2000). It is not possible to differentiate the contribution of forest vegetation. Indeed, the definition of forest varies depending on the country and the geographical region (Figure 4). It is affected by two main processes⁷:

(1) human activities modify the ecosystems through two categories:

- a. Human activities are increasing the biomass and thus contribute to carbon sequestration (plantation, agroforestry, management of soil organic matter, etc.).
- b. The activities which reduce biomass and reduce the storage capacity increase GHG emissions (burning, decomposition and volatilization, etc.).

(2) natural phenomena that affect carbon stocks: wind, fire, drought, insects and diseases.

If it appears impossible to act on natural events, it is crucial to address human activities. The UNFCCC defined a number of forestry activities that have direct or indirect impacts on the carbon cycle:

- The activities that directly increase the storage capacity or limit the release process: reforestation, agroforestry, conservation and the fight against deforestation;
- Indirectly through activities that maintain forest biodiversity and improve the stability of ecosystems.

Forest ecosystems are an important place in managing the flow of carbon in the biosphere and thus the opportunities for action on climate change.

⁴ A reservoir is a sink of carbon dioxide, and this during a certain period of time when it absorbs more carbon than it releases. Five reservoirs can be distinguished: (1) aboveground living plant biomass, (2) belowground living plant biomass (3) dead organic matter, (4) soil and (5) litter.

⁵ Biomass is defined here as the total amount of live and inert organic matter above and below ground expressed in tons of dry matter per unit area.

⁶ Pg : Pentagram, 10^{12} grams

⁷ A third process has been suggested by some authors. These are the effect of fertilization-induced increase in atmospheric CO₂, which could increase the productivity of forests and thus their storage capacity. We have not included it because still subject to controversy.

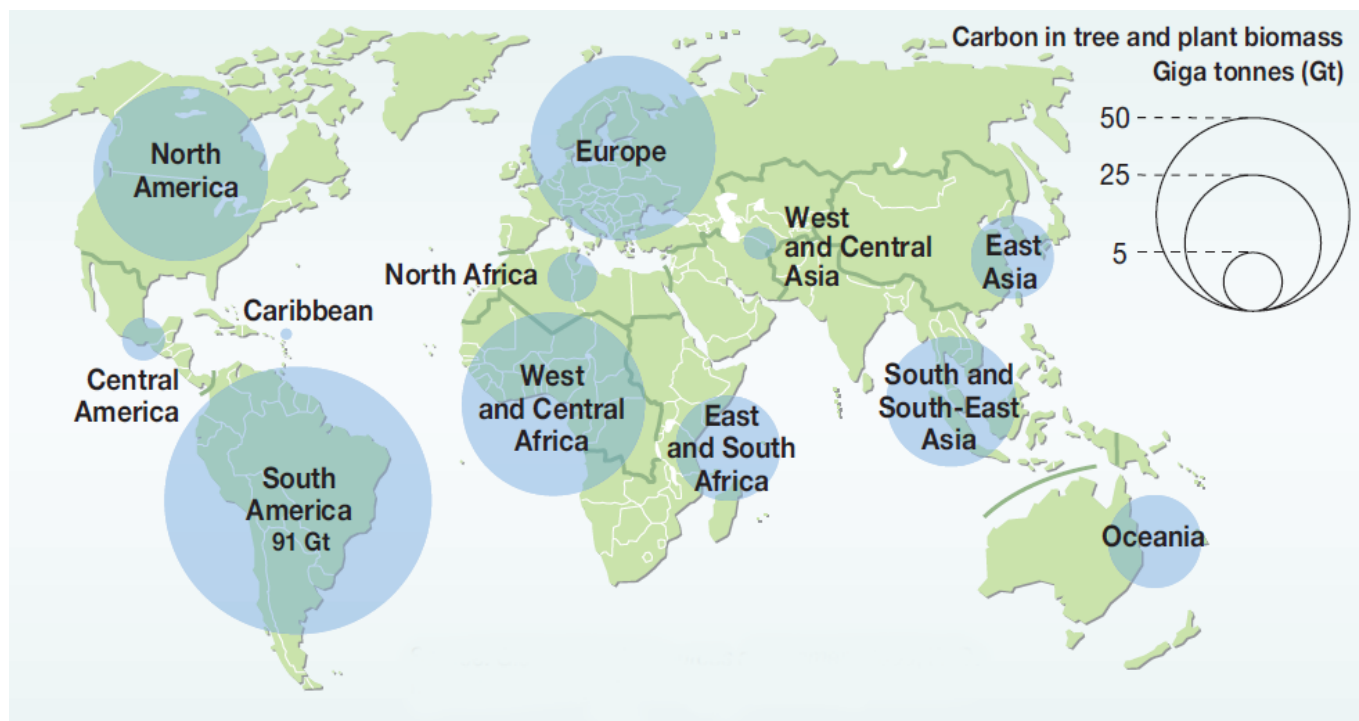


Figure 4 : Forest carbon stock per region

5.2 The political tree

In 1992, the UNFCCC adopted and recognized three main principles: (1) precaution, (2) common but differentiated responsibilities and (3) the right to development. In 1997, the negotiations at the Third Conference of Parties (COP 3) lead to the Kyoto Protocol. The Kyoto Protocol recognizes in its Articles 3.3 and 3.4 the importance of forests. The potential development of forest activities depends on the biophysical and socio-economic context of the countries, the legal aspects of the agreement and the economic costs of their implementation. However, the forestry issues quickly became a key controversy and the lead to delegates at the COP-4 in Buenos Aires in November 1998 to refer all decisions on forestry to the COP-6.

During the first part of the COP-6, many countries were opposed to the inclusion of the sinks in the quantitative system of accounting for GHG emissions. They feared the emergence of a right to interfere in the way they manage the natural resources (national sovereignty) and the creation of hot air. The arguments used to reject the inclusion of forestry were essentially based on the scientific uncertainties and methodological weaknesses. Seven forest activities⁸ are recognized in the quantification system for the developed country but not for developing countries. When considering developing countries, the only activities that are considered are afforestation and reforestation project activities under the Clean Development Mechanism (CDM).

⁸ The various forest activities are: (1) multipurpose agroforestry plantation, (2) reforestation on degraded lands, (3) industrial afforestation, (4) wood energy (5) increasing the efficiency of the wood processing in industries, (6) conservation of forests and (7) reduced impact of logging.

Moreover, tropical forests are excluded from the Protocol. This decision provoked mixed reactions. On the one hand, deforestation is identified as significantly contributing to GHG emissions and must be taken into account in reaching the ultimate objective of the Convention. On the other hand, deforestation is mainly a question of development and fight against climate change must be achieved without limiting the development of non-Annex I. The debate on tropical forest and avoiding deforestation return at the center of the negotiations at the 11th COP in Montreal with a new proposal presented by the Coalition of Rainforest Nations⁹. The idea would be to establish a sectoral CDM mechanism, identified by the acronym REDD (Reducing Emissions from Deforestation in Developing Countries) ¹⁰, which could enable a country to obtain financial compensation for the establishment of domestic policies of reduction of deforestation.

This proposal is accepted with some modifications and new process negotiation on establishment of avoided deforestation is launched. The discussions focus on identifying when the terms of reference, social issues, economic, technical and methodological, policy approaches and modes of compensation. Two economic issues emerge: (1) the fungibility of carbon credits with existing markets and (2) the type of funding. In parallel, the scientific issues are challenging and mainly concern the estimation of carbon stocks, identifying and predicting changes in land use, present and future, and the impact of land use on carbon stocks.

In 2007, the COP13 led to the adoption of the Bali Action Plan. This action plan includes reducing emissions from deforestation and forest degradation to the political agenda for the negotiation of the post-2012 agreement. This decision follows a large scientific contribution, and the publication of significant report such as the World Bank (Chomitz, 2006), the Stern report (2006) and the last IPCC reports (2007). These efforts are greeted with enthusiasm by the countries. While the effectiveness of such a mechanism remains to be proven (Karsenty, 2007), REDD is the subject of special attention and forests reach the top of the political agenda such as the G8. Recently in Copenhagen, some developed countries committed themselves to massive funding for early action to halt deforestation. The inclusion of forests in international politics has never reached the level it has reached today.

5.3 Biophysical forest vs. political forest

On the one hand, forest ecosystems, as seen above, represent an important potential for carbon storage well above the other terrestrial ecosystems, but represent a much smaller than soils and oceans. During the first commitment period, their inclusion has been largely limited (Bernoux, et al., 2002) (Locatelli and Pedroni, 2006) (CATIE, 2006). However, deforestation and forest degradation became a staple of international negotiations! This can be explained by the increasing recognition of forest ecosystems in the cities that were presented above. Forests provide a wide variety of services: carbon sequestration,

⁹ The Rainforest Coalition counted nine countries at COP 11 and 30 countries at COP15.

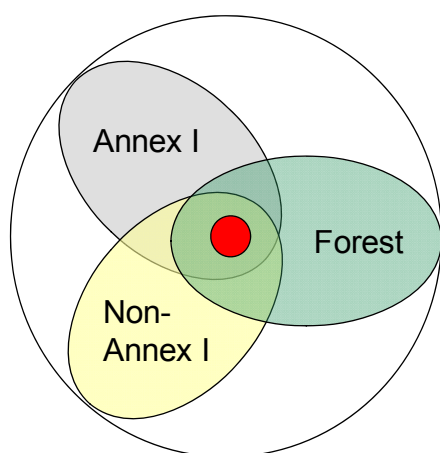
¹⁰ REDD is then changed for Reducing Emissions from Deforestation and forest Degradation, then reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries

biodiversity, hydrology (Bruijnzeel and Critchley, 1994, FAO, 2005b), landscape, cultural services, production of wood, non- Wood (Belcher and Schreckenberg, 2007),, a land reserve and even a religious representation. Forests have become a leitmotif for many actions and represent a mediator for some actors who could not participate to the negotiations.

The forest products represent a significant share of international market, particularly for forested countries such as Gabon and Indonesia. The forest carbon occupies a particular position in the voluntary carbon markets. On the other hand, forestry projects contribute to increase the productivity and sustainable management. Forests represent the heritage and are recognized by the world heritage of the UNESCO. In addition, the forests allow the recognition of some actors such as the indigenous peoples in the climate convention. The forests are even considered by the religion as testified by the forest plantation project of the Vatican in Hungary. Finally, the tree is the symbol of unity and the commons as represented by citizen movements "A Parisian, one tree". Trees are recognized in all levels of justification.

5.4 On the importance of the “carbon” language

The Climate Convention has its own language, results from an intensive interaction between the politic and scientific actors. This new language is dynamic, complex and universal. As for example, the acronym REDD changed five times since 1997 before reaching the consensus in Copenhagen in 2009. While a part of the vocabulary is purely technical and scientific, the other part is elaborated for the establishment of the convention and concern legal aspects. Part of the scientific language is directly inherited from the work conducted by the IPCC and the scientific community in general. The requirement to effect measurements of carbon stocks is embedded in the Kyoto Protocol. This is “in the light of scientific evidence that the parties review the protocol”. The technical, social and economic issues are treated subsequently treated according to their relevance. The legal language that is related to the implementation is the result of compromises between science and politics.



The acquisition of the “carbon” or “climate” language is essential to have access to the United Nations framework on climate change. It represents a constraint to effective participation of various delegations particularly those from sub-Saharan Africa. The limited scientific data and knowledge limit countries to understand their potential to develop mitigation and adaptation strategies against climate change. It is therefore a double problem: access to the language of the UN Convention, particularly by related to forest issue, and access to data and tools for analyzing the circumstances and capabilities of nations.

Figure 5: Schematic representation of the importance of quantifying forest carbon in the climate arena. The red dot represents the measurement of carbon.

In the forestry context, the issue of measuring forest carbon stocks is present since the beginning of the convention and the many scientific gaps limit the consideration of forest during the first commitment period. The acquisition of scientific data and language are needed in order to allow the interactions between the developed countries, developing countries and the forest ecosystems (Figure 4). For many tropical forest countries, which are active in the climate arena, the acquisition of the language and the technical knowledge to estimate carbon stocks is a crucial element to allow them to weight their potential contribution with the other countries. Today, under the acronym MRV (Measurement, Reporting and Verification) are regrouped the different steps for carbon stock measurements, the set of processes and procedures through which the information is evaluated and monitored to determine if the parties fulfil their obligations effectively (Wemawere, 2009).

The term MRV comes from the Bali Plan of Action. The MRV is supposed to represent a common framework and plays a key role in building a system of trust between the parties. “Measurable” is an adjective that applies to a given object (action/commitment/ support to action) to be realized in response to a specific obligation, which requires Parties to collect and compile national information/data/ statistics in relation to this object, that are complete, accurate and consistent over time, in particular for the purpose of reporting. “Reportable” implies the compilation and availability of national data and statistics for information and/or scrutiny. “Verifiable” implies the establishment of a process whereby reported information is subject to a technical review, including a comprehensive and objective assessment of completeness, accuracy and quality. Thus, all the efforts should be measured and communicated in order to demonstrate whether the commitments are met or whether further efforts are needed. Today, one of the issues involved in building a new climate regime after 2012 based on the definition of these criteria.

5.5 The Sub-Saharan Africa has something to say!

Of the 49 least developed countries 29 are African (UN, 2009). The continent's total emissions amount to 4% of global emissions (Williams, et al., 2007) for a population representing 14% of the world population. Yet, Africa is the most vulnerable continent to climate change IPCC (IPCC, 2007e). In many localities in Africa, climate change is already a reality. Climate change in Africa can lead to starvation and lead to catastrophic social and economic disruption. The risk of spread of desertification, poverty of much of the population, which depends largely on the use of natural resources, the weakness of its economy and its institutions, lack of capacity of governments to shape the contours a worrying situation (Karsenty, et al., 2001). During the COP12 in Nairobi, the UNFCCC launched a call to promote actions in the African continent, but it remains largely outside the process. 2.6% of the CDM are in Africa and only one forestry project was implemented (UNFCCC, 2007b). Exclusion or weak will? At the Bali conference, African countries have expressed their support to establish of voluntary GHG emission reductions that are measurable, reportable and verifiable. During the COP15, the African countries expressed profound disagreement after their exclusion from the parallel ministerial meeting.

Several studies argue that Africa has great potential for mitigating climate change (Walker, et al., 2008) (Ringius and Lasse, 2002, Vagen, et al., 2004). 16% of global forest area is located on the continent (FAO, 2006c) and forest carbon stocks can rise up to 300 MgC ha⁻¹. Yet, they are far from having the necessary capacities to implement the necessary actions for their effective participation. Most countries only dispose the national communications made to the forest resource assessment of the Food and Agriculture Organization (FAO). The absence of scientific data on forest carbon stocks largely limited their capacity to assert their interest in the international negotiations on climate.

6. Conclusion

The magnitude of the climate warning and the severity of the environmental crisis it reveals did not result in a careful consideration of the Nature of the social contract in developed countries, in the public opinion, in the political process and in the intellectual world: few discussion on the economic growth, on the finite resources at the exception of oil, on the necessary lifestyle changes necessary and questioning of the consumer society. The international negotiations revealed us a slow process that is not adequate to the necessary measures. While it is becoming increasingly urgent to take action against global warming, the only possible response that could halt the changes towards a state of no return would be the establishment of a new natural contract by which the anthropic activities could responsibly act to limit their GHG emissions to a level that does not jeopardize humanity. St. Augustin wrote the City of God after the fall of Rome, should we expect major climatic disasters to write the carbon contract?

The threat of climate change makes the revelation of a new city. While for centuries the occident focused on humans, it has gradually integrated the Nature into a global world. Developed by the scientific spheres, the overall physical theories show the limits of human activities. The environmental impacts are such that they question the future of all sectors in the medium term. Using the theory of the justification seems to reveal the emergence of a new growing city in which the reduction of GHG emissions is of priority. The Carbon City is a particularly fertile ground for forest projects. Development of forest activities is however limited by two major constraints. The first is related to the acquisition of the necessary language to access the climate arena. The second concerns the resolution of scientific issues related to the measure of carbon stocks, and the impact of human activities on carbon stocks and especially forest. These constraints are unevenly distributed among countries. Sub-Saharan Africa is largely marginalized. The establishment of a more equitable climate regime can be performed by a progressive strengthening of the scientific foundations of the city under construction.

Organization

The first chapter has given us the elements to draw the conceptual framework. Climate change is being the main environmental crisis and carbon has become the representation of climate change within the already existing order of justification and within the new one which is growing under the auspices of the climate convention and the Intergovernmental panel on climate change. Carbon is being the basis of a new growing model of society where the forests occupy an important place. Forests are being perceived as a vector of consensus and participation between the different actors of the climate arena, particularly when considering the sub-Saharan African countries. Sub-Saharan African countries are mostly at the margins of the process and the forests represent a crucial element for them to be considered within the arena. The definition of Forest and more specifically the carbon in forest are the results of measurement and scientific experiments. Moreover, I focus on measuring carbon in forests in sub-Saharan Africa. Building knowledge on this issue does increase the potential participation of Sub-Saharan African countries to the climate arena.

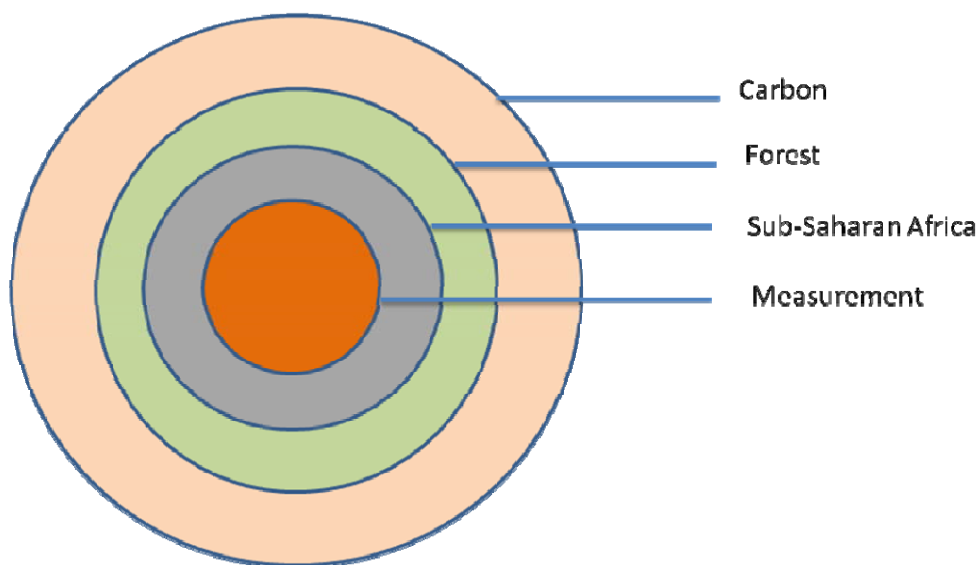


Figure 6: Conceptual framework

Objectives

The general objective of this thesis has been to reveal the importance of forest carbon stocks in sub-Saharan Africa with emphasis on implementation of integrated multi-scale biomass and carbon measurements to improve our understanding of the potential contribution of forest ecosystems to climate mitigation process. Using Ghana as a national case study, the data has then been used to scale up at continental scale.

The specific objectives are:

1. To assess the effect of deforestation and forest degradation on carbon stocks ;
2. To inventory volume and biomass allometric equations, volume biomass and carbon ; measurements at national and continental scale ;
3. To harmonize data in order to make them comparable and useful for scaling up exercises;
4. To identify and categorize the factors explaining the variability of wood, biomass, and carbon stocks, above and below ground, at different scales, from the plant to the functional type, from the forest to the continents;
5. To explore physical and economic feasibility for enhancing forest carbon, decrease emissions from forest cover change with particular attention to selective logging;
6. To explore alternatives for targeting emission reductions and carbon sequestration for integrated REDD+ activities, with emphasis on forest degradation.

Methodological approach

The carbon and biomass are the result of the synthesis of organic matter by plants. The entry point is the photosynthesis, which captures light radiation and converts it into organic matter. The organic matter is then allocated and stored into the various plant organs, above and belowground. The plant life is determined, whether by the seasons or by anthropic events such as deforestation. Bulk of the biomass in above- and below-ground plant parts is eventually transferred to the dead organic matter pool or it is oxidized or burnt. Dead organic matter, which consists of deadwood (standing as well as fallen) and litter, is either decomposed or oxidized, or stored for longer periods above or below the ground as detritus. CO₂ fixed by plants ends up in soil as organic matter or in finer forms as humus through the process of decomposition. Thus, CO₂ removed from the atmosphere is stored as dead and living biomass or soil carbon in the biosphere. Five carbon pools have been defined by the IPCC (IPCC, 2003) (Figure 6).

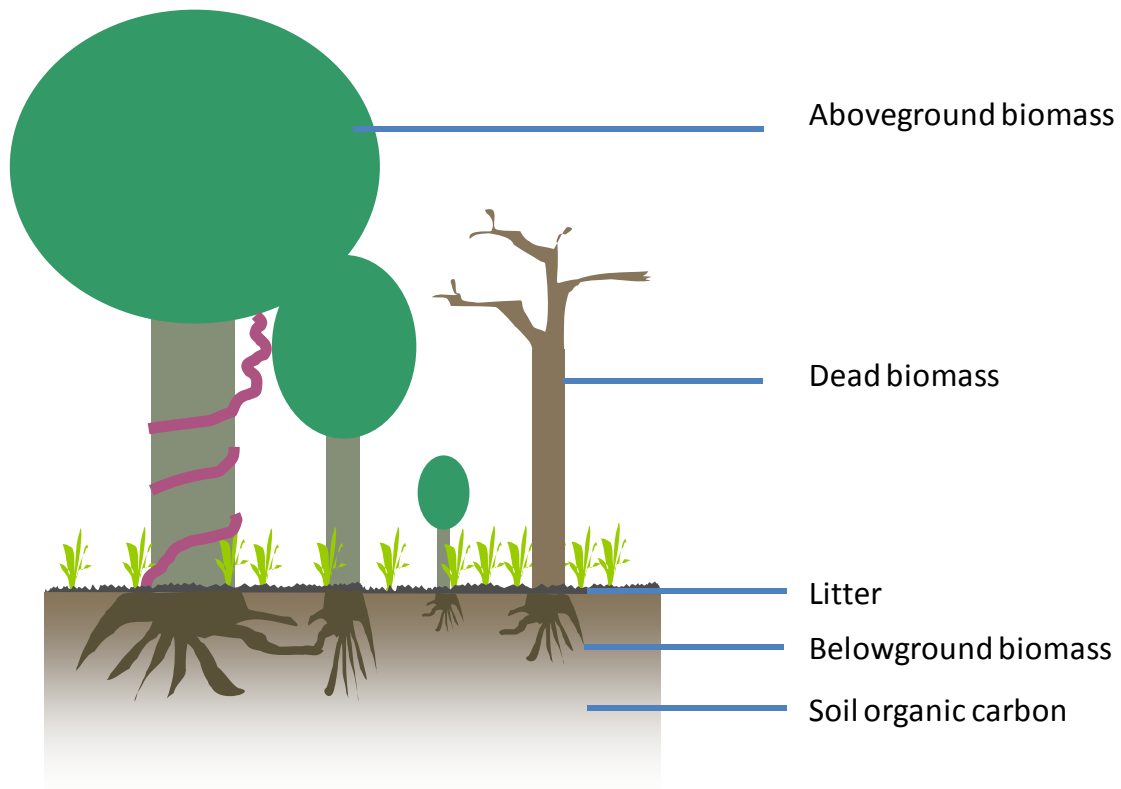


Figure 7: The carbon pools

There are several methods to estimate carbon stocks, which accuracy depends on the scale considered (Lim, et al., 1999). Figure 8 represents the different scale used to scale up from plant cells to the land cover or land use that could be identified at national, regional, continental or global scale. Generally, regional estimates of biomass and carbon depend upon local scale measurements that are expanded geographically (Keller, et al., 2001). The expansion from plant cells to continental scale can be achieved using several methods based on average values per biomes or vegetation types (Gibbs, 2006a), modeling (Krinner, *et al.*, 2005), or neural networks (Papale and Valentini, 2002).

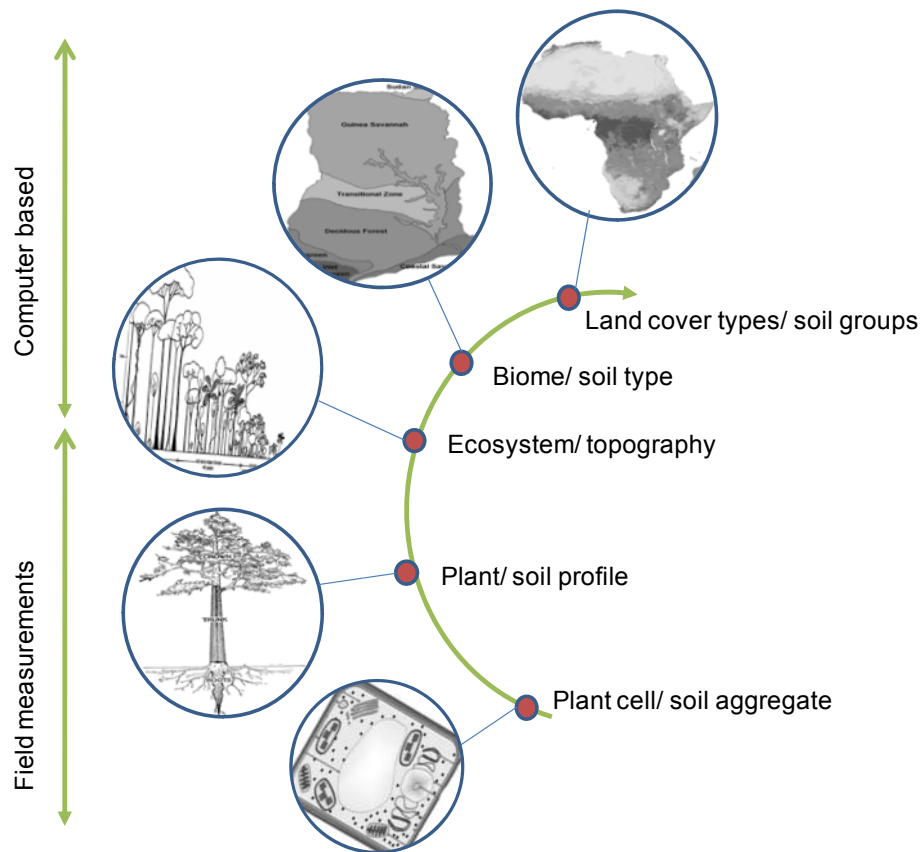


Figure 8: Integrated approach to estimate soil and biomass carbon at national, regional and continental scales

However, all the methods use destructive field measurements for their calibration. It is impossible to achieve destructive measurement at the scale of the forest or the ecosystems. Moreover, various models are compiled to integrate the biomass measurements at the plant or plot level to estimate biomass at larger scales. It thereby implicates a preliminary step to harmonize and homogenize the data. When considering the soil compartment, it has always been considered separately from the aboveground biomass. However, the procedure to scale up soil measurements is broadly the same than for the carbon biomass (Figure 8).

The different steps in the methodology are:

- (1) Inventory the soil organic measurements in soil profiles at continental scale and develop soil carbon estimation based on available databases and maps ;
- (2) Inventory the available volume and biomass allometric equations at continental scale and identify the gaps ;
- (3) Develop the first tree biomass allometric equations from tropical humid African forests ;

- (4) Estimate the biomass and the carbon in the different pools within different plots, forests and biomes ;
- (5) Build the necessary tools that would allow the harmonization of other data from other sources ;
- (6) Inventory and harmonize the available biomass measurements at continental scale ;
- (7) Integrate the data into continental land cover products and vegetation classifications in order to derive continental estimates ;
- (8) Estimate the impact of forest degradation and particularly the impact of selective logging on carbon stocks ;
- (9) Estimate the potential for emission reductions through the REDD+ by developing scenarios analysis .

Outline of the thesis

The various chapters of this thesis have been grouped in six parts, following approximately the methodology steps presented above. The first step consists in analyzing the position of sub-Saharan Africa in the context of reducing emissions from deforestation and forest degradation, based on available data (Chapter 2). The second step focuses on soil organic carbon and the influence of soil databases and soil classifications in assessing soil organic carbon (Chapter 3). The third step is composed by three chapter (4, 5 and 6), that respectively treat the importance of improving the allometric equations, inventorying the status of sub-Saharan Africa in developing allometric models and developing a methodology and develop the first tree biomass allometric models for tropical humid forests of Africa. The fourth step (chapter 7, 8 and 9) consists in analyzing the biomass at local, biome and continental scale. While the chapter 7 focuses on field experiments in three forests in three ecological zones of Ghana, the chapter 8 provides the tools to harmonize the other forest inventory of experiments and the chapter 9 integrates the various harmonized sources at continental scale. The fifth step (Chapter 10) concerns the impact of anthropic activities on carbon stocks and particularly the first measurements of the impact of selective logging on GHG emissions in Africa. At last, the sixth step analyses the potential for implementation of emission reductions and enhancing carbon stocks under a REDD+ mechanism and identify potential alternatives (Chapter 11 &12).

In many parts, this thesis summarizes works that have been published or are under review for publication (Chapter 2, 3, 4, 5, 6, 7, 8, 10, 11 and 12).

Chapter 2

Deforestation and forest degradation: assessing for emission reductions

This chapter is modified from the article: Henry, M. Maniatis, D. Valentini, R. 2009. Deforestation and forest degradation: assessing for emission reduction in Sub-Saharan Africa submitted to Environment and Development Economics (EDE), submitted

Abstract

In light of the importance of forest changes in sub-Saharan Africa (SSA) and their influence on the carbon (C) cycle, there is an increasing necessity to provide accounting of C stocks under the potential scheme of Reduced Emissions from Deforestation and Degradation (REDD+). The aim of this study is to analyse available data to estimate the impact of forest change on the C cycle and to discuss the potential implementation of a REDD accounting system for SSA countries. Using globally available data, I estimated that the SSA forests contained 58 (10 - 105) PgC and that deforestation, forest degradation and selective logging emitted approximately 0.3 (0.06 - 0.5), 0.03 and 0.008 PgC Yr⁻¹, respectively. However, this approach to estimate C stock change is limited by the definitions of forest changes, and available data on associated C emissions. There exists an urgent need for homogenizing data on C dynamics in SSA countries.

Keywords: global change, greenhouse gas emissions, tropical forest, monitoring

1. Introduction

Deforestation and forest degradation significantly affect the carbon (C) cycle by emitting greenhouse gas (GHG) emissions to the atmosphere. The processes of combustion and decomposition are the main direct sources of emissions, but there are also indirect drivers of GHGs such as soil respiration and erosion (Schulze, et al., 2002). Globally, land use change contributes 0.3 to 3 PgC yr⁻¹, or approximately 21 % of the total fossil fuel emissions (Houghton, 2007) and about 0.6 to 6 times the Kyoto protocol target for 2012. Even if Africa contributes only less than 4 % to the global anthropogenic fossil fuel emissions (Canadell, et al., 2009), 20 % of both global net primary production (NPP) and global land use emissions (mainly from forest degradation and deforestation), and around 40 % of fire emissions have been attributed to the African continent, significantly affecting the atmospheric chemistry (Andreae, 1991, Houghton, 2003, Kituyi, et al., 2005, van der Werf, et al., 2006). Moreover, about 50 % of interannual variability of global atmospheric CO₂ is attributed to the variability of the African C balance (Cao, et al., 2001, Rödenbeck, et al., 2003, Baker, et al., 2006, Williams, *et al.*, 2007). African forests contain large C stocks in biomass, up to 255 MgC ha⁻¹ in tropical rainforests (IPCC, 2003). There is a growing concern on the future of such C stocks both from possible climate perturbation inducing changes in ecosystems and from direct human induced processes such as deforestation and forest degradation.

Evidence has been presented that the mean climate and climate trends of Africa's tropical rainforest zone over the period 1960-98 is the driest tropical rainforest region and has become drier in recent decades (Malhi and Wright, 2005). Climate perturbations could lead to further drying, making the forests more vulnerable to extreme climate phenomena and increase the risk of forest fragmentation and fires. The African continent was identified as the most vulnerable to climate change and a priority region by the United Nations Framework Convention on Climate Change (UNFCCC) (2006). However, the current and projected health of forest ecosystems in Africa is not well understood, but is expected to play a major role in mitigating climate change (Williams, *et al.*, 2007, Lewis, et al., 2009).

Forests are recognized by the political and scientific communities as being important for both mitigating and adapting to climate change (IPCC, 2007e). During recent UNFCCC negotiations in Bonn, forestry-related issues were addressed through discussions on reducing emissions from deforestation and forest degradation, the role of conservation, sustainable forest management and enhancement of forest C stocks (REDD+). Together, these different concepts were integrated within the negotiations and were labelled with the acronym REDD+ (UNFCCC, 2009).

The prospect of including forests within the post-Kyoto regime has progressed significantly over the last four years, and the options to compensate emission reduction from deforestation and forest degradation has been presented in several proposals (*e.g.* (Santilli, et al., 2005, Angelsen, 2007, Mollicone, et al., 2007)). Recent contributions proposed default values and methods on accounting emission reductions (IPCC, 2007, GOC-GOLD, 2009). Several contributions from around the world were proposed to the UNFCCC to implement REDD+ (Parker, et al., 2008). Accounting for emission reductions for REDD+ is challenging due to the complexity of tropical forest ecosystems and the interactions with a variety of anthropogenic activities. In this light, it is crucial to investigate the spatio-temporal variation of C stocks stored as vegetation biomass in tropical forests. Obtaining sufficient ground-data to do so is an expensive and time consuming task.

The floristic composition and structure of sub-Saharan forests are complex and extremely diverse depending on the different ecological regions (ORSTOM and UNESCO, 1983). As a result, assessing for C stock changes resulting from human interactions with forest ecosystems is often difficult to assess. Developing methods which are not adapted to the diversity of the African continent will reinforce its exclusion and make the consideration of its forests difficult. Relatively little scientific work has been carried out in sub-Saharan Africa with regards to C, biomass and carbon dioxide (CO₂) emissions and this is generally known. Reliable data will enable the governments of sub-Saharan Africa (SSA) countries to develop a realistic and practical negotiating position on a future REDD mechanism.

The aim of this study is to present 1) the current knowledge of the SSA carbon budget, 2) the role of deforestation and forest degradation 3) the current methods that are proposed to monitor REDD+ and 4) to analyse the way they can be adapted to the SSA context.

2. The current sub-Saharan carbon budget

Most of the forest biomass in Africa is situated in the SSA region and more precisely in the Central African belt. Estimates of aboveground biomass in African tropical forests vary among authors, ranging from 60 to 255 MgC ha⁻¹ (Palm, et al., 2000, IPCC, 2003, Vagen, *et al.*, 2004). Above ground C stocks decrease from tropical forest with a minimum in the mountain forests due to limitations of climate and soil on forest productivity. Tropical rain forests show the highest belowground C, both for the root (57 MgC ha⁻¹) and the soil component (53 MgC ha⁻¹ for 0 - 30cm) while minimum values are shown by mountain forests (Bombelli, et al., 2009). Both above and belowground C stocks vary between different forest management types. The conversion of forests to other land use types involves significant changes in C stocks, particularly soil organic carbon (SOC). While the maximum SOC was observed in natural forest (80 MgC ha⁻¹), the minimum SOC was observed in cropland (44 MgC ha⁻¹). A similar trend was observed by Houghton (1999) who estimated SOC to be approximately 100 and 50 Mg ha⁻¹ in undisturbed closed and open forests, respectively.

In an attempt to improve the above forest C stock estimates, for SSA I used the Globcover map (Defourny, et al., 2006) and the C density data from IPCC (2003) and Carbon Dioxide Information Analysis Center (Gibbs, 2006b) (Figure 10). I estimated that aboveground forest C stocks for SSA were 57.679 PgC (ranging from 9.967 – 105.391 PgC). Using the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISSCAS/JRC, 2008) and the Globcover map, it was possible to estimate the SOC in the 0 - 30 cm soil layer in forest ecosystems. It resulted that 33,962 PgC is contained in the soil compartment of the forests. Unfortunately, it was not possible to have an indication about the variability of the soil C content as only one value of C content per soil type was reported in the original database. Furthermore, 63 % of the C stock in forest ecosystems is contained in the aboveground component while the rest is SOC in the 0 - 30 cm soil layer. It is important to note that this estimate does not consider the litter, the root and the soil below 30 cm depth. However, most of the C is found in the aboveground biomass and the 0 - 30 cm soil layer.

C stocks vary considerably between countries. The highest aboveground and soil C stocks were found in the Democratic Republic of Congo (19,211 and 8,402 TgC, respectively) while 0.41 and 0.27 Tg C, respectively were found in Djibouti (Appendix I).

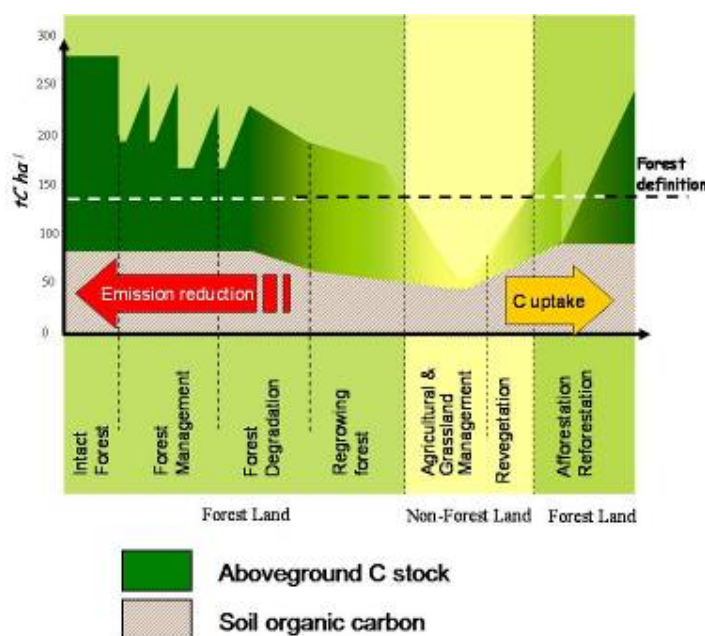


Figure 9: Sources and sinks of carbon from forest area and cover change in tropical humid ecological zone of sub-Saharan Africa.

The C stock data were obtained from Kotto-Same et al. (1997), Kanmegne (2004), Glenday (2006) and IPCC (2006a). The line representing the forest definition is presented here as an indication.

Due to the low fossil fuel emissions, the SSA carbon balance is dominated by two large fluxes: emissions from land use change and uptake by terrestrial ecosystems. According to the National Communication to the UNFCCC, emissions from Land Use and Land Use Change and Forestry (LULUCF) are $497\ TgC\ yr^{-1}$ and removals $671\ TgC\ yr^{-1}$ (Appendix I). Combining all the emissions (including fossil fuel) and removals, SSA is currently a net sink of $87\ TgC\ yr^{-1}$. When considering the whole African continent, it appears to be a net C sink of $168\ TgC\ yr^{-1}$. This result is due almost exclusively (99 %) to SSA, with its highest removal rates of terrestrial vegetation. The C balance varies between countries. While Democratic Republic of the Congo accounts for 31 % of the LULUCF emissions of SSA, Burundi account for only 0.06 %. In addition, Madagascar represented the highest removal with 27 % of SSA and Gabon the highest net emissions with $135\ TgC\ yr^{-1}$. It should be noted that the data for 14 countries were not taken into account in this calculation as the data were not communicated to the UNFCCC or were not considered as reliable.

3. Deforestation and forest degradation

Deforestation and forest degradation are two different processes with different ecological consequences. Contrary to deforestation processes in south east-Asia and in South America, deforestation in SSA rarely induces the total removal of the aboveground biomass and cannot be only attributed as clear cutting practices. It is recognized that considerable areas of dense forest have been (1) deforested by conversion into agricultural land and other non-forest cover or (2) degraded into areas with low tree-cover (Mertens and Lambin, 2000). Deforestation involves cutting, damaging and burning of forest and is mainly associated with slash and burn agriculture in SSA,

whereas forest degradation is mainly related to logging activities and forest encroachment by local population. However, the two processes are closely interlinked.

On the one hand, the dynamics of farming systems are characterized by smallholder farms, fertility management mainly through slash and burn activities in surrounding forest areas, low capital and labour availability that limit the total conversion of forest areas. It results in a process of forest clearing in various steps that does not always leads to deforestation. Forest encroachment by farming activities, through fodder, firewood extraction and pasture activities is facilitated by the presence of infrastructure (e.g. roads) (Wilkie and Laporte, 2001).

On the other hand, the key factor driving forest fragmentation and degradation in the humid forests of Africa is selective logging. Industrial logging in the basin currently affects about half of the forest block. It is generally of low intensity, the number of trees being felled for sale being around 0.5 to 3 per hectare, with a maximum of 4 per hectare (CBFP, 2007), but an important part of the impact is due to the roads, skid trails and logging bays. Logging operators undertake selective logging which is generally based on a 40 - 50 years time period rotation. The impact of logging activities is also influenced by the type of logging operators. While large logging operators have enough capital to implement improved selective logging practices such as directional felling, implement certification, and implement elaborate forest management planning, small operators are usually badly equipped and could have a higher impact on the forest.

3.1 Defining forest degradation and deforestation

Forest types differ widely, determined by factors including latitude, temperature, rainfall patterns, soil composition and human activity. A study of the various definitions of forests (FAO, 2006b) found that more than 800 different definitions for forests were in use in the world. Different definitions are required for different purposes and at different scales. In the context of REDD+, definition of a forest and a degraded forest is based on biophysical characteristics.

But what does 'deforestation' or 'forest degradation' really mean in the international policy context? It is needless to say that consistent terminology for REDD+ will be crucial for effective negotiations, implementation and future reporting and monitoring of C stocks. Diverging interpretations of such simple terms such as, for example, a 'forest', 'degradation' or 'deforestation', and their ramifications for C accounting, have occupied dozens of pages in IPCC reports, with ambiguities still lingering on (Schoene, et al., 2007).

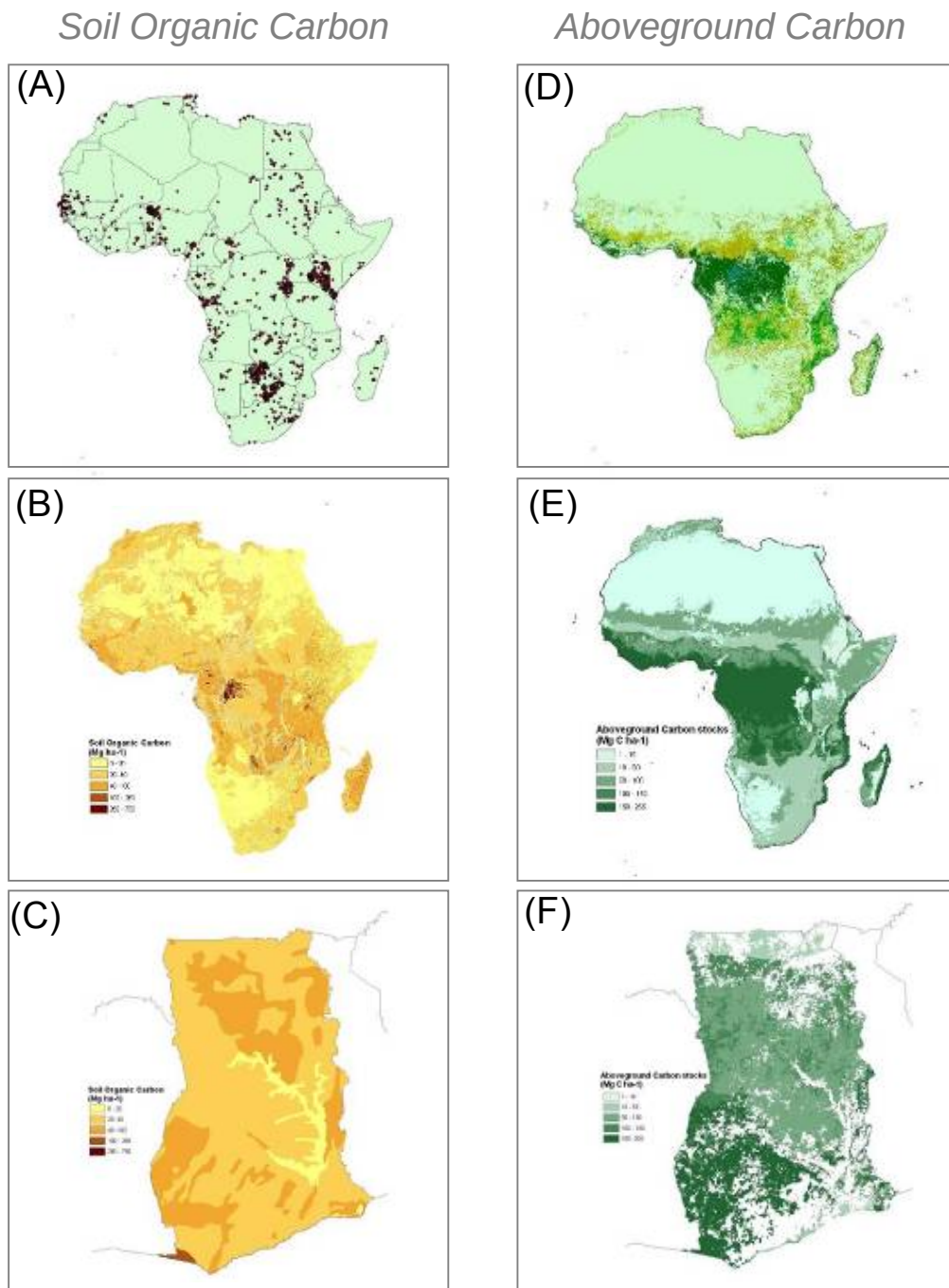


Figure 10: Assessing C stocks of sub-Saharan Africa

On the left: assessing soil organic carbon using the ISRIC database and the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISSCAS/JRC, 2008).

On the right: assessing aboveground carbon using the Globcover map and the IPCC and CDIAC default value for C stocks. (A) Localization of the soil profiles, (B) map of soil organic carbon of Africa, (C) map of soil organic carbon of Ghana, (D) map of forest from Globcover, (E) map of aboveground carbon stocks of Africa and (F) map of aboveground carbon stocks of Ghana.

Under Decision 11/CP.7 of the UNFCCC, deforestation was defined as: the direct human-induced conversion of forested land to non-forested land. The FAO (2001c) defined it as: the conversion of forest to another land use or the long-term reduction of the tree canopy cover below the minimum 10 % threshold. Although these definitions differ, there is general consensus on their use and applicability. In order to find a consensus on defining forests under the Kyoto protocol, the UNFCCC gave the responsibility to the countries to define their forests (FAO, 2006a). However, it appeared that only nine countries in SSA communicated a definition of forest under the UNFCCC.

Another issue for SSA is that forest 'degradation' is a more widespread and important phenomenon than 'deforestation' and that there is currently no agreed definition for it under the UNFCCC, although several definitions for 'degradation' exist (for example FAO, ITTO and IPCC). Significantly, the IPCC task force established under 11/CP.7 to develop definitions for direct human-induced 'degradation' of forests ... and methodological options to inventory and report on emissions resulting from these activities....", could not agree on any definition of forest degradation for this purpose. In the context of C monitoring in forests remaining forests, the *Second Expert Meeting on Harmonizing Forest-related Definitions* recommended using another term than 'degradation', such as "stock reduction" (Schoene, *et al.*, 2007).

3.2 Deforestation

Africa accounts for about 17% of the world's forests but for about 50 % of net recent global deforestation (Cropper, 2006) and has already lost more than two-thirds of its original forest (Wilkie and Laporte, 2001). Around 4 million ha yr⁻¹ of forest has been lost in the period of 2000 – 2005 (FAO, 2006c). The primary cause of deforestation in Africa as a whole since 1980 was direct conversion from forest to small-scale permanent agriculture, estimated to be 60 % of the forest area changes (Kelatwang and Garzuglia, 2006). Using the FAO definition of forest, it appeared that in 2005 Africa had the highest rate of deforestation with 0.62 % of annual loss of forest area. Conversion from forest to cultivation through slash-and-burn activities could decrease aboveground C stocks to 194 MgC ha⁻¹ and soil C stock to 36 MgC ha⁻¹ (**Figure 9**).

Most of the forest losses were reported in Central Africa, particularly for the Congo Basin countries. The Congo Basin forest is the world's second largest tropical forest after the Amazon, covering 291 million of hectares in six countries (Equatorial Guinea, Cameroon, the Central African Republic, the Democratic Republic of Congo, the Republic of Congo and Gabon), and containing a quarter of the world's remaining tropical forest. An average size of 0.805 and 0.611 million hectares was deforested every year for the period 1900 - 2000 and 2000 - 2005 respectively (FAO, 2006c). Currently, Africa has the smallest deforested area of all tropical regions (Achard, *et al.*, 2004), but shows a higher forest clearing rate than South America (Achard, *et al.*, 2002).

Africa has contributed up to 35 % of total tropical land clearing from deforestation, with an annual C loss from deforestation of 0.37 PgC yr⁻¹ in the last decades (Houghton, 2003). When using the definition of forest from Globcover, the IPCC and CDIAC default values for forest C stocks and the national rate of deforestation, it appeared that 299 (62 – 553) TgC yr⁻¹ were lost from deforestation (Appendix I). Moreover, 59 % of the C losses from deforestation were found in western and central Africa with the Congo Basin representing 26 % of the C losses from deforestation in SSA. These estimates were lower than those reported by Houghton (2003), of 370 TgC yr⁻¹, which was based on

the total forest area in Africa. If I correct for the total forest area of Africa (756 Mha), my estimate is 301 TgC yr⁻¹ which is approximately 70 TgC yr⁻¹ lower than Houghton's (2003) estimate.

3.3 Forest Degradation

So far, few studies have attempted to estimate the impact of forest degradation in SSA. Degradation is less well documented than deforestation and is also more difficult to map. While deforestation due to cropland conversion can be reported by satellite imageries, forest degradation cannot be easily accounted by remote sensing tools. I differentiated two main types of degradation: selective logging and forest degradation by forest encroachment by farmers.

Estimating the logging impact on C stocks is difficult because of the missing information on illegal logging practices and the poorly documented amount of legal logging. When considering the impact of logging activities on C stocks, in tropical forests Brown et al. (2005) and Gineste et al. (2008) reported C losses of about 10 MgC ha⁻¹ in Congo and Ghana respectively. By extrapolating this value using the area under forest management and a rotation period of 40 years as reported in appendix I for the Congo Basin, I obtained an annual emission rate for selective logging equal to 8 TgC yr⁻¹.

To our knowledge no data was available on the impact of degradation on C stocks; therefore, I used an alternative method to derive degradation emission rates by assuming that C stocks in degraded forest were close to those measured in secondary forest (Figure 10). From the difference between C stock of a natural forest and a degraded one, I estimated that the conversion from forest to degraded forest has led to C losses of about 98 MgC ha⁻¹ and about 27 TgC yr⁻¹ in the Congo Basin. Moreover, this implies that the C losses from forest degradation were about four times more important than selective logging in the Congo Basin. Unfortunately, I was not able to estimate the impact of degradation for the other countries, as no data on the extent of forest degradation is currently available.

After logging, a natural regeneration of a secondary forest takes place and can revert C losses to recovering C stocks at a certain point in time. Very few studies reported the natural capacity of African ecosystems to regenerate after perturbations. Kotto-Same et al. (1997) reported that about 74 % of aboveground C was regenerated after a period of fallow of 18 years. According to the regression between time of fallow and C stocks, the total system C would be equal to the original natural forest after a period of 24 years (Kotto-Same, *et al.*, 1997). In a semi-deciduous forest of Ghana that was logged in the 1950's, inventory of forest with three types of forest management revealed that there were no significant difference in aboveground biomass among a natural protected forest, a forest that was logged in the 1950's and forest that was under tree shelter-wood system in the 1950's (Bombelli et al, 2009). However, the increasing pressure of the timber companies and the farming activities often does not allow the forest to regenerate. But it is very difficult to estimate this.

4. Current methods that are proposed to monitor REDD+

The REDD+ activities were covered by the following three categories in the IPCC good practices guidance (GPG) for Land Use and Land Use Change and Forestry (LULUCF): (i) forest land converted to other land, which includes deforestation, (ii) forest land remaining forest land, which includes

forest degradation, forest conservation, sustainable forest management and enhancement of C stocks; and (iii) other land converted to forest land, which includes enhancement of forest carbon stocks (Table 2). While (i) and (iii) corresponded to land use change activities, forest cover change under (ii) remained under the definition of forestland (Table 2). Furthermore, (i) and (iii) were identified in this study as forest area change while (ii) was identified as forest cover change remaining as forest.

Table 1: Mitigation activities potentially included under REDD+

Type of forest cover change	Reduced negative change	Enhanced positive change
Forest change (included as LULUCF)	Reduced deforestation	Increase C uptake/ plantation
Forests remaining as forest	Reduced degradation	Increase C uptake/ regeneration

The issue of assessing emissions reduction for REDD+ is twofold: first, the estimation of forest cover area under different management and second its changes and its associated C emissions.

4.1 Methods to measure the change of forest cover and forest area

The IPCC Guidelines described three different approaches for representing the activity data, or the change in area of different land categories. However, under a REDD+ mechanism, land cover/land use changes will need to be identifiable and traceable in the future. Thus, only the third approach which consists in providing spatially explicit land conversion information, derived from sampling or wall-to-wall mapping techniques will meet this goal. In order to develop this approach, the use of remote sensing is necessary to track forest area and cover change.

The major characteristics of imaging remote sensing instruments operating in the visible and infrared spectral region are described in terms of (1) spatial resolution, (2) radiometric resolution, (3) spectral resolution and (4) temporal resolution. The *spatial resolution* refers to the size of the smallest possible feature that can be detected by the remote sensing sensor. Three different spatial resolutions could be identified (i) coarse resolution, (ii) mid-resolution and (iii) high resolution (Table 2). The *radiometric resolution* refers to the numbers of digital levels used to express data collected by the sensor and is commonly expressed in as the number of bits (binary digits) needs to store the maximum level. The *spectral resolution* refers to the width of the spectral bands, *i.e.* the electromagnetic radiation of the channels that are used. The *temporal resolution* of a remote sensing system is related to repetitive coverage of the ground by the sensor and thus refers to the frequency with which images of a given geographic location can be acquired.

Table 2: Main sensors of different spatial resolution for monitoring forest cover change

Sensor resolution	Examples of current sensors	Minimum mapping unit (change)	Cost	Utility for monitoring
Coarse (250-1000 m)				
Optical	SPOT-VGT (1998- now), Terra-MODIS, Envisat-MERIS (2004-now)	~100 ha, ~10-20 ha	Low or free	Consistent pan-tropical annual monitoring to identify land clearings and locate hotspots for further analysis with mid resolution
Radar	AVHRR			
Medium (10-60 m)				
Optical	Landsat TM or ETM+, SPOT HM, Terra-Aster, AWiFs LISS II, CBERS HRCCD, DMC	0.5-5 ha	Landsat and CBERS free from 2009, historical: <\$0.001/km2, recent data: \$0.02-0.5/km2	Primary tool to map deforestation and estimate area change
Radar	ALOS PALSAR, ERS1/2 SAR, JERS-1, ENVISAT-ASAR, RADARSAT 1			
High (<5 m)				
Optical	SPOT HRV, IKONOS, Quickbird, Aerial photos,	< 0.1 ha	High to very high \$2-30/km2	Validation of results from coarser resolution analysis, training of algorithms

Different types of sensors can be differentiated such as optical, radar and laser/Lidar (Table 2). The choice of methods depends on cost for data acquisition, technical capacities, size and patterns of deforestation, seasonality of forest, size of the country and forest area, deforestation processes, size of clearings, and sensor for monitoring (DeFries, et al., 2005). The appropriate scale of ground-truthing depends on national circumstances and the scale of the project.

4.2. Emission factors

The emission factors are derived from assessments of the changes in C stocks in the various C pools of a forest. The IPCC recognized five forest pools where C is stored: aboveground biomass, belowground biomass, litter, dead wood, and SOC. Carbon stock information can be obtained at different tier levels representing increasing levels of data requirements and analytical complexity. Moving from Tier 1 to Tier 3 increases the accuracy and precision of the greenhouse gas (GHG) estimates, but also increases the complexity and the costs of monitoring. Tier 1 uses IPCC default values obtained from the IPCC Emission Factor Data Base. For deforestation, Tier 1 uses the simplified assumption of instantaneous emissions from woody vegetation, litter, and dead wood. Tier 2 employs static forest biomass information, but it improves on Tier 1 by using country-specific data. Tier 3 uses scientific inventories with repeated measures of permanent plots to directly measure changes in forest biomass and/or uses well-parameterized models in combination with plot data. Tier 3 does not assume immediate emissions from deforestation; instead, it models transfers and releases among pools that more accurately reflect how emissions occur over time.

5. Adapting REDD+ methods to the sub-Saharan Africa context - an accounting problem

5.1 Estimating C stocks and emission factors in sub-Saharan Africa

Measuring C stocks in complex vegetation forms of SSA is particularly difficult. According to White (1981) there are 80 different ecological zones with different vegetation structures and floristic compositions and furthermore different C stocks.

When estimating the biomass or the C stock of a tree or a stand, the use of biomass allometric equations or stand tables is the starting point. For the moment, the use of remote sensing to estimate C stocks in tropical forests is not operational. However, very few tree biomass allometric equations were reported for SSA (AGO, 2002, Ponce-Hernandez, 2004, IPCC, 2007). While inventories of allometric equations were performed for Europe (Zianis, et al., 2005) and for South-America (Návar, 2009), no inventory exists for SSA. As Chave et al. (2005) pointed out, there are to date no destructively sampled trees to develop allometries for SSA forests. When analysing the national communication for the Forest Resource Assessment of the FAO, it appeared that 13 countries used biomass coefficient for the national biomass accounting and only seven of them used national specific data while the other used data from FAO, IPCC and Millington et al. (1994). Even the default values proposed by the IPCC do not cover all the ecological zones. For example, no data were reported for tropical deserts and subtropical humid forests while they represented 6,837 and 5,035 ha respectively.

Some countries established national forest inventories (e.g. Cameroon, Zambia etc.) that can be used to estimate C stocks. However, C stock assessment remains limited by the availability of data on wood density and biomass allometric equations. Regarding countries that did not undertake national forest inventories, particularly the countries of the Congo Basin (except Cameroon), it is possible to assess biomass based on conventional forest inventories (Brown, et al., 1989). This approach is still limited by the fact that conventional national forest inventories were performed in specific ecosystems that are not representative to large areas, to commercial trees with diameter over the minimum diameter to be felled. In addition, estimating the total forest biomass using the commercial volume is a difficult exercise as the structure of the forest and the diameter distribution vary between forest ecosystems and very few biomass expansion factors were reported for natural forests in SSA.

When considering the other C stock components (dead biomass, belowground biomass, litter and soil) it appeared that they were particularly poorly known. This is mainly due to the fact that the aboveground component is easier to measure than the others. However, 37 % of the estimated C stock in appendix I is contained in the form of SOC. It is known that the conversion of tropical forest land not only emits carbon via the burning and decays of forest biomass, but can also result in a gradual release of a significant portion of SOC and a small change in SOC could induce important changes in the C balance. Various reviews agree that the loss amounts to 20 - 50 % of the original carbon in the topsoil, but deeper layers would be little affected, if at all (Sombroek, et al., 1993, Guo and Gifford, 2002, Murty, et al., 2002). Conversion of forests to pasture did not change SOC (Guo and Gifford, 2002) or may actually increase the soil organic matter content (Sombroek, *et al.*, 1993). Changes in soil carbon under shifting cultivation were half as large (Detwiler, 1986). Commercial logging and tree harvesting did not result in long-term decreases in soil organic matter (Knoepp and Swank, 1997, Yanai, et al., 2003). According to us, no study reported estimates of the impact of forest degradation on SOC. Estimating the SOC along chronosequences could produce data for different states of forest conversion including forest degradation and better understand the dynamic of SOC. The three other ecosystem components that should be taken into account when assessing C stocks are litter, dead tree and the roots. Little data is available on litter and root C stock for SSA. Usually root biomass is estimated using a root-to-shoot ratio. For the moment only one article makes the inventory of root-to-shoot ratio (Mokany, et al., 2006). Dead biomass is generally neglected and very few inventories took it into account or mention it.

Different projects have been implemented in Africa to improve the understanding the C cycle. One of the most relevant projects is the CarboAfrica project that aims to develop local measurements and to scale up to continental scale using modelling. Some project like GEFSOC tended to improve the estimation of SOC particularly in Kenya, while AfricaNuances tended to understand the dynamic of the C in farming systems and the management of soil fertility. The UN-REDD tends to collect data in the Democratic Republic of Congo, Tanzania and Zambia in order to assist those countries in accounting their forest C stock change.

Some methodologies were developed to estimate C stocks. The FAO requested homogenizing data for monitoring biomass and C stocks change (GTOS, 2008) in order to: (i) improve the comprehension of the ecosystem to climate change and (ii) implement effective climatic policies. Different documents were developed in this attempt (AGO, 2002, Ponce-Hernandez, 2004, IPCC, 2006). However,

implementing those methodologies face several constraints in SSA. The first corresponds to availability of local means, skilled personal and infrastructure. The second constraint is related to the structure of the ecosystems and the flexibility of methodology implementation in the various contexts. The third constraint is related to the size cost and time limit. C stock variability is important and some occasional events could affect the C stock balance. As can be observed from Figure 11, the variability of the aboveground biomass in a wet evergreen forest of Ghana ranges 30 - 1000 kg m⁻² in a one hectare plot and 17 plots of one hectare are necessary to measure the biomass of the forest (12,184 ha) with a precision of 5 %. Moreover, the C stock measurements have to be achieved taking into account the C stock variability and the occasional events. This induces an increase in the cost of measurement.

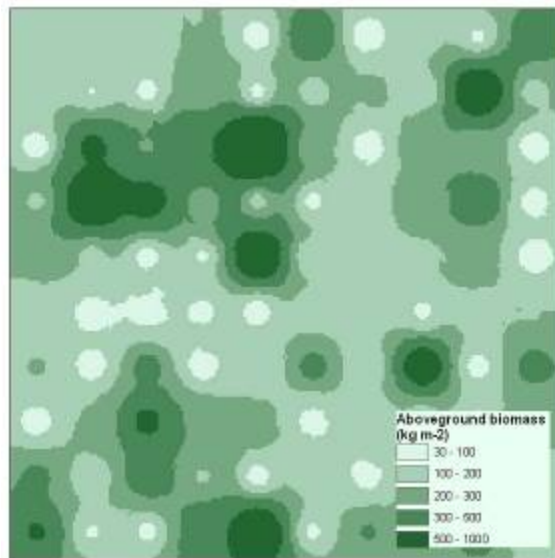


Figure 11: Biomass variability in a wet-evergreen forest reserve in Ghana

The figure shows the biomass in a one hectare plot located in the Boi Tano forest of Ghana. Aboveground biomass ranged 30 -1000 kg m⁻². 17 plots of 1 ha are necessary to measure the biomass of the forest (12,184 ha) with a precision of 5%.

A recent study on using commercial logging inventories to estimate aboveground biomass in Gabon (Maniatis et al. unpublished) suggested that inherent issues with the data quality of these inventories calls for caution on their use and applicability. However, they suggested that with little extra cost to the logging companies, the inventories can be significantly improved in quality and structure to better suit the purposes of aboveground biomass calculations and expansion factors for REDD+ accounting.

5.2 Detecting forest area and forest cover change in SSA

➤ Forest area change

According to Brown (2007) it is possible to estimate forest area change from remote sensing imagery with confidence from 1990s onwards. Achard et al. (2007) listed a number of global land cover maps from remote sensing (coarse spatial resolution, 1 km to 300 m). According to them it is possible to estimate deforestation rate using coarse resolution sensors such as NOAA-AVHRR (Mayaux, et al., 2005). Coarse-resolution such as AVHRR, MODIS and SPOT-VGT can obtain enough cloud-free views at monthly-to-annual intervals (Fuller, 2006).

In order to reduce costs and time for area-extensive analysis, effective use of mid-resolution satellite images may be practical and will be a primary data source for monitoring deforestation in SSA. However, those images may be too coarse for direct estimation at national level but can be used to detect major deforestation areas and provide consistency check with more costly mid-resolution estimates (10 - 50m). DeFries et al. (2007b) distinguished two main approaches (i) wall-to-wall mapping over the forest area and (ii) hot spot analysis. Down-scaling forest estimation could be achieved using mid-resolution images. NASA and the USGS have been working to compose imagery for a mid-decadal (around 2005/2006) dataset from Landsat-5 TM and Landsat-7 ETM+. Landsat imagery is preferred for moderate cost and acquisition policy, easy availability through the Internet and a suitable resolution for the detection of changes in canopy condition, extent and land use around forest areas (Fuller, 2006).

In response to wide availability of satellite imagery, a number of change detection techniques have been developed (Lu, et al., 2004). However, the mid-resolution imageries do not distinguish different forms of forest degradation and it is difficult to make the difference between, for example, forest and fallow (Imbernon, 2004). The use of fine-resolution images could be an alternative. However, fine-resolution multi-spectral commercial systems such as IKONOS and Quickbird may not satisfy REDD+ routine monitoring requirements due to their low temporal resolution and relatively small-area coverage but still provide a source for verification of forest maps from coarse to mid- resolution imagery (Fuller, 2006). In addition, fine resolution imageries are prohibitive for SSA countries due to their high cost.

One of the main constraints for detecting forest cover change in the tropical SSA is the presence of cloud cover. Other types of sensors such as radar or laser sensors are potentially useful particularly to overcome major limitations of optical sensors in persistently cloudy parts of the tropics. The capabilities of radar such as ERS1/2 SAR, JERS-1, ENVISAT-ASAR and ALOS/PALSAR have been used in several pilot studies in temperate forests (Balzter, et al., 2007) but is yet to be tested and proven for e.g. tropical forests. The use of spaceborne radar backscatter data is becoming increasingly accepted as a method for measuring woody biomass in the tropics because of their capability to penetrate through the forest canopy and all-weather acquisition (Santos, et al., 2002, Lu, 2006). However, the use of this type of sensor is limited by the: (i) saturation of the signal in the humid forests; (ii) cost of the laser technology; (iii) use of the laser is limited for monitoring and (iv) the use of these technologies is yet to be proven, particularly in the tropics.

Recent progress with Lidar technology is often presented as a new method for biomass inventory. Lidar technology has the potential to measure the three-dimensional vertical structure in the vertical dimension of a forest. While this technology seems to be promising in tree species homogenous temperate forests it is limited in SSA by the fact that it does not include the tree species composition and could not replace tree forest inventories. Lidar technology could be used with additional field measurement and in combination with high spatial resolution imagery e.g. to update forest inventories (Hilker, et al., 2008) but it has never been tested in SSA.

➤ Forest cover change

For the purpose of national monitoring in the REDD+ context, in many parts of the world remotely sensed data is likely to be the primary practical option to monitor areas of forest degradation. However, monitoring of forest cover change remaining as forest with remote sensing is more challenging and not yet as well established as monitoring of forest area change (DeFries, *et al.*, 2007b). Differences in reflectance among degraded forests and several intact, carbon-rich forest types with more open canopies are very subtle and both types can be easily confused when a detailed vegetation map of natural canopy types is not available.

Accuracy assessments using field data or a sample of higher quality data should be part of every national monitoring system. However, this depends on the national circumstances, the extent and the type of forest degradation. The choice of the optical sensor depends on the degradation intensity, the extent of the area and the technique (visual interpretation or automated image processing). Souza *et al.* (2005) reported that coarse to mid-resolution sensors do not deliver information about forest structure and composition and have difficulties to differentiate old degraded forest from intact forests. In addition, time series of cloud-free images would be needed, at least once a year or even more, to distinguish the different state of forest cover change from effects of seasonality (Olander, *et al.*, 2008), to differentiate fire types and account for repeated degradation events. However, Landsat time series are usually not available (Asner, 2001). High resolution data are necessary to detect small-scale forest cover change with sufficient detail. A few studies with high resolution sensors (Ikonos, Quickbird) have been conducted (Asner and Warner, 2003). However, wider application is limited by high costs for image acquisition, small coverage, demanding processing and frequent cloud cover in the humid tropics. Remote sensing techniques are evolving quickly and several attempts were developed using optical, radar imageries and Lidar. While most of the current attempts to monitor forest cover change with remote sensing focused on selective logging (Laporte, *et al.*, 2007) and forest fires (Roy and Boschetti, 2009), other forms of forest degradation, like overgrazing and unsustainable extraction of non wood forest products, have been considered as almost undetectable (Peres, *et al.*, 2006).

In large areas with low intensity degradation, indirect methods are preferred, like a simple categorization into intact and non-intact forests based on topographic maps and GIS data showing infrastructure *etc.* and a fine-shaping of boundaries via visual interpretation of Landsat data or high resolution sensors (GOFC-GOLD, 2009). Such a simple approach would allow accounting for C losses from forest degradation in the IPCC guidelines, reporting this as a conversion of intact to non-intact forest. A large number of global fire observing systems and data products (~1 km resolution) have been developed including a global wildlife fire assessment by FAO, active fire and burnt area satellite products by EC JRC, NASA, EUMETSAT, NOAA, and ESA. Multi-year burned area products, based on coarse resolution satellite data, are about to be released (MODIS, L3JRC, GLOBCARBON). At national level, pilot activities and systems for fire-monitoring are emerging including pre-fire, active fire and post-fire assessments.

6. Conclusion

Most of the C losses from LULUCF in the African continent were from SSA. I estimated that currently the forests of SSA contained 58 PgC in the aboveground biomass and 34 PgC in SOC. In SSA deforestation contributed to 299 TgC yr⁻¹ and most of the C losses were from the Congo basin (26 %). In the Congo Basin, deforestation was the most important source of C emission (76 TgC yr⁻¹) and ranged from 59 - 538 TgC yr⁻¹. Forest degradation represented the second source of emission with 27 TgC yr⁻¹ and selective logging was the third with 8 TgC yr⁻¹.

An attempt to scale-up deforestation and forest degradation rates of SSA in a REDD+ mechanism would allow a potential maximum of about 0.33 PgC yr⁻¹ of reduced emissions equivalent to about 1.2 Pg CO₂ yr⁻¹. Recently Meinshausen et al. (2009) analysis suggested a cumulative emission pathways of 1000 Pg CO₂ by 2050 to maintain climate forcing within 2° C. This equals to an effort of emission reductions of about 50% of total emissions. The contribution of REDD+ in SSA in this pathway could lead to an equivalent reduction of about 50 Pg CO₂ until 2050, which could by far be one of the most important contribution of emission reduction by biological means.

However, the recent paper of Lewis et al. (2009) estimated a net growth and hence C sequestration of intact tropical forests in SSA of a similar size of deforestation and forest degradation (0.34 PgC yr⁻¹). In principle if deforestation is leading to a land use change and is not reversible in terms of forests, the total contribution to C sequestration should also include the biological net sink. Neglecting forest degradation which is somewhat reversible by secondary vegetation, the total C uptake effect of SSA tropical forests, including “the missing uptake” after deforestation can be estimated as 0.64 Pg C yr⁻¹ or 2.3 Pg C yr⁻¹. This could lead to a cumulative reduction of about 92 Pg CO₂ by 2050. Including the net effect the contribution of SSA tropical forests could reach 10 % of the required reduction target which is comparable to a single renewable energy source contribution.

Despite the large potential of emission reduction, there is still a high uncertainty on the amount of C stored in the SSA forests. When considering accounting emission reduction for REDD+ in SSA it appeared that many issues remain to be solved to allow the countries to implement effective emission reductions. Little data exists on C stocks in Africa and collaboration with the private sector could provide more reliable C stock data particularly in the area where timber is commercially extracted in the humid tropical forests. Additionally, remote sensing is a commonly accepted technology to report national emission reductions for REDD+. While deforestation could be monitored using remote sensing, the use of remote sensing technology such as ALOS/PASLAR and Lidar still needs to be tested to detect forest degradation in SSA forests.

Furthermore, the definition of forest, deforestation and forest degradation still have to be clarified in the context of REDD+. While the FAO-Global Terrestrial Observation System is calling for homogenizing data production and reporting, the UNFCCC gave responsibility to the individual countries to produce

their own definition. This makes the use of global products difficult for national accounting systems, particularly for countries that do not have the capacity to implement their C accounting system.

It is obvious that more ground data is necessary to estimate C stocks, deforestation and particularly forest degradation for SSA. Using C stock estimates based on tree cover would allow the estimation of C stocks without taking into consideration the national and international definition of forests. Improving our understanding on the process of forest changes and their impact on C stocks would help the SSA countries to establish emission reduction efforts and better understand the role of forest to the C cycle.

While scaling up local measurements to global scale can be made using various methods to estimate aboveground carbon stocks, including the use of satellite imageries and land cover or land use interpretation products (e.g. (Avitabile, et al., 2005, Baccini, et al., 2008, Goetz, et al., 2009)), the use of soil organic carbon field and laboratory measurements are more limited than for aboveground carbon stocks. The soil categories used to estimate soil organic carbon cannot be identified by through satellite image interpretation. The next chapter will present continental scale soil carbon estimates using different soil maps and soil databases.

Chapter 3

Soil carbon stocks in Africa

This chapter is modified from the article: Henry, M. Valentini, R., and Bernoux, M. (2009) Soil carbon stocks in ecoregions of Africa, *Biogeosciences for discussions*, vol 6, 797-823.

Abstract

The African continent plays a growing role in the carbon (C) cycle. However, Africa is one of the weakest links in our understanding of the global carbon cycle particularly when considering the soil compartment. Most of the soil organic carbon (SOC) estimates concern the global size of the soil C reservoir without indication on its distribution, or if given, limited to the contribution of a large ecosystems or region. The aim of the study is i) to assess the soil C stocks (SOC) of Africa for the different countries and Ecoregions, and ii) to compare SOC estimates from different soil properties databases and digital maps. Four recent global digital soil maps and five soil properties databases were used to estimate the SOC for different soil layers in Africa. Those databases hold between 1799 and 4043 soil profiles which are considered to represent the soil units showed on a 0.5 by 0.5 degree soil maps of Africa. SOC of Africa ranged 133 420–184 116 Tg for 0–100cm soil layer. The most recent databases estimated 166 397 Tg C which corresponded to 9% of the global SOC stock and 68% of the terrestrial C pool of Africa. Average SOC ranges 0.4–8.2 kgm⁻² at national scale and 1.53–6.61 kgm⁻² for ecoregions. Using different soil database or spatial data leads to up to 30% of difference. These quantities indicate a great potential to develop sink activities through soil C sequestration activities.

Keywords: Soil Organic Carbon, National Level, Global Change, Soil Degradation

1. Introduction

Carbon dioxide (CO₂) is, by far, the largest contributor to the anthropogenically enhanced greenhouse effect (IPCC, 2007b). The importance of CO₂ to the climate has provided the impetus for research on the global C cycle with particular attention on C stocks in main terrestrial compartments, mainly soils and phytomass. The increasing interest of the contribution of terrestrial ecosystems to mitigate climate change has given rise to the possibility of emission credits for soil organic carbon (SOC) sequestration. Carbon sequestration in terrestrial ecosystems is being considered as a way to mitigate the greenhouse effect and, simultaneously, combat land degradation (Lal, 2004).

Soil organic matter is a key component of any terrestrial ecosystem, and any variation in its abundance and composition has important effects on many of the processes that occur within the system. The magnitude of organic matter and soil carbon stock result from an equilibrium between the inputs (mostly from biomass detritus) and outputs to the system (mostly decomposition and transport), which are driven by various parameters of natural or human origins (Schlesinger and Palmer Winkler, 2000, Amundson, 2001b). The decrease of organic matter in topsoils can have dramatic negative effects on water holding capacity of the soil, on structure stability and compactness, nutrient storage and supply and on soil biological life such as mycorrhizas and nitrogen-fixing bacteria (Sombroek, *et al.*, 1993).

The carbon balance of terrestrial ecosystems can be changed markedly by the direct impact of human activities. Land use change is responsible for 20% of the global anthropogenic CO₂ emissions during the 1990s (IPCC, 2007b) and is the main primary net C release in Africa, much of it through burning of forests (Williams *et al.*, 2007). The impact of land use change varies according to the land use types. The clearing of forests or woodlands and their conversion into farmland in the tropics reduces the soil-carbon content, mainly through reduced production of detritus, increased erosion rates and decomposition of soil organic matter by oxidation. Various reviews agree that the loss amounts to 20 to 50% of the original carbon in the topsoil, but deeper layers would be little affected, if at all (Sombroek, *et al.*, 1993, Guo and Gifford, 2002, Murty, *et al.*, 2002). Conversion of forests to pasture did not change soil carbon (Guo and Gifford, 2002) or may actually increase the soil organic matter content (Sombroek, *et al.*, 1993). The cultivation of tropical soils reduces their carbon content by 40% 5 yr after clearing (Detwiler, 1986). Commercial logging and tree harvesting did not result in long-term decreases in soil organic matter (SOM) (Knoepp and Swank, 1997, Houghton, 2001, Yanai, *et al.*, 2003). Changes in the amount of soil organic matter following conversion of natural forests to other land uses depend on several factors such as the type of forest ecosystem undergoing change (Rhoades *et al.*, 2000), the post conversion land management, the climate (Pastor and Post, 1986) and the soil type and texture (Schjonning, *et al.*, 1999).

In Sub-Saharan Africa, the increasing demand for food can encourage farmers to reduce the length of fallow 5 periods, cultivate continuously, overgraze fields, or remove much of the above-ground biomass through fuel collection or for building materials. Such practices can result in the reduction of SOC, water holding capacity, nutrients, as well as enhance soil erosion (Lal, 2004). Nevertheless, appropriate land management could revert this trend and contribute to soil carbon sequestration. Increasing the SOM could help reverse these problems and may be crucial for future African agriculture and food production (Sanchez, 2000, Bationo, *et al.*, 2007). Some operations that increase organic matter inputs such as reforestation of agricultural lands, improved fallow, reduced tillage or

fertilization can increase SOM levels. Several studies have shown that a synergetic effect exists between mineral fertilizers and organic amendments in Sub-Saharan Africa that leads both to higher yields and SOC content (Palm, et al., 2001, Vagen, *et al.*, 2004, Bationo, *et al.*, 2007). However, soil protection or conservation decisions cannot be made without maps of land properties. If projects have to be implemented with the objective of enhancing the storage of carbon in the terrestrial biosphere, potentially for carbon trading related to the Kyoto protocol, it is important to have the capabilities of verifying and monitoring the changes of soil organic carbon (SOC) over time and space (Post, et al., 2001). While, Annex I country of the Kyoto protocol are committed to report national estimates of changes in the amount of soil organic carbon (SOC) in cropland, I can expect that in the future, all the countries will have to report their emissions. Several attempts were developed to report the soil organic mass of the world.

The global soil C storage estimates over the past 70 years range 400–9120 PgC (Amundson, 2001a). However, most recent studies give estimates ranging from 1115 to 2200 PgC in the first meter and generally converge on a value of about 1500 Pg (Post, et al., 1982, Batjes, 1996, Schlesinger and Palmer Winkler, 2000) while plant biomass is estimated to range between 560 and 835 Pg C (Whittaker and Likens, 1975, Bouwman, 1990). Furthermore, the world's mineral soils represent a large reservoir of C of about two third of the global terrestrial C stocks. Soils contain nearly as much carbon as the vegetation under rainforest, but considerably exceed the biomass in other ecosystems, by a factor 2 to 10 (Sombroek et al., 1993). According to Sombroek (1993), this large variation of SOC estimates between authors is explained by the difference in base maps selected (FAO/Unesco Soil Map of the World, Holdridge Life Zones, Vegetation Maps) and the various assumptions made about soil attributes directly related to the total content of organic-matter per soil type such as organic matter content and distribution in the soil profile, bulk density of soil layer, and average soil depths. Nonetheless, the size and dynamics of the soil carbon pool of the world, it is still poorly known (IPCC, 2007b). Uncertainties concerning (1) estimates of C in ecosystems, (2) per hectare changes in C stocks in response to different types of landuse change and (3) legacy effects, are important particularly in Africa (Houghton and Goodale, 2004). There are great needs to improve the understanding comprehension of the C cycle in Africa.

Most of the time, the reported values consist of estimates of the global size of the soil C reservoir without indication on its distribution, or if given, limited to the contribution of a large ecosystems or region. Models of the global C cycle require accurate estimations of the masses in the different reservoirs. Regarding the soil compartment, global C pools are difficult to estimate because of still limited knowledge about specific properties of soil types (Sombroek, *et al.*, 1993, Batjes, 1996), the high spatial variability of soil C even within one soil map unit (Cerri, et al., 2000), and the different effects of the factors controlling the soil organic C cycle (Pastor and Post, 1986, Parton, et al., 1987). Thus, regional studies are being proved necessary in order to refine global estimations obtained by aggregation of regional estimates, mainly at country scale (Milne, et al., 2007). Aggregate of more precise studies, at a country or regional scale, certainly would improve the global estimates. But only few and not homogeneous (different layers used to report results) data exists.

In order to provide reliable predictions, successful global carbon cycle models must accurately represent fundamental controlling processes and conditions in robust model structures that can be validated by comprehensive data sets collected over a widerange of controlling environmental conditions. However, global observational data sets of SOC are currently incomplete and large-scale

validating data sets are needed in global carbon cycle models (Bombelli et al, this issue). Models of global climate change need accurate and complete SOC inventories because the SOC pool represents the largest component of the global C pool and acts as a regulator of atmospheric CO₂ levels (Amundson, 2001a). The objectives of this study are 1) to assess the soil C stocks of Africa for the different countries and ecoregions, and 2) to compare SOC estimates from different digital map and soil properties database.

2. Materials and methods

2.1 Source of data

Different soil databases were collected from the World Soil Information (ISRIC) website (Table 3). Soil properties were compiled in a harmonized way, based on using uniform taxonomy based pedotransfer rules and were compiled into the World Inventory of Soil Emission (WISE) database (Batjes, 1996, , 2002, , 2005, , 2006) and the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISSCAS/JRC, 2008). The databases reported soil properties for different soil layers, from 0–20 to 0–200 cm. Soil parameter estimates for all secondary SOTER database (SOTWIS) that were included into the Harmonized World Soil Database (HWSD) were derived from the WISE database v.02 (Batjes, 2002). The number of soil profiles for Africa that were found in the WISE (Batjes, 1996, 2002, 2005, 2006) and HWSD databases (FAO/IIASA/ISRIC/ISSCAS/JRC, 2008) were 1799, 3998, 3998, 4043 and 3998, respectively. Four spatial components were used to represent soil spatial distribution (Table 3).

Table 3: The organic soil databass and digital data used to make soil carbon maps.

Map	Soil Database	Year	Total soil	% soil	Map	Scale	Total	Map
1	Batjes	1996	4353	41	DSMW	1:5M	6998	1,598
2	Batjes	2002	9607	42	DSMW	1:5M	6998	1,598
3	Batjes	2005	9607	42	ISRIC-WISE	1:5M	45948	7,964
4	Batjes	2006	10100	40	ETOPOS-	1:5M	4931	1,588
5	FAO/IIASA/ISRIC/I	2008	9607	42	HSWD	1:1 -	31044	6,994

The Digital Soil Map of the World (DSMW – FAO), the ISRIC-WISE and ETOPOS-DSMW spatial data are 0.5 by 0.5 degree grid version of the edited and corrected 1:5M Soil Map of the World. The spatial data used for Harmonized World Soil Database is a mosaic of the Digital Soil Map of the World and the SOTER regional studies (Northeastern Africa, and Southern Africa). The numbers of maps units within those four spatial data for Africa are 1598, 7964, 1588 and 6994 respectively. The FAO-UNESCO legend (Latham, 1974) was used to link the soil properties data with the soil map units on the grid maps.

2.2 Calculation of carbon stock

The estimates correspond to the SOC present in the layer after correction using the volume percentage of fragments coarser than 2 mm. SOC was estimated using the following formula:

$$C = V \times (1 - Gr) \times Bd \times Cc \quad (1)$$

where C is carbon density (kgm^{-2}), V is the volume of soil per square meter (m^3), Gr is the volume of gravel (m^3), Bd is the bulk density (kgdm^{-3}) and Cc is the carbon content (gCkg^{-1}).

Organic carbon content is universally determined by oxidation of CO_2 , and is directly measured as CO_2 or by weight loss of the sample or by back-titration of the excess of the added oxidant. Bulk density is critical for converting organic carbon percentage by weight to content by volume, but it varies with the structural condition of the soil, in particular the mineralogy, water content and packing. In general, bulk density is determined by the core sampling method which is comparable with values obtained by the clod method. The mean bulk density was computed for each profile and when there was no bulk density for a particular soil profile the mean bulk density of the corresponding soil unit was used in the derived database. Gravel is not considered to contain organic carbon (Anderson and Ingram, 1993) and its volume is subtracted from the total volume.

2.3 Computation of soil carbon stocks

The soil properties are given per soil classes. The spatial data are identified as map units. Within one map unit different soil classes could be found. In order to report the soil properties of one map unit, the SOC estimate was calculated according to the relative proportion of all soil classes per soil layer. Furthermore, the calculation of C density (kgm^{-2}) for each soil profile results from the soil properties per soil classes and the composition of soil classes per layer. For an individual soil profile with k layers, the organic carbon by volume is:

$$C_d = \sum_{i=1}^k V_i \times (1 - Gr_i) \times Bd_i \times Cc_i \quad (2)$$

where C_d is the total amount of organic carbon (kgm^{-2}) over depth, Bd_i is the bulk density (kgdm^{-3}) of layer i , Cc_i is the carbon content (gCkg^{-1}) of the layer i and Gr_i is the volume of gravel (m^3) of the layer i . The C stock representative for each soil mapping unit was determined by:

$$M_{ud} = A \times C_{id} \quad (3)$$

where M_{ud} is the total mass of organic carbon (kg of C) held in the upper d cm of the soil, A is the area of the map unit (m^2), C_{id} is the carbon density of the soil profile (kgm^{-2}). It is assumed that each soil profile is representative of its respective map unit.

Soil carbon mass for one biome, one country or the continent is determined by aggregating the soil carbon stock of the corresponding map units:

$$M_d = \sum_{j=1}^n M_{udj} \quad (4)$$

where M_d is the total mass of carbon (ton of C) held in the upper d cm of the soil and j is the number of map units within one biome, country or the continent.

2.4 The soil carbon map of Africa

Five different soil carbon maps for Africa were obtained using the different data sources (Table 3). It represents the evolution of the available data for the years 1996, 2002, 2005, 2006 and 2008. While

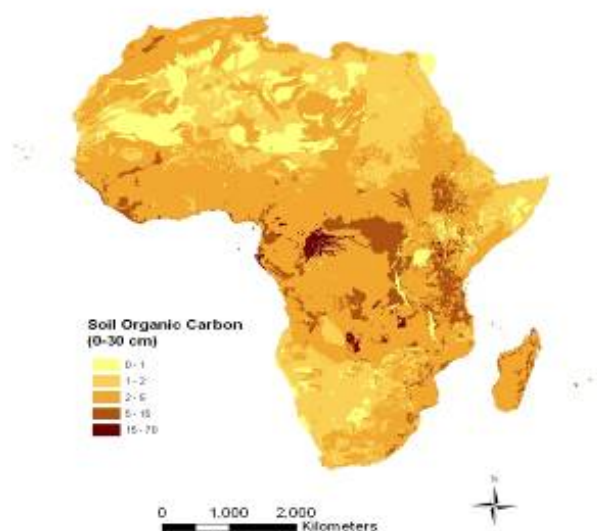
the first map was obtained using the soil properties reported by Batjes (1996) and the digital soil map of the world (FAO, 1995), the most recent and precise map is considered to be the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISSCAS/JRC, 2008). The digital soil map units were linked to the soil properties in order to represent the spatial distribution of the C stocks. Each map unit is linked into a geographic information system to its respective soil profile type and soil properties using ArcGis 9.2.

2.5 Calculation of the carbon stocks per biomes and per country

Various biome classifications could be found for Africa (Holdridge, 1947, White, 1981, FAO, 1999, WWF, 2000, Olson, et al., 2001). The Terrestrial Ecoregions of the World (WWF, 2000) was considered as one of the most updated vegetation classification which reflecting the various vegetation types, not only the forest biomes, in a simplified form. The Global Administrative Layer updated for the year 2008 (FAO, 2008) was used to delineate the country boundaries. After digitally intersecting the Soil C map with countries boundaries and, the Terrestrial Ecoregions of the World, it was possible to derive for each country and each ecoregions the C stocks for the different soil depths.

3. Results and discussion

3.1 Map of soil C stocks of Africa



The Figure 12 represents the unequal distribution (in kgCm^{-2}) of SOC in Africa based on the data from the HWSD. According to the HWSD soil map, soil carbon stocks for the layers 0–30 cm and 0–100 cm were, respectively, 85 986 and 166 397 Tg C for Africa. Average SOC was 2.37 kgm^{-2} and 4.60 kgm^{-2} for 0–30 and 0–100cm soil layers, respectively.

Figure 12: Soil carbon stock distribution in Africa for the 0–30 cm soil layer using the HWSD database.

However, SOC varied between countries. Results for each country that were obtained using the FAO/IIASA/ISRIC/ISSCAS/JRC soil database and the HWSD soil map are reported in Table 4. The maximum SOC density was found in Congo (8.20 kgm^{-2}) while the minimum SOC density was found in Western Sahara (0.40 kgm^{-2}). Most of the C stock in Africa (0–100 cm) was located in Middle Africa (33%) while only 6% was located in southern Africa. While the SOC density was 3.93 kgm^{-2} in Middle Africa, it was 2.23 kgm^{-2} in Southern Africa. Most of the map units were classified as soil in both regions (96 and 97.4%, respectively). Furthermore, the difference could be mainly explained by different soil types. While Dystric Histosols (by definition soil rich in organic matter, WRB 2006) contained 116 kgCm^{-2} , Yermosols (also classified under the term Gypsisols – WRB, 2006, which correspond to desert soils found in the driest parts of the arid climate zone), contained only 1.39 kgCm^{-2} . In addition, SOC varies with depth. On one hand, the totality of SOC in the soil profile was contained in 0–30 cm soil layer in Rankers soils. On the other hand, only 26.6% was contained in 0–30 cm soil layer in Histosol soils. In average, 52% of the SOC contained in the whole profile was located in 0–30 cm soil layer while Batjes (1996) reported 47%.

3.2 African SOC and the global cycle

Global carbon stocks were also calculated with the DSMW and the HWSD database (Figure 13). Using the DSMW, these stocks were respectively 803, 1101, 1589 and 2521 PgC for the layer 0–30 cm, 0–50 cm, 0–100 cm and 0–200 cm. Using the HWSD, the SOC of the world represented 814 and 1850 PgC for 0–30 and 0–100 cm, respectively. Africa represented 8.6 and 9% of the SOC in the 0–100 cm soil layer according to the DSMW and the HWSD database respectively. Those results are lower than the 13% reported by Williams et al. (2007). On the other hand, Williams et al. (2007) reported that live plant carbon contained 610 ± 47 and 80 ± 28 at global scale and in Africa respectively. It means that 75 and 68% of the C stocks are contained in the 0–100 cm soil layer in the world and in Africa, respectively.

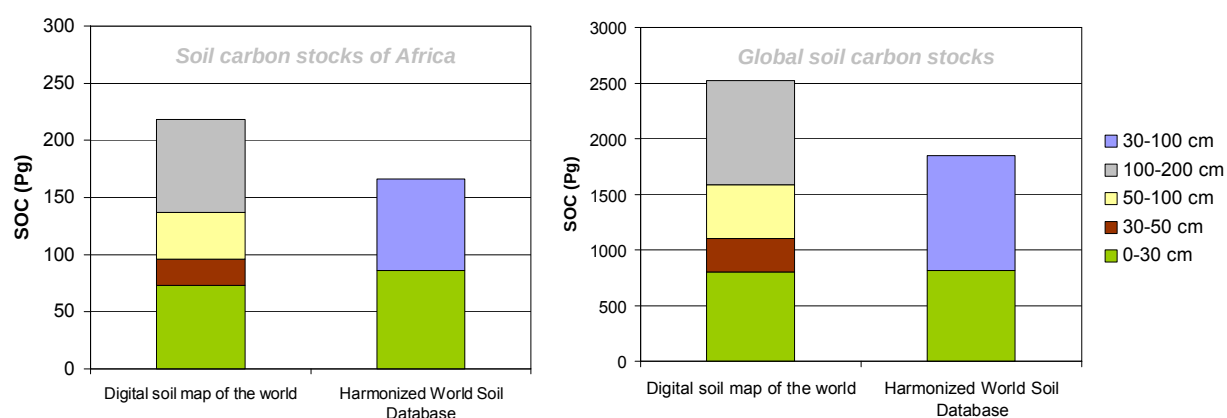


Figure 13: Global and African soil carbon stocks estimates based on the digital soil Map of the World and the Harmonized World Soil Database.

Table 4: Inventory of soil carbon pools for the different countries of Africa using the HWSO database.

Regions and Countries or Territories	Spatial component information				
	Number of map	Area		0-30 cm	0-100 cm
	Total	All map unit km ²	% with soil	Tg (or millions tonnes) of C	
<i>Eastern Africa</i>					
British Indian Ocean	22	12	0	0	0
Burundi	159	25,098	92.83	146	268
Comoros	50	1,530	97.88	12	21
Djibouti	123	20,676	99.09	30	25
Eritrea	982	116,719	99.73	262	426
Ethiopia	2,361	1,069,066	99.03	3,511	6,459
Europa Island	2	16	0	0	0
Kenya	3,698	541,841	98.01	1,833	3,989
Madagascar	1,311	578,170	99.7	2,588	5,172
Malawi	136	112,278	79.39	435	825
Mauritius	24	1,534	93.44	10	18
Mayotte	27	336	95.64	1	2
Mozambique	1,350	760,193	98.4	2,558	4,840
Réunion	33	2,442	99.01	25	45
Rwanda	198	23,464	94.55	143	246
Seychelles	87	140	0	0	0
Somalia	1,022	595,328	99.7	1,047	1,901
Uganda	810	224,933	84.83	694	1,309
United Republic of	1,227	880,012	94.23	4,227	7,810
Zambia	228	715,202	98.49	4,500	11,235
Zimbabwe	1,017	381,257	99.2	859	1,640
<i>Subtotal</i>	14,867	6,050,248	97.31	22,881	46,230
<i>Middle Africa</i>					
Angola	660	1,183,219	99.99	3,601	6,655
Cameroon	211	437,840	99.32	2,410	5,098
Central African	114	583,371	99.78	2,141	3,859
Chad	242	1,237,900	84.52	3,097	5,434
Congo	122	318,214	99.57	3,424	9,300
Democratic Republic	362	2,173,660	98.17	10,511	21,932
Equatorial Guinea	56	25,105	99.8	166	270
Gabon	148	246,380	99.26	1,276	2,738
Sao Tome and	18	882	98.81	6	12
<i>Subtotal</i>	1,933	6,206,571	96.15	26,632	55,298
<i>Northern Africa</i>					
Algeria	608	2,484,691	66.4	4,021	6,638
Egypt	2,533	1,033,941	93.12	1,393	2,385
Hala'ib triangle	136	18,177	99.77	31	50
Ilemi triangle	23	2,978	100	4	11
Libyan Arab	666	1,713,136	75.41	2,704	4,986
Ma'tan al-Sarra	12	1,995	100	4	6
Morocco	569	451,916	99.81	1,423	2,564
Sudan	3,576	2,404,150	99.72	5,927	11,318
Tunisia	407	177,065	89.66	498	727
Western Sahara	214	278,353	85.34	601	966
<i>Subtotal</i>	8,744	8,566,401	83.73	16,606	29,652

Regions and Countries or Territories		Spatial component information				
		Number of map Total	Area	0-30 cm		0-100 cm
			All map unit km²	% with soil	Tg (or millions tonnes) of C	
Southern Africa						
	Botswana	310	575,324	98.9	753	1,723
	Lesotho	161	32,123	99.88	150	237
	Namibia	655	820,695	92.46	1,093	2,009
	South Africa	11,664	1,281,521	99.8	2,874	5,240
	Swaziland	61	17,761	99.9	96	158
	Subtotal	12,851	2,727,424	97.4	4,966	9,367
Western Africa						
	Benin	42	109,714	100	374	687
	Burkina Faso	174	262,057	100	801	1,498
	Côte d'Ivoire	131	303,559	99.17	1,159	2,265
	Cape Verde	73	3,479	98.95	22	34
	Gambia	74	10,357	97.03	39	75
	Ghana	139	225,377	94.93	759	1,384
	Guinea	174	233,055	99.99	1,032	1,832
	Guinea-Bissau	337	32,275	99.61	134	247
	Liberia	63	90,067	99.98	504	839
	Mali	183	1,232,616	77.52	2,634	4,489
	Mauritania	200	1,041,888	56.53	1,560	2,346
	Niger	117	1,165,832	75.87	1,937	3,172
	Nigeria	363	863,313	98.81	2,873	5,108
	Saint Helena	7	260	0	0	0
	Senegal	103	190,340	99.54	561	1,019
	Sierra Leone	206	68,259	99.76	325	536
	Togo	51	53,930	99.9	184	317
	Subtotal	2,437	5,886,378	82.38	14,897	25,850
Total		40,832	29,437,022	90.14	85,981	166,397

3.3 Soil C stocks in ecoregions of Africa

The corresponding stocks and areas for each biome are reported in Table 5. Tropical & Subtropical Grasslands, Savannas & Shrublands represented the most important SOC stock (79 325 Tg C for 0–100 cm soil layer) and Temperate Conifer Forests biome represented the lowest (183 Tg C for 0–100 cm soil layer). There were marked differences in mean SOC content among biomes. While Tropical & Subtropical Moist Broadleaf Forests had the highest mean C stock ($4.04 \pm 5.36 \text{ kgCm}^{-2}$), Temperate Conifer Forests had the lowest C stocks ($1.15 \pm 1.74 \text{ kgCm}^{-2}$). Higher net primary production in tropical regions is responsible for higher inputs of organic matter into the soil compartment. Moreover, tropical soils are deep and could contain important amount of SOC. On the other hand, in dry and arid regions, biomass production is limited by climatic constraints and leads to lower organic matter inputs. Soils are thin and the presence of rocks and deserts is higher.

Table 5: Soil C stocks and mean C content for African ecoregions using the HWSO database.

Biome	Area	Carbon	Carbon stock	Mean C	±SD	Numbe
Deserts & Xeric Shrublands	10,084	15,450	25,469	1.37	1.14	11,072
Flooded Grasslands & Savannas	695	2,896	7,209	1.96	4.32	1,766
Mangroves	70	465	1,054	2.27	3.94	1,564
Mediterranean Forests,	953	2,700	4,924	1.37	1.38	3,578
Montane Grasslands &	864	2,999	5,412	2.91	1.85	6,813
Temperate Conifer Forests	27	105	183	1.15	1.74	111
Tropical & Subtropical Dry	186	928	2,033	2.06	3.40	792
Tropical & Subtropical Grasslands,	13,291	41,815	79,325	2.99	2.75	15,126
Tropical & Subtropical Moist	3,267	18,623	40,788	4.04	5.36	5,589
Total	29,437	85,981	166,397	2.51	3.02	46,411

Land use change is responsible to higher emission rates in tropical regions than dry and arid regions (Ogle, et al., 2005). The IPCC (2006a) reported relative stock change factors for different management activities on cropland. Those are ranging 0.48–0.80 for long term cultivated cropland for tropical region and dry temperate climate respectively. Amundson (2001a) reported that cultivation reduces the original soil C content by 30% but it was not mentioned under which ecological region. Impact of land use change depends on biomass productivity, mainly on ecosystem types, structure and composition, the soil substrate and the climate (Keeling and Phillips, 2007) and management, mainly fertility management and tillage (Shepherd and Soule, 1998, Reicosky, et al., 1999). Moreover, estimating the impact of land use change should consider the ecology and the soil types, the management and the farming practices for each ecological regions.

3.4 Variation of soil C stocks of Africa estimates

Table 6 reports the SOC estimates using four spatial data and five soil databases. It represents the evolution of the SOC estimates based on the most precise data for 1996, 2002, 2005, 2006 and 2008. The SOC estimates for 0–100cm soil layer of Africa, based on the soil databases and spatial data reported in Table 6 ranged 133,420– 184,116 Tg C. While the oldest SOC estimate for Africa was reported to be 179,288 Tg, the most recent SOC estimate was 166,397 Tg. Moreover, the range of SOC estimates for Africa is higher than the 170–240 Pg C range proposed by Williams (2007).

Table 6: Continental carbon stock estimate based on different digital map and soil properties databases

Map ID	Soil data	Spatial Data	Year	SOC (Tg)			
1	Batjes	DSMW	1996	0-30cm: 94,537	0-50cm: 124,954	0-100cm : 179,288	0-200 cm: 284,400
2	Batjes	DSMW	1996	0-30cm: 86,948		0-100cm: 166,133	
3	Batjes	ISRIC-WISE	2005	0-30cm: 68,891		0-100cm: 133,420	
4	Batjes	ETOPOS-DSMW	2006	0-20cm: 57,032	0-40cm: 112,007	0-60cm: 144,994	0-80cm: 169,022
5	FAO/IIASA/ISRIC/ISSC AS/JRC	HWSO	2008	0-30 cm: 85,981		0-100cm: 166,397	

The difference between SOC estimates at continental or global scale could be attributed to various factors (Sombroek, *et al.*, 1993). It is important to highlight that SOC estimates can be very imprecise mostly for the small islands i.e. Cape Verde or Canarias. However, the coastal boundaries that were used to correct the spatial data were the same. Furthermore, the difference of SOC estimates is attributed to the spatial scale of the spatial data and the soil properties of the soil database. The data contained in the soil databases have changed over time. The main differences observed when estimating SOC stocks are (1) the number of soil profiles, (2) the data of organic content, bulk density and gravel, (3) the soil layer that are considered. Increasing the number of soil profiles and the spatial resolution of the soil maps should improve the precision of the SOC estimates. Since 1996 the number of soil profiles increased from 4,353 to 9,607 (Table 3). The soil properties changed between databases and led to different SOC density estimates for an identical soil type. For example, Lithosols contained 2.7, 0, 4.1, 3.6 and 4.5 kgCm⁻² in the databases 1996, 2002, 2005, 2006 and 2008, respectively. While the database of 2005 considered Lithosols as rocks and were included into the miscellaneous, Lithosols were considered only for the 0–10cm layer in the database of 2006 and 2008. Acrisols contained 6.50, 4.83, 6.83, 6.80 and 6.05 kgCm⁻² in the databases 1996, 2002, 2005, 2006 and 2008, respectively.

The variability of soil properties in soil profiles was reported in Batjes (1996). The bulk density varied within soil types. The histosols soil type had the lowest bulk density (0.31 ± 25 (SD) Mg m⁻³) while the vertisols had the highest bulk density (1.67 ± 27 Mg m⁻³) (Table 7). The Yermosols had the lowest soil organic carbon (1.3 ± 157 kg m⁻²) and histosols had the highest ($28.3 \pm 1,330$ kg m⁻²). It appeared that the number of soil profiles varied a lot between the soil classes. While 0.0014 bulk density measurements were achieved for 1000 km² of fluvisols, 72.61 were achieved for phaeozems. In addition, the number of carbon content data for 0–30 cm soil layer was the highest for phaeozems soil type and the lowest for lithosols. The number of data on carbon content was much higher for the 0–30 cm soil layer (n=3,876) than the 0–200 cm soil layer (n=200). The number of soil measurements is not proportionally distributed according to the land area per soil type and to soil depth. The data provided by Batjes (1996) are not enough numerous and the standard deviation is too much important to really capture the spatial variability when linking the data with the spatial units. However, this analysis is limited to the database of Batjes (1996) because the soil properties of the soil profiles for the other database were not available.

Small difference in the soil properties can induce important errors when considering the continental scale. The soil properties estimates have to be accurate and consider the spatial variability of SOC. When changing scale, few soil profiles are available for Africa and are not randomly distributed. It is moreover difficult to increase the precision of the soil properties estimates without increasing the precision of the spatial data and vice versa. Both spatial and soil properties improvements have to be achieved to increase the precision of the SOC estimates at continental scale.

The soil layers are also different between the databases. While the SOC estimates of Batjes (1996) reported SOC for four soil layers, and Batjes (2006) reported SOC for five soil layers, the most recent SOC estimates (FAO/IIASA/ISRIC/ISSCAS/JRC, 2008) reported SOC only for 0–30 and 0–100 cm soil layer. This could be mainly explained by the increasing interest in climate change and the will to obtain SOC inventory for the 0–30 and 0–100 cm soil layers as reported by the IPCC methodology (IPCC, 2006).

Table 7: Soil properties variability in group of soils adapted from Batjes (1996)

Major soil	Bulk density			Organic carbon content (kg m ⁻²)												Area
	Mean	CV	n	0-30 cm			0-50 cm			0-100 cm			0-200 cm			
				Mean	CV	n	Mean	CV	n	Mean	CV	n	Mean	CV	n	
Acrisols	1.41	15	990	5.1	83	309	6.7	84	302	9.4	82	269	10.4	113	56	857
Cambisols	1.36	20	1219	5.0	91	531	6.9	82	481	9.6	77	332	15.7	92	36	1055
Chernozems	1.45	17	120	6.0	60	64	8.6	56	61	12.5	60	44	19.6	18	6	-
Podzoluvisols	1.65	9	48	5.6	65	9	5.9	52	7	7.3	43	7	7.8	31	3	1644
Rendzinas	1.34	28	48	13.3	114	19	13.3	114	0	13.3	114	0	13.3	114	0	28
Ferralsols	1.26	18	34	5.7	60	256	7.6	61	251	10.7	63	228	16.9	61	79	4205
Gleysols	1.38	24	724	7.7	109	243	9.7	100	211	13.1	109	142	19.9	212	14	587
Phaeozems	1.46	16	486	7.7	53	202	10.5	48	194	14.6	47	147	21.6	54	15	7
Lithosols	1.42		500	3.6	128	4	3.6	128	0	3.6	128	0	3.6	128	0	3445
Fluvisols	1.40	17	1	3.8	114	300	5.6	122	278	9.3	136	200	16.1	172	18	695
Kastanozems	1.55	21	496	5.4	52	22	7.5	55	19	9.6	50	8	9.6	50	0	26
Luvisols	1.54	14	48	3.1	103	604	4.3	85	555	6.5	78	377	9.9	56	42	2559
Greyzems	1.50	6	1030	10.8	49	4	13.6	53	4	19.7	53	3	23.3	87	2	-
Nitisols	1.43	17	5	4.1	85	77	5.6	80	74	8.4	72	67	11.3	47	20	1140
Histosols	0.31	80	219	28.3	47	42	46.4	47	42	77.6	47	34	218.0	31	4	17
Podzols	1.32	24	106	13.6	101	82	17.3	92	75	24.2	94	43	59.1	60	6	27
Arenosols	1.61	8	103	1.3	108	262	1.9	93	237	3.1	77	166	5.5	58	14	4018
Regosols	1.51	14	167	3.1	122	86	4.0	114	66	5.0	133	41	7.0	48	9	1625
Solonetz	1.64	12	173	3.2	92	59	4.2	78	53	6.2	83	39	6.2	83	4	90
Andosols	0.73	22	353	11.4	69	160	16.5	65	154	25.4	69	120	31.0	52	13	47
Vertisols	1.67	16	636	4.5	87	267	6.7	71	254	11.1	58	205	19.1	46	29	991
Planosols	1.57	16	67	3.9	99	54	5.2	86	48	7.7	56	28	16.9	66	4	432
Xerosols	1.49	12	253	2.0	64	113	2.8	61	103	4.8	53	73	8.7	53	8	1306
Yermosols	1.51	14	175	1.3	121	44	1.8	93	37	3.0	44	24	6.6	12	3	4684
Solonchaks	1.48	19	150	1.8	73	63	2.6	67	59	4.2	67	42	5.7	97	3	160

3.5 Error of SOC estimates

In order to assess the error due to the soil properties estimates, five maps were built using the same digital map (FAO, 1995) and different soil databases (Table 8). The SOC estimates ranged 211,956–117,356 Tg C. It appeared that the highest SOC estimate was obtained using the most recent HWSD database. When comparing the SOC estimates to the mean SOC estimates it appeared that the SOC estimates ranged +32% and –27%.

Table 8: Continental carbon stock estimates based on various soil properties databases and the DMSW spatial database

Source of soil data	0-30cm	0-100cm
Batjes 1996	94,676	179,288
Batjes 2002	86,948	166,133
Batjes 2005	56,909	117,356
Batjes 2006	na	128,032
FAO/IIASA 2008	102,357	211,956

When estimating the error due to spatial data it was not possible to compare SOC from the different maps using the same database because the spatial data uses different legends. The error due to spatial data was estimated making a comparison with the SOC estimates from Table 6 and Table 8. The SOC estimates using the same soil properties and different soil maps varied a lot (Tables 4 and 6): i.e. the SOC estimates using the soil properties from HWSD and the spatial map from DSMW and the HWSD were 166 450 and 211 956 Tg. It appeared that the percentage of error due to spatial data ranged –30% to +27%. It means that the spatial data could over or underestimate the SOC estimates at continental scale of about 30%.

When developing or monitoring land use change project, SOC data should be available for regional, national or local scale. According to our results I can assume that the estimate of SOC, based on the soil map of the world from FAO and IIASA and the soil properties from the WISE and the HWSD, could vary of up to 60% when considering the spatial and soil properties data. When considering national scale studies, SOC estimates vary also (Table 9). For instance, SOC assessment of Congo was estimated 3300 Tg of C by Schwartz and Namri (2002) while 9300 Tg of C were estimated in this study for 0–100cm soil layers, respectively. But Schwartz and Namri (2002) based their calculation on only ca. 90% of the country area due to lacking information for specific landscape units, mainly in Northern areas, and concerning mostly hydromorphic soils and in a less extent peats; both soil types usually with high level of OC. Moreover Schwartz and Namri (2002) recognized that small areas of Podzols with humic horizon containing considerable quantities of OC (up to 120 kgm⁻²) could not be taken into account in their established procedure of calculation. SOC estimates of Benin ranged 251–260 and 526–543 Tg C in Volkoff et al. (1999) while the estimates of this study were 374 and 687 Tg C for 0–30 and 0–100 cm soil layers, respectively. In addition, average SOC density was estimated to be 3.5 kgCm⁻² in this study while 4.5 kgCm⁻² in Volkoff et al. (1999). SOC estimates of Kenya ranged 1896–2006, and 3452–3797 Tg C in Batjes (2004) while 1832 and 3989 Tg were estimated in this study for 0–30, 0–100 cm soil layers.

Table 9: Comparison of SOC estimates at national scale.

Region or	Area (km ²)	Spatial component	Published estimated (Tg)		Reference	Our estimate (Tg)	Soil area km ²
Congo	302,616	Map of 31 elementary	0-10 cm:	800	Schwartz and Namri,	0-30 cm: 3,423	318,213
			0-100 cm:	3,300			
			0-200 cm:	3,900		0-100 cm: 9,300	
Benin	115,141	Soil map Scale: 1/200,000	0-20 cm:	251-260	Volkoff et al. 1999	0-30 cm: 374	109,714
			0-50 cm:	408-424			
			0-100 cm:	526-543		0-100 cm: 687	
Kenya	582,646	KENSOTER Scale: 1/1,000,000	0-30 cm:	1,896-2,006	Batjes, 2004	0-30 cm: 1,832	541,841
			0-50 cm:	2,654-2,883			
			0-100 cm:	3,452-3,797		0-100 cm: 3,989	
Senegal	199,823	Ecological stratification Landsat images Scale: 1/100,000	0-40 cm:	452	Woomer et al. 2004	0-30 cm: 561	190,339
						0-100 cm: 1,019	
Sudan	262,144	Soil Map of the World	0-20 cm:	146	Ardö and Olsson, 2003	0-30 cm: 5,927	2,404,149
						0-100 cm: 11,318	
Central Africa (Burundi, DR Congo.	2,399,000	SOTER Scale: 1/2,000,000	0-30 cm:	10,400-10,600	Batjes, 2007	0-30 cm: 10,799	2,222,221
			0-50 cm:	14,000-14,300			
			0-100 cm:	19,300-19,600		0-100 cm: 22,446	
			0-150 cm:	21,500-21,800			
			0-200 cm:	22,900-23,300			

The HWSD produced much higher estimates of SOC of at least 2.8 and 15.4% for 0–30 and 0–100cm layer in central Africa, 28.5% for 0–100cm layer for Benin and 181% for Congo. The difference between estimates could be explained by (1) imprecision in the boundaries of the territory that lead to an overestimation of the area of about 12.4%, (2) lacking information for specific soil type, and (3) imprecision of SOC content which increased with soil depth. I observed that SOC estimates for Kenya (Batjes, 1996) were quite similar (% of error less than 5%) which could be explained by the same origin for soil characteristics.

Reliability of the information presented here is variable. While some parts of the world are highly reliable (Southern Africa, Latin America and the Caribbean, Central and Eastern Europe), other part of the world are considered less reliable (North America, Australia, West Africa and South Asia). Most of the improvement of the comprehension of the soil compartment at global scale could be attributed to the development of the SOTER database that already covers Africa: Northern Africa, Southern Africa, Kenya and Central Africa. However, in order to improve the estimates of the soil biophysical properties and the impact of anthropic activities, the data on spatial resolution of the soil map units and the land use units, the proportion of soil types within on soil map units, the soil properties and the stock change factors for different management activities have to be improved.

4. Conclusion

There are uncertainties in any estimate of soil carbon stocks at national and continental scale. The SOC estimates using the Harmonized World Soil Database clearly overestimated the SOC for the different layers when comparing with other national studies. When comparing different soil databases and soil maps it appeared that SOC estimates ranged 133 420–184 116 Tg for 0–100 cm soil layer of Africa. On the other hand, a variation of about $\pm 30\%$ was reported when comparing the soil properties or the spatial data of the different databases. With an estimate of 166 397 Tg for the 0–100 cm, soil appeared to contain 68% of the terrestrial C pool of Africa. Most of the CO₂ emissions in Africa are due to land use change that affects both aboveground and belowground compartments. It is difficult to estimate the amount of C that could be released from the soil as no data exist on SOC before conversion to agriculture and the impact of anthropic activities on the different soil types is not known. Adoption of recommended management practices can result in important C sequestration particularly in degraded/marginal soils. Soil degradation and food security are among major challenges in sub-Saharan Africa. Commoditisation of SOC through trading C credits under the Kyoto's CDM could improve livelihoods and provide incentives for exchanging soil quality and restoring degraded soils and ecosystems. It is however limited by the number of SOC measurements and their uncertainty when monitoring SOC change at farm, local, regional and national scale. CDM and C forestry projects face many other scientific gaps. The validity of allometric equations is one of those. It is the starting step for estimating forest biomass. While many authors report that it is possible to use generalized allometric equations (Brown, 1997, Ponce-Hernandez, 2004, Gibbs, et al., 2007), the next three chapters deal with highlighting the importance of allometric equations in assessing carbon and carbon changes, the factors influencing tree biomass and allometric equations and the state of knowledge at continental scale.

Chapter 4

The importance of tree biomass allometric equations in assessing carbon stock and carbon stock changes

This chapter is modified from the article: Henry, M., Trotta, C., Maniatis, D., Picard, N., Manlay, R.J. Valentini, R., Bernoux, M., Saint-André, L. (2010) Can Carbon be reliably assessed in Sub-Saharan Africa?, submitted to Nature Geosciences.

Abstract:

Studies dealing with the estimation of biomass, site productivity and the contribution of forests to the global carbon balance require the use of allometric equations. There have been a great number of equations developed to estimate biomass components of trees and shrubs in various ecosystems in the world. However, there importance to estimate carbon stocks and carbon stock change is not present in the greenhouse gas guidelines of the Intergovernmental Panel on Climate change.

- This study reports that the choice of the allometric equations can influence the greenhouse gas emission balance assessment. The choice of the allometric model can over-estimate the greenhouse gas by 40% in the Congo Basin.
- The carbon balance assessment is influenced by the forest type, its structure, the ecological and climate zone classification, the type of land use change and the selected allometric equation to achieve the calculation.
- The selection of the appropriate allometric model has to be done in a conservative way in order to minimize the risk of hot air in the context of payments for emission reductions under the climate convention.
- This information is critical for the establishment of environmental projects and the confidence between donors and project developers particularly in the context of reducing emissions from deforestation and forest degradation.

Keywords: REDD+, biomass, allometric equation, greenhouse gas balance, forest

1. Introduction

Accurate quantification of the world's carbon (C) budget has become an increasing priority in the context of human-induced climate change. The management of terrestrial ecosystems is known to play an important role in mitigation actions against human-induced climate change (Houghton, 2007), and this particularly in the land use, land-use change and forestry sector (LULUCF). Tropical deforestation alone is thought to contribute up to 20% of global GHG emissions (IPCC, 2007b) with estimates ranging from 12 – 25% (Corinne Le Quéré, et al., 2009, van der Werf, et al., 2009). Most of the uncertainty is coming from interannual variability and more in particular from the lack of consistent and wide applicability of models for estimating biomass (Brown, et al., 1995, Ramankutty, et al., 2007).

Africa plays an important role in the global C cycle system (Williams, et al., 2008) and probably could have a higher potential for C sequestration than expected, even if this is still highly uncertain (Bombelli, *et al.*, 2009). As sub-Saharan African countries face the fastest population growth in the world, it is likely that their share of global emissions over the coming decades will increase (Canadell, *et al.*, 2009), with a substantial part of the increased emissions originating from the LULUCF sector.

Currently, only Annex-I Parties to the United Nations Framework Convention on Climate Change (UNFCCC) must report on C emissions and removals caused by verifiable human-induced changes in the through a national GHG inventory. With regards to LULUCF sector, five forest related activities have been identified for mitigation actions in the current climate change negotiations (FCCC/AWGLCA/2009/L.7/Add.6): deforestation, forest degradation, conservation, sustainable management of forests and enhancement of forest carbon stocks – or in other words, REDD+. An important step towards REDD+ was made at the 15th Conference of Parties (COP) where a decision was adopted on the Methodological guidance for REDD+ (FCCC/SBSTA/Decision-/CP.15). The decision indicates that countries will have to use the Intergovernmental Panel on Climate Change's (IPCC) most recent guidance and guidelines as adopted or encouraged by the COP as a basis for estimating anthropogenic forest-related greenhouse gas (GHG) emissions by sources and removals by sinks, forest carbon stocks and forest area changes (SBSTA/Decision-/CP.15 Article 1 (c)). The IPCC's guidance and guidelines in question were specifically developed to assist countries in producing GHG inventories that should be both accurate (neither over- nor underestimated so far as can be judged) and precise (IPCC, 2007). However it is rather questionable whether the current knowledge of the empirical biomass models for tropical forests and in particular for those of sub-Saharan Africa (SSA) is appropriate for assessing carbon stocks and relative changes.

Indeed the risk of “hot air” in estimating carbon credits from avoiding deforestation is becoming critical when observations and models are not available and biomass estimates are based on few empirical allometric equations developed in other regions from where they are going to be applied.

In temperate countries, well recognized volume tables and allometric equations have been developed (*e.g.* (Zianis, *et al.*, 2005)). Tropical countries and in particular sub-Saharan African countries face two main challenges with respect to choosing allometric equations to estimate and report on forest carbon stocks and forest carbon stock changes for a REDD+ mechanism. First, there are few equations to choose from as only a small number of equations have been developed specifically for the region, especially in comparison to South America and South-East Asia (Chave, *et*

al., 2005). The second challenge is that choosing an inappropriate allometric equation presents a difficult task and may introduce a strong bias in biomass estimates. Given the context and challenges outlined above, the aim of this study is to (i) demonstrate that estimating forest carbon stock and carbon stock changes strongly depend on the chosen and applied allometric equation, which I illustrate in a Sub-Saharan African context, and (ii) develop/propose a consistent and conservative way to choose allometric equations.

2. Methods

Aboveground biomass (AGB) stock and change were both estimated through a combination of three factors: (i) ecological zone (four cases, see below); (ii) scenario of forest change (three scenarios, see below) and (iii) biomass allometric equation (between 5 and 9 cases depending on the ecological zone, see below).

Data were collected at three sites in Ghana (Boi Tano, Boin River and Bobiri forest reserves) and one in Cameroon (Mafa Kilda), corresponding to 4 ecological zones respectively: wet evergreen (mean annual precipitation (MAP) = 2,160 mm), moist evergreen (MAP = 1,800 mm), moist semi-deciduous (MAP = 1,428 mm), and dry (MAP = 996 mm) ecological zones. The ecological classification used was obtained from (Hawthorne, 1995). Field inventories were undertaken at each site: three 1-ha plots in Ghana and 33 plots of 0.06 ha in Cameroon. Data were averaged to represent the structure of a forest up to 2 cm of trunk diameter at 1.30 m (diameter at breast height or DBH) on a 1-ha area basis (Figure 14).

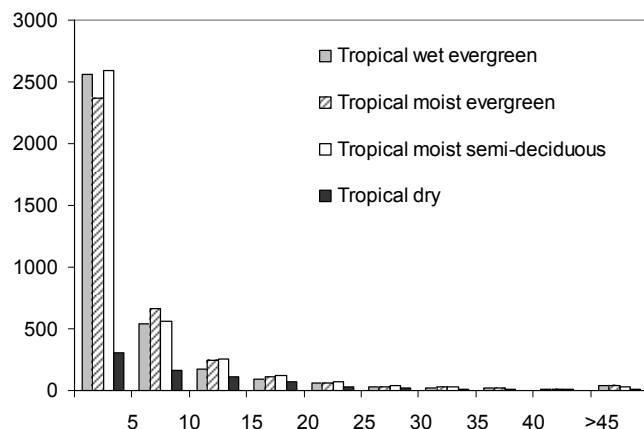


Figure 14: Diameter distribution in four forest types in Ghana and Cameroon

Data on tree DBH was collected in Ghana (Boi Tano, Boin River and Bobiri forest reserves) and in Cameroon (Mafa Kilda).

Aboveground biomass (AGB) allometric equations were obtained from a tree allometric database for sub-Saharan Africa (<http://www.carboafrika.net>). The tree biomass was estimated using the total AGB allometric equations (Table 10) for the respective ecological zone described by the IPCC (2006a). The equations presented and applied represent the available generalized equations for the different

ecological zones (FAO, 2001a). The change in biomass C (ΔC) was simulated using three hypothetical scenarios (SC) minus the reference biomass C ($C_{reference}$) ($\Delta C = C_{SC\ 1,2,3} - C_{reference}$) (Figure 15).

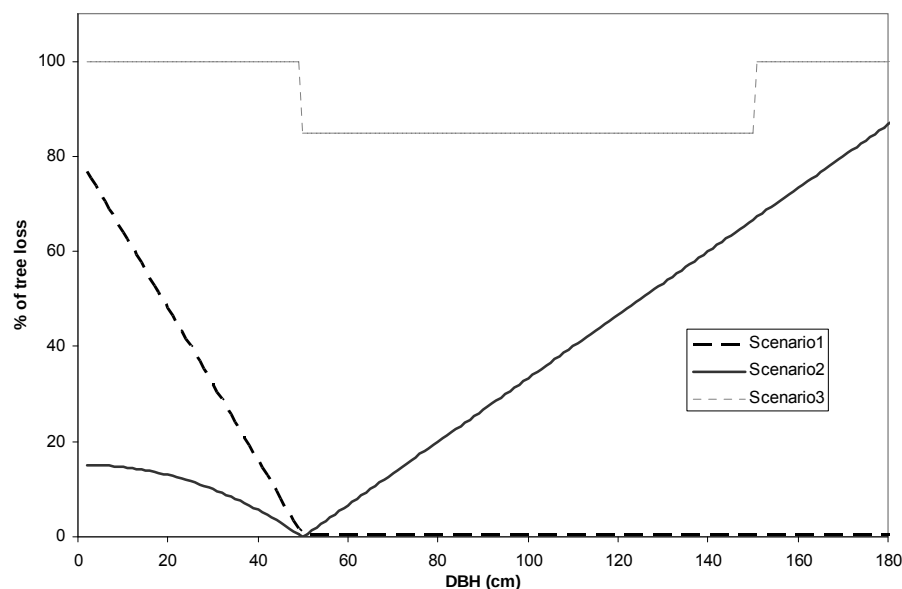


Figure 15: Hypothetical forest change scenarios

Three scenarios were developed to represent different anthropogenic disturbances on forest structure. The first scenario illustrates forest degradation from livestock breeding and firewood extraction and decrease of small diameters. The second scenario illustrates the impact of forest degradation from selective logging which mainly affects the big trees and the very small trees when building the skid trails. The third scenario illustrates the impact deforestation from conversion to agriculture where some big trees remain after forest clearance.

SC1 simulates forest degradation from livestock breeding and firewood extraction. It assumes that 80% of the small trees (DBH < 50cm) and 0% of the big trees (DBH > 50 cm) were affected. SC2 illustrates forest degradation from selective logging which mainly affects the big trees. It assumes that 15% of the trees with 2 cm of DBH are damaged by skidding operations and decreased to reach 0% at DBH = 50 cm. The curve shape was quadratic because small trees are more affected than the largest ones. Harvesting operations concerned trees with DBH > 50 cm and reaches 100% at DBH = 200 cm. SC3 illustrates deforestation from conversion to agriculture. SC3 assumes that only 15% of the trees with DBH ranging 50 – 150 cm are kept by farmers.

At time t C stock in biomass (C_t) is estimated as a function of tree biomass ($AGB(i)$). Tree biomass itself is a function of diameter i , average tree densities at the initial state (D_0) and at the end of the scenario (D_t), and on the carbon content default value (C_f) from (IPCC, 2007b). The carbon content corresponds to the absolute amount of C in a pool or parts of it. Diameters were classified in diameter classes with a constant width of 1 cm, starting from 2 cm and till the maximum diameter value found in the field measurement (DBH = 178 cm).

Table 10: selected tree aboveground biomass allometric equations:

The allometric models were obtained from A: Neya, et al. (1998), B: Siteo and Tchaúque (2007), C: Brown (1997), D: Brown, et al. (1989b), E: Chave, et al. (2005), F: Ponce-Hernandez (2004), G: de Boer (2000) and H: Chapter 5. The range of calibration was tested in Chapter 6 and the new value were indicated with *.

Zones	Equations	Inputs	References
Tropical dry forest	$Y(g) = 1.8 \cdot x^{(2.5)}$	C in cm (6, 36)	A
	$Y(kg) = -41.077 + 2.816554 \cdot X + 0.35657 \cdot (X^2)$	DBH in cm (8, 200)*	B
	$Y(kg) = \exp(-1.996 + 2.32 \cdot \log(X))$	DBH in cm (1, 40)*	C
	$Y(kg) = 34.4703 - 8.0671 \cdot X + 0.6589 \cdot (X^2)$	DBH in cm (6, 40)*	D
	$Y(kg) = 10^{(-0.535 + \log_{10}(X))}$	BA in cm ² (1, 707)*	C
	$Y(kg) = X \cdot \exp(-0.667 + (1.784 \cdot \log(Z)) + (0.207 \cdot (\log(Z))^2) - (0.0281 \cdot (\log(Z))^3))$	WD in g.cm-3, DBH in cm (5, 63)*	E
	$Y(kg) = \exp(-2.187 + (0.916 \cdot \log(X \cdot Z^2 \cdot W)))$	WD in g.cm-3, DBH in cm, H in m (5, 63)*	E
Tropical moist deciduous forest		WD in g.cm-3, DBH in cm, H in m (5, 156)*	E
	$Y(kg) = \exp(-2.977 + \log(X \cdot Z^2 \cdot W))$		
	$Y(kg) = \exp(-2.134 + 2.530 \cdot \log(X))$	DBH in cm (1, 80)*	F
	$Y(kg) = \exp(-2.409 + 0.9522 \cdot \log((X^2) \cdot Z \cdot W))$	DBH in cm, H in m, wd in g cm-3 (5, 148)	D
	$Y(kg) = X \cdot \exp(-1.499 + (2.148 \cdot \log(Z)) + (0.207 \cdot (\log(Z))^2) - (0.0281 \cdot (\log(Z))^3))$	WD in g.cm-3, DBH in cm (5, 156)*	E
	$Y(kg) = 42.69 - 12.800 \cdot (X) + 1.242 \cdot ((X^2))$	DBH in cm (5, 148)*	C
Tropical rainforest	$X \cdot \exp(-1.239 + (1.98 \cdot \log(Z)) + (0.207 \cdot (\log(Z))^2) - (0.0281 \cdot (\log(Z))^3))$	WD in g.cm-3, DBH in cm (5, 133)*	E
	$Y(kg) = 21.297 - 6.953 \cdot (X) + 0.740 \cdot ((X^2))$	DBH in cm (5, 112)*	C
	$\exp(9 - 2.557 + 0.940 \cdot \log(X \cdot Z^2 \cdot W))$	WD in g.cm-3, DBH in cm, H in m (5, 133)*	E
	$Y(kg) = \exp(-3.1141 + (0.9719 \cdot \log((X^2) \cdot Z)))$	DBH in cm, H in m (5, 130)	D
	$Y(kg) = \exp(-2.134 + 2.530 \cdot \log(X))$	DBH in cm (1, 80)*	F
	$Y(kg) = \exp(-2.409 + 0.9522 \cdot \log((X^2) \cdot Z \cdot W))$	DBH in cm, H in m, wd in g cm-3 (5, 130)	D
	$Y(kg) = (X \cdot (0.214 \cdot (Z^{3.1416}) - 0.113)^2) / 10$	H in m, DBH in cm (3, 54)*	G
	$Y(kg) = 0.30 \cdot X^{(2.31)}$	DBH in cm (2, 180)*	H

$$C_0 = \sum_{i=2}^{178} (AGB(i) \times D_0(i) \times Cf) \quad (1)$$

where $AGB(i)$ is the tree C mass (kg C) for a diameter i , $D_0(i)$ is the tree stem density (t ha⁻¹) for a diameter i , and C_0 is the initial amount of C.

$$D_n(i) = D_0(i) \times (1 - h(i)) \quad (2)$$

where $D_n(i)$ is the number of tree stems density after forest degradation or deforestation (tree ha⁻¹), $h(i)$ is the percentage of tree stems felled or harvested according to the scenario (Figure 15).

$$C_n = \sum_{i=2}^{178} (AGB(i) \times D_n(i) \times Cf) \quad (3)$$

where C_t is the C density (Mg C ha⁻¹) at time t .

$$\Delta C = C_t - C_0 \quad (4)$$

where ΔC is the difference in C density (in Mg C ha⁻¹) between time t and initial state.

The estimates on impact of deforestation were extrapolated to the Congo basin using the forest extent and rate of deforestation from FAO (FAO, 2006c) and COMIFAC (Nasi, et al., 2009) and the distribution of forest in the different ecological zones. The distribution of forests in the different ecological zones was estimated based on the proportion of trees with tree cover higher than 30% from the MODIS tree cover (Hansen, et al., 2002).

3. Results

AGB estimates varied between the different chosen allometric equations (Table 11). Estimates ranged from 10 - 34 Mg C ha⁻¹ in tropical dry, 156 - 185 Mg C ha⁻¹ in tropical moist semi-deciduous, 159 - 181 Mg C ha⁻¹ in tropical moist evergreen and 99 - 191 Mg C ha⁻¹ in a tropical wet evergreen forest (Table 11). Chave et al.'s (2005) allometric equations for AGB produced the highest C stock in tropical dry, tropical moist semi-deciduous and moist evergreen forest, while it produced the second lowest value for tropical wet evergreen forest.

Table 11: variation of carbon stock change using different allometric equations (Mg C ha⁻¹)

The allometric models were obtained from A: Neya, Kaboré et al. (1998), B: Siteo and Tchaúque (2007), C: Brown (1997), D: Brown, et al. (1989), E: Chave, et al. (2005), F: Ponce-Hernandez (2004), G: de Boer (2000) and H: chapter 5.

Zones	Initial	SC1	SC2	SC3	References
Tropical dry					
	10< ΔC <34	-11< ΔC <-3	-4< ΔC <-1	-33< ΔC <-9	
	10	-3	-1	-9	A
	16	-4	-2	-16	B
	22	-7	-3	-22	C
	23	-8	-3	-23	D
	24	-9	-3	-23	C
	29	-10	-3	-28	E
	34	-11	-4	-33	E
Tropical moist semi-deciduous					
	156< ΔC <185	-37< ΔC <-24	-42< ΔC <-37	-169< ΔC <-141	
	156	-24	-37	-141	E
	178	-28	-42	-162	F
	165	-29	-37	-151	D
	185	-30	-41	-169	E
	179	-37	-37	-166	C
Tropical moist evergreen					
	159< ΔC <181	-36< ΔC <-27	-30< ΔC <-27	-166< ΔC <-146	
	159	-27	-27	-146	E
	170	-28	-29	-156	F
	160	-29	-27	-147	D
	181	-30	-30	-166	E
	177	-36	-27	-165	C
Tropical wet evergreen					
	99< ΔC <191	-30< ΔC <-19	-25< ΔC <-12	-176< ΔC <-92	
	101	-19	-12	-94	E
	99	-20	-12	-92	C
	113	-21	-14	-105	E
	140	-24	-18	-130	D
	150	-25	-19	-139	F
	142	-25	-18	-131	D
	191	-30	-25	-176	G
	169	-34	-21	-158	H

Deforestation decreased C stocks proportionally by 92 – 98%, whereas forest degradation decreased C stocks proportionally by 15 – 38% for SC1 and 11 – 24% for SC2. The largest decrease of the C stock was found for scenario SC3 in tropical moist evergreen forests and the lowest decrease of the C stock was found for scenario SC2 in tropical dry forests.

When considering the minimum absolute value of ΔC as the reference, overestimation could reach up to e.g. 34, 11 and 93% for SC1, SC2 and SC3 respectively in tropical dry forests. AGB estimates vary

between diameter classes and authors. For example Brown (1997)'s estimate of AGB was the highest among all authors at DBH = 30 cm in the tropical moist forest, while being the lowest at DBH = 140cm. As the different SC impact the forest structure differently (Figure 16), it follows that ΔC from the different authors ranked differently according to the SC. For instance, for the AGB estimates in a tropical moist semi-deciduous forest, Brown (1997)'s estimate of ΔC was 7 Mg C ha⁻¹ higher than Chave, Andalo *et al.* (2005)'s estimate for SC1; Ponce-Hernandez (2004)'s estimate was 5 Mg C ha⁻¹ higher than Brown (1997)'s estimate for SC2; and Chave *et al.* (2005)'s estimate was 3 and 25 Mg C ha⁻¹ higher than Brown (1997)'s estimate for SC3 (Table 11).

When considering tropical rainforests, important differences were also reported. Chapter 5's was 4 Mg C ha⁻¹ higher than de Boer(de Boer, 2000)'s in SC1, while de Boer was 4 and 18 Mg C ha⁻¹ higher than in chapter 5 in SC2 and SC3. Important differences of ΔC were also found using equations from the same authors in different ecological zones. Brown (1997) gave the highest ΔC for SC1 in tropical moist forests and the lowest ΔC for SC3 in tropical wet evergreen forests. In addition, Chave *et al.* (2005) gave the highest ΔC for SC1, 2 and 3 in the tropical dry forests while they gave the lowest in the tropical wet evergreen forests for SC1, 2 and 3.

4. Discussion

4.1 Allometric equations are fundamental to determine forest carbon stock and stock changes

This study demonstrates that important variations in C stock and ΔC estimates were obtained when using different biomass allometric equations. The Figure 16 represents the ΔC resulting from using different allometric equations in the dry forest zone. The difference in C stock estimates from different allometric equations was also discussed by Hofstad (2005) who described differences in the relation between the diameter and the volume for different forest types within the dry forests. Chapter 6 reviewed the allometric equations that were available for sub-Saharan Africa and reported differences depending on the geographical position, climate, age, tree species, plant functional type and wood gravity.

Choosing the most suitable allometric equation for a given forest type is a crucial step to assess and report on forest C estimates for REDD+ to the UNFCCC Secretariat. The credibility of such estimates could largely influence financial support mechanism for REDD+ implementation under the UNFCCC. This choice is fundamental since I have demonstrated that choosing an inappropriate allometric equation could, for example, lead to an overestimation of AGB of up to 93% in the case of wet evergreen forests. The difficulty of choosing the most suitable allometric equation has been raised by several authors (Ares and Fownes, 2000, Hofstad, 2005). Unfortunately, these difficulties are enhanced in the context of Sub-Saharan Africa due to the lack of information and absence of clear decision rules for allometric equations. Furthermore, by extrapolating to the whole Congo Basin, CO₂ emissions from

deforestation ranges from 0.2 - 0.33 and 0.09 - 0.16 Pg CO₂ yr⁻¹ respectively. This means that allometric models influence up to 40 and 42% of the Congo Basin's CO₂ balance using data from FAO and COMIFAC respectively.

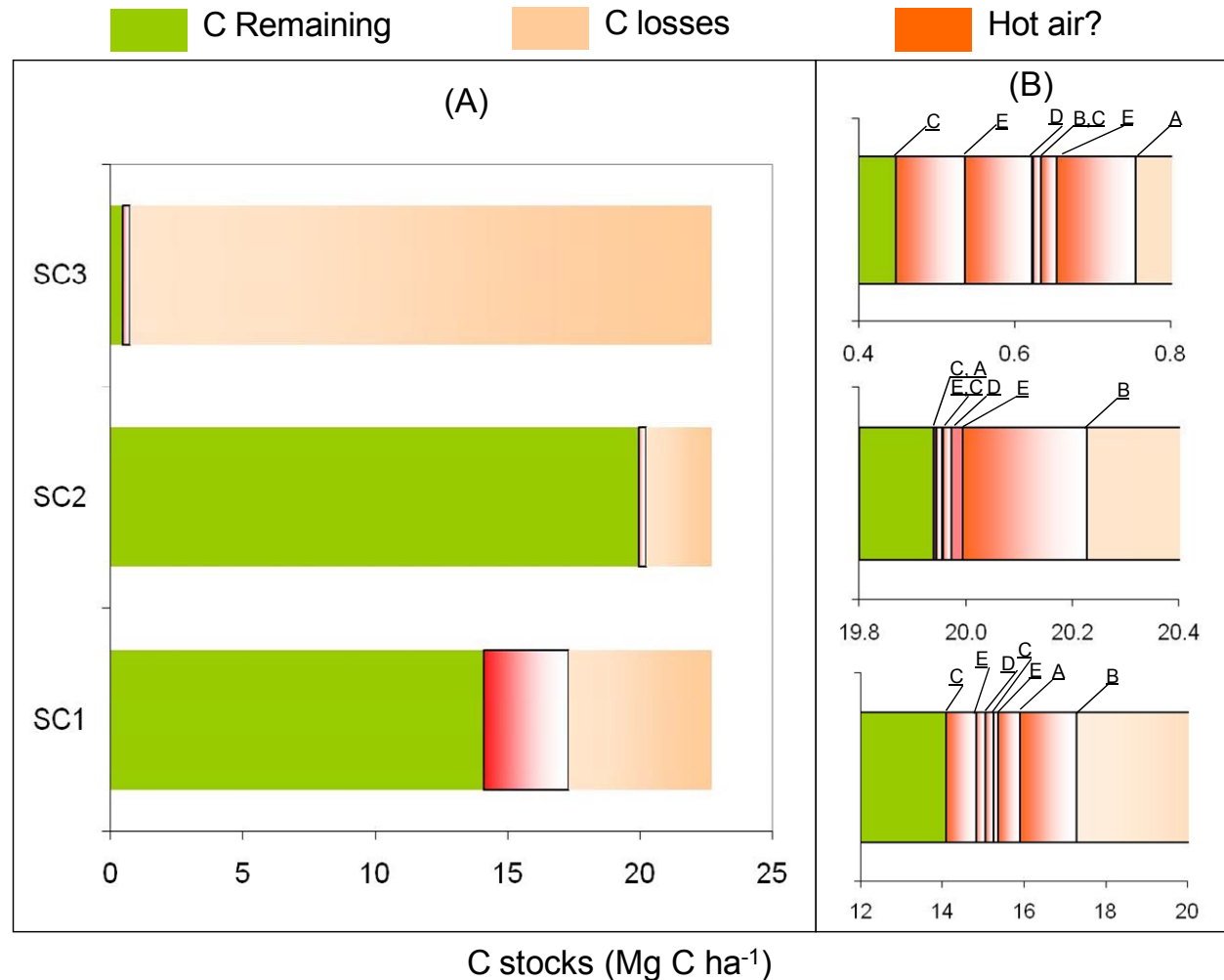


Figure 16: Impact of allometric equations on carbon change assessment in dry ecological zone

Green corresponds to the minimum remaining carbon stocks under scenarios. Pink is the minimum carbon stock loss. Red is the uncertainty from the used biomass model. To report the impact of each equation in the red panel I used the relative value calculated as delta carbon of each equation divided by the initial C stock given by the respective equation. The relative value was then multiplied by the average biomass in order to obtain the impact in Mg ha⁻¹. (B): represents a magnifying glass for the red panel of (A). The allometric models were obtained from

A: Neya, et al. (1998), B: Siteo and Tchaúque (2007), C: Brown (1997), D: Brown, et al. (1989), E: Chave, et al. (2005), F: Ponce-Hernandez (2004), G: de Boer (2000) and H: chapter 5.

4.2 Consistent methods between GHG inventories are necessary but not enough to be conservative and avoid hot air

In the context of producing reliable data on C stock and C stock changes to report to the UNFCCC Secretariat and eventually be used in a future C accounting system, it is more reliable to estimate C using location-specific allometric equations. Nonetheless, when crossing countries and vegetation types, only 1% of the cases are currently covered by specific allometric equations in Sub-Saharan Africa (Chapter 6) and, where the data are not available nationally, data on land categories has to be derived from global datasets (IPCC, 2007). The IPCC guidelines specify that it is important that there is a consistent time-series in the preparation of land-use category and conversion data so that an artefact from a change in the methodological approach is not included as an actual land-use conversion. While consistency allows for robustness and transparency in the GHG balance assessment, it does not address the potential incompleteness and high uncertainties of GHG balance estimates from forest change, and thus the credibility of estimates (Grassi, et al., 2008). The over or under-estimation of C stocks could clearly lead to the creation of hot air as illustrated when considering the tropical dry forest (Figure 16).

4.3 Conservativeness increases environmental integrity of reported estimates and emission reductions

This study reported that the choice of the allometric equation influences the variation in C stocks resulting from change in land use across different forest types. The important differences in ΔC estimates are related to how representative the allometric equation is of the population considered by the study. While some equations are better suited to small trees, other equations are more representative for large trees. It would moreover be possible to consciously 'choose' the allometric equation in order to minimize or increase the estimation of the C stock and ΔC (basically cheating the system). Based on expected future forest change processes, one could once again consciously select an allometric equation which would under or overestimate the 'real' C stock or C stock change (resulting in a double cheating of the system).

In light of the above, I suggest the use of conservative allometric equations to estimate both forest C stocks, under the reference level, and under the scenarios used to derive stock changes. Hot air would be created when an inappropriate equation would be applied and used to report on forest carbon stock and stock change (Figure 16). When it is impossible to produce complete or accurate estimates, the reduction of emissions should not be overestimated, or at least the risk of overestimation should be minimized (Grassi, *et al.*, 2008). However, the creation of the hot air depends on the previous forest change and future forest management.

The conservativeness of an allometric equation depends on whether C stocks are increasing or decreasing. If the forest cover change remains equal or similar under a current forest management method in comparison to one in the past, the allometric equations will not influence reported C stock and stock changes. Unfortunately, the neutral situation does not exist for two reasons. First, if I consider a country with a 'poor' forest management method in the past and an 'improved' forest management method in the future, conservativeness implies choosing the allometric equations that under-estimates ΔC . Second, if I consider a country with a 'good' forest management method in the past and a 'poor' forest management method in the future, conservativeness means choosing the allometric equation that over-estimates ΔC . Returning to our example of the tropical dry forest (Figure 16), being conservative would mean using equations 29, 29 and 28 for SC1, SC2 and SC3 respectively.

Moreover, when no adapted and verified allometric models are available, the forest C stock and C stock change has to be achieved in a consistent way over time whilst considering all the generalized allometric equations. In this context, I propose that the emission reduction has to be calculated based on the conservativeness principle in order to allow credibility, environmental integrity and avoid hot air.

5. Conclusion

When reporting forest C stock changes under REDD+, it will be mandatory to respect the transparency, comparability, completeness and accuracy principles developed by the IPCC. However, this is not enough to ensure avoidance of hot air. Sub-Saharan Africa faces challenges in terms of both data availability and region-specific allometric equations. Developing specific allometric equations for all ecological zones and vegetation types will be a necessary and unavoidable step (as it was done for other continents) for the reporting and verification of C estimates that could support a financial result-based incentive system. The reality is that it will be costly and time consuming to do so. Hence, before this is achieved, countries may use default allometric equations whilst being aware and transparent of their limitations. I argue that it is a priority to develop a system for choosing allometric equations, as important differences in ΔC estimates were found between forest types, project scenarios and authors. When no specific data are used, ΔC has to be estimated in a consistent and conservative way which considers the comparison of estimates from different allometric equations and uncertainty assessment over time. Without doing this, more than one-third of CO₂ emissions would be determined by the allometric equation. To conclude, it is crucial to develop specific AGB allometric equations to report on forest carbon stock and carbon stock changes for REDD+ implementation that would result in 'real' emissions reductions and financial incentives with environmental integrity. The next chapter will propose a methodology to build a tree biomass allometric equation in a tropical rainforest of Ghana. It also explain which are the factors that drive wooddensity and biomass variation within a tree and within a forest.

Chapter 5

Wood density and biomass variations within and among trees in a tropical rainforest

This chapter is modified from the article: Henry, M., Besnard, A., Asante, W.A., Eshun, J., Adu-Bredu, S., Valentini, R., Bernoux, M., Saint-André, L. (2010) Wood density and biomass variations within and among trees in a tropical rainforest of Africa, *Forest Ecology and Management*, submitted

Abstract

The development of tree allometric equations is crucial to accurate forest carbon assessment. Very few carbon data exist for sub-Saharan Africa and as a result generalized allometric equations, often established for forests in other continents, are used by default. The objectives of this study were (1) to propose a sampling methodology and calculation procedures to assess biomass for tropical tree species of contrasted tree shapes in Africa (2) to identify which are the factors affecting the wood density between and within trees, (3) to propose an allometric model that integrates these factors and (4) to evaluate the reliability of using generalized allometric equations in this type of forests. Models were developed to predict the wood density and the biomass of the trees based on the harvesting of 42 trees from 16 species and 3 plant functional types in the wet evergreen forest of Boi Tano in Ghana. Results showed that the wood density was mainly influenced by the tree species, plant functional type, size of the tree and pith to bark distance. The biomass of the tree was mainly influenced by the diameter at breast height, the crown diameter and the wood density depending on the position within the tree and the plant functional types considered. The use of published generalized allometric models is limited by the identification of the climate zone, the consideration of tree height and species specific wood density. After considering those factors, using generalized allometric equations could result in an error of 3%. Further researches should better consider the bigger trees and the influence of the topography and ecosystem history.

Keywords: Tropical forest, West Africa, Plant functional type, Mixed procedure, Wood density, Carbon assessment, REDD+

1. Introduction

Accurate estimation of forest biomass is crucial for commercial uses (e.g., fuel wood and fibre) national development planning, as well as for scientific studies of ecosystem productivity, carbon (C) and nutrient flows and for assessing the contribution of changes in forest lands to the global C cycle (Basuki, et al., 2009). Particularly in the latter context, the estimation of the above-ground biomass with a sufficient accuracy to assess the variations in C stored in the forest is increasingly important (Ketterings, et al., 2001).

Variability of biomass depends on several factors. Climate, topography, soil fertility, water supply, wood density, distribution of tree species, tree functional types and the state of forest disturbances have impact on forest variability (Sicard, et al., , Reichle, 1981, Fearnside, 1997, Bernoux, et al., 2001, Luizão, et al., 2004, Ferry Slik, et al., 2008). For a determined tree species, biomass is influenced by the size of the tree, its architecture, form (Birot and Caillez, 1970), health (e.g. hollow trees) (Fearnside, 1997), social status and variation of the wood density (Patino, et al., 2009).

Wood density is a key variable for the estimation of tree mass. Within individual trees, wood density differs among branches, trunk and roots and can also vary radially within the trunk as wood is added at the periphery during growth. In a tropical forest plantation in Venezuela, Espinoza (2004) reported an increase in wood density from pith to bark, a decrease from the stump to half of the total tree height and then an increase towards the top of the stem for *Gmelina arborea*. Amorin (1991) and De Castro (1993) reported pith to bark radial decrease of the wood density at breast height of 1.3 m for trees in tropical forests. In addition, De Macedo (1991) and Higuchi et al. (1994) indicated higher basic density at the breast height than at the top of the commercial bole. Fearnside (1997) found different wood densities in the different tree organs and reported that a better estimation of the proportion of heartwood, sapwood and bark would improve biomass estimation. Different tree species showed different radial variations in temperate forests (Woodcock and Shier, 2002). These authors reported that radial increases associated with low values of specific gravity are an early successional characteristic and radial decreases associated with high value of wood density with late succession. The difference in wood density and its radial trends reflect growth strategy and biomechanical considerations. When considering sub-Saharan Africa, there is no available report of wood density variations within tree in natural vegetation.

Changes in wood density are directly associated with structural variations at the molecular, cellular and organ levels. These structural differences are strongly correlated with a tree's mechanical properties (Gartner and Meinzer, 2005), water transport efficiency and safety factors for buckling and bending (Pittermann, et al., 2006, van Gelder, et al., 2006), photosynthesis and rates of carbon dioxide exchange (Ishida, et al., 2008) and perhaps resistance to pathogens and herbivores (Rowe and Speck, 2005). Different species from different taxonomic, phylogenetic and architectural groups show convergence of these functional characteristics in response to the environment (Meinzer, 2003).

Estimation of biomass in a given forest consists in carrying out an inventory of the vegetation in sampled plots, application of appropriate allometric equations, and up-scaling to estimate biomass C stocks stand and their variation. Key point of this method is the allometric equations (Návar, 2009). Despite their apparent simplicity, they have to be fitted carefully using the latest regression

techniques available (Parresol, 1999, Wirth, et al., 2004). Inappropriate application of allometric equations developed for a particular forest type to a different forest type may lead to considerable bias in C stocks estimations. For example, application of an allometric equation developed for a tropical moist forest (Brown 1997) when applied to a tropical wet forest (Clark and Clark, 2000) over estimated aboveground biomass by 79% (Clark, et al., 2001).

Measurements to develop allometric equations could be achieved by direct and indirect methods. Direct methods measure the biomass directly by weighing trees in the field while indirect methods involve the estimate of difficult to measure parameter, like stem volume and tree mass, from easy to measure tree parameter, like diameter at breast height and tree height (Peltier, et al., 2007). Weighing trees in the field is undoubtedly the most accurate method of estimating aboveground tree biomass but it is extremely time consuming and is generally limited to small areas and small-sized trees (Parresol, 1999). For the development of allometric equation, samples of various tree components or organs at different points of the tree are taken, bulk density determined and together with volume, used to estimate dry mass of the component. Dry mass of the various components are summed up to obtain total tree dry mass (phytomass). This is then related to easy to measure parameter of the tree to develop allometric equations.

The allometric equations are then used to estimate the tree biomass over large areas. Most allometric equations concerning tropical forests have been developed for the tropical forests of south America and Asia (Brown, 1997, Baker, et al., 2004, Chave, *et al.*, 2005). Moreover, there is a lack of such equations for the tropical humid forests of Africa hence equations developed for other places are as consequence used by default. Moreover, reliability of such equations has never been tested. Some authors concluded that species-specific allometric relationships are not needed to generate reliable estimates for forest C stocks (Gibbs, et al., 2007), while others showed that species-specific allometric equation will improve biomass estimation (Ketterings, *et al.*, 2001, Pilli, et al., 2006). Site variables have been shown to improve the performance of equations in both tropical and temperate even-aged forests (Saint-André, et al., 2005). Big trees represent important proportion of the forest biomass (Martinelli, et al., 1994), hence data for generic allometric equations are skewed towards big trees, but many forest disturbances affect mostly small trees (Villela, et al., 2006). Currently, the domain of validity of the generalized equations limits their use to the all tree population i.e. the generalized equations provided by Brown (1997) and Chave (2005) are valid up to a maximum diameter at breast height (*DBH*) of 148 and 152 cm, respectively. The tropical forest consists of a variety of tree species per unit area; more than 300 tree species per hectare could be found in a tropical forest. In assessing the forest C stocks and biomass change it is necessary to consider the different ranges of trees species, their distribution and the variation of wood density. Fearnside (1997) reported that the best situation is to match both density and volume information identified to species level.

The main aim of this study was therefore to develop an allometric model to estimate tree biomass in the wet evergreen forests of Ghana. The specific objectives were (i) to propose a sampling methodology and calculation procedures to assess biomass of tropical rainforest tree species of contrasted tree shape (ii) to identify factors that affect wood density between and within trees of contrasted functional type, (iii) to propose two allometric models – one that integrates the most significant variables – one that consider convenient variables for field measurement and (iv) to evaluate the reliability of using generalized allometric equations in this type of forests.

2. Materials and method

2.1 Study site

This study was carried out in Boi Tano forest reserve located in the Enchi Forest District, in the Western Region of Ghana. It lies between latitudes 5°20' and 5°36' North and longitudes 2°34' and 2°50' West, and the total area is 122 km². The forest reserve is classified as wet-evergreen forest type (Hall and Swaine, 1976). The climate is characterised by a bimodal rainfall distribution and the mean annual precipitations are up to 1750 mm (Hall and Swaine, 1981), and averaged 2155mm by the FAO-CLIM (FAO, 2005d). The Forest Reserve concerns the lower Tano basin and consists of a series of hills. The soils are mostly oxisols (Hawthorne and Abu Juam, 1995). The forest falls in the *Cynometra* - *Lophira* - *Terriatia* association vegetation classification (Taylor, 1960), the tropical rainforest ecological zone (FAO, 2001a), the equatorial monsoon climatic zone (Kottek, et al., 2006) and the moist climate zone (FAO/Agrhymet Network & ESRI). Very few is known about the history of the Boi Tano Forest Reserve before its first concession in 1947. There was timber exploitation before its selection and demarcation in 1967, but the area did not appear to have come under intensive selective logging and clearing for farming because of the low soil fertility and the hilly terrain. The Forest Reserve is currently being logged by Samartex timber and plywood.

2.2 Sample Trees

The study was carried out in the early dry season in November 2008. Selection of the bigger trees for destructive measurements was dictated by the trees earmarked by the company to be harvested according to the Ghanaian forestry law. The small to big sized trees were selected from the trees affected by the logging operations. Severely damaged trees were avoided. A total of 42 trees were sampled. Diameter at breast height, *DBH*, ranged from 2.6 to 180 cm, height from 1.5 to 61 m, crown diameter from 1.5 to 98 m and stem volume from 0.01 to 112 m³ (Table 12). A total of 16 tree species were captured. The trees were grouped into three Guild status namely Pioneer, *P*, Non-Pioneer Light Demander, *NPLD*, and Shade-Bearer, *SB*, (Hawthorne, 1995). There were 22 *NPLDs*, 11 *Ps*, and nine *SBs*. The trees were felled with a chainsaw according to conventional logging practices leaving a stump of up to about 2.0 m height, depending on tree size. The measurements carried out on the felled trees were *DBH*, height (*H*), crown diameter (*CD*), buttress height (*H_b*) and length (*L_b*). The *DBH* was measured with a calliper, height of the trees, *CD*, *L_b* and *H_b* with measuring tape. The characteristics of the sampled trees are presented in Table 12. Two different methods described below were used to estimate the biomass of small-size (*DBH* <20cm) and big-size trees (*DBH* ≥20cm). The characteristics of the sampled trees are presented in Table 12.

Table 12: Characteristics of the selected trees

P: Pioneer, NPLD: Non Pioneer Light Demander, SB: Shade bearer, *DBH*: diameter at breast height, H: height, CD: crown diameter, WD: wood density, Volume: the total volume including small branches, BEF: individual biomass expansion factor (conversion of the trunk biomass to the total biomass), BCEF: individual biomass conversion and expansion factor (conversion of the trunk volume to the total biomass). When the biomass of the tree compartment is not mentioned this is because it was included into the measurement of the branch.

Tree	Botanical Names	Ghanaian	Guild	DBH	H	CD	Mean	Volume	Mass in tree components (Mg)					BCEF	BEF
									Branches	Leaves	Trunk	Buttress	Total		
1	<i>Tieghemella heckelii</i>	Makore	NPLD	180.0	61.0	41.0	0.62	112.81	27.28	0.74	35.07	7.16	70.24	0.62	2.00
2	<i>Heritiera utilis</i>	Nyankom	NPLD	71.9	42.3	20.0	0.60	9.84	1.34	0.05	4.43	0.11	5.93	0.60	1.34
3	<i>Heritiera utilis</i>	Nyankom	NPLD	83.0	39.4	15.9	0.60	11.89	2.20	0.09	4.83	0.04	7.16	0.60	1.48
4	<i>Ceiba pentandra</i>	Onyina	P	132.0	45.0	16.0	0.54	28.55	1.53	0.04	13.37	0.44	15.39	0.54	1.15
5	<i>Heritiera utilis</i>	Nyankom	NPLD	100.0	50.5	19.1	0.58	31.71	8.71	0.11	8.39	1.40	18.61	0.59	2.22
6	<i>Tieghemella heckelii</i>	Makore	NPLD	80.5	50.7	13.0	0.66	12.25	1.54	0.05	6.45	0.09	8.13	0.66	1.26
7	<i>Piptadeniastrum</i>	Dahoma	NPLD	89.0	50.0	18.8	0.57	15.72	3.69	0.05	5.16	0.16	9.06	0.58	1.75
8	<i>Tieghemella heckelii</i>	Makore	NPLD	73.5	45.0	11.1	0.66	11.08	1.27	0.04	5.91	0.14	7.36	0.66	1.25
9	<i>Guarea cedrata</i>	Kwabohoro	SB	71.5	45.5	14.0	0.50	10.12	0.65	0.02	4.30	0.13	5.10	0.50	1.19
10	<i>Piptadeniastrum</i>	Dahoma	NPLD	90.0	50.2	16.0	0.57	22.34	5.73	0.38	6.23	0.74	13.08	0.59	2.10
11	<i>Heritiera utilis</i>	Nyankom	NPLD	12.4	12.0	5.0	0.62	0.11	0.02	0.00	0.05	-	0.07	0.64	1.42
12	<i>Heritiera utilis</i>	Nyankom	NPLD	31.0	22.0	9.0	0.61	1.34	0.10	0.01	0.71	0.02	0.83	0.62	1.17
13	<i>Heritiera utilis</i>	Nyankom	NPLD	7.3	5.1	3.7	0.58	0.03	0.02	0.00	-	-	0.02	0.64	-
14	<i>Cecropia peltata</i>	French	P	20.5	21.2	6.2	0.23	0.44	0.03	0.00	0.07	-	0.11	0.24	1.55
15	<i>Cecropia peltata</i>	French	P	29.3	22.5	8.9	0.27	1.11	0.13	0.01	0.16	-	0.31	0.28	1.87
16	<i>Cecropia peltata</i>	French	P	35.5	12.0	7.3	0.26	1.39	0.12	0.02	0.25	-	0.38	0.28	1.53
17	<i>Cecropia peltata</i>	Odwuma	P	7.8	2.3	2.5	0.17	0.07	0.00	0.00	0.01	-	0.01	0.18	1.31
18	<i>Tieghemella Heckelii</i>	Makore	NPLD	93.0	45.0	17.0	0.66	17.79	3.66	0.06	7.80	0.21	11.73	0.66	1.50
19	<i>Nauclea diderrichii</i>	Kusia	P	94.6	50.5	12.0	0.50	17.19	1.06	0.02	7.49	0.06	8.64	0.50	1.15
20	<i>Aubrevillea kerstingii</i>	Dahomanua	NPLD	65.0	32.5	9.0	0.62	4.79	1.52	0.02	1.45	-	2.99	0.62	2.06
21	<i>Nauclea diderrichii</i>	Kusia	P	2.6	4.9	8.4	0.76	0.00	0.00	0.00	-	-	0.00	0.86	-
22	<i>Piptadeniastrum</i>	Dahoma	NPLD	70.0	39.7	10.5	0.58	10.98	2.97	0.06	3.29	0.07	6.39	0.58	1.94
23	<i>Heritiera utilis</i>	Nyankom	NPLD	56.5	35.1	8.0	0.60	5.43	0.85	0.03	2.28	0.14	3.31	0.61	1.45
24	<i>Azelia bella</i>	Papao-nua	NPLD	83.6	40.0	13.5	0.67	14.57	3.17	0.03	6.00	0.58	9.79	0.67	1.63
25	<i>Garcinia epunctata</i>	Nsokonua	SB	7.1	5.7	3.8	0.65	0.08	0.05	0.01	-	-	0.06	0.73	-
26	<i>Drypetes chevalieri</i>	Katreka	SB	13.2	15.7	5.0	0.65	0.22	0.15	0.02	-	-	0.16	0.73	-
27	<i>Strombosia</i>	Afena	SB	7.6	11.3	3.9	0.66	0.07	0.05	0.01	-	-	0.05	0.74	-
28	<i>Tieghemella heckelii</i>	Makore	NPLD	12.0	17.0	4.7	0.78	0.15	0.12	0.01	-	-	0.13	0.86	-
29	<i>Guarea cedrata</i>	Kwabohoro	SB	12.8	13.0	3.1	0.62	0.12	0.08	0.01	-	-	0.08	0.69	-
30	<i>Daniellia thurifera</i>	Sopi	P	9.0	9.3	8.0	0.42	0.11	0.05	0.01	-	-	0.05	0.47	-

Tree	Botanical Names	Ghanaian	Guild	DBH	H	CD	Mean	Volume	Mass in tree						
									Branches	Leaves	Trunk	Buttress	Total	BCEF	BEF
32	<i>Cola nitida</i>	Bese	SB	23.6	23.4	6.3	0.56	0.68	0.09	0.01	0.28	0.00	0.39	0.57	1.36
33	<i>Heritiera utilis</i>	Nyankom	NPLD	48.1	35.6	7.9	0.61	3.83	0.24	0.01	2.07	0.01	2.33	0.61	1.13
34	<i>Nesogordonia</i>	Danta	SB	24.3	30.2	6.5	0.69	0.73	0.12	0.01	0.36	0.02	0.51	0.70	1.41
35	<i>Heritiera utilis</i>	Nyankom	NPLD	105.0	50.5	19.2	0.58	35.36	8.81	0.13	11.18	0.65	20.76	0.59	1.86
36	<i>Strombosia</i>	Afena	SB	26.5	26.0	12.2	0.73	1.09	0.20	0.01	0.58	0.00	0.80	0.74	1.37
37	<i>Heritiera utilis</i>	Nyankom	NPLD	62.0	40.4	11.1	0.60	6.84	0.68	0.04	3.28	0.15	4.15	0.61	1.26
38	<i>Heritiera utilis</i>	Nyankom	NPLD	32.5	27.5	7.1	0.61	1.12	0.07	0.01	0.61	0.01	0.70	0.62	1.14
39	<i>Ceiba pentandra</i>	Onyina	P	170.0	51.0	27.1	0.26	64.84	3.20	0.10	11.87	1.88	17.05	0.26	1.44
40	<i>Nauclea diderrichii</i>	Kusia	P	110.0	58.8	14.1	0.40	28.71	3.47	0.06	7.90	0.07	11.49	0.40	1.45
41	<i>Nauclea diderrichii</i>	Kusia	P	112.0	40.0	13.2	0.47	22.74	3.41	0.10	7.19	0.13	10.82	0.48	1.50
42	<i>Dialium aubrevilliei</i>	Dua bankye	SB	98.0	43.7	98.0	0.65	18.49	2.55	0.05	9.07	0.40	12.07	0.65	1.33

2.3 Wood density

The trees were stratified into four tree compartments or organs namely; (1) stump with buttress (2) trunk (3) big branches with basal diameter greater than 10 cm and (4) small branches with basal diameter smaller than 10 cm. Sampled disks were extracted from the stump, trunk and branches with chainsaw machine. The distance from the base of the tree to where the disk samples were collected was measured. The number of disks collected was one each from the stump and trunk and three from the branches. The disks were taken to the laboratory/ Rectangular sub-samples of dimension 2 by 2 by 10 cm were then extracted from each disk sample at 2.0 cm intervals from the pith to the periphery. For accuracy, the rectangular wood samples were re-measured with a digital calliper at three points along the length for the width and breadth and at two points for the length, for fresh volume calculations. The wood samples, which numbered 811, were oven-dried at 105°C to constant weight and the dry mass determined with an electronic balance. The wood samples for *Daniellia thurifera* were abnormal and were not taken into account. The volume and the dry mass measurements were used to calculate wood density as,

$$WD_k = \frac{M_{wk}}{V_{wk}} \quad (1)$$

Where M_{wk} is the dry mass of the wood sample k (g), V_{wk} is the green volume of the wood sample (cm^3) and WD is the basic wood density (g cm^{-3}).

2.4 Analysis of the wood density

The wood density was analysed to reflect the inter- and intra-variability according to the following factors: tree species (SP), Guild status (GS), a surrogate of tree volume ($Dim = DBH^2 \times H$), tree height (H), crown diameter (CD), radial and vertical positions, tree social status and compartment (stump, trunk and branch). The social status of a tree is expressed as the ratio of CD to H ($SO1$), and H to DBH ($SO2$). The vertical position of the samples in the tree was expressed in relative height (Hr), which is expressed as the ratio of that height position to total tree height, while the radial position corresponded to the distance from the pith to the periphery. A first statistical description and test of comparison was carried out using Friedman ANOVA test followed by Tukey HSD test.

The wood density was modelled using the following formula:

$$WD_{ijklmno} = \delta + \alpha_i + \beta_j + \gamma_k + \beta_j(\gamma_k) + \mu_l + \theta_m + \rho_n + \lambda_o + \delta_o + \lambda_o \times \mu_l + \lambda_o + \theta_m + \gamma_k \times \mu_l + \gamma_k \times \lambda_o + \delta_o \times \lambda_o + \lambda_o \times \mu_l + \varepsilon_{ijklmno} \quad (2)$$

Where α_i , $i=1,2,...44$ - corresponds to the tree (categorical variable), β_j , $j=1,2,...13$ - corresponds to the tree species (categorical), γ_k , $k=$ Non Pioneer Light Demander, Pioneer and Shade Bearer - corresponds to the plant functional type (categorical), μ_l , corresponds to the size of the tree (Dim , continuous), θ_m , $m=$ stump, trunk and branch - corresponds to the location within the trunk (categorical variable), ρ_n corresponds to the relative height (Hr , continuous), λ_o corresponds to the

distance from the pith (continuous), δp corresponds to the social status (So1 and 2, continuous) and $\epsilon_{ijklmno}$ corresponds to the residual term

The influence of each of the factors in the model was tested using MIXED procedure of the SAS software (SAS® Institute Inc., Cary, NC, USA, 2004). Some of the parameters were considered as fixed effects and others as random effects (Appendix II). All measurements from the same individual tree were considered as repeated measurements. Since the wood density samples were incomplete to represent the different tree components for 3 trees, they were discarded from the analyzed dataset. Thus the analysis was performed on 13 species from 39 trees totalizing 788 wood samples. A total of 114 models were run allowing the testing of several combinations of the effects (Appendix II). The model selection was achieved using Akaike Information Criterion (AIC) criteria which represents a good balance between model adjustment and number of parameters (Burnham and Anderson., 2002).

2.5 Estimation of Small-sized tree mass

The small trees were felled close to the ground and stratified into trunk, branches and foliage. The fresh mass of the trunk (M_t), branches (M_b) and foliage (M_f) were weighed using a spring balance. Samples were taken from each of the three organs for the determination of dry to fresh mass ratio (Figure 17). The leaf samples were dried at 65°C for 48h, while the wood samples were dried at 105 °C to constant weight. The fresh and the dry mass of the samples were measured with an electronic balance. From the ratio of fresh to dry mass and the total fresh mass of a component, dry mass of the component was determined. The total above ground phytomass of a tree (AGB) was calculated by summing the dry mass of the various components.

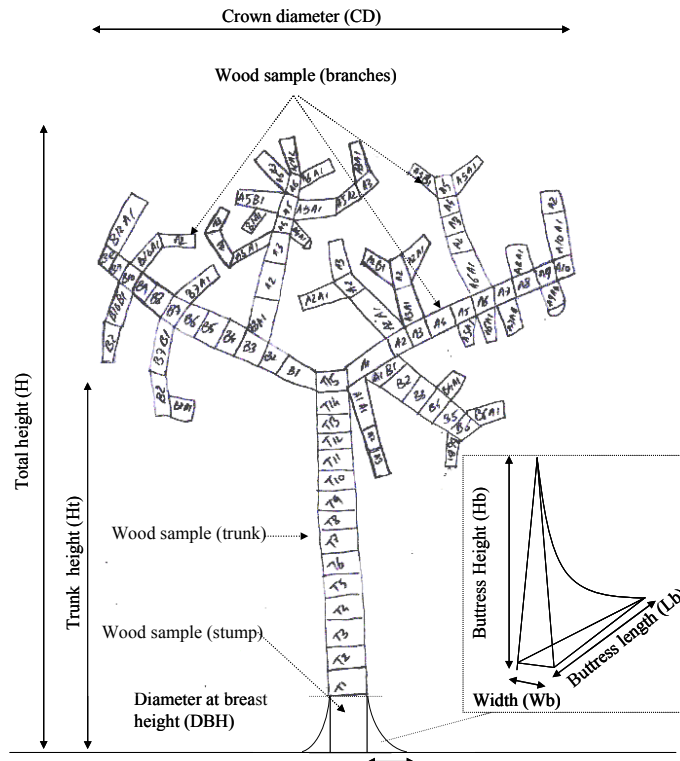


Figure 17: Schematic of partition procedure for mass determination of the trees

2.6 Estimation of big-sized-trees mass

Diameter measurements were carried out at the 1.0 and 2.0 m intervals for branch and trunk, respectively. Schematic representation of the sectioning is given in Figure 17. Dry mass of the buttresses, stump, trunk and the big branches (diameter >10cm) were assessed from volume and wood density measurements. For the small branches, three branches were randomly selected from each tree and the dry mass determined. The dry mass was then related to the basal diameter to develop allometric equation.

The best fitting models between the branch basal diameter (BD) and the biomass of the branches (M_{br}) were performed for each plant functional types.

Many buttresses were present in large trees. The volume of each buttress q was estimated by measuring the height of the buttress (H_b), the width (W_b), and the length (L_b) (Figure 17).

$$V_q = \left(\frac{4 \times (L_b \times H_b) - (\pi \times H_b \times L_b)}{4} \right) \times \frac{W_b}{3} \quad (3)$$

The stump (V_r) was regarded as a cylinder with the cut end being the diameter (D_{cut}). Together with height of the stump (H_{cut}) the volume was calculated. The volume of sections of the trunk and big branches was determined by Smalians formula (or truncated cone) as;

$$V_s = \frac{\pi \times L_s}{8 \times (D_1^2 + D_2^2)} \quad (4)$$

Where L_s is the length of the section, D_1 and D_2 are the diameters at the smaller and larger.

The volume of the trunk and big branches was determined by the summation of the sections of the respective organs. The wood density for each section was obtained using the model presented in 2.2.2. Mass of the buttresses, stump, trunk and big branches was assessed by multiplying the volume of the section by the respective wood density.

$$AGB = \sum_{q=0}^m (V_q \times WD_q) + V_r \times WD_r + \sum_{s=1}^n (V_s \times WD_s) + \sum_{l=1}^o M_{brl} \quad (5)$$

2.7 Choice of a functional form for the allometric equation

Relationship between the tree characteristics and mass of the tree components was fitted using the procedure NLP of SAS software. Linear (with additive error), nonlinear (with additive error) and nonlinear (with multiplicative error) models were tested using one to three inputs leading to nine basic models (Table 13). All possible combinations of variables were tested. Primary variables of DBH , H , CD and WD , surrogates of tree cross sectional area (DBH^2 and CD^2) and surrogates of tree mass ($DBH^2 \times H \times WD$ and $CD^2 \times H \times WD$) were used. A total of 960 models were tested to fit mass of the trees, leaves, branches and trunk. The best and easy to implement models (i.e. when only the DBH or the DBH and WD were available) were selected (Table 14).

Table 13: Selected models for estimating tree biomass

The selected inputs were: the diameter at breast height (DBH), tree height (H), the wood density (WD), the basal area (BA) and the crown diameter (CD).

Models	Number	Group	X	W	Z	a	b	c	d	Sigma2	k	RMSE	AIC	ΔAIC
Y=a+b*X	1	ALL	DBH ² xHxWD				0.05			0.32	1.79	2344	624	13
		NPLD	DBH ² xH				0.03			0.02	2.08	1846	344	1
			DBH ² xHxWD				0.05			0.01	2	1911	344	1
		P	DBH ² xWD			-4.99	1.64			0.00	2.84	1182	140	3
		SB	DBH ² xHxWD			48.87	0.04			4.03	1.09	34	107	16
Y=a+b*X+c*W	2	ALL	DBH ² xHxWD	CD			0.05	4.06		0.11	1.90	2496	617	6
		NPLD	DBH ² xHxWD	CD		-9.38	0.05	5.89		0.00	2.67	621	343	0
		P	DBH ² xHxWD	CD		-5.61	0.04	5.74		0.00	2.41	34	138	1
		SB	DBH ² xHxWD	CD			0.04	12.44		2.00	1.11	2496	103	13
Y=a+b*X+c*W+d*Z	3	Not different from model 2												
Y=a*X ^b	4	ALL	DBH ² xHxWD			0.08	0.96			0.19	0.93	2880	628	16
		NPLD	DBH			0.11	2.58			0.03	1.02	1095	345	2
			DBH ² xHxWD			0.07	0.97			0.00	1.17	2476	346	2
		P	DBH ² xHxWD			0.24	0.86			0.04	0.91	629	147	10
		SB	DBH ² xWD			0.79	1.10			1.77	0.64	90	109	19
Y=a*X ^b *W ^c	5	ALL	DBH ² xHxWD	CD		0.12	0.82	0.48		0.17	1.83	1517	612	1
		NPLD	DBH ² xHxWD	CD		0.11	0.83	0.46		0.00	2.52	1308	368	24
		P	DBH ² xHxWD	CD		0.20	0.79	0.39		0.07	1.68	255	142	5
		SB	DBH	WD		0.60	2.22	0.63		2180	-	1296	105	14
Y=a*X ^b *W ^c +Z ^d	6	ALL	DBH	CD	WD	0.49	2.04	0.47	1.02	0.17	1.83	1750	611	0
		NPLD	DBH	H	CD	0.10	1.77	0.70	0.36	0.02	2.08	1495	344	1
		P	DBH	H	CD	0.04	2.77	0.47	-0.92	11.40	0.86	72	137	0
		SB	DBH	CD	WD	0.43	2.11	0.35	0.79	358	-	1112	90	0
Y=a+b*X*W	7	ALL	DBH ² xH	WD			0.05			0.32	1.79	2344	624	13
		NPLD	DBH ² xH	WD			0.05			0.01	2.23	1911	344	1
		P	DBH ²	WD		-4.99	1.64			0.00	2.84	1182	140	3
		SB	DBH ² xH	WD		48.87	0.04			4.03	1.09	34	107	16
Y=a+b*X*W+c*X*Z	8	ALL	DBH ²	WD	CD		0.89	0.04		0.04	2.07	3391	625	13
		NPLD	DBH ²	WD	CD		0.03	0.25		0.00	2.29	2338	343	0
		P	DBH	H	CD		0.10	0.60		0.00	3.93	4021	144	6
		SB	DBH ²	WD	CD		0.99	0.04		0.81	1.36	112	107	16
Y=a+b*X*(c*W+d*Z)	9	not different from model 8												

Table 14: Selected models for estimating biomass of tree components

Models	Component	PFT	a	b	c	sigma	k	AIC	RMSE
$Y=a*DBH^b*CD^c$	Branches	ALL	0.02	2.06	1.00	0.00	3.14	504	2654
		NPLD	0.00	3.75	-0.47	0.00	2.48	308	1378
		P	0.03	1.81	1.04	0.00	3.39	120	840
		SB	0.25	1.48	0.76	0.00	3.34	63	166
$Y=a*DBH^b*CD^c$	Leaves	ALL	0.01	1.62	0.79	0.00	2.98	296	140
		NPLD	0.00	2.00	0.65	0.00	2.11	201	76
		P	0.04	1.05	0.86	0.00	1.67	74	726
		SB	0.12	1.82	-0.94	5.21	-	30	6
$Y=a*DBH^b*WD^c$	Trunk	ALL	0.19	2.20	0.17	0.05	1.99	536	2778
		NPLD	0.21	2.29	0.04	0.10	1.83	313	1263
		P	0.03	3.58	-1.63	0.00	2.90	133	3176
		SB	0.19	2.02	0.57	0.00	2.20	67	1396
$Y=a*DBH^b$	Total	ALL	0.30	2.31		0.05	2.11	647	5322
		NPLD	0.11	2.58		0.03	1.02	345	1080
		P		1.95		0.09	0.94	168	688
		SB		1.99		0.98	0.73	115	445
$Y=a*DBH^b*H^c$	Total	ALL	0.17	1.97	0.55	0.05	2.09	644	5324
$Y=a+b*(DBH^2*H)$		NPLD		0.03		0.02	2.08	344	1846
$Y=a+b*DBH+c*H$		P	-30.75	4.24	4.73	0.00	3.82	153	4415
$Y=a+b*DBH^2*H$		SB	47.21	0.03		0.03	2.04	114	230

2.8 Validity of generalized allometric models

In order to test the validity of the generalized allometric equations, the estimations using equations in literature were compared with those of this study. The statistical test consisted in a student test for the intercept and slope of the regressions. It was not possible to identify the forest type, whether in the moist or in the wet climatic zones, hence equations from both zones were used for comparison.

3. Results

3.1 Wood density

Average wood density was $0.59 \pm 4.84 \cdot 10^{-3} \text{ Mg m}^{-3}$ and ranged from 0.11 to 1.01 Mg m^{-3} (Table 15). Wood density was significantly (<0.001 , $\text{ddl}=609$) influenced by the guild status: pioneers ($0.42 \pm 0.012 \text{ Mg m}^{-3}$) had lower wood density than non pioneer light demander ($0.63 \pm 3.88 \cdot 10^{-3} \text{ Mg m}^{-3}$) and shade bearer trees ($0.64 \pm 1.07 \cdot 10^{-2} \text{ Mg m}^{-3}$) but the difference was not significant between the later two ($p=0.303$, $\text{ddl}=641$). For example, the lowest wood density for the pioneer group was observed for *Cecropia peltata* ($0.25 \pm 1.56 \cdot 10^{-2} \text{ Mg m}^{-3}$) while the highest was for *Ceiba pentandra* ($0.48 \pm 1.92 \cdot 10^{-2} \text{ Mg m}^{-3}$). In considering the *NPLD* and the *SB* group, the lowest wood densities were observed for *Piptadeniastrum africanum* ($0.59 \pm 7.03 \cdot 10^{-3} \text{ Mg m}^{-3}$) and *Guarea cedrata* ($0.53 \pm 1.22 \cdot 10^{-2} \text{ Mg m}^{-3}$) while the highest were observed for *Afzelia bella* ($0.69 \pm 1.57 \cdot 10^{-2} \text{ Mg m}^{-3}$) and *Drypetes chevalieri* ($0.92 \pm 2.58 \cdot 10^{-2} \text{ Mg m}^{-3}$), respectively. Moreover, wood density varied significantly within a guild type and some species from the *SB* group (*Guarea cedrata*) presented lower values than all the tree species from the *NPLD* group ($p<0.0001$, $\text{ddl}=553$). From the 114 models that were tested, the best parameters for the prediction of wood density included tree species type, guild status, pith to bark distance and tree size (Appendix II).

$$WD = \text{Intercept} + b_1 \times \text{Dist} + b_2 \times \text{Dim} + b_3 \times \text{PFT} + b_4 \times \text{Dim}(\text{PFT}) + b_5 \times \text{SP}(\text{PFT}) +$$

$$b_1 \times \frac{\text{mean}(\text{Dist})}{\text{SD}(\text{Dist})} \times \text{SD}(\text{WD}) + b_2 \times \frac{\text{mean}(\text{Dim})}{\text{SD}(\text{Dim})} \times \text{SD}(\text{WD}) + b_4 \times \frac{\text{Mean}(\text{Dim})}{\text{SD}(\text{Dim})} \times \text{SD}(\text{WD}) \quad (6)$$

There was a decrease in wood density from pith to bark (Figure 18a). The rate of decrease was not significantly different among guild types ($p<0.05$), but the intercept value of 0.427, 0.643, 0.645 for *P*, *NPLD* and *SB*, respectively was significantly different. For instance, for a tree of *DBH* 200 cm the wood density would be 10% lower in outer wood than in inner wood. Wood density variation with tree size was significantly different among the guild types ($p<0.0001$) (Figure 18b). The wood density increased with tree size by 0.1% for *P* species, whilst it decreased by 0.01 and 0.03 % for *NPLD* and *SB*, respectively. Moreover, for a *P* tree species with a volume of about 190 m^3 the wood density would be 38% greater than a tree of 1 m^3 . The model explained 62% of the variability of the wood density ($\text{RMSE}=0.08$, $n=788$). The model didn't consider effects such as the social position. There were some form of relationship between the ratio of height to *DBH*, *SO2*, and wood density (<0.05). The *SO2* was negatively related to wood density for pioneer's trees, null for shade bearers and positive for *NPLD*.

Table 15: Wood densities of the different tree species included into the analysis of the wood density.

The mean wood density found in the literature was obtained by averaging the wood density values reported in the respective documents : 1: (Sallenave, 1955), 2: (Brown, 1997), 3: (A.T.I.B.S., 1982), 4: (CTFT, 1989b), 5: (Compendium, 2009), 6: (Flynn Jr. and Holder, 2001), 7: (Gyimah-Buadi, 1999), 8: (Hidayat and Simpson, 1994), 9: (Howard, 1951), 10: (Kryn and Fobes, 1959), 11: (Kukachka, 1970), 12: (Reyes, et al., 1992), 13: (Sylla and Picard, 2007), 14: (Tree Talk, 2005), 15: (ICRAF, 2009a), 16: (Lavers, 1983), 17: (Rijsdijk and Laming, 1994), 18: (Soerjanegara and Lemmens, 1994), 19: (Chudnoff, 1984). – The original data are presented in Appendix III.

Guild status	Tree species	n	Wood density		Min	Max		Mean	Min	Max	References
Non Pioneer Light Demander	<i>Aubrevillea kertingii</i>	16	0.65	±1.99E-02	0.46	0.74	a,b	-	-	-	-
	<i>Piptadeniastrum africanum</i>	93	0.59	±7.03E-03	0.45	0.74	c	0.60	0.55	0.65	1,2,3,9,10,13,14,16,18
	<i>Tieghemella Hecklii</i>	165	0.65	±5.22E-03	0.5	0.79	b	0.55	0.51	0.58	1,2,13,19,6,9,15,
	<i>Heritiera utilis</i>	211	0.62	±6.98E-03	0.41	0.84	b	0.54	-	-	13
	<i>Afzelia bella</i>	26	0.69	±1.57E-02	0.57	0.81	a	0.64	-	-	1
	Average	511	0.63	±3.88E-03	0.41	0.84	a				
significance							***				
Pioneer	<i>Cecropia peltata</i>	38	0.25	±1.56E-02	0.11	0.42	b	0.32	-	-	2
	<i>Ceiba pentandra</i>	56	0.48	±1.92E-02	0.23	0.79	a	0.28	0.24	0.35	1,2,3,4,5,6,7,8,
	<i>Nauclea diderrichii</i>	52	0.46	±1.03E-02	0.38	0.78	a	0.66	0.32	0.78	1,2,3,9,13,14,15,17
	Average	157	0.42	±1.17E-02	0.11	0.79	b				
significance							***				
Shade Bearer	<i>Strombosia glaucescens</i>	30	0.73	±1.71E-02	0.53	0.93	c	0.77	0.74	0.80	2,13
	<i>Cola nitida</i>	14	0.53	±8.75E-03	0.44	0.57	e	-	-	-	-
	<i>Nesogordonia papaverifera</i>	12	0.68	±1.32E-02	0.62	0.78	c,d	0.64	0.48	0.66	1,2,3,9,10,13,14,15,17,
	<i>Guarea cedrata</i>	43	0.53	±1.22E-02	0.42	0.92	e	0.53	0.46	0.77	1,2,3,9,10,
	<i>Drypetes chevalieri</i>	6	0.92	±2.58E-02	0.85	1.01	a	-	-	-	-
	<i>Garcinia epunctata</i>	6	0.81	±1.70E-02	0.74	0.85	b	0.79	0.78	0.82	2,9,13
	<i>Dialium aubrevilliei</i>	32	0.66	±1.03E-02	0.56	0.77	d	-	-	-	-
	Average	143	0.64	±1.07E-02	0.42	1.01	a	-	-	-	-
Average		811	0.59	±4.84E-03	0.11	1.01	***	***	0.60	0.58	0.67

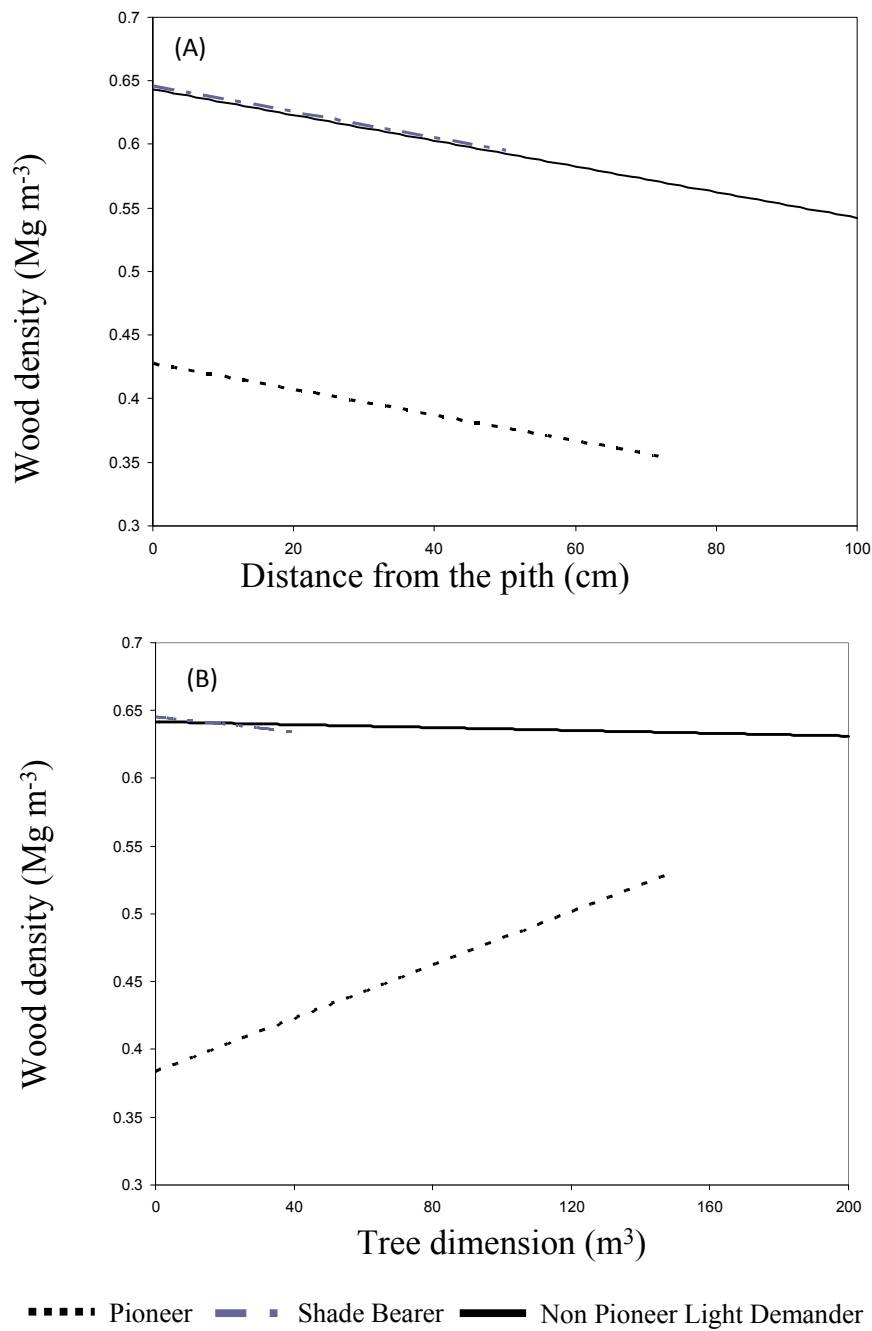


Figure 18: Influence of radial distance from the pith and volume on wood density

(a) top: variation according to the pith to bark distance; (b) below: variation according to the dimension of the tree ($DBH^2 \times \text{Height}$).

3.2 Tree biomass

Three allometric equations were developed (Figure 19) for the branches of *NPLD*, *P* and *SB*. The foliage accounted for 10.3% of the biomass of the branches and *SB* had lower foliage mass than *NPLD* ($p < 0.05$, $ddl = 74$) while *P* was not significantly different from *SB* and *NPLD* ($p = 0.506$, $ddl = 104$). The wood accounted for the rest of the mass and *NPLD* had significantly higher biomass than *P* and *SB* (< 0.05 , $ddl = 103$). While the woody compartment showed a significant relationship with the basal diameter ($R^2 = 0.809$, $RSS = 1.63E+09$), the foliage mass was less significant ($R^2 = 0.348$, $RSS = 1.15E+07$).

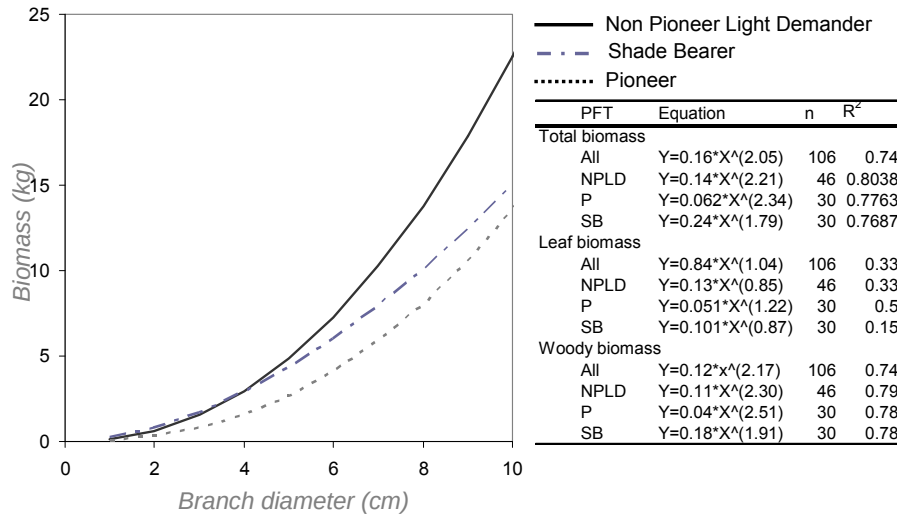


Figure 19: branch biomass allometric equations

The mass of the trunk and the branches dominated the total mass of the tree with 69 and 27%, respectively (Figure 20a). The mass of the foliage and the buttress accounted only 1 and 3% of the total mass, respectively. The distribution of the mass into the different organs was influenced by the size of the trees. However, it was not very evident in the *P* and *SB* trees because all the diameter classes were not well represented. Within the *NPLD* group, (Figure 20b), buttresses were absent for small trees and the buttress represented 7 % of the total for trees greater than 100 cm *DBH*. The percentage of the foliage was approximately constant, while the proportion of trunk mass tended to decrease with tree size, and that of the branches tended to increase but not significant ($p < 0.05$).

3.3 Tree allometric equation

➤ Model fitting

The best models among the 960 tested equations (lower AIC) are presented in Table 13. Model 6 was found to be the most accurate one for all the tree species. However, the ranking differed among guild status. The best model for *NPLD* was model 8 and 2 (same AIC) while the best model for *P* and *SB* was model 6. However the difference between model 8 and 6 for *NPLD* was not significantly different. The best model for *NPLD* and *SB* considered the variables *DBH*, *CD* and *WD* while the best model for *P* did not consider the wood density.

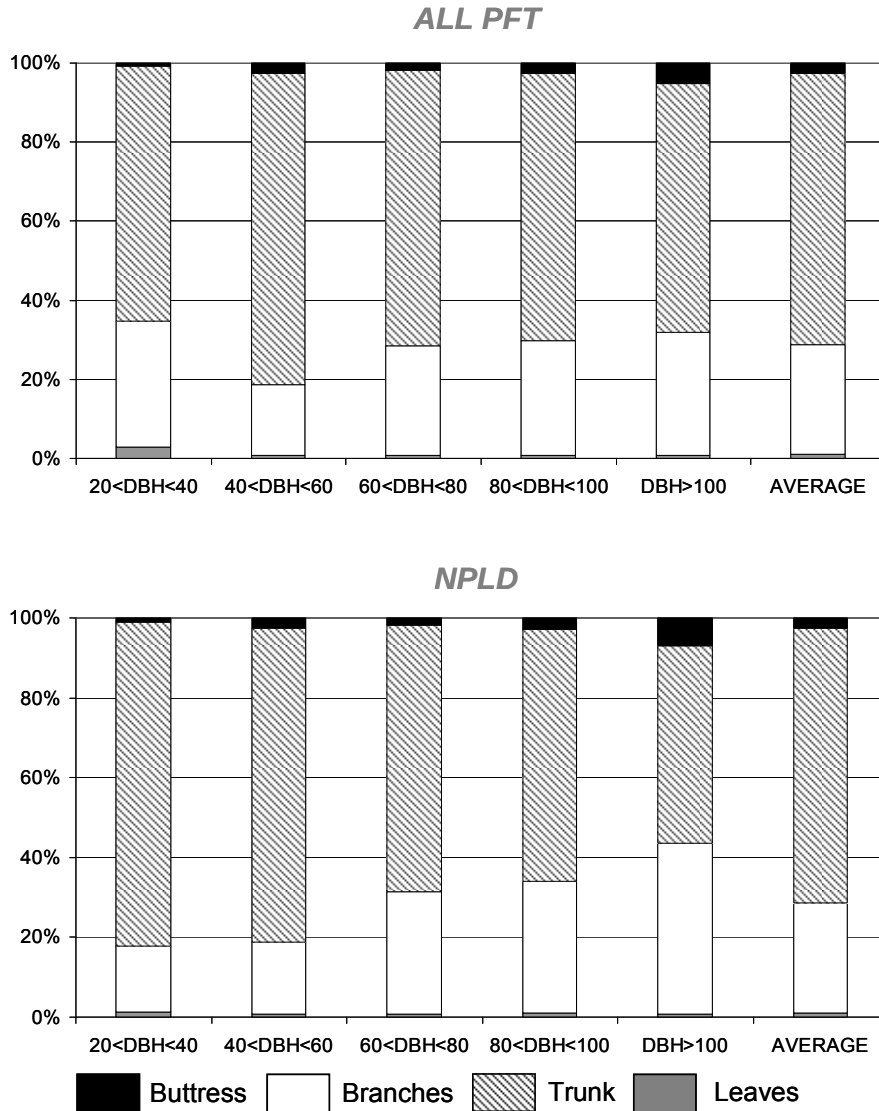


Figure 20: Distribution of biomass in the different tree components

➤ Comparison with existing allometric equations

Fitting the dataset into existing equations from other source yielded results significantly different from those developed in this study, except for equations 4, 10 and 14) (Table 16). All the equations developed for the wet climatic zone under estimated the tree mass (Figure 21), the deviation of which ranged from -26 to + 51%. All the equations were significantly biased ($p < 0.0001$). In addition the mean absolute error was important and ranged from 27 to 51% of the mean. By considering tree height and wood density, the deviation decreased by 17 and 7%, respectively. The equations found in Chave (2005) were less biased and more precise than the other equations.

Table 16: Comparison with other tree biomass allometric equations found in the literature

References	Brown et al., 1989				Brown, 1997		Chave et al. 2005					IPCC	Pearson	This		
Climate zone	Wet	Wet	Moist	Moist	Wet	Moist	Wet	Wet DBH, H DBH, H & WD	Wet	moist	Moist DBH, H & WD	moist	moist	undefine	DBH, CD and WD	DBH, H, CD, WD and GS
Variables	DBH	DBH, H	DBH	DBH, H	DBH	DBH	(literature)	(this study)	(this study)	DBH, H & WD (literature)	H & WD (this study)	DBH & WD (this study)	DBH	DBH	WD	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
Mean (observed values)	6.82	6.82	6.82	6.82	6.82	6.82	6.82	6.82	6.82	6.82	6.82	6.82	6.82	0.20	6.82	6.82
Mean (simulated values)	3.34	4.50	5.77	7.87	3.60	5.98	4.89	5.02	3.86	7.66	7.03	6.51	9.40	0.21	6.66	7.05
Mean Errors	-3.47	-2.31	-1.04	1.06	-3.21	-0.83	-1.93	-1.80	-2.95	0.85	0.22	-0.31	2.59	0.01	-0.16	0.24
Mean Absolute Errors	3.50	2.59	2.20	2.06	3.28	2.17	2.34	1.82	2.97	2.25	1.12	1.41	2.83	0.03	1.38	1.36
Modelling Efficiency	0.44	0.67	0.73	0.84	0.49	0.75	0.74	0.80	0.58	0.81	0.97	0.90	0.59	0.97	0.95	0.93
RMSE	8.69	6.67	6.01	4.68	8.32	5.85	5.96	5.16	7.58	5.13	2.10	3.71	7.45	0.03	2.64	3.18
MAE/Mean (%)	51%	38%	32%	30%	48%	32%	34%	27%	44%	33%	16%	21%	42%	13%	20%	20%
Linear Regression																
R ²	0.84	0.84	0.78	0.85	0.78	0.78	0.90	0.96	0.91	0.91	0.97	0.93	0.81	0.84	0.95	0.93
Slope	2.31 ***	1.66 ***	1.33 **	0.93	2.13 ***	1.28 *	1.63 ***	1.59 ***	2.2 ***	0.92 NS	1.08 *	1.24 ***	0.69 ***	1.04 NS	0.97	1.04
Intercept	-0.92 NS	-0.68 NS	-0.84	-0.52	-0.85 NS	-0.92	-1.15 NS	-1.18 **	-1.69 *	-0.2 NS	-0.75	-1.23 *	0.37 NS	-0.02 NS	0.33	-0.54
Bias	32.63	22.94	5.3 **	1.77	28.48	32.63	32.51 ***	83.11	79.67	1.36 NS	3.74 *	10.49	23.97	0.24 NS	0.35	0.58
Deviation	-51%	-34%	-15%	16%	-47%	-12%	-28%	-26%	-43%	12%	3%	-5%	38%	5%	-2%	3%

* P(H0: Fobs > Fth = 0) < 0.05, ** P(H0: Fobs > Fth = 0) < 0.01, *** P(H0: Fobs > Fth = 0) < 0.001, NS means non significant.

The inputs were: the diameter at breast height (*DBH*), tree height (*H*), the wood density (*WD*), the basal area (*BA*) and the crown diameter (*CD*). RMSE means root mean square error. The selected equations from this study were:

All functional types: $Y = 0.49 \times DBH^{2.04} \times CD^{0.47} + WD^{1.02}$,

NPLD: $Y = -9.38 + 0.05 \times DBH^2 \times H \times WD + 5.89 \times CD$,

P: $Y = 0.04 \times DBH^{2.77} \times H^{0.47} + CD - 0.92$

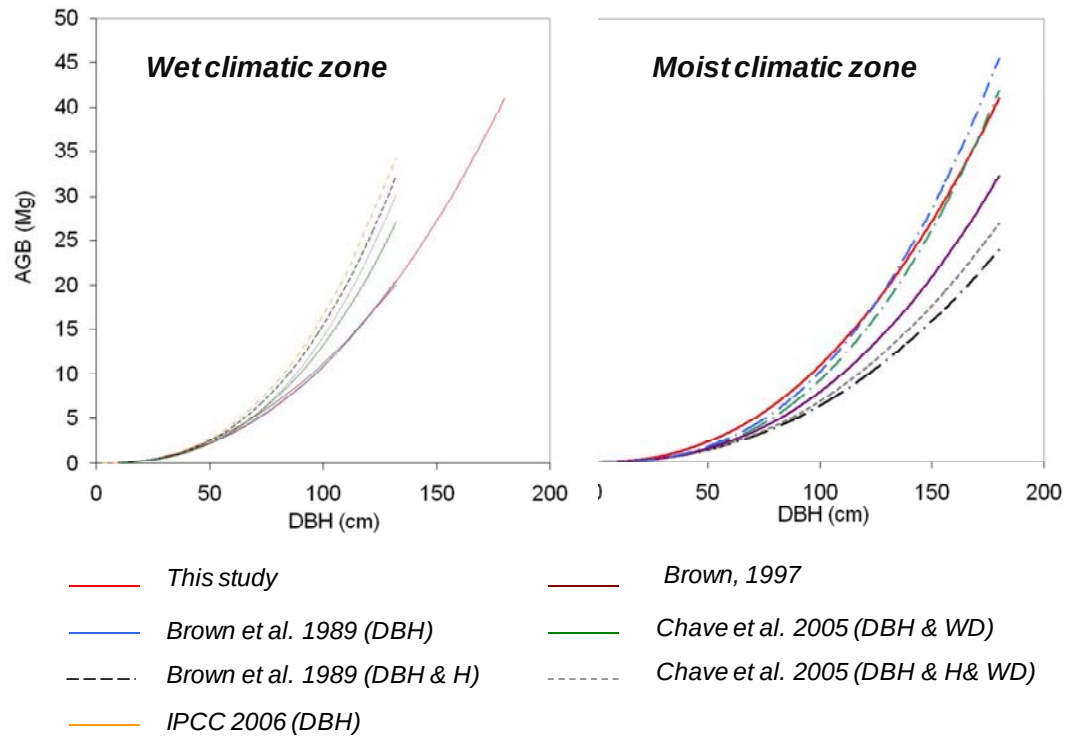


Figure 21: Comparison with allometric equations found in the literature

There was better estimation with equations for the moist zone, the deviation of which ranged from -15 to +38%. All the equations were significantly biased ($p < 0.05$) except equations 4 and 10. The estimated error was lower with equations from the moist zone than those from the wet zone, which ranged from 16 to 42% of the mean. The inclusion of tree height improved the estimation by 2 and 5%, and decreased the bias by 1 and 2% for equation 4 and 10, respectively. The estimation was improved by 17% and the bias decreased by 9% when specific wood density was considered. The use of tree species specific allometric equations did not significantly affect the estimation ($p < 0.05$). The highest modeling efficiency was exhibited by equation 11 ($r^2 = 0.97$) (Table 16). On the other hand equation 11 was significantly biased while equation 4 and 10 were not. The modeling efficiency for equation 4 and 11 were 0.84 and 0.81 respectively. Moreover, the best model found in the literature (equation 4) exhibited an overestimation of 16%.

4. Discussion

4.1 Wood density

The overall average wood density of 0.59 g cm^{-3} reported in this study is very close to the reported values for trees in Africa namely; 0.61 ((A.T.I.B.S., 1982), 0.58 (Brown, 1997), 0.67, (Goldsmith and Carter, 1981), 0.60 (Howard, 1951), 0.61 (Kryn and Fobes, 1959), 0.59, (Reyes, *et al.*, 1992), 0.60, (Sallenave, 1955), 0.65, (Sylla and Picard, 2007) and 0.61 g cm^{-3} , (Tree Talk, 2005). The average wood density of 0.62 g cm^{-3} reported by IPCC (2003) is 5% higher than that of this study, but the reported wood density for trees in Africa ranges between 0.58 and 0.67 g cm^{-3} with an average value of 0.6 g cm^{-3} and (Table 15). The use of average wood density values instead of specific ones normally

introduces bias of the biomass estimation. Average wood density found in international databases are normally for trees with commercial importance that are normally denser, hence their application can result in overestimation. For instance only one reference was found for *Cecropia peltata* whereas 14 references were found for *Ceiba pentandra*, due to the level of their commercial importance. Average wood density values reported for trees in Africa are lower than those from South America, which have average value of 0.65 g cm^{-3} (Fearnside 1997) and 0.69 g cm^{-3} for Puerto Rico (Brown, et al., 1989). However, the variability of the wood density between databases is mainly influenced by the tree species considered.

The average wood density reported in literature is within the range of wood density given in this study. However, the average value for *Tieghemella Hecklii* and *Ceiba pentandra* were 17 and 21%, respectively higher than the average wood density found in the literature, whilst that of *Nauclea diderrichii* is 30% lower than that reported in the literature. In addition, the variability of wood density in this study is much greater than those in literature that considered much higher number of samples. This could be mainly due to the fact that most of the wood samples were collected from the stump while not taking into account the variability within the trees.

The lower wood density for pioneer trees is similar to reported values (Denslow, 1980). Wood density is known to be a strong indicator of state of succession in tropical trees, with pioneer species being lighter than the trees that belong to the other guild types. The lighter species have great variation in wood density within the trunks of individual trees (Wiemann and Williamson, 1988) due to their initial fast growth, producing low-density wood, and later addition of a shell of harder wood for structural support (Rueda and Williamson, 1992). On the other hand, smaller difference between *NPLD* and *SB* was observed. This may originate from the fact that there is still some problems with the definition of *NPLD* and *SB* trees. The *NPLD* and *SB* trees seem to tread on different paths of growth strategies without really affecting its wood density. Baker et al. (2003) and Woodcock (2002) observed a difference between fast growing (pioneer) and late succession species without mentioning the *NPLD* group. However, the Guild classification is not a sufficient variable to understand the variation of wood density.

Size of the trees influenced the wood density. While no literature was found concerning this aspect, the bigger *P* tree species have lower sapwood to heartwood Ratio than the smaller trees. On the other hand, wood density decreases slightly with tree size for *SB* and *NPLD* but not very pronounced. This could be related to increasing proportion of dead wood.

There was radial variation in wood density for all the guild types. The influence of the radial distance on the wood density was reported by Amorim (1991), and Fearnside (1997) also reported a 20% lower wood density for the bark. The rate of decrease of wood density from the pith to the periphery was not significant among the guild types in this study. However, Woodcock (2002) reported that wood density reflected different growth strategy and there is a radial increase for pioneer trees and a decrease for late succession trees. Moreover, he also reported that the occurrence of increases in some individuals and decreases in others of same species is common. The variation of wood density among individuals of the same species was also observed in this study (Figure 22a). Moreover, increase in wood density for the pioneer's tree was not observed as Woodcock (2002) did. From the results of this study the wood density decreased from pith to the periphery and seems to converge at a common average (Figure 22b).

The wood density model was based on only 13 tree species and cannot be used for other tree species. However, it provides good insights into the estimation of the wood density, particularly in the tree sections where samples were not taken. Rather than taking an average wood density at a given height, the model showed that guild type, tree species, pith to bark distance and tree size influenced the wood density and should be taken into account when estimating the biomass of a tropical rainforest. There was also variation among trees of the same species (Table 17, Figure 22a). The results of this study revealed a lot of uncertainties when estimating wood density. It means that many other factors not taken into account by this study could explain the residual variability. Forest and tree history, topography and soil fertility have been reported to influence wood density of trees of different species and these have to be considered in further studies. Slik et al. (2008) reported influence on wood density by different states of ecosystem disturbances. Withmore (1998) and Suzuki (1999) reported different wood densities depending on life history strategies. Improvement of wood density estimation have to consider the position of the trees in the landscape, history of the ecosystem (windfall, fires, etc.) and, if possible, age of the trees (De Castro, *et al.*, 1993).

4.2 Modelling tree mass

Allocation of plant mass to the various organs namely, buttresses, trunk branches and foliage was compared with that of other ecological zones since similar work in the tropical humid forest is scarce. The average proportion of trunk mass of 69% reported in this study is very close to the value of 70% given by Peltier (2007) for a tropical dry forest and higher than the value of 62% given by Henry et al. (2009) for tropical agroforestry systems in western Kenya. The proportion of trunk mass value of 63% for trees with *DBH* greater than 10cm is higher than the proportion of 54% in a tropical rainforest of Brazil reported by Maia Araújo et al. (1999). Volume of the buttress for trees with *DBH* between 68 and 175cm was given as 11.05 m³ in tropical rainforest of Africa (Newbery et al. 2009), but in this study the values given ranged between 0.08 and 12.8 m³. The wide range can be due to the fact that different tree species have different types of buttress and the form of the buttress is reported to be influenced by the position of the tree in the landscape and soil fertility (Newbery, et al., 2009). In addition, the method used in this study might have underestimated the volume of the buttress, whilst Newbery (2009) might have overestimated it because only trees with buttress were considered in their study. Although buttress can represent a significant part of the tree mass, it is generally not taken into account in forest inventory and allometric equations. The average proportion of foliage mass (3.17±0.6%) is lower than the value of 6.7 ±1.1 and 11.2±1.3 % reported for forests in North Cameroon (Peltier et al. (2007) and Western Kenya (Henry et al. (2009). This could be mainly due to the fact that in their studies smaller and probably younger trees were considered.

Whereas the AIC was similar among the models, the *RMSE* was variable (Table 13) and sensitive to the few big trees. On the average, it ranges between 0.5-34.4% of the average biomass (9-34% for P, 22-25% for NPLD, and 16% for SB). The model is therefore very dependent on few big trees hence; further work is required to consider big trees that represent an important part of the biomass in forest ecosystems. Trees with *DBH* greater than 150 cm were not considered in the works of Chave et al. (2005) and Brown (1997), hence the inclusion of such big trees in this study increases the domain of applicability of the model.

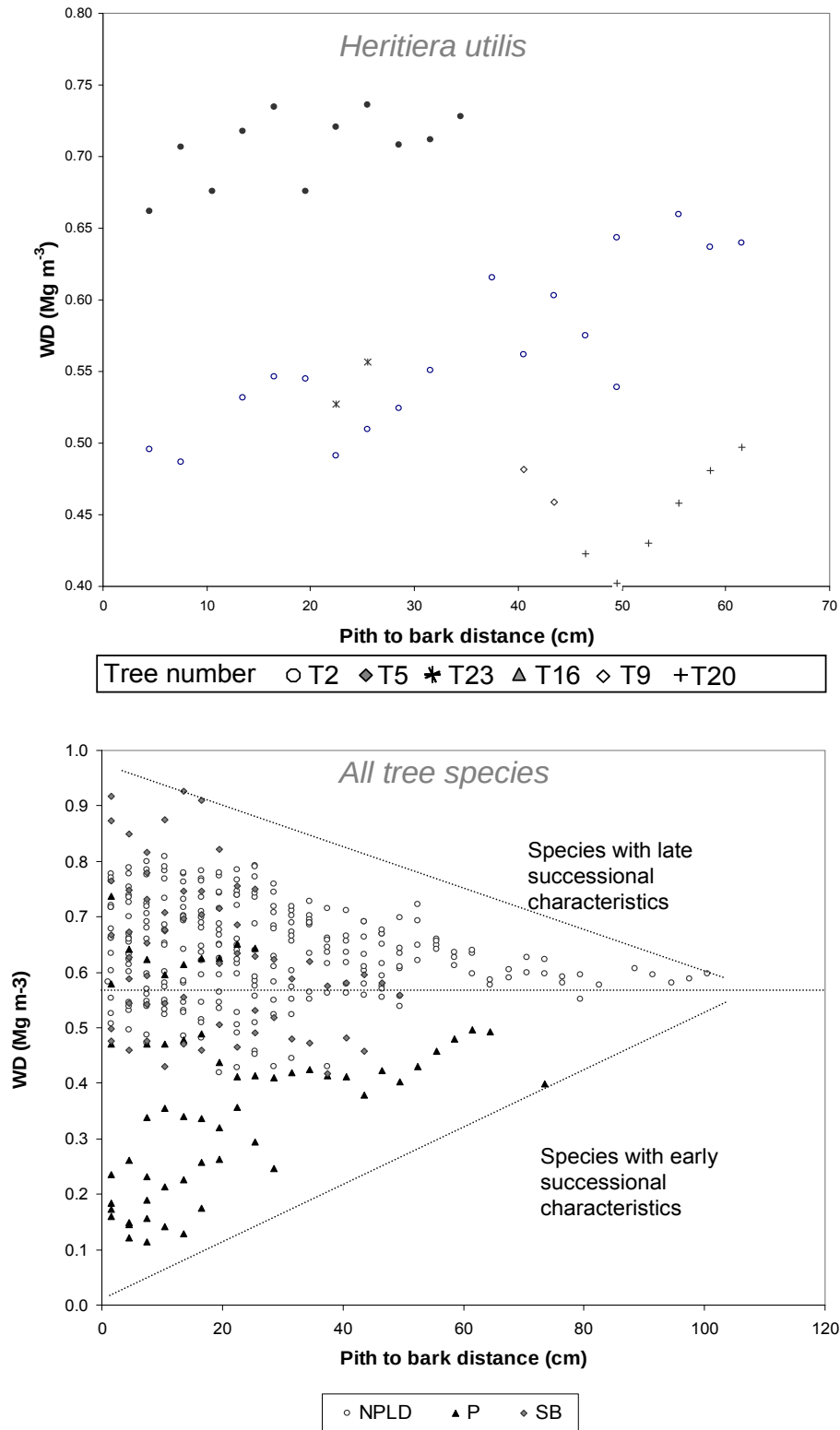


Figure 22: Variation of wood densities

- (a) top: variation of wood density for individual trees of the same species (*Heritiera utilis*);
- (b) below: variation of wood density for the different plant functional types (NPLD: non pioneer light demander, P: pioneer, and SB: shade bearer).

Table 17 - : Selected models for the analysis of the wood density

Guild status	Tree species	intercept	Distance	Dimension	GS	Dimension*GS	Tree species	constant	
Non-pioneer light demander	<i>Aubrevillea kertingii</i>	0.08	-1.18E-03	-2.45E-03		0.01	2.42E-03	-0.06	0.61
	<i>Piptadeniastrum africanum</i>							-0.10	0.61
	<i>Tieghemella Hecklii</i>							-0.01	0.61
	<i>Heritiera utilis</i>							-0.08	0.61
	<i>Afzelia bella</i>							0.00	0.61
	<i>Total</i>							-0.06	0.61
Pioneer	<i>Cecropia peltata</i>	0.08	-1.18E-03	-2.45E-03		-0.14	-8.29E-04	-0.43	0.75
	<i>Ceiba pentandra</i>							0.17	0.75
	<i>Nauclea diderrichii</i>							0.00	0.75
	<i>total</i>							-0.04	0.75
Shade Bearer	<i>Strombosia glaucescens</i>	0.08	-1.18E-03	-2.45E-03		0.00	0.00E+00	-0.06	0.71
	<i>Cola nitida</i>							-0.24	0.71
	<i>Nesogordonia papaverifera</i>							-0.10	0.71
	<i>Guarea cedrata</i>							-0.21	0.71
	<i>Dialium aubrevilliei</i>							0.00	0.71
	<i>total</i>							-0.12	0.71
Total		0.08	-1.18E-03	-2.45E-03		-0.02	1.42E-03	-0.06	0.65

The qualitative inputs were: the plant functional type (GF), the tree species (SP), and the location of the samples (Location). The quantitative inputs were: the radial distance from the earth (distance), the social status of the tree (H/CD and H/ DBH), the relative height (Hr) of the sample (height of the sample/tree height) and the dimension (dimension) of the tree ($DBH^2 \times \text{Height}$).

$$WD = \text{Intercept} + b_1 \times \text{Dist} + b_2 \times \text{Dim} + b_3 \times \text{PFT} + b_4 \times \text{Dim} \times (\text{PFT}) + b_5 \times \text{SP}(\text{PFT})$$

$$WD = \text{Intercept} + b_1 \times \text{Dist} + b_2 \times \text{Dim} + b_3 \times \text{PFT} + b_4 \times \text{Dim} \times (\text{PFT}) + b_5 \times \text{SP}(\text{PFT}) + b_1 \times \frac{\text{Mean}(\text{Dist})}{\text{SD}(\text{Dist})} \times \text{SD}(\text{WD}) + b_2 \times \frac{\text{Mean}(\text{Dim})}{\text{SD}(\text{Dim})} \times \text{SD}(\text{WD}) + b_4 \times \frac{\text{Mean}(\text{Dim})}{\text{SD}(\text{Dim})} \times \text{SD}(\text{WD})$$

4.3 Status of Generalized allometric equations

The site falls under the moist climatic zone according to the definition of IPCC (2003), which defines wet climatic zone as areas with rainfall above 2000 mm per annum. The equations of Brown (1989) were developed based on 69 and 168 trees with a maximum *DBH* of 110 and 148 cm for wet and moist zones, respectively. On the other hand, the equations of Chave et al. (2005) were developed based on a much wider sampling size that involved 2410 trees. Comparison of existing allometric equations with that of this study (Figure 22a and b) indicates that the allometric equations from moist climate zone give closer estimation than that from the wet climatic zone. The inclusion of tree height improves the estimation of tree mass particularly in the wet zone. However for the moist climatic zone, improvement in the estimation was mainly due to the inclusion of specific wood density rather than tree height. Equations that integrate more than one tree dimension improve the estimation. In using allometric equations by default, consideration should be given to variation of wood density and the relation between *H* and *DBH* from the original data. When it is not possible to have specific wood density, then equation 4 can give a better estimate. Inclusion of specific wood density improved the model efficiency with equation 11 being more precise (deviation of 3%). Using species specific allometric equation such as equation 14 is the best option.

4.4 Estimating biomass and carbon stocks

The inadequacy of allometric equations for African forests is evident in the Good Practice Guidance for Land Use and Land Use Change and Forestry or GPG-LULUCF (IPCC, 2003) in which only two allometric equations for tropical forests were presented (Figure 23). In tropical humid forests, irradiance is one of the most important limiting factor and species showed greater height growth (Baker, *et al.*, 2003). On the other hand, trees in tropical dry forest have less tree competition and are more limited by access to water, which limit tree growth. Trees on sites that are continuously flooded by saline or fresh water e.g. mangrove, allocate a great deal of plant mass to the roots to maintain a bottom-heavy tree form or a low ratio of shoot to root mass (Komiya, *et al.*, 2008). Furthermore, In many African ecosystems in the tropical dry forest zone, trees are pruned to collect firewood and their growth, architecture and biomass are modified (Smektala, *et al.*, 2002).

The accuracy or uncertainty of models is an important aspect that is mentioned in the Good Practices Guidelines and different instruments of the Kyoto Protocol. To reduce uncertainty, accurate C accounting methods are required. Some methods estimate biomass of stands, using proxies such as tree volume, wood density and biomass conversion and expansion factors or biomass expansion factors. In estimating the volume of a tree, height and *DBH* are generally measured, and using a form factor, volume can be deduced (e.g. formula given in Ponce-Hernandez, 2004). The form factor have been reported to be 0.6 (Cannell, 1984), 0.55 (Ponce-Hernandez, 2004) and 0.33 for conic trees in (CTFT, 1989a).

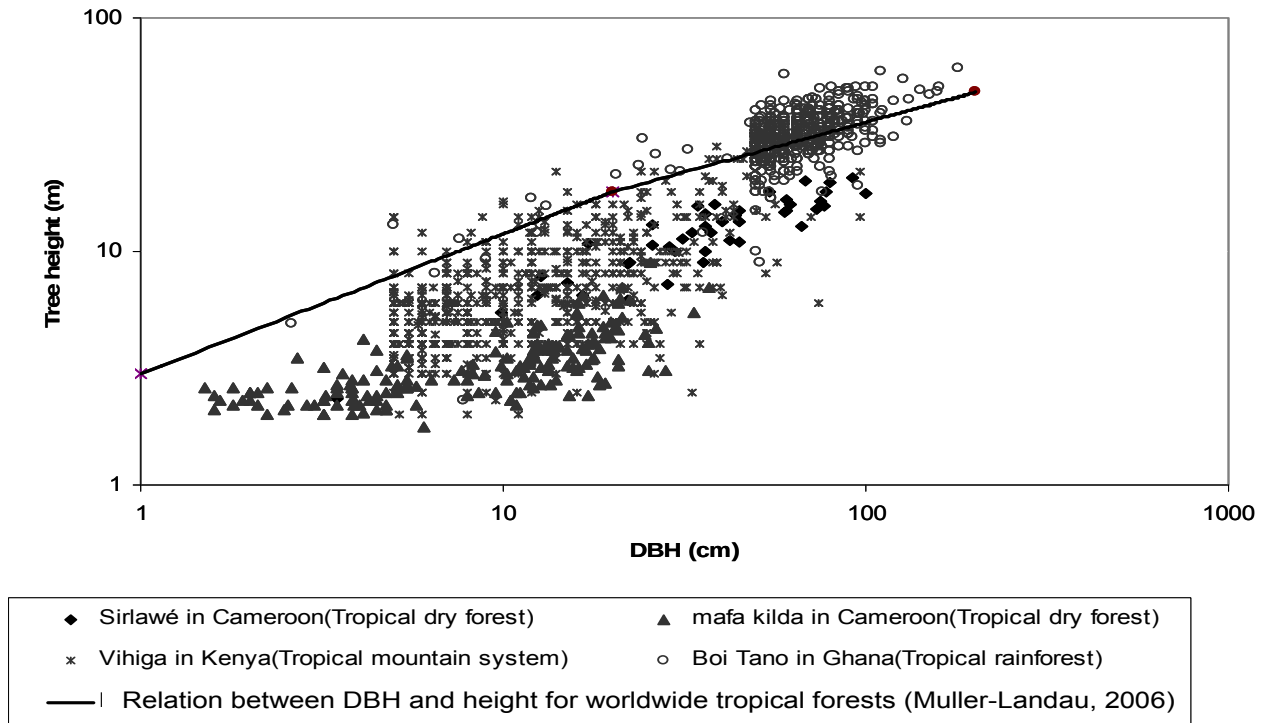


Figure 23: Relation between tree circumference and tree height in various ecological zones of Africa

Solid lines show separate fits to small (< 20 -cm diameter) and large (≥ 20 -cm diameter) individuals for tropical forests worldwide (except Africa) found in (Muller-Landau, et al., 2006). Data from Sirlawé were collected in agricultural land (Aka Etom, et al., 2006). Data from Mafa Kilda were collected in agricultural land, forest and mountain forests (Manlay, et al., 2002a). Data from Vihiga were collected in agroforests and agricultural land (Henry, et al., 2009). Data from Boi Tano were collected mainly for big trees (unpublished).

In this study the form factor ranged between 0.11 and 1.66, with an average value of 0.24. In this study, the whole tree and not only the trunk were considered and this might have contributed to the low form factor value. Using a form factor of 0.6 (Cannell, 1984) and average wood density of 0.62 (IPCC, 2007) resulted in a significant overestimation of tree mass by 28%. Although this method provided more precise estimations than Brown (1989, 1997), the form factors and the wood density data have to be improved for tree species and tree size. The IPCC (2003) reported biomass expansion factors (BEF) of about 3.4 for tropical forest stands whereas this study reported BEF values ranging from 1.13 to 2.20 for tree volume of 3.83 to 31.71 m³. Moreover, the BEF proposed by the IPCC largely overestimated the mass of the branches in this study. The IPCC (2003) reports biomass conversion and expansion factors (BCEF) ranging from 0.95 to 9.0 for forest volume of between 10 and 200 m³ ha⁻¹, whereas this study reports BCEF for individual trees ranging from 0.24 to 0.86 for tree volume 0.001 to 65 m³ (Table 12). The use of default biomass expansion factors may lead to an overestimation of stand biomass.

Most of the biomass variability is related to basal area and wood density (Baker, et al., 2004). Wood density is a key variable of biomass estimation. The use of average wood density is critical because in most of the wood density databases, no information about the location where the samples are available. There are significant differences of wood density within the tree; hence consideration of tree

size and the pith to bark distance improved the wood density estimation. Although, the allometric equations developed in this study for the African tropical humid forest were based on only 42 trees, various ranges of diameter and tree species were integrated into the equation. Future improvements should integrate greater number of larger trees and all the guild types should be well represented. Based on the results of this study, it is also recommend that further biomass studies in tropical forests of Africa should take wood samples at regular intervals from the pith to the bark for the trunk and branches.

In the estimating of C stocks of forests, not only the aboveground but the below ground component should as well be considered. The belowground component is found to represent about two thirds of the terrestrial C stocks (Jobbagy and Jackson, 2000), and the rooting system is a significant part of it. However this study did not consider the belowground component, further work should consider it. Only few studies have considered the relationship between the belowground and the aboveground component (eg. Cairns et al. (1997) or the root to shoot ratios as proposed by Mokany et al. (2006). Measuring the rooting system is costly and time consuming and requires important investments. However, making benefit of the windfall would allow facilitating access to the rooting system.

5. Conclusion

This study presented, for a tropical forest in Africa, variation of wood density according to different tree species, plant guild types, pith to bark distance and tree size. A model was developed to predict the wood density for 16 tree species. The wood density explained 62% of the variability. Factors affecting wood density such as topography and soil fertility should be investigated. This model allowed the estimation of mass of 42 trees by the allometric equations developed. It appeared that wood density was not a necessary variable to estimate tree mass of pioneers but was a significant variable for Non Pioneer tree species. In addition, the crown diameter predicted tree mass better than height. All the previously published tree biomass models for wet forest in tropical regions predicted significant different biomass than those measured in this study. This could be mainly due to the fact that those allometric equations were not specific to African ecosystems and were limited by their domain of validity. The best tree allometric equation that was found in the literature was the equation of Brown et al. (1989) which considered *DBH* and tree height. However, when specific wood densities are available the equation of Chave et al (2005) yielded the best estimate. Choosing a default allometric equation is difficult and improvement of the estimates have to include a precise identification of the climate zone, the wood density and the tree height.

While the previous chapter presented the first biomass allometric equation for tropical rainforest in SSA, the next chapter will present the various methods that can be used to estimate the tree biomass and carbon for the different ecosystems of the continent. The available allometric equations were inventoried in order to organize them in a way to allow their use, and to identify the gaps and the necessary efforts to be made to improve the estimates.

Chapter 6

Reviewing volume and biomass allometric equations at continental scale

This chapter is modified from the article: Henry, M., Picard, N., Trotta, C., Manlay, R.J., Valentini, R., Bernoux, M., Saint-André, L. (2010) Estimating tree biomass of sub-Saharan African forests: a review of available allometric equations, *Forest Ecology and Management*, submitted

Abstract

Volume and biomass equations and wood densities for tree, sprout and stand were reviewed for sub-Saharan Africa (SSA). The equations are harmonized into a free-access database on the CarboAfrica website (<http://www.carboAfrica.net>) to allow users to estimate tree biomass based on 816 equations and 105 references. The collected information provides a basic tool for the estimation of biomass and carbon stocks but can also serve other purposes such as bioenergy and fodder supply assessment. A Tier method approach was developed to facilitate the selection of the equations. It appears that the current available biomass expansion factors used to convert a volume to the total aboveground biomass are limited and that incomplete species-specific allometric equations are preferred to generalized equations. The database highlights important gaps and reveals that only 1% of the necessary effort to account national greenhouse gas emissions from forest changes is achieved. A quality control assessment reveals that 22% of the equations are misreported and a list of recommendations is proposed to improve further researches. Further statistical analysis such as the Bayesian approach would help producing more adapted and accurate estimates.

Keywords: Carbon stocks, Greenhouse gas emissions, volume, Plant allometry, tropical forest

1. Introduction

After an absence of about 30 years from scientific research, forest biomass appears to be regaining interest (Zianis and Mencuccini, 2004). Traditionally, the determination of aboveground tree biomass has been related to ensure sustainable planification of forest resources. The management of fuelwood has motivated biomass equations, whereas the management of timber has mainly motivated volume equations. Today, the accurate estimation of forest biomass is crucial for many applications, from the commercial use of wood (Fallot, et al., 2009) to the global C cycle (Basuki, *et al.*, 2009). Particularly in the latter context, the estimation of the above-ground biomass with accuracy sufficient to establish the increments or decrements in C stored in the forest is increasingly important. Forests form a major component of the C reserves in the world's ecosystems (Houghton, 2007) and greatly influence the lives of other organisms as well as human societies (Whittaker and Likens, 1975, Komiyama, *et al.*, 2008). The trees are playing a key role into the C cycle and are seen as a main option for mitigation and adapting to climate change through agroforestry, forestry and plantation systems (IPCC, 2007b, Canadell and Raupach, 2008).

Afforestation and reforestation (A/R) project activities are eligible under the Clean Development Mechanism (CDM) of the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC). As a consequence allometric equations are needed to estimate the C stocks of afforestation activities with the aim to implement A/R CDM projects in the world, Africa included (Henry, *et al.*, 2009, Lufafa, et al., 2009). The current (2010) negotiations on Reducing Emissions from Deforestation and forest Degradation and the role of conservation, sustainable management of forests and enhancement of forest C stocks in developing countries (REDD+) under the next commitment periods of the Kyoto protocol gave even more attention on the way biomass and C stocks are estimated (FCCC/SBSTA/2009/L.19/Add.1). Under the UNFCCC, countries have to report regularly the state of their forest resources and, under emerging mechanisms, such as REDD+, they are would likely to require temporally and spatially fine-gained assessments of C stocks.

Except in very rare cases where the whole tree population can be harvested to determine its biomass, the tree biomass is mainly determined based on forest inventory data and allometric equations. Weighing tree biomass in the field is undoubtedly the most accurate method of estimating aboveground tree biomass but it is much time-consuming and is generally based on small samples size. The allometric method estimates the whole or partial (by compartments) mass of a tree from measurable tree dimensions, including trunk diameter and height, using allometric equations (Kangas and Maltamo, 2006). Thus, dendrometric parameters of all the trees are measured and using the allometric equation the biomass of the stand is estimated by summing the biomass of individual trees. When considering stands with homogeneous tree size distribution such as plantations it is possible to reduce the cost of the field measurement focusing only on selected trees that are representative of the stand, i.e. mean-tree or randomly chosen trees.

When building allometric equations of an individual tree, a sprout or a stand, different methods (destructive or not) could be considered. While destructive methods measure directly the parameters and the variables of interest by e.g. harvesting the tree to determine biomass through the actual mass of each of its compartments, for example, roots, stem, branches, and foliage (Kangas and Maltamo, 2006), indirect methods try to estimate the variable by measuring other variables that are more accessible and less time-consuming – e.g. measuring the wood volume and density (Peltier, *et al.*, 2007).

The use of species-specific equations are preferred because trees of different species may differ greatly in tree architecture and wood density (Ketterings, *et al.*, 2001). However, in tropical forests, more than 300 tree species could be found and allometric equations should represent the variability of biomass for those species. As highlighted by McWilliam et al. (1993), often few destructive

harvesting were achieved and sample plot sizes have been small in relation to the scale of pattern of the forest and results may therefore not be representative. Grouping all species together and using generalized allometric relationships, stratified by broad forest types or ecological zones, was identified to be highly effective for the tropics (Brown, 2002). However, as Chave et al. (2005) pointed out, there are to date no destructively sampled trees to develop allometries for sub-Saharan African rainforests. Zianis et al. (2004) reported 279 allometric equations from all the continents except the African continent. While some authors achieved inventory of the tree allometric functions for South-America (Návar, 2009) and for Europe (Zianis, *et al.*, 2005), I am not aware of any inventory of the tree allometric equations for SSA, nor of any attempt to make biomass estimation using already existing and incomplete allometric equations. The problem is not only relevant for scientific purposes: the current interest in obtaining financial rewards for the amount of C sequestered or for the emission reductions from terrestrial biomass assumes controlling the uncertainties and biases involved in using inaccurate biomass relations.

The aim of this work is (1) to make a survey of the allometric equations that could be used for biomass and C stock estimation in SSA, and (2) to organize them in a way that could make them useful in the framework of the Clean Development Mechanism of the Kyoto protocol or the nascent REDD+. The objectives are (1) to classify allometric equations available for SSA per ecosystem types, ecological zones and species, and (2) to analyse the potential of using already existing allometric equations to estimate tree biomass and C stocks in a more precise way by comparing them to generalized allometric equations.

2. Material and methods

2.1 Data compilation and classification

Data collection focused on wood gravity, volume and biomass allometric equations for individual tree, sprout and stand assessments. Biomass is defined as organic matter expressed on an oven-dry basis. Wood gravity is defined as the air-dried mass: fresh volume ratio. The data collection was restricted to SSA since databases on allometric equations have already been published for the European continent, north America and Australia tree species (Zianis, *et al.*, 2005). In order to compile the available information, a literature survey was conducted in various libraries in the world (The World Agroforestry Centre ICRAF, *Centre de Coopération Internationale en Recherche Agronomique pour le Développement* CIRAD, *Institut de Recherche pour le Développement* IRD, *Institut National de Recherche Agronomique* INRA, *the Paris Institute of Technology for Life, Food and Environmental Sciences* AgroParisTech-ENGREF, The Forest Research Institute of Ghana FORIG, and The Food and Agriculture Organization of the United Nations FAO) and on forest-related journals. The data compilation included thesis, reports, conference proceedings and publications. No selection criteria like R^2 -value, species, age, size, site conditions, or sampling method were *a priori* applied.

The allometric equations reported different tree compartments including the trunk, the bark, the stump, the thin and gross branches, the leaves and the roots (Figure 24). The volume equations didn't considered the whole tree compartments as it is difficult to measure the volume of the leaves, and focused on the bole and the merchantable compartments. Merchantable volume excludes non-merchantable above-ground compartments such as tree tops, branches, twigs, foliage, sometimes stumps, and roots. On the other hand, biomass equations considered often more compartments that have fodder (leaves) or firewood (twigs) purposes. Moreover, volume and biomass equations reported different diameter thresholds and those were considered.

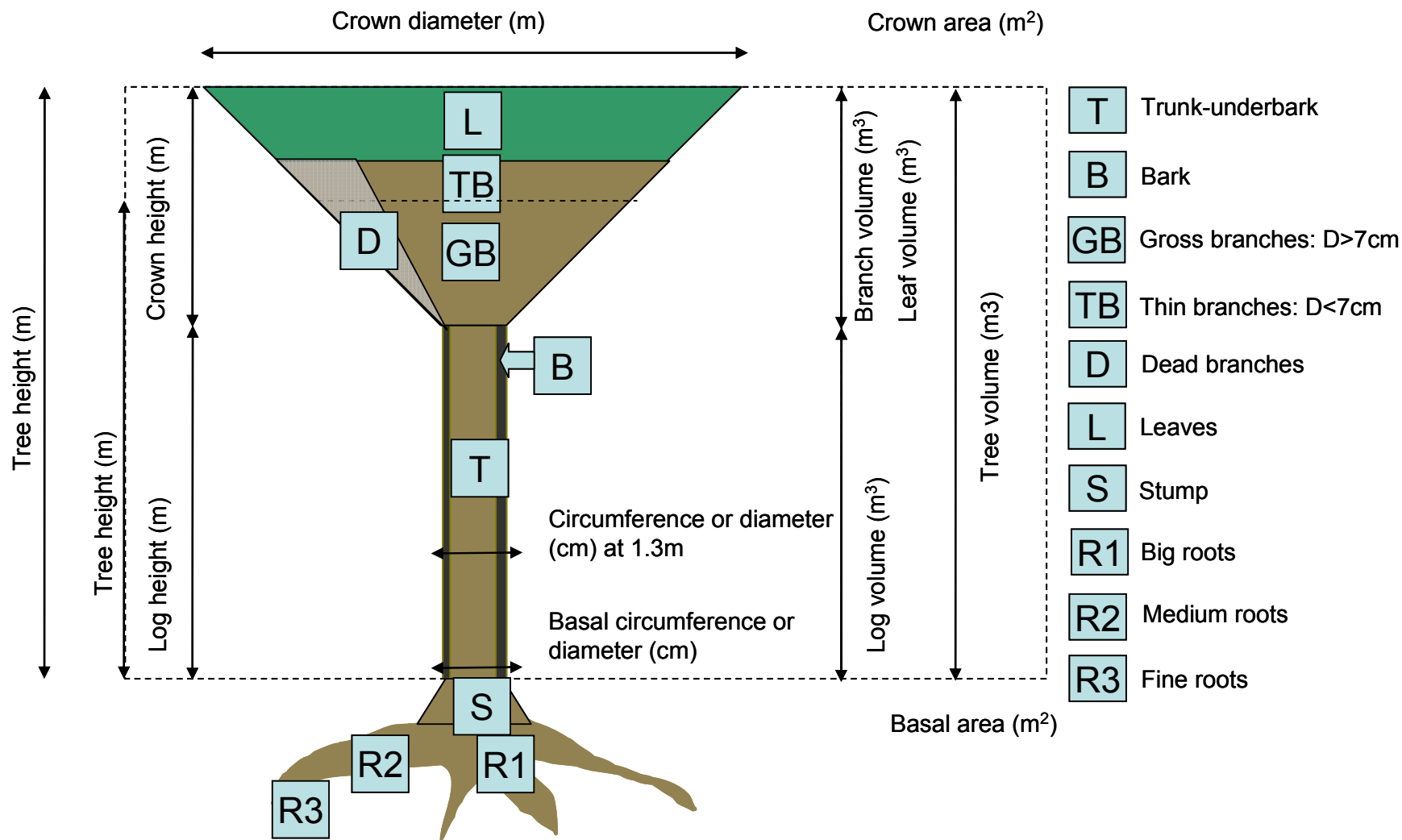


Figure 24. Representation of the different tree components referred to in this study.

The different dendrometric parameters are represented on the diagram. The diameter at breast height (DBH) is measured at a height of 1.3 m while the basis diameter (BD) is measured at basis or at collar height. The different tree components are represented by a letter. The volume under bark corresponds to the volume of the trunk component T while the volume over bark corresponds to the components T and B. The log height and volume correspond to the height of the component T. The rooting system is divided into R1, R2 and R3 according to the size of the roots.

The data were georeferenced using the geographical location (longitude, latitude, name of the location). When only the name of the location was available the geographical coordinates were obtained using administrative maps and © Google Earth. Among the 850 equations that were collected, 495 allometric equations were georeferenced (Figure 25) corresponding to 89 sites in SSA. Spatialization was achieved using ArcGIS 9.3 (ESRI, 2008) and site's categorization according to the ecological classification from FAO Forestry Resource Assessment (FAO, 2001a). Twenty-four allometric equations that were not built data built in SSA were considered as generalized allometric equations (Brown, 1997, Ponce-Hernandez, 2004, Chave, *et al.*, 2005). Those equations are the most commonly used to estimate biomass and C in SSA. Climatic parameters such as precipitation were obtained using the Local Climate Estimator FAO software (FAO, 2005d).

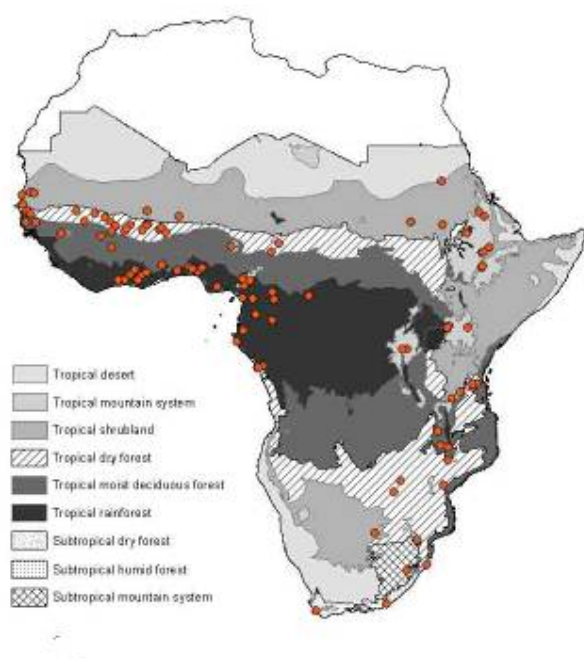


Figure 25. Geographic distribution of available volume and biomass allometric equations according to the Global ecological zoning for the global forest resources assessment (FAO, 2001a).

Additional classifications were achieved according to the ecosystem type (plantation or natural vegetation) and the population considered (individual tree, sprouts and stand). All combinations can be found: while some equations predict the volume or the biomass of a stand according to age or precipitation, other equations predict the biomass of a sprout according to the longest stem, and others predict the biomass and the volume of individual trees based on their diameter.

The following dendrometric parameters were considered:

- For individual trees: the diameters at basis (D_0) and 1.30 m ($D_{1.3}$), the stem cross-sectional area at 1.30 m, the circumferences at basis and 1.30 m, the tree, trunk and merchantable heights, the crown diameter and vertically-projected areas, the crown height, the mean annual rainfall, and the wood density.
- For stands: the stand dominant height, the stand basal area, the age, the total the stem cross-sectional area at 1.30 m, or at the basis and the wood density.

In many cases, one equation could be cited in various documents and allometric equations were filtered to avoid redundancy of the information. Finally, one equation embedded in the database represents only one tree species in one location. On the other hand, the same equation can be used in two or more different places. In some cases, allometric equations were developed for groups of species that comprised up to 21 tree species.

2.2 Quality control assessment

The comparison of the equations is difficult if they do not consider the same variable (volume or biomass), the same compartment and the same interval of calibration. A first step consisted in harmonizing the output variable into total biomass. The volume was converted using the species-specific average wood density. The species-specific wood densities for Africa were collected from various databases (Chudnoff, 1984, Lemmens, et al., 1995, Faridah Hanum, 1997, CIRAD, 2009, Hong, et al., 2009, ICRAF, 2009b, Oxford Forestry Institute, 2009) and elsewhere. In total, 3812 specific wood densities were collected for 1256 plant species growing in Africa. When the total aboveground compartment was not considered by the authors, the biomass of the missing tree compartments was estimated assuming identical distribution of wood density within the trees and using the average proportions found in an Eucalyptus plantation in Congo: 55, 8, 4.76, 13.38, 6.69, 9.70, 2.17, 9.7, 2.34 and 10.37% for the trunk, coarse branches, thin branches, leaves, bark, stump, dead branches, and gross, medium and fine roots, respectively. The second step consisted in controlling the interval of calibration (Figure 26). The interval of calibration was not always mentioned and it is not possible to have access to the data used to build the 850 models. Moreover, the quality control assessment calculated a new interval of calibration and, when it was possible, made comparison with the information given in the articles. After comparison, the highest minimum and the lowest maximum found in the original document and the quality control assessment were selected (Appendix IV and Appendix V). The interval of calibration was calculated considering that volume and biomass were positive and increased with DBH. The third step consisted in identifying the percentage of values that were considered to be possible. Some of the allometric equations were erroneously reported in the literature, thus yielding unrealistic biomass values when used. To diagnose these equation editing problems, I defined an interval of possibility that corresponds to realistic acceptable values of biomass. This interval of possibility was defined as ± 2 averages and considered only positive values, where:

$$Volume_{average} = \pi \times \left(\frac{DBH}{2} \right)^2 \times H \times 0.5 \quad (1)$$

$$Biomass_{average} = Volume_{average} \times 0.62 \quad (2)$$

where 0.62 is the average wood density ($t\ m^{-3}$) given by the IPCC (2006a) and 0.5 is the average form coefficient for conic trees (CIRAD and MAE, 2004).

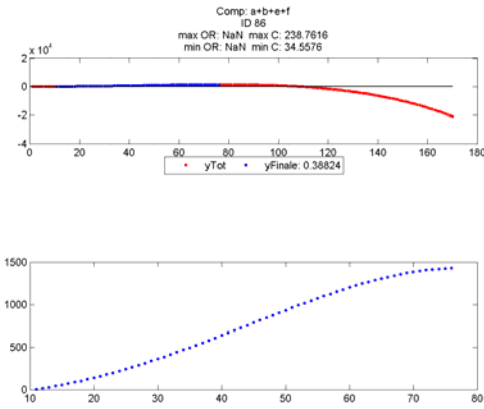


Figure 26. Quality control assessment.

The figure represents the method used to identify the minimum and the maximum when the range of calibration was not mentioned by the author. The blue line represents the selected part of the function. The red line represents the part that was considered as erroneous.

2.3 Comparison of tier methods

Three tier methods were proposed to estimate the total biomass of a tree, a sprout and a stand. While some authors reported biomass allometric equations for the whole tree compartments, others considered only the trunk. While some authors developed species-specific allometric equations, others developed multi-species allometric equations. In order to achieve biomass estimates, the different types of allometric equations can be used following the three tier methods. The precision increases with the number of the tier method. The Tier-1 method was selected when no species-specific allometric equations existed and a generalized allometric equation for the ecological zone was used. In that case, only total biomass equations were considered. The Tier-2 method consisted in using a species-specific volume allometric equation. The volume is then converted to biomass using a wood density and a biomass expansion factor (IPCC, 2003), or a biomass conversion and expansion factor (IPCC, 2007).

Aboveground biomass was computed from merchantable biomass using:

$$Biomass_{partial} = V \times WD \text{ and } Biomass = Biomass_{partial} \times BEF \quad (3)$$

$$\text{Or directly } Biomass = V \times BCEF \quad (4)$$

Where $Biomass_{partial}$ was the biomass of the merchantable volume (kg), V was the merchantable volume (m^3), WD was the wood density ($kg\ m^{-3}$), BEF was the biomass expansion factor and $BCEF$ was the biomass conversion and expansion factor.

The third tier method consists in using a species-specific biomass allometric equation providing either total or partial biomass. Partial biomass was obtained by summing the biomass estimates obtained from specific allometric equations for the different compartments or using a BEF when the equation was giving a merchantable biomass. The various tiers were named Tier1, Tier2, Tier3-partial and Tier3-total in the following text. When different allometric equations were presented for the same tier method, the allometric equation with the highest percentage of values within the interval of possibility was selected.

A comprehensive set of specific allometric equations is reported for *Acacia senegal*, including allometric equations for trunk, gross branches, thin branches, aboveground, underground and total dry biomasses, for aboveground fresh biomass, or for the trunk volume. Moreover this tree species was selected to test the method of tier comparison. Then, the tier method was applied for other tree species and multi-species allometric equations in different ecological zones.

2.4 Data analysis and access

The allometric equations and the wood density data were compiled and made available on the website of CarboAfrica project (www.carbofrica.net). The volume and biomass allometric equations and the information used in this article were presented in Appendix IV and V respectively. Computation of the interval of possibility and quality control assessment were achieved using MATLAB (The MathWorks, 2005). This allowed the identification of the range of calibration, and the data quality control assessment.

3. Results

3.1 Description of the database

➤ Source of information

Data collection was based on 125 references, most of which were reports (n = 52) or articles (n = 51) while 9 were MSc and PhD theses, 6 were books and book sections, and 7 were conference proceedings. Data collection from various sources of information is preferable when doing meta-analysis (Scargle, 2000). If the analysis had focused only on scientific journals, 72% of the information would have been missing. Then, this study would have been biased and would have not reflected verified and reliable data (17% of the equations published in the scientific journals were considered as quality 1 (see Appendix IV and V).

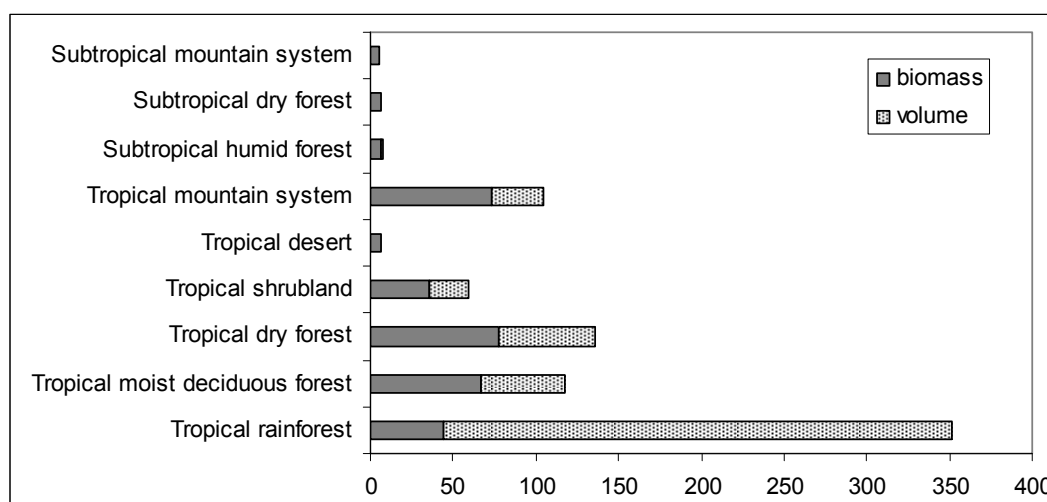


Figure 27. Distribution of allometric equations in the FAO ecological zones

➤ Geographic distribution of the equations

Volume and biomass allometric equations were particularly unevenly distributed among countries (Figure 25). Most of the volume allometric equations were developed in Nigeria (n = 88), Gabon (n = 84), Cote d'Ivoire (n = 73) and Mali (n = 42), representing 44% of the total number of volume allometric equations (Table 18. Quality of data and allometric equation's gap). Most of the biomass allometric equations were developed in Ethiopia (n = 63), Senegal (n = 56), South Africa (n = 38), Mali (n = 38), Botswana (n = 24) and Congo (n = 22), representing 70% of the total number of biomass allometric equations. Twenty nine out of the 52 SSA countries had one or more volume or biomass allometric equations, which represents 73% of the area. From the 850 allometric equations that were found in SSA, most of them were found in Western Africa (52%) while only 4 allometric equations were found for Northern Africa (Sudan is part of Northern Africa and in SSA). Western Africa was the most explored region and particularly Nigeria (26%), Mali (20%), Cote d'Ivoire (18%) and Senegal (16%).

At current state, most of the equations were found in tropical rainforests (43%), tropical dry forests (16%), tropical moist forests (11%), shrublands (13%) and tropical mountain forests (13%), while tropical desert, subtropical humid and dry forests, and subtropical mountain forests represented less than 1% (Figure 27). While most of the volume equations were developed in the tropical rainforests (63%), 14, 11, 6.5 and 5% were developed in the tropical dry, tropical moist, tropical mountain forests and tropical shrublands respectively. On the other hand, most of the biomass equations were developed in the tropical shrublands (23%), tropical dry (23%), and tropical mountain forests (21%), while the tropical rainforest and the tropical moist deciduous zones represented only 13 and 12% of the total. Only six equations were found for the sub-tropical zones. In total, 17 countries had biomass allometric equations that predict the total aboveground biomass for at least one of the ecological zones and the vegetation types. When considering that at least one allometric equation is needed to estimate the biomass of each ecological zone within each country, it means that less than 18% of the allometric equations needed were available when the study was achieved. This estimate is very conservative and becomes 1% if I take into account the 18 classes of vegetation which are generally considered in national forest inventories (FAO, 2004b). The disproportion of forestry researches between countries is mainly due to political interests, the technical, human and financial allocations to research and development of forest sector.

3.2 Predictors of tree biomass

The DBH was the most frequent predictor (63%) while 12% of the equations used the tree circumference (Appendix IV and V). When considering the volume equations, the DBH was also the most common predictor (65%) while circumference and height were used in 12 and 9% of the equations. Biomass allometric equations used the diverse predictors in a more balanced way. DBH was used in 49% of the equations, while height, circumference, basis circumference and basal area represented 15, 8.6 and 6% of the equations, respectively. Additionally the basis diameter and basis circumference were used only in tropical shrublands and tropical dry forests. Most of the equations used only one predictor while 24 and 2% of the equations used two and more than two predictors respectively. The DBH was reported to explain about 95% of the biomass (Gibbs, *et al.*, 2007). Other authors found that considering the tree height (Brown *et al.*, 1989) or the wood density (Chave, *et al.*, 2005) improve the biomass estimates. While the wood gravity does not give information about the tree size and architecture, it is necessary to include dendrometric variables into biomass allometric models.

Table 18. Quality of data and allometric equation's gap

Region	Country	Number of equations				Number of tree		number of natural tree	% of unknown tree species
		Quality control (%)	total	biomass	volume	plantation	natural		
Eastern Africa	Burundi		0	0	0	-	-	-	100
	Comoros		0	0	0	-	-	62	100
	Djibouti		0	0	0	-	-	-	100
	Eritrea		0	0	0	-	-	-	100
	Ethiopia	1 (36), 2 (50) ,3 (15)	0	0	0	-	64	1027	93.77
	Kenya	1 (5), 2 (71) ,3 (24)	15	0	0	-	15	-	100
	Madagascar		0	0	0	-	-	5000	100
	Malawi	1 (0), 2 (91) ,3 (9)	21	0	0	-	21	-	100
	Mauritius		0	0	0	-	-	194	100
	Mozambique	1 (0), 2 (71) ,3 (29)	5	0	0	-	5	-	100
	Rwanda	1 (18), 2 (67) ,3 (15)	22	0	0	-	22	300	92.67
	Seychelles		0	0	0	-	-	93	100
	Somalia	1 (0), 2 (100) ,3 (0)	2	0	0	-	2	-	100
	Uganda	1 (30), 2 (70) ,3 (0)	7	0	0	-	7	-	100
	Tanzania	1 (4), 2 (60) ,3 (36)	27	0	0	-	27	-	100
	Zambia	1 (0), 2 (100) ,3 (0)	7	0	0	-	7	665	98.95
	Zimbabwe	1 (0), 2 (100) ,3 (0)	4	0	0	-	4	1747	99.77
	Total	1 (9), 2 (78) ,3 (13)	110	0	0	0	174	- -	
Middle Africa	Angola		0	0	0	-	-	-	100
	Cameroon	1 (), 2 (), 3 ()	24	0	0	-	24	600	
	CAR	1 (0), 2 (79) ,3 (21)	11	0	0	-	11	-	100
	Chad	1 (0), 2 (100) ,3 (0)	1	0	0	-	1	109	100
	Congo	1 (47), 2 (51) ,3 (2)	29	0	0	-	29	334	99.70
	DRC		0	0	0			870	96.67
	Equatorial	1 (0), 2 (100) ,3 (0)	2	0	0	-	-	-	100
	Gabon	1 (2), 2 (68) ,3 (31)	84	0	0	-	84	-	100
	Sao Tome and		0	0	0			-	100
	Total	1 (10), 2 (79) ,3 (11)	151	0	0	0	149	- -	
Northern	Sudan	1 (0), 2 (75) ,3 (25)	6	0	0	-	6	533	
	Total	1 (0), 2 (75) ,3 (25)	6	0	0	-	6	- -	
Southern	Botswana	1 (2), 2 (83) ,3 (14)	35	0	0	-	6	-	100
	Lesotho		0	0	0	-	-	60	
	Namibia	1 (0), 2 (100) ,3 (0)	7	0	0	-	35	200	100
	South Africa	1 (34), 2 (51) ,3 (16)	39	0	0	-	-	649	
	Swaziland		0	0	0	-	7	-	100
	Total	1 (12), 2 (78) ,3 (10)	81	0	0	0	48	- -	
Western	Benin		2	0	0	-	-	-	100
	Burkina Faso	1 (0), 2 (83) ,3 (17)	19	0	0	-	-	90	100
	Cape Verde		0	0	0	-	-	240	
	Côte d'Ivoire	1 (10), 2 (77) ,3 (13)	74	0	0	-	19	-	100
	Gambia		0	0	0	-	-	140	100
	Ghana	1 (22), 2 (71) ,3 (7)	39	0	0	-	74	680	89.12
	Guinea		0	0	0	-	-	-	100
	Guinea-Bissau	1 (0), 2 (89) ,3 (11)	16	0	0	-	39	2243	98.26
	Liberia		0	0	0	-	-	-	100
	Mali	1 (0), 2 (85) ,3 (15)	79	0	0	-	16	1739	99.08
	Mauritania		0	0	0	-	-	52	100
	Niger	1 (33), 2 (67) ,3 (0)	2	0	0	-	79	227	65.20
	Nigeria	1 (19), 2 (71) ,3 (10)	108	0	0	-	-	560	100
	Saint Helena		0	0	0	-	2	-	100
	Senegal	1 (0), 2 (78) ,3 (22)	76	0	0	-	108	315	100
	Sierra Leone		0	0	0	-	-	213	
	Togo		0	0	0	-	76	1451	94.76
	Total	1 (11), 2 (77) ,3 (12)	415	0	0	0	413	- -	
All sub-	Total	1 (22), 2 (61) ,3 (17)	763	0	0	0	790	- -	

The number of natural tree species was obtained from FAO (2006).

3.3 Tree species

While 80% of the allometric equations focused on natural ecosystems, 20% of the equations dealt with plantations (Table 18). Respectively 12 and 32% of the volume and biomass allometric equations focused on plantations. In total, 233 tree species were considered. The tree species was not mentioned for 14.8% of the equations. The exact number of tree species in sub-Saharan Africa is not known (Newton and Oldfield, 2008) but assuming a total of 9,200 tree species in SSA (White, 1981) suggests that only 2.3% of tree species could be included in this review. Tropical rainforests and dry forest accounted for respectively 42 and 16% of the number of tree species (Appendix IV and V). Most of the generalized volume allometric equations were developed in tropical dry forests (n=28) and tropical rainforests (n=17), particularly in Mali, Tanzania, Gabon, Ghana, Cote d'Ivoire, Nigeria, and Rwanda (Table 19). Generalized volume equations were not found for subtropical zones and tropical desert. Most of the generalized biomass allometric equations were developed in tropical dry forests (n=20) and tropical rainforests (n=14), particularly in Mali, Senegal, Botswana, Congo, Ethiopia, Nigeria and South Africa (Table 20). Generalized biomass allometric equations were not found for subtropical dry forests, subtropical mountain forests, tropical desert, and tropical mountain forests. Volume allometric equations were found for 191 tree species (Table 20). The tree species most frequently studied for volume were *Terminalia superba* (n = 28), *Grevillia robusta* (n = 16), *Triplochiton scleroxylon* (n = 10) and *Vittelaria paradoxa* (n = 10). Those tree species represented 14% of the total number of volume equations. Biomass equations were found for 71 tree species (Table 20). The most commonly studied tree species for biomass were *Eucalyptus globulus* (n = 33), *E. sp* (n = 18), *E. camadulensis* (n = 16) and *Nauclea diderichii* (n = 12). Those tree species represented 23% of the total number of biomass allometric equations. Volume allometric equations were found for a greater number of tree species than biomass equations. The analysis reflects a disproportion of interests between tree species (Table 18, Table 19, and Table 20). The country with the highest proportion of studied species was Senegal (allometric equations were found for 24% of the tree species found in Senegal) while the average for SSA was about 7%. Most researches focused on common forestry and agroforestry tree species, leaving most of the existing species unstudied.

3.4 Tree compartments

Allometric researches focused on different tree compartments according to the aim of the research (e.g. bioenergy, commercial timber and fodder). Most of the volume equations focused on the stump plus the trunk and the branches (44%), only the trunk (38%), or the trunk plus the bark and the stump (15%) (Table 21). In total, 16 countries had equations to estimate the volume of the stump plus the trunk and the branches, while eight countries had equations that only partially estimate the volume, and 24 countries did not have any volume equations. From the 322 biomass equations found in SSA, 38% considered all aboveground compartments, 20% the leaves, and 11% the trunk plus the stump and the branches. When considering the tropical rainforest zone, 10 equations predicted the total tree biomass. Out of those 10 allometric equations, 8 considered small trees in forest regeneration and plantations, while one considered tree biomass in an agroforestry system in Western Kenya (Henry, 2009), only one considered the tree biomass of a mature tropical rainforest in Ghana (Chapter 5).

Table 19. Number of volume allometric equations per tree species and countries in sub-Saharan Africa.

Country	Tree species (number of allometric equations)	Total
Benin	Acacia auriculiformis (2)	2
Botswana	Generalized (1) Baikiaea plurijuga (1) Burkea africana (1) Colophospermum mopane (1) Pycnanthus angolensis (1)	5
Burkina Faso	Generalized (9)	9
Cameroon	Generalized (1) Baillonella toxisperma (2) Entandrophragma cylindricum (2) Lophira alata (1) Terminalia ivorensis (3)	11
Congo	Entandrophragma cylindricum (1) Terminalia superba (6)	7
Equatorial	Generalized (1) Aucoumea klaineana (1)	2
Ethiopia	Eucalyptus globulus (1)	1
Gabon	Afzelia bipindensis (1) Afzelia pachyloba (1) Generalized (1) Antiaris africana (1) Antrocaryon klaineana (1) Aucoumea klaineana (3) Autranella congolensis (1) Baillonella toxisperma (1)	84
Ghana	Generalized (7) Group (19) Terminalia superba (11)	37
Guinea-	Generalized (1) Chlorophora excelsa (1) Chrysophyllum sp (1) Daniellia ogea (1) Distemonanthus benthamianus (1) Entandrophragma angolensis (1) Entandrophragma utile (1) Hallea ciliata	16
Côte d'Ivoire	Acacia mangium (1) Afzelia africana (3) Generalized (4) Antiaris africana (2) Ceiba pentandra (1) Chlorophora excelsa (2) Diospyros mespiliformis (7) Distemonanthus benthamianus (1)	72
Kenya	Cupressus lusitanica (2) Eucalyptus saligna (1) Pinus patula (1)	4
Malawi	Generalized (8) Brachystegia boehmii (1) Brachystegia floribunda (1) Brachystegia spiciformis (2) Brachystegia utilis (1) Group (4) Julbernardia paniculata (2) Pterocarpus angolensis (1)	21
Mali	Afzelia africana (4) Generalized (13) Bombax buonopozense (1) Combretum fragrans (1) Combretum ghazalense (2) Combretum glutinosum (1) Cordyla pinnata (1) Daniellia oliveri (2)	42
Mozambique	Generalized (1)	1
Nigeria	Afzelia africana (1) Albizzia ferruginea (1) Albizzia zygia (1) Generalized (2) Alstonia boonei (1) Amphimas pterocarpoides (1) Antiaris toxicaria (1) Antrocaryon klaineana (1) Blighia sapida (1)	88
RCA	Generalized (1) Autranella congolensis (1) Cedrelopsis grevei (1) Chlorophora excelsa (1) Entandrophragma angolensis (1) Entandrophragma cylindricum (2) Entandrophragma utile (1) Lova	11
Rwanda	Cederella serrata (2) Cupressus lucastica (2) Cupressus lusitanica (1) Grevillia robusta (16) Pinus patula (1)	22
Senegal	Acacia senegal (1) Afzelia africana (1) Balanites aegyptiaca (1) Boscia senegalensis (1) Commiphora africana (1) Grewia bicolor (1) Rhizophora racemosa (2)	8
South Africa	Eucalyptus camadulensis (1)	1
Sudan	Acacia mellifera (1) Acacia nilotica (1) Acacia senegal (1) Generalized (1) Dalbergia melanoxylon (1)	5
Tanzania	Generalized (9) Brachystegia spiciformis (2) Cupressus lusitanica (1) Dalbergia melanoxylon (2) Julbernardia globiflora (3) Pinus patula (1) Pycnanthus angolensis (2)	20
Uganda	Eucalyptus grandis (1) Pinus caribaea (2)	3
Zambia	Baikiaea plurijuga (1) Guibourtia coleosperma (1) Pterocarpus angolensis (1)	3
Zimbabwe	Acacia karoo (2)	2

(): number of allometric equations per species.

Table 20. Number of biomass allometric equations per tree species and countries of sub-Saharan Africa.

Tree species (number of allometric equations)
Acacia erioloba (1) Acacia erubescens (2) Acacia karoo (3) Acacia luederitzii (1) Acacia mellifera (3) Acacia tortillis (5) Generalized (2) Beilschmiedia diversiflora (1) Boscia albitrunca (1) Colophospermum mopane (1) Acacia laeta (1) Acacia senegal (1) Acacia tortillis (1) Generalized (3) Combretum aculeatum (1) Guiera senegalensis (2) Pterocarpus lucens (1) Generalized (7) Terminalia ivorensis (1) Terminalia sp (4) Vitellaria paradoxa (1) Acacia tortillis (1) Acacia auriculiformis (2) Acacia mangium (2) Eucalyptus sp (18) Dichrostachys cinerea (5) Eucalyptus Camadulensis (16) Eucalyptus globulus (29) Euclea shimperi (5) Grewia bicolor (4) Otostegia integrifolia (4) Generalized (1) Terminalia superba (1) Khaya senegalensis (2) Acacia drepanolobium (3) Generalized (1) Croton macrostachyus (1) Eucalyptus saligna (1) Group (2) Markhamia lutea (1) Psidium guajava (1) Sesbania sesban (1) Acacia albida (3) Acacia seyal (3) Acacia senegal (1) Generalized (5) Balanites aegyptiaca (2) Boscia senegalensis (1) Combretum aculeatum (1) Combretum glutinosum (2) Combretum nigricans (2) Commiphora africana Generalized (4) Acacia erubescens (1) Acacia fleckii (1) Acacia mellifera (1) Acacia reficiens (1) Colophospermum mopane (1) Dichrostachys cinerea (1) Terminalia sericea (1) Guiera senegalensis (1) Terminalia superba (1) Gmelina arborea (8) Nauclea diderichii (12) Acacia senegal (11) Generalized (6) Balanites aegyptiaca (3) Boscia senegalensis (3) Combretum geitonophyllum (7) Combretum glutinosum (7) Commiphora africana (4) Grewia bicolor (5) Group (5) Guiera Acacia senegal (1) Excoecaria bussei (1) Acacia karoo (1) Acacia tortillis (1) Generalized (1) Coddia rudis (1) Diospyros dichrophylla (1) Eucalyptus donai (4) Eucalyptus emithii (4) Eucalyptus globulus (4) Eucalyptus nitens (4) Eucalyptus viminalis (4) Olea Generalized (1) Generalized (7) Generalized (1) Generalized (3) Generalized (2) Generalized (23)

(): number of allometric equation per species.

Table 21. Number of volume and biomass allometric equations per tree compartments and countries of sub-Saharan Africa

Volume	Pool													
	Trunk	Trunk +	Bark	Big	Thin	Dead	Leaves	Stump	Roots	Trunk	All the	Trunk	Above and	Total
Countries														
Benin											2			2
Botswana											5			5
Burkina Faso	2				2						5			9
Cameroon	8										3			11
Congo	5										2			7
Equatorial	2													2
Ethiopia		1												1
Gabon	84													84
Ghana	24	5									8			37
Guinea-Bissau	16													16
Côte d'Ivoire	54	1									15	2		72
Kenya											4			4
Malawi		1									20			21
Mali		2									35	5		42
Mozambique											1			1
Nigeria	79	7									2			88
RCA	10	1												11
Rwanda		14										8		22
Senegal		5									3			8
South Africa		1												1
Sudan		4									1			5
Tanzania		2									16	2		20
Uganda											3			3
Zambia											3			3
Zimbabwe											2			2
Total	284	44	0	2	0	0	0	0	0	0	128	17	0	477
Biomass allometric														
Botswana	2										7		21	30
Burkina Faso		1						6			2		1	10
Cameroon											1	2	8	13
Chad								1						1
Congo			2	1		2		4	1	6	3	2	1	22
Ethiopia		4	9			5		13			19	3	10	63

Volume	Pool													
	Trunk	Trunk +	Bark	Big	Thin	Dead	Leaves	Stump	Roots	Trunk	All the	Trunk	Above and	Total
Ghana													2	2
Ivory Coast											2			2
Kenya											3		8	11
Mali		1				1	25						10	37
Mozambique												2	2	4
Namibia													7	7
Niger												1	1	2
Nigeria						5	4					5	6	20
Senegal						12	11		9	7	10	7	11	68
Somalia													2	2
South Africa				6		6	2	6		1	7	6	4	38
Sudan											1			1
Tanzania						2	2				1		2	7
Uganda											4			4
Zambia											2		2	4
Zimbabwe													2	2
General													23	23
Total	2	6	17	1	33	4	70	10	14	62	25	38	91	373

General allometric equations are annotated “general” in the column tree component and concern only biomass.

3.5 Data quality

The data quality control revealed that 22, 61 and 17% of equations classified as quality 1, 2 and 3 respectively (Table 18). Most of the equations were quality 2 for both biomass and volume (81 and 69%, respectively). When considering only publications, 27% of the equations were considered as quality 1. Moreover, focusing only on publications would be less precise. The sample size, correlation coefficient and range of calibration were given for only 60, 49 and 31% of the equations respectively. Thirteen percent of the minimum calculated in this study were higher than in the original documents. The data quality control assessment identified important variability in the quality of data reporting. In total, 456 equations reported the coefficient of determination (ranging 0.22-0.99) and 550 the sample size (ranging 4-6511). Forty five out of the 318 equations which indicated the range of calibration (DBH ranging 1.8-180 cm) reported negative values and the range of calibration was corrected (Appendix IV and V). For 14.8% of the equations, the list of species name was not complete or absent. Table 18, Table 19, Table 20 and Table 21 allow identification of available allometric equations for each country. For instance, Gabon has 84 volume allometric equations for the trunk, but none for the other compartments or for biomass. It facilitates identification of data gap.

3.6 Chronology of forest biomass research in tropical sub-Saharan Africa

The allometric equations were all developed during the period 1961–2010; this clearly illustrates the evolution of interests of those who study trees in SSA. The concern on allometric equations has been continuously increasing from 4 articles during the 60's (all devoted to volume prediction only) to 50 in the period 2000-2010 (Figure 28). During the period 2000-2010, 54% of the articles and 53% of the allometric equations were developed for biomass purposes. In tropical shrublands, the main interest was on biomass (79%), whereas volume was the main interest in tropical rainforests (88%). While biomass estimates in the tropical dry zone are crucial to estimate the availability of bioenergy, estimation of merchantable timber volume in the humid tropics is used to estimate the profitability of forestry operations. For tropical rainforests only two biomass equations exist that were specifically developed in Africa to estimate the total tree biomass of spontaneous vegetation. The first one was developed to estimate forest regeneration in Cameroon (Deans, Moran et al. 1996). The second one was developed to estimate the biomass of a tropical rainforest in Ghana (Chapter 5). The other total aboveground biomass equations were developed for tree plantations.

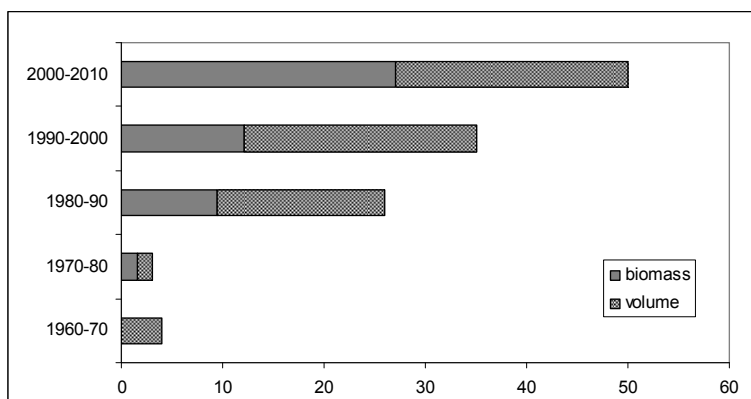


Figure 28. Evolution of the number of references during the period 1950-2009

3.7 Wood gravity

In total, 3846 wood gravity values in 54 references were identified for SSA. Most data were found in reports (69%), while books accounted for 11% of the information. Data collected were published between 1951-2010 (mostly in the 50's). According to the sources, most of the wood density data were obtained from logging companies in the tropical rainforest zone, and from scientific research in the tropical dry zone. The data concerned 1066 tree species. Wood gravity ranged $0.15\text{--}1.2\text{ g cm}^{-3}$ with a minimum for *Schinziophyton rautanenii* (ranging $0.15\text{--}0.19\text{ g cm}^{-3}$ for this species) and a maximum for *Dalbergia melanoxylon* (ranging $0.8\text{--}1.2\text{ g cm}^{-3}$ for this species). As very little or no information was given regarding the geographical locations where samples were collected, it is difficult to give a picture of the spatial variability of gravity. With respect to plant functional types identified by Hawthorne (1995), it was possible to classify 1340 wood samples (Figure 29). The highest wood densities were found in savannah/non-forest ($WD = 0.65 \pm 0.03\text{ (SE) g cm}^{-3}$) while the lowest wood densities were found for pioneer trees ($WD = 0.51 \pm 0.01\text{ (SE) g cm}^{-3}$). Using a Fisher LSD statistical test, the following classification of plant functional types was obtained with respect to wood density: savannah, shade bearer > non pioneer light demander, swamp > pioneer ($\alpha < 0.0001$, $F=35.89$, $n=1340$). Rueda and Williamson (1992) and Woodcock and Shier (2002) reported lower wood density for pioneers due to their initial fast growth. Higher wood density was also found in drier ecosystem by other authors (López, et al., 2005, Martínez-Cabrera, et al., 2009).

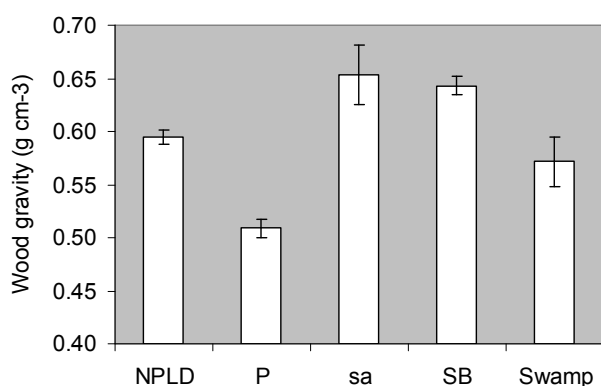


Figure 29: Variations in wood density (kg dm^{-3}) in tropical sub-Saharan Africa by plant functional types using classification made in Ghana by Hawthorne (1995).

P: pioneer, NPLD: Non-Pioneer Light Demander, SB: Shade Bearer, Swamp, sa: Savanna. Swamp and savanna tree species have many common characteristics which make it convenient to consider them separately from the other tree species. The other three guilds refer to the nature of each species with respect to canopy gaps, disturbance and light.

3.8 Volume and biomass allometric equations

➤ Variation of tree biomass across different ecological zones

Differences in predicted biomass were found between and within ecological zones (Figure 30). Among all ecological zones the highest tree biomass was reported in equation 539 in tropical moist forest (30 Mg; DBH=100 cm) while the lowest was reported in equation 684 in tropical desert (256 kg; DBH=100 cm) (Appendix V).

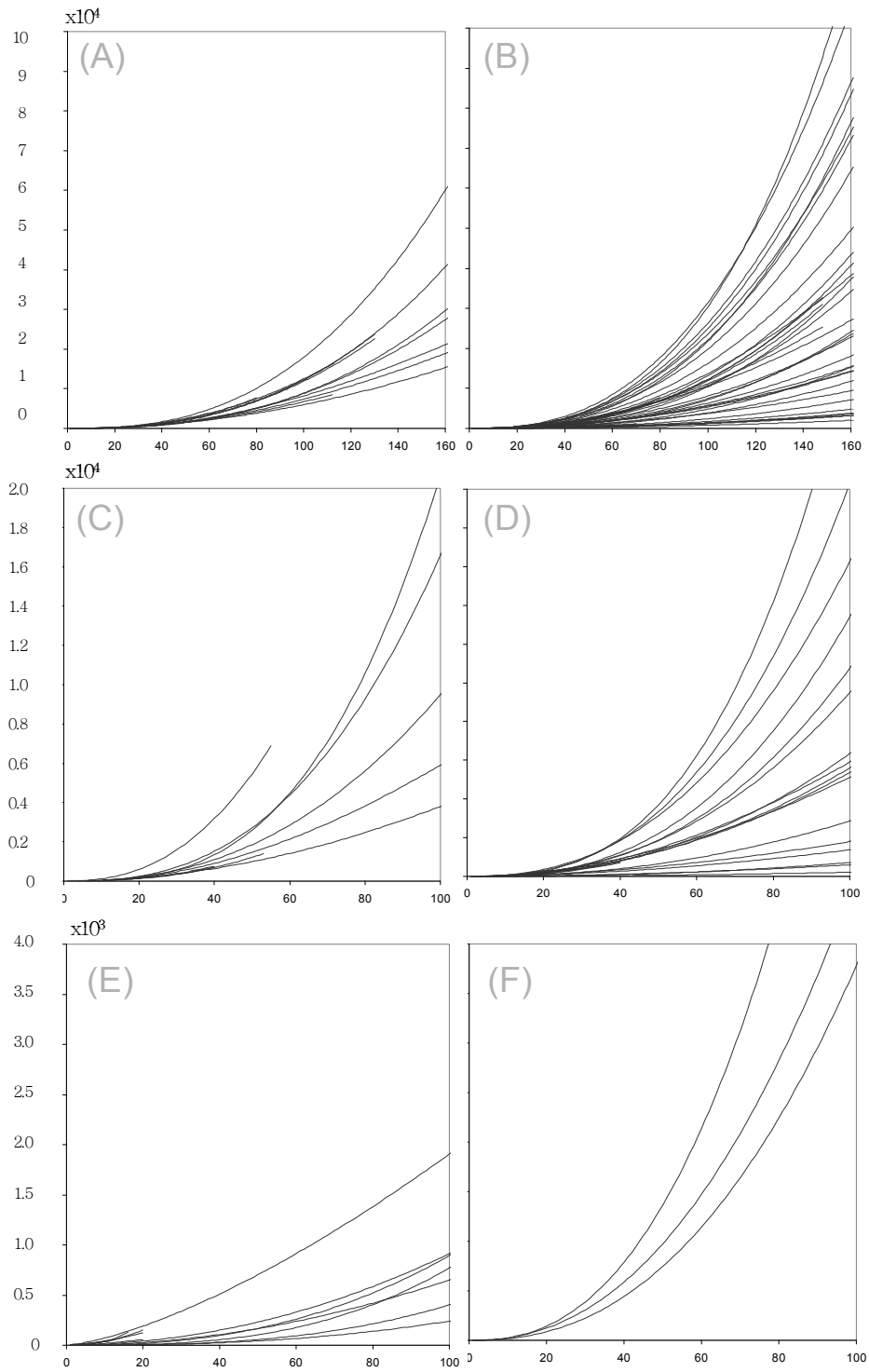


Figure 30. Tree biomass (kg by tree) equations in different ecological zones of sub-Saharan Africa

Tropical rainforest, (B) tropical moist deciduous forest (C) tropical dry forest, (D) tropical shrubland, (E) tropical mountain system, (F) subtropical dry forest. The equations that were considered as erroneous were not considered in the graphics (e.g. Onyekwelu, 2007, Chamshama, Mugasha, et al. 2004, de Klerk, 2004).

Tree biomass differed largely within ecological zones. In the tropical desert zone equation 669 predicted 99 times higher biomass than equation 684. The lowest variability in tree biomass was observed for subtropical dry forest, where the difference could reach up to 50%, but it was limited by the number of sample (n=3). In the tropical rainforest the maximum difference between equations reached 66% of tree biomass. When considering some specific and selected Tier-3 total aboveground equation equations, the average biomass of a tree in a tropical rainforest of Ghana (equation 508, mean annual precipitation –MAP = 2155 mm) was 1.6 times higher than that of a tree in a tropical moist deciduous forest in Mali (equation 747, MAP = 896 mm), whatever its diameter. While lowest biomass was found in the driest location of Gaborone in Botswana (equation 744, MAP = 552 mm), in tropical moist deciduous forest zone it appeared that biomass was higher with lower precipitation (equation 747 predicted lower biomass than equation 632).

➤ Variability of biomass and volume prediction within forest types

Important difference in volume between tree species are predicted across and within forest types (Figure 31). Volume allometric equations were selected for nine tree species in tropical rainforests, tropical plantations, and tropical dry forests plus mangroves. For tropical rainforests (Figure 31a), only two of the nine selected allometric equations were given a range of calibration. For a DBH of 40 cm, volumes ranged 1.02–3.47 m³ with a minimum for *Turraeanthus africanus* (equation 174) and a maximum for *Entandrophragma cylindricum* (equation 76). For DBH=100 cm, volumes ranged 6.74–14.85 m³ with a minimum for *T. africanus* and a maximum for *Lophira alata*. When comparing with the stem volume measured in a tropical rainforest of Costa Rica (Segura, 2005), *T. africanus* was 1.2 times lower and *L. alata* was 2.2 times higher (Figure 31a). Moreover, the volume found for *L. alata* could be considered as a very high volume. Similar results were found when comparing with the generalized volume equations for Africa (Appendix IV). It is however difficult to compare the data found for *T. superba* as no yield data have been published for SSA (Ugalde and Perez, 2001). For tropical plantations (Figure 31b), six of the nine allometric equations reported the range of calibration. At 50 cm of DBH, the minimum volume was 1.16 m³ (*C. lusitanica*), the maximum was 4 m³ (*Triplochiton scleroxylon*) while average volume was 2.8 m³. Similar results were reported for *C. lusitanica* in Teshome (2005) with a volume about 1 m³ at 40 cm of DBH. Differences in rainfall between the two sites were not important enough to explain the difference in volume between the two species.

For tropical dry forests and mangrove ecosystems (Figure 31c), six of the nine selected allometric equations had an interval of calibration. At DBH=25 cm the minimum volume was 0.11 m³ (*Rhizophora racemosa*), while the maximum was 0.41 m³ (*A. africana*). At DBH=50 cm the average individual aboveground volume in tropical dry forests was 1.74 m³, whereas it was 1.97 m³ and 2.86 m³ in tropical plantations and rainforests, respectively. *A. africana* is a large and tall, savanna, deciduous tree with a spreading crown and (Arbonnier, 2000). *R. racemosa* is a small aquatic tree or shrub, that can reach heights between 5–20m and a trunk diameter between 20–50cm and is the primary colonist in the open lagoon systems (Keay, 1953). Moreover, the difference in tree ecology explains part of the difference in volume between different species. Taking into consideration the variation of wood gravity between tree species and plant functional types (3.3) add more variability to the biomass estimates. When considering the average wood density for tropical rainforest species, *T. africanus* had lower wood density (0.65±0.01 kg m⁻³, n=7), than *L. alata* (0.86±0.05 kg m⁻³, n=33). Moreover, considering Figure 30a, the difference in woody biomass between species could be as high as 2.83 Mg in the tropical rainforest zone at DBH=50 cm.

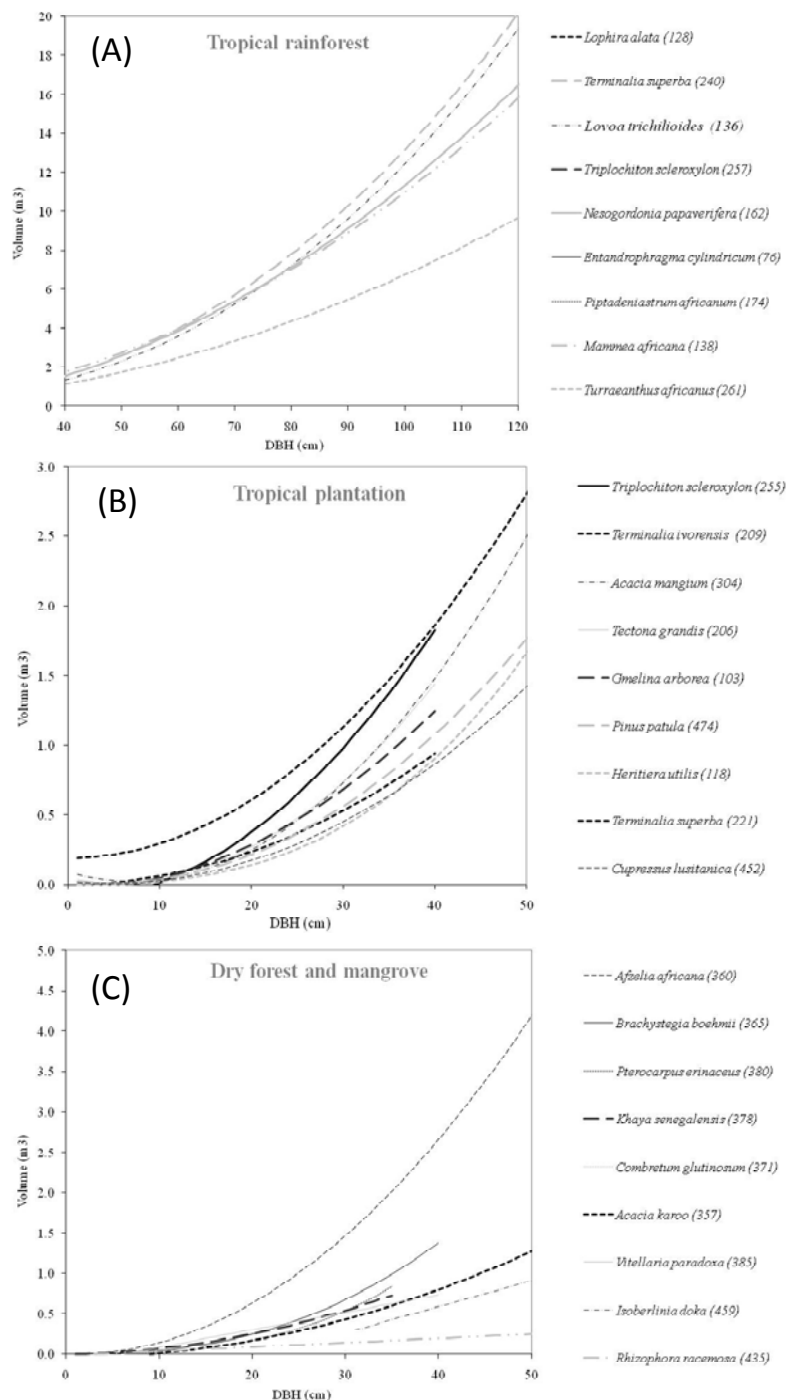


Figure 31: Volume of tree species in various forest types.

(A) Tree species volume in tropical rainforests. The volume concerns the trunk component. Ranges of calibration were presented for the equations 76, 174 and 257 while not for the equations 128, 136, 138, 162, 240 and 261. (B) Tree species volume in tropical plantations. The volume concerns the trunk component. Ranges of calibration were presented for the equations 255, 474, 452 and 234 while not for the equations 209, 103, 221 and 118. (C) Tree species volume in dry forests and in mangroves. The volume concerns the trunk, the bark, the stump and the big branches. Ranges of calibration were presented for the equations 357, 364, 371, 378, 380 and 459 while not for the equations 360, 365 and 435. []: equation number.

➤ Influence of age of sampling on biomass: a focus for Senegal

Figure 32 represents the temporal evolution of the biomass of a fallow at different locations in tropical dry and tropical moist deciduous zones. The biomass of a 27 years old fallow ranged between 24 Mg ha⁻¹ (at Boulador) and 42 Mg ha⁻¹ (at Sare Yorobana). The results showed that the biomass increased quickly during the first years and then reached a threshold. The maximum level seemed to be reached around 7 to 15 years and then the biomass increased slowly. In the case of Boulador and Sare Yorobana the asymptot was reached later. Biomass increased faster in Guiero Yerobocar during the first years but reached faster the asymptote while biomass in Sare Yorobana increased slower but reached a higher biomass after a period of 20 years. This illustrates the importance of recording tree age in managed forest ecosystems.

➤ Between-sources variation of volume and biomass within four selected species

The four most studied tree species were selected to illustrate the variation of volume and biomass within species. *T. superba* is a common tree found in plantation in tropical rainforest and moist deciduous zone (Groulez and Wood, 1984). The highest volume for *T. superba* was found in RCA (equation 240) while the minimum was found in Mayombe in Congo (equation 216). *V. paradoxa* is commonly found in the Sahelian transitional ecosystems (Peltier, *et al.*, 2007). The highest volume was obtained in Ténéfi in Mali (equation 392) while the lowest was found in Badougou in that country too (equation 385). The volume for *V. paradoxa* was modelled as linear functions with very different intercepts. In Badougou, the volume of a tree of 7 cm of DBH was almost null. The volume of a tree of 40 cm of DBH in Ténéfi was 3.7 times higher than the volume found in Badougou. *E. globulus* is one of the most common tree species in plantation in SSA (Komakech, *et al.*, 2009, Zewdie, *et al.*, 2009). The lowest biomass was found in Ager (Equation 807 and 802) and the highest in the Heritage Forest Park (equation 785) (both in Ethiopia). *A. Senegal* is an emblematic tree species of the tropical shrubland zone. Available equations predict similar values with lowest values in Fété Olé in Senegal (equation 679) and highest in Boboyo in Cameroon (equation 582). The lowest variability was found for *A. senegal* while the highest was found for *V. paradoxa*. Considering the important variability found among tree species (at least 20% of variation between sites), consideration of the tree species and the only dendrometric parameters such as DBH is not enough to explain variability of biomass. Additional site specific information would be helpful to explain this variability.

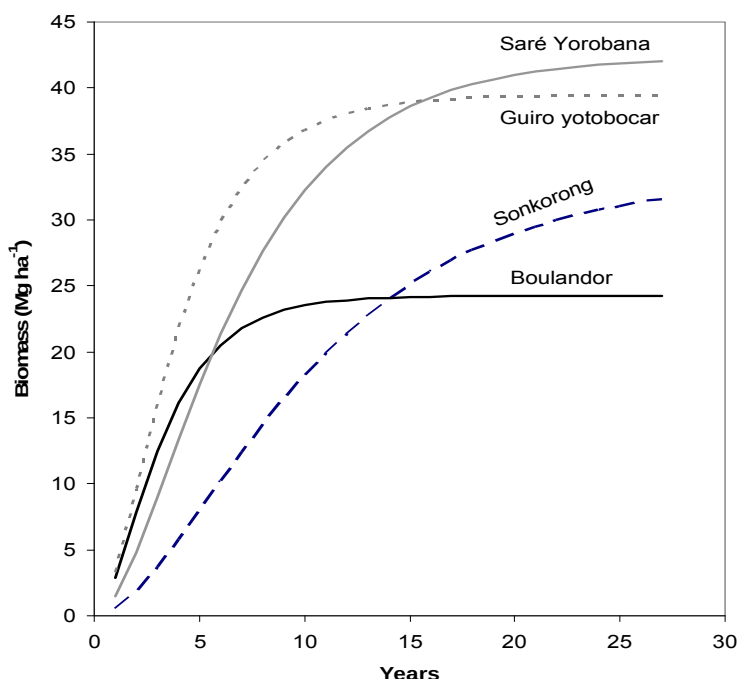


Figure 32: Stand biomass in various locations of Senegal at different time periods.

The volume equations for Sonkorong, Boulador, Sare Yorobana and Guiero Yerobocar were found in equation 631, 574, 576 and 575 respectively. Annual rainfall was 682, 1124, 1021 and 1021mm in the respective locations. Vegetation was measured up to 27 years old.

➤ Checking tiers method to estimate biomass for tree species

A comprehensive set of specific allometric equations was reported for six species: *Acacia Senegal*, *Combretum glutinosum*, *Gmelina arborea*, *Guiera senegalensis*, *T. ivorensis* and *T. superba* (Appendix IV and V). Some allometric equations included all the aboveground compartments while other models considered independently or by group the trunk, the gross and thin branches, the leaves or the roots. Given the number of available equations for those six species, they were considered as good candidates to assess the consistency of the 3 tiers for different ecological zones (tropical rainforests, moist semi-deciduous, dry and mountain forests, and tropical shrublands), for plantation and natural ecosystems, and for exotic and indigenous trees species. The most diverse types of allometric models were found for *A. Senegal* which was selected to illustrate the Tier approach.

➤ Choosing equations for tiers for *A. Senegal*

Four equations predict the total aboveground biomass of *A. senegal* (equations 582, 669, 674, 679 and 669 in Appendix V), three equations predict the trunk biomass (668, 675 and 678), two equations predict thin and gross branches biomass (671 and 675), one equation predicts the trunk volume (425), and six equations for the leaf biomass (666, 667, 677, 680, 681 and 682). Moreover four equations for Tier 3-total, three equations for Tier 3-partial, and one for Tier 2 were available (Figure 33). As for the Tier3-total the equation 674 predicts the total above-ground biomass based on the number of tree rings. Using the relation between the number of tree rings N and the basis diameter BD found in Poupon (1979) ($N = -7.4 + 3.8BD$), it was possible to estimate the total aboveground biomass. Equation 669 corresponds to the refinement of the model 674 developed by Poupon (1979), as Poupon (1979) increased the number of samples (8 trees in 1976, 21 trees in 1979) and

used a more appropriate mathematical model (third order polynomial with possible over-parameterisation in 1976, and power function in 1979). Equation 582 was developed by Smektala *et al.* (2002) to predict the fresh biomass. To convert fresh biomass into dry biomass, the moisture content from INERA (1998) was used. In addition, as data for those equations were collected during the dry season (Smektala, *et al.*, 2002) and as *A. senegal* that loses its leaves at the onset of the dry season, this means that the tree compartments considered in those equations include the trunk and the branches (compartments B_t , B_c , B_b , B_a , and B_d in Figure 24), but not the leaves (component B_l). To estimate the total aboveground biomass including leaves, biomass estimates from the equations 666, 667, 677, and 680-682 can be added to estimates from previous equations. However, all the transformation steps add unknown errors when estimating biomass. To avoid the step of transformation it was preferred to use the equations 679 and 682 to give the total aboveground biomass. Equations 679 and 682 were quality 2 and 3 while the others were assessed as quality 1. In addition, the number of measures used to build equations 679 and 682 were higher than for the others. Comparison with the other equations revealed overestimation of about 110, 34 and 6% as compared to equations 582, 669 and 674. Converting tree rings into diameter is one additional step that also added possible bias to the estimation of equation 674. In equation 582, converting fresh biomass into dry biomass adds the uncertainty bound to the estimate of the moisture content (Nygård, *et al.*, 2004). In addition, Bird and Sheperd (1989)'s model was thus selected to predict aboveground dry biomass for Tier 3-total.

The same procedure was followed to select the equations for Tier-3 partial, Tier 2 and Tier 1. Equations were selected according to the quality rank and the number of sample. Comparison with the other equations was achieved to control and explain the differences when it was possible. As a result, the equation 678 was selected. The quality of the other equations was lower and the equation 668, 671, and 675 from Poupon (1979) that were developed for the trunk, the gross branches and the thin branches respectively, did not verify the additive constraint. When considering the Tier-2 approach, the average wood density from the wood density database and the biomass expansion factor of the IPCC were used. When considering the Tier-1 approach, four equations were available for the tropical dry zone. Even if none of the measures used to build Chave *et al.*'s equation originated from SSA, I considered it as the most accurate pantropical equation for the tropical shrubland ecological zone. Comparison with other generalized allometric equations revealed a difference up to 60 kg at 20 cm of DBH with the equation from Brown (1997).

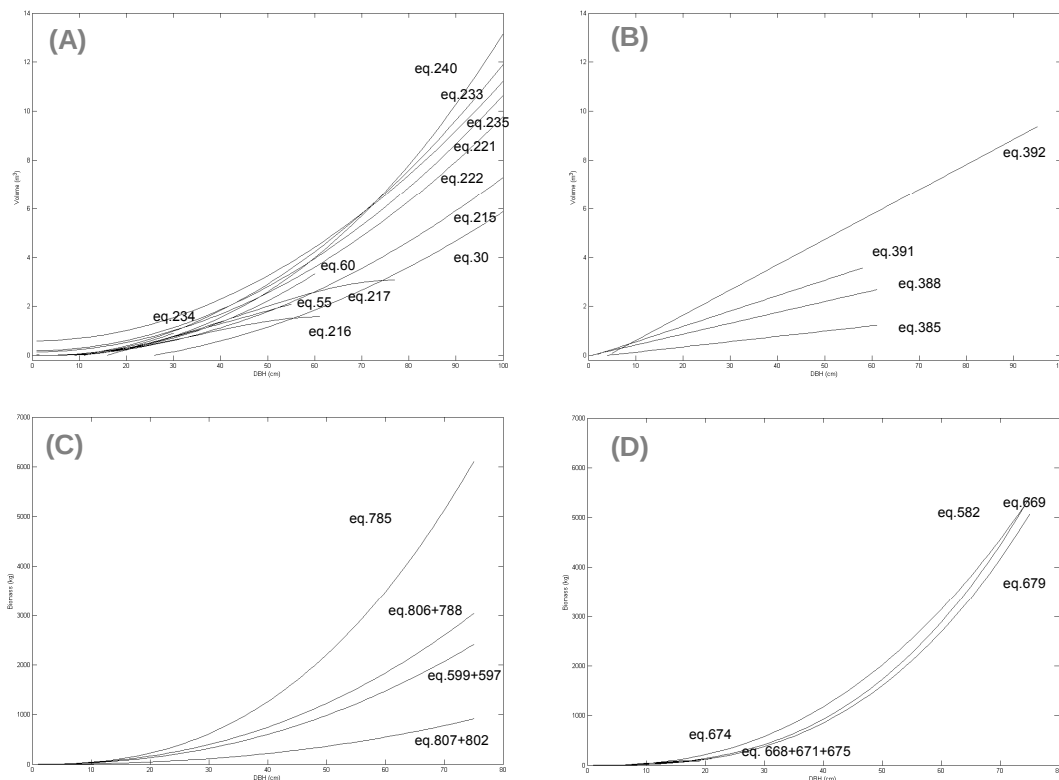


Figure 33: Tree volume and biomass of four tree species in various geographic locations.

Terminalia superba, *Vitellaria paradoxa*, *Eucalyptus globulus* and *Acacia Senegal* were selected to represent the variability among tree species within tropical rainforest, moist deciduous forest, and tropical dry forests and tropical shrubland. Those tree species were considered to best represent the variability among tree species (based on the data available in the database) because they were measured in the highest number of location than other tree species. (A) *Terminalia superba* is a common tree species found in plantations. The ranges of calibration were presented for the equations 220 and 232 while not for the equations 215, 221, 222, 232, 233 and 235. (B) *Vitellaria paradoxa* is commonly found in Sahelian transition zones. The ranges of calibration were presented for all the equations (385, 388, 391 and 392). (C) *Eucalyptus globulus* is commonly used in African plantations (Pohjonen and Pukkala 1990) and productive in tropical plantation. The ranges of calibration were present for 597, 599 and 788 while not for 802, 806, 808, and 827. (D) *Acacia senegal* is a typical tree species of the Sahel found in agroforestry and natural ecosystems: the ranges of calibration were presented for equations 674 and 668. The ranges of calibration were not present for the equations 582 and 669.

➤ Checking equations for tiers for the other species

On the basis of the results given in the previous paragraphs, the following equations were selected to make comparison between Tier-1, 2, 3-partial and 3-total approaches for *A. senegal*. Equations 425 and 678 came from Poupon (1979), 679 from Bird and Shepherd (1989) and were specific to *A. senegal*. Equation 652 came from Chave et al. (2005) and was a pantropical equation for tropical dry forests

Tier 3-Total B_{AG} (kg) = $Y(kg) = \text{Exp}((2.83568 \cdot \log(DBH) - 3.75637) + 0.043274)$ (n=44, $R^2=0.99$) eq. 679

Tier 3-Partial $\text{Log}_{10}(B_t) = -3.45 + 2.73 \text{Log}_{10} C_b$ (n=21, $R^2=0.98$) eq.678

$$\text{Tier 2 } \text{Log}_{10}(V_t) = 0.07 + 2.55 \text{Log}_{10} C \quad (n=56, R^2=0.9) \text{ eq. 425}$$

$$\text{Tier 1 } B_t = \text{pexp}[-0.667 + 1.784 \ln \text{DBH} + 0.207(\ln \text{DBH})^2 - 0.0281(\ln \text{DBH})^3] \quad (n=316, R^2=0.99) \text{ eq. 652}$$

where: B_{AG} is the aboveground dry biomass in kg (without leaves), B_t is the trunk dry biomass in kg, V_t is the trunk volume in cm^3 , C_b is the basis girth in cm, DBH is the diameter at breast height in cm, ρ is the wood density (0.643 g cm^{-3}), Log_{10} is the base ten logarithm, and $\ln$ is the natural (or neperian) logarithm.

The procedure described for *A. Senegal* was applied to the five other tree species. Figure 34 compares the estimates of the aboveground dry biomass for the different tree species including *A. senegal*.

In Figure 34a, Tier 3 relied either on a specific aboveground dry biomass (Tier 3–total) or on a trunk dry biomass equation (Tier 3–partial). Tier 2 relied on the trunk volume equation. Tier 1 relied on a pantropical aboveground dry biomass equation. Taking Tier-3–total biomass as the reference, then the best proxies ranked as follows: Tier-3–partial biomass > Tier 2 > Tier 1. Hence, quite logically, taking a lower tier results in a less accurate prediction. Tier 3–partial biomass and Tier 2 were very close to Tier 3–total biomass for small trees. Tier 1 was inaccurate for small trees, where the deviation reaches 51% for $BD = 10 \text{ cm}$. However for $\varnothing > 30 \text{ cm}$ the deviation between Tier 3–total biomass and Tier 1 decreased as diameter increases, and reached –24% for $BD = 70 \text{ cm}$. For *C. glutinosum* (Figure 34b), four equations were selected to compare tiers. Tier 3-total and Tier 3-partial predicted similar values for small diameters; Tier 2 and Tier 1 predicted higher biomass. For diameters above 50 cm, Tier 1 had lower deviation than Tier 3-partial. Tier 2 used an average wood gravity of 0.73 g cm^{-3} that does not explain overestimation up to 322% at 70 cm of DBH. For *G. arborea* (Figure 34c), Tier 1 and 3-total predicted very similar values for small and large diameters. Tier 1 overestimated the aboveground biomass by 11% at 10 cm of DBH while it underestimated it by 7% at 70 cm. On the other hand, Tier-2 method largely overestimated the biomass. Tier 2's overestimation could reach up to 194% at 6 cm of DBH. When considering *G. senegalensis* (Figure 34d), two Tier-3-partial approaches were used to compare the use either of the BEF, or of the compartments specific equations (equation 728 with BEF, or equations 629 and 724 for compartments) and no suitable equation was found for volume estimation (Tier 2). Tier-3-partial approach that uses compartments specific equations (equations 629 and 629), gave the closest estimates to Tier 3-total. The equation 728 overestimated biomass as high as 66%. The Tier-1 approach largely overestimated the biomass and reached 944% overestimation at 70cm of DBH. For *T. ivorensis* (Figure 34e), biomass estimates from Tier-1 approach were lower than those from Tier 3-total. Underestimation of Tier-1 approach decreased with diameter and was of approximately 20% at 70 cm of DBH. The Tier-2 approaches largely overestimated biomass (by 160 and 190% at 70cm of DBH for eq. 211 and 212 respectively). Moreover, in the absence of a Tier-3 equation it is preferable to use a Tier-1 equation in this case. For *T. superba* (Figure 34f), Tier-3-total biomass was close to Tier 1 for small diameters; deviation between the two equations increased for large diameters. The Tier-2 approach largely overestimated the biomass (up by 900% at 70 cm of DBH).

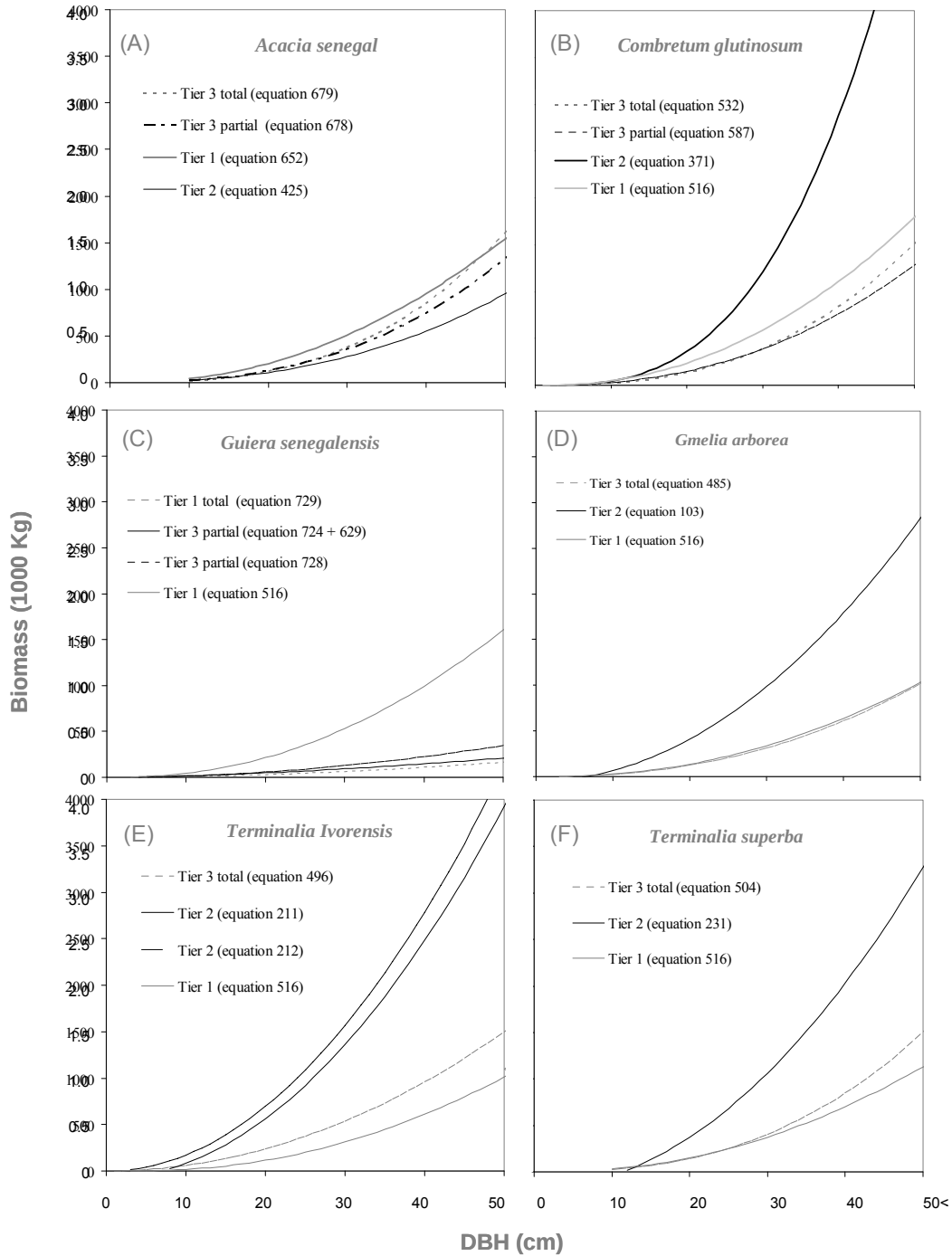


Figure 34: Aboveground biomass estimation for individual tree stem using tier method for tree species.

(A) *Acacia senegal*: the confidence intervals were absent. The average wood density was 0.63 g cm^{-3} . (B) *Combretum glutinosum*: the ranges of calibration were presented for the equations 516, 532 and 371 while not for the equations 587. The average wood density was 0.73 g cm^{-3} . (C) *Gmelina arborea*: the ranges of validity were absent. The average wood density was 0.42 g cm^{-3} . (D) *Guiera senegalensis*: the ranges of validity were absent. The average wood density was 0.66 g cm^{-3} . (E) *Terminalia ivorensis* the ranges of validity were absent. The average wood density was 0.45 g cm^{-3} . (F) *Terminalia superba*: the ranges of validity were absent. The average wood density was 0.46 g cm^{-3} .

➤ Checking tiers method to estimate biomass for ecological zones

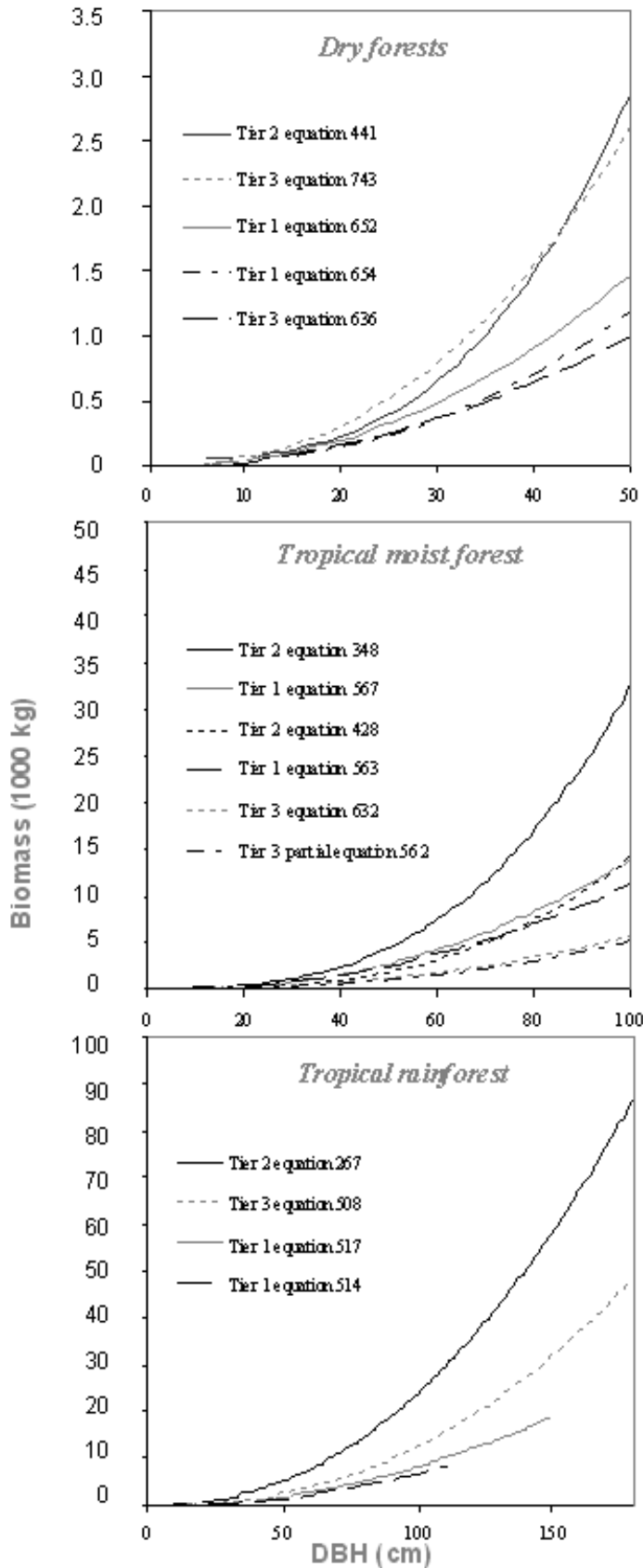


Figure 35 represents the variation of aboveground biomass in four ecological zone of SSA as predicted by different Tiers-. Variability is significant particularly in the dry regions. Few generalized allometric equations were developed in SSA. It is however possible to make a tier comparison analysis for tropical dry forests, tropical mountain forests, and tropical rainforests. The same approach previously developed for *A. Senegal* was used to compare the different Tiers approaches for different generalized allometric equations in different ecological zones (Figure 35). There was an important difference between the two Tier-3-total equations (636 and 743) for tropical dry forests. At 50 cm of DBH equation 743 predicted 2.9 times more biomass than equation 636. The difference between the two Tier-1 equations was less important (about 30% at 50 cm of DBH). Tier 2 overestimated the biomass by about 10% at 50cm of DBH and used an average wood gravity of 0.6 g cm^{-3} . Assuming equations 636 and 743 as the references, the best estimation were obtained with Tier 1 (equation 743) and Tier 2 (equation 441) respectively. When considering tropical moist forests, Tier 3-total and Tier 3-partial brought a difference in about 200 kg at 50 cm of DBH. Tier 3-partial provided the closest biomass estimates to Tier 3-total. Tier 2 (equation 356) overestimated biomass up to four times. Using a more appropriate Tier 2 model (equation 445) provided better biomass estimates but still with overestimation.

Figure 35. Aboveground tree biomass estimation for individual tree stem using tier methods for three ecological zones.

- (A) Dry forest: the range of calibration was presented for the equation 654 while not for the others.
- (B) Tropical Moist forest: the confidence intervals were presented for the equation 356 and 563 while not for the others.
- (C) Tropical rainforest: the confidence intervals were presented for the equation 508, 514 and 517 while not for the others.

(B)

Tier 1 biomass estimates (equation 571, 568) were close to the Tier-2 estimates (equation 445). In the absence of Tier-3-total model, the Tier-3-partial model was the less biased. Using Tier-1 and Tier-2 approaches largely overestimated the biomass. For tropical rainforests, Tier-2 estimates were much higher than Tier 3-total. Overestimation of Tier 2 was about 100% and was constant. On the other hand, the Tier-1 method underestimated by about 40 and 30% for equation 514 and 517 respectively. Given that no Tier-3-total equation was available, it was difficult to propose an alternative as both Tier 2 and Tier 1 led to important bias. However, it would be preferable to use a conservative approach and decide for a Tier-1 approach.

4. Discussion

4.1 Current knowledge on tree biomass allometric equations in sub-Saharan Africa

This database is the first attempt to inventory all the allometric equations of SSA. The study suggests that less than 1% of the tree species in this region have national allometric function. It clearly limits the development of forestry inventories of biomass and C in SSA. While the IPCC states that under Tier-2 or Tier-3 approaches national greenhouse gas inventories must report estimates based on country-specific data, this study highlights the important gaps for the region (Table 18, Table 19, Table 20 and Table 21). Seven tree species account for about 20% of all equations available and our knowledge on the biomass of some tree species remains limited. West Africa is the region where most of the studies were carried out; yet in 24 countries no equation has been built. The analysis of the database reflects the disparity of efforts on forest biomass assessment tools between countries, regions (Table 18) and ecological zones (Figure 25 and Figure 28). At current state, none of the SSA's countries have enough national allometric models to report forest C stocks and their variation under the Tiers 2 and 3 of the IPCC. Applying the current rate of scientific data production of about 67 equations per year, it would take more than a century to cover the 11,342 species reported in the Forest Resources Assessment of the FAO (2005). When analysing the quality of the data reported in the documents it is surprising to find that 22% of the equations were considered as quality 1. The quality analysis is biased by the fact that I used average equations to estimate the percentage within the interval of possibility. However, it is highly improbable to have access to the original data used to build the models, making estimation of model accuracy and precision difficult. Further researches should develop metadatabases for tree biomass to allow foresters to check the validity of volume and biomass estimates from models or from field measurements and to develop more appropriate allometric models. Hofstad's (2005) review of models for trees and shrubs of Southeast Africa was limited to a visual observation of the biomass found in 34 models. Sylla and Picard (2005) did an exhaustive inventory of available allometric equations but restricted the analysis to the Sahel. The present study goes much farther as it reviews the current knowledge for the entire SSA, explores tree volume and biomass variability and provides a tool for C stock estimation.

4.2 Variability of tree volume and biomass

The important differences in volume and biomass found in Figure 30, Figure 31, Figure 32 and Figure 33 result from a combination of various ecological, environmental and human factors that determines and shapes the biomass of a tree. Reduced water stress in tropical rainforests would allow high growth and

biomass (Figure 30), with an optimal rainfall value as tree biomass in wet forests were lower than in moist forests. Trees are taller in the tropical rainforests for a fixed diameter than in drier regions. However, climate is not the main factor affecting the tree biomass. Although rainfall is lower in the moist deciduous and semi-deciduous climates, taller and bigger trees are often found. In addition, it results that the biomass prediction from the wet climatic zone is lower than for the moist zone when considering the equations provided by Brown (1997). Soil properties also affect tree biomass as availability of nutrients such as phosphorus and nitrogen limits tree growth (Baker, *et al.*, 2003). Recently Gourley-Fleury *et al.* (submitted) illustrated how soil properties sort the distribution of aboveground biomass in central Africa. While various attempts have been made to explain the influence of wood density (Woodcock and Shier, 2002, Baker, *et al.*, 2004), climate variables (Ciais, *et al.*, 2009b), or soil properties (Laurance, *et al.*, 1999, Gourlet-Fleury, *et al.*, submitted), this study is the first to make a compilation of volume and biomass models at continental scale.

Functional types seem to influence wood density (Figure 29). The significant differences in wood density between plant functional types was also found by Woodcock and Shier (2002) who found that wood densities of tree species of early succession were lower than the others. Higher tree growth in the condition of canopy opening is generally linked with lower wood density (Parresol, 1999). Important differences in tree biomass were also found in Boi Tano Forest reserve in Ghana in chapter 5 where the difference in tree biomass reached 25% between tree species at 80 cm of diameter.

Tree age and vegetation forms are important factors affecting the volume and the biomass particularly for young formations. Following the example of fallow growth in Senegal (Figure 8), biomass grows up to reach a threshold after which vegetation growth is much lower. However, the important differences in biomass between sites reveal factors that would be anthropic or pedologic. The difference in rainfall does not explain any trend in biomass growth between sites, and fallow management or soil properties would be critical factors.

Important differences in volume and biomass estimates were found between equations for the same species (Figure 33). The comparison was made between equations that considered the same tree compartments and ecological zones, as the use of different methods would have led to increased uncertainty. Different methods could be used when building volume allometric equations (Somogyi, *et al.*, 2006, Návar, 2009). Using direct or indirect tree measurements would lead to difference in tree measurement. However, in Figure 33c the equations were developed by the same author using the same methodology. In addition, different mathematical forms are used when building allometric models. However, the different mathematical forms do not justify alone the difference in volume between sites and authors. Most of the difference would be explained by the different environmental conditions in the different sites. Environmental factors are not limited to climate factors, as, for example, Figure 32b shows no link between rainfall and tree volume. Differences between equations remain unexplained, but various hypothetical factors -soil, climate, methodology- and due to the modelling process may account for them.

4.3 Using the Tier approach provides consistent biomass estimations

Some authors report that using generalized allometric equations built either on grouping all species together, or on stratification by broad forest types or ecological zones, is highly effective for the tropics because DBH alone explains more than 95% of the variation in aboveground tropical forest C stocks,

even in highly diverse regions (Brown, 2002). However, the analysis of the present database reveals important variation in wood gravity, volume and biomass between and within ecological zones and tree species (Figure 29, Figure 30, Figure 31, Figure 32 and Figure 33).

To develop biomass estimation using the current set of allometric functions the tier approach proposed in this study gives a decision tree to guide the users to develop the most consistent biomass estimations. The tier approach makes references to the IPCC tier method. While the tier method of IPCC does not consider the allometric equations, this study reported differences between the accuracy levels of the equations. It is difficult to quantify the accuracy and the precision of the estimates as very few destructive measurements exist in SSA and very few authors did comparisons between allometric models. Moreover, when several allometric equations are available it is preferable to use the same guidelines in order to be consistent. The authors suggest considering the allometric into the IPCC tier approach.

The tier approach allows choosing the best allometric models taking into consideration available datasets for SSA, like the case of *A. Senegal*, illustrates it. Although no similar efforts exist for other tree species, it was possible to make the analysis for other five tree species (Figure 34) and for three ecological zones (Figure 35). When considering the tree species, the results illustrates the difficulty when choosing the best suitable allometric equation and the difference between tree species. The analysis for *A. Senegal* showed that Tier-3-partial approach yielded better estimates than Tiers 2 and 1, the latter largely overestimating biomass. Except for *A. Senegal* the Tier 2 approach overestimated biomass as compared to the other approaches. The underestimation in the case of *A. senegal* would be due to a problem of data reporting rather than a methodological limit. When considering factors to convert partial biomass to total biomass, the BEF from IPCC (2003) does not consider the tree size. Allocation of biomass between the tree compartments varies during the tree life (Boar, et al., 1999). Furthermore there is still improvement to be made to build BEF that are specific per species or functional types, and tree size. Lack of accuracy of the BEF clearly limits the use of the Tier-2 approach.

An additional limit for the Tier-2 approach is the selection of a BEF adapted to the tree compartments that are considered in the volume equations. BEF in IPCC (2003) were developed by Brown (1997) for tropical rainforests and convert a merchantable volume into biomass. However, in tropical dry forests the merchantable volume is not limited to the trunk but could also include the stump and the branches up to 3cm (equation 411). Moreover, the use of the BEF (IPCC, 2003) obviously leads to an overestimation of the biomass particularly in the dry forests. An additional limit of the Tier-2 method is the availability of wood density values (Figure 33). When it is not possible to find a species-specific wood density it is preferable to use an average wood density for the family or the functional group rather than the average presented in the IPCC (2006). Tier-3 and Tier-1 approaches integrate the variability of the biomass within the trees and between species (when generalized).

The results confirms that using high tiers results in more accurate estimates except when using the volume because biomass expansion factor does not reflect the different conditions and biomass variations between species and regions. The deviation between two allometric equations could be important. Expansion from partial biomass, or expansion and conversion from partial volume, are accurate for large trees if the exponent of the power function is accurate. An error on this exponent will amplify itself as tree size increases. The *A. senegal* example leaves some questions unsolved. For instance, is it better to use Tier 3 or 2, when the biomass equation (Tier 3) relies on 8 trees and the volume equation (Tier 2) relies on 800 trees? The latter has presumably better precision and lower accuracy, whereas the former has presumably lower precision and better accuracy. Hence, even if Tier 3 is better than Tier 2 in terms of accuracy, it may be advantageous in terms of quadratic error to use Tier

2 when the volume equation relies on much more data than the biomass equation. In other words, the selection of one specific tiers shown in Figure 34 should also depend on the number of observations used for calibrating each model.

Furthermore, the use of Tier 3-partial is preferable to Tier 1 that is in turn preferable to Tier 2 when no BEF parameters are specifically developed for the tree species and the different ranges of volume, tree dimension and tree compartments. The questioning on the selection of tree allometric models was also raised by other authors. Ares and Fownes (2000) for instance concluded that similar biomass estimates were found using species-specific and generalized equations. I however suggest the development of species-specific allometric models and BEF.

This review suggests that there are several allometric equations available to estimate biomass or volume. This is particularly the case when both species-specific, and generalized plurispecific equations are available. Rather than choosing an equation that is presumably the most appropriate (with the risk of choosing the wrong one), an option is to combine these equations into a single model. Combining several models through e.g. bayesian techniques would improve the reliability of the estimate. These techniques have been fruitfully applied to climatic forecast models (DeSole, 2007, Furrer, et al., 2007, Berliner and Kim, 2008, R. L. Smith, et al., 2009). Further researches should mobilize statistical methods that correct and produce more generalized allometric equations adapted to the various forms of vegetation, tree species and ecological zoning.

4.4 Toward improvement of methods and data reporting for volume and biomass estimates

Science of biomass prediction is young and evolving. The present work gives some dynamic views of the evolution of researches on biomass in SSA (Figure 28). Equations developed during the 50's were driven by commercial exploitation, were exclusively focused on tropical rainforests and considered only volume. Only gradually did biomass estimation gained interest. In SSA, efforts in inventorying forest resources started when policy makers became concerned about forest degradation and deforestation (Cailliez, 1991). This was made possible when the first sets of satellite imageries became available and when the first estimates of deforestation rates were achieved (Lanly 1982 FAO 1990). Estimation of woodfuel supply, particularly in the Sahelian countries (Millington, *et al.*, 1994), became an increasing concern as population increased and unsustainable management of trees and forests was thought to be the main driver of the dynamics of natural resources (UNEP, 2006). In the tropical rainforest zone, estimation of timber volume was allowed by the rationalization of timber exploitation. Only in the 70's were timber tree species classified according to their growth potential, commercial interests and strategies to regenerate (IIED, 1994b). The first tree destructive experiment that explicitly measure tree C stocks in SSA was achieved only recently (Henry, *et al.*, 2009).

➤ Improving methods and data reporting for volume and biomass estimates

The current increasing attention to the global C cycle encourages the development of biomass models. While only industrialized countries are committed to report their GHG inventories, it is highly likely that reducing emissions from deforestation and forest degradation will become eligible during the second commitment period of the Kyoto protocol (FCCC/SBSTA/2009/L.19/Add.1). The road is still wild to reach

an accurate, precise, transparent, consistent and robust GHG balance assessment of forest C stocks and their variations. The REDD+ mechanism would be an intermediate between finance and the forestry sector with the C credits as transaction unit. Moreover, measuring, reporting and verifying are critical and would require the use of robust and consistent methods. Reliable methods of estimating forest biomass and C stocks as well as volume of the growing stock at different spatial and temporal scales and for different biomes are needed. In national forest inventories, emphasis has been placed on the assessment of merchantable timber, and inventories provide accurate estimates of the growing stock. In national biomass inventories, emphasis has been placed on the assessment of fuelwood and timber availability, and inventories provide accurate estimates of wood biomass stock. The current need is to estimate the forest C stock and change as a result of the Climate Convention and the Kyoto Protocol. In this context, the demand of allometric equations is particularly increasing while this study reveals that very few equations were developed for SSA and does not allow accurate reporting of GHG balance in any of the countries. In addition, it highlights the problems when making allometric equation and the need of standardization and homogenization of the methods. Moreover, taking example of the previous experience and errors, a list of recommendations can be built.

➤ **The interval of calibration**

The use of the current available allometric equations is limited by the interval of calibration. While the generalized allometric equations from Brown (1997) for tropical rainforest are limited to 148 cm of DBH, the allometric equation from Chave *et al.* (2005) is limited to 156 cm and the equation from chapter 5 to 180 cm. The presence of trees with larger DBH is rare but can happen. For instance Chave *et al.* (2003) report that trees with DBH > 150 cm represent 9.75% of total biomass in a tropical rainforest found in Brazil. Thus, they may account for a significant proportion of the forest biomass. Current available equations can not predict the biomass of the very big trees. Using the biomass of the maximum diameter considered into the interval of calibration of the equation would allow a conservative estimation of biomass and should be recommended.

➤ **Identification of the predictors**

Various authors reported that increasing the number of predictors and particularly the circumference or the diameter and the height improves precision of the models. Chave (2005) reported that the most important predictors of tree biomass were, in decreasing order of importance, its trunk diameter, wood specific gravity, total height, and forest type. Gibbs *et al.* (2007) report that DBH alone explains more than 95% of the variability. The present results (found e.g. in Figure 30) well represents important biomass variability when using only the DBH as input. While the model developed by Brown (2002) explains 95% of the variability found in less than 150 tree samples collected by the author, the results clearly illustrates that one generalized model based only on DBH cannot explain the important variability found in one ecological zone.

Only 24% of the equations reviewed here use more than one predictor, diameter and circumferences being the most common predictors. Developing models including the crown diameter or area too in open forests could be used with the integration of high resolution remote sensing analysis to estimate biomass over large spatial scales (Defourny, 1991). Analysis of the database also reported that basis diameter mainly used in tropical dry forests mainly, while DBH is used in 91% of the equations in tropical rainforests. In tropical dry forests, trees are shorter than in tropical rainforests and branched ramification is often lower than 1.3 meters height. Using allometric equations based on the DBH in

tropical dry forests leads to overestimating the number of tree stems and the biomass. In tropical rainforest, buttresses largely prohibit reliable measurements at basis. It is thus advised to develop and use adapted allometric equations to the different ecological contexts.

➤ **Selection of method and data reporting**

Destructive measurements are limited by technical and financial means, but also by legal aspects in some cases (Attua and Laing, 2005, Peltier, et al., 2007, Chapter 5). It is however the most accurate method. The development of destructive measurements should be supported to limit the use of conversion coefficients that decrease the accuracy of the estimates. Statistical analysis has to consider various possible models and select the most precise and less biased ones. Making graphics and reporting the data has to respect the units presented in the text in a homogeneous and consistent way. The following information should be explicitly reported: interval of calibration, coefficient of correlation, number of samples, address where primary data used to make the regression is stored to facilitate data checking and metaanalysis on tree biomass. Units in the figures and in the text body should be coherent. Editors should make sure that equations have been reported correctly. Tree taxonomy should be provided in a scientific, authoritative and well-identified system.

➤ **Belowground biomass**

While this study focused on the aboveground compartment, the belowground compartment has the same importance when dealing with forest C stock change and is one of the five C pools considered by the IPCC guidelines (2006). Belowground biomass can represent an important part of the biomass, especially in the dry areas (House and Hall, 2001). While the tree height of *Balanites aegyptiaca* goes up to 8 m, the rooting system often goes up to 20 meters depth (Fournier, 1993). Several savannah tree species develop important rooting systems particularly in the context of aridity. However, only 1.3% of the equations consider the rooting system. It is clear that more root biomass studies are needed (Snowdon, et al., 2000). However, measuring biomass of the rooting system is very costly and time consuming. In most of the cases C inventories uses root-to-shoot ratios. Cairns *et al.* (1997) made an inventory of available root to shoot ratio. When considering the difficulty of root biomass measurement and the current state of knowledge, fractal geometry could be a promising tool to overcome the practical problems arising from the destructive sampling of belowground tree biomass (Hairiah, et al., 2001).

5. Conclusion

This study contains a comprehensive allometric database for SSA. The various equations found in the database reflect the variability in volume and biomass between ecological zones, tree species, age, management type and sites found in SSA. This work highlights the important gaps in estimating the biomass and C stocks using allometric equations in the various ecological zones and countries found in SSA. The choice of the allometric equation is difficult. The study proposes the use of a Tier approach and rules to make consistent and comparable estimation. It encourages the use of species-specific biomass allometric equations rather than volume- and generalized allometric equations. The study evaluates the quality of the equations and highlight important mistakes made by the authors. Recommendations made in this study should facilitate harmonization and better use of the equations in the context of global observation systems. Future research should develop Bayesian statistical approaches to better take profit of the richness of this database and propose alternatives to build allometric equations more adapted to the ecological and climate contexts.

While the three previous chapters focused on the tree allometric equation and the scaling up from wood samples to tree biomass, the next three chapters will focus on already estimated volume, biomass and carbon stocks. Moreover, while the previous three chapters focused on plant level, the next three chapters focus on ecosystem or biome scale. The chapter 7 focuses on three rainforest ecosystems in Ghana. The chapter 8 focuses provides tool for data harmonization. The chapter 9 analyse the variability of carbon stocks at continental scale.

Chapter 7

Structure and functioning of rain forests ecosystems in Ghana

This chapter is modified from the article: Structure and functioning of rain forests ecosystems in Ghana (2010), Henry, M., Adu-Bredu, S., Chesnes, M., Gineste, M., Martel, S. , Asante, W.A., Eshun, J., Valentini, R. Bernoux, M, Saint-André, L., International Journal of forestry Research, submitted

Abstract

Tropical humid forests play a crucial role in global biogeochemical cycles particularly when considering biodiversity and carbon cycling. Their functioning is still poorly known and most of the studies focus on small sampled area without considering the temporal and spatial variability within and between forests. This aim of this study was to examine the relationships between rain-forest structure, biomass, carbon, canopy opening, soil nutrients and biodiversity conditions. Fifty six plots of one hectare were implemented in three different forest types (wet evergreen, moist evergreen and moist semi-deciduous) in the Ghanaian Guineo-Congolese basin. The objectives were (i) to assess biodiversity and carbon stocks in the various forests and (ii) to understand the relationships with abiotic, biotic and anthropic factors. While three plots were selected in each forest to analyze the spatial variability, the others were selected to make comparison between plots and forests. The vegetation exceeding two centimeters of diameter at breast height was measured and aboveground biomass was estimated using a local allometric equation. Litter and soil chemical parameters were also measured. Biodiversity and carbon stocks were analyzed within, between plots and forests.

1. The structure of the forests, the biomass and the biodiversity were linked with soil conditions and topography and climate.
2. Higher carbon stocks were found in the moist evergreen forest. This was mainly explained by the parent rock influence on the soil organic carbon content which was found to be higher in schist than in granitic soils.
3. Soils in wetter forests (wet evergreen forests and moist evergreen forests) were found to be more acid and to contain less soil nutrients than the moist semi-deciduous forest; Total tree height and aboveground biomass were then lower in wet evergreen forests than in moist evergreen and moist semi-deciduous forests.
4. The lower biodiversity observed in the wetter forest was explained by the presence of *S. amoneaceae* which is specific to the measured forest.
5. The previous selective logging impacted the structure of the forests and encouraged the presence of lianas.
6. More shade bearer trees were found in wetter climate and more NPLD were found in drier climate.
7. Higher biomass was found in slope than in upper slope and swampy areas.
8. Most of the biomass variation is explained by the presence of few big trees that contained up to 50% of the forest biomass.
9. There was no relation between biodiversity and carbon stocks.
10. Within and between plots variability is important the soil component and the topography has to be better when scaling up field data to do national estimates.
11. The relation between canopy opening and biodiversity or biomass was valid only for contrasted plots which limits the utilization of this indicator to estimate forest biomass.

Keywords: West Africa, Forest ecology, Ecosystem, biomass, carbon, nutrients

1. Introduction

Tropical forests play a crucial role in biogeochemical cycles, global climate, hydrology, biodiversity and anthropic activities in most of the tropical countries. Because ecosystems collectively determine the biogeochemical processes that regulate the Earth system, the potential ecological consequences of biodiversity and carbon losses have aroused considerable interest (Loreau, et al., 2001, Bunker, et al., 2005, Millenium Ecosystem Assessment, 2005). The role of tropical forests is critical because they are carbon-dense, highly productive (Lewis, *et al.*, 2009) and have the highest biodiversity on the planet (Lewis, 2009). The response of terrestrial vegetation to a globally changing environment is central to predictions of future global environment and human activities (IPCC, 2007c). To develop policies and actions requires understanding the processes, past and present, underlying the spatial and temporal heterogeneity. Although these ideas are generally recognized by most ecologists, current ecological studies often lack the underpinnings of a clear understanding of the important scales of spatial variation within and between study sites. While in Europe, most of the forests are under management and are object to production tables and well identified silvicultural itineraries, in tropical forests, researches continue facing several constraints to understand the functioning of the ecosystems and to identify appropriate management systems (Cailliez, 1991). Understanding the current and future patterns as well as causes of spatial variability in the structure of tropical rainforests can contribute to the resolution of important questions about these ecosystems.

There is a general consensus that in tropical rainforest the floristic composition varies significantly but our understanding of tropical tree species is far beyond our comprehension. This is not only because tree species are numerous (150 tree species is quite often) but they seem to recruit with not obvious pattern. The interactions of various factors, including the tree species distribution and growth strategies results in significant biomass variations at local, landscape, watershed, regional and global scale (Chave, *et al.*, 2003, Malhi, et al., 2004, Houghton, 2005, Ferry, et al., 2009). Many factors affect the biomass distribution in tropical forests. Malhi et al. (2006) reported that basal area was influenced by climate and particularly the length of the dry season in Amazonia. Ferry *et al* (2009) reported that the interactions between topography, soil properties, tree growth and mortality rates, and treefalls were a likely reason for biomass variability in tropical rainforest in French Guiana. Paoli *et al* (2008) reported soil texture and soil chemical properties and particularly percentage sand and extractable P to influence most of the aboveground biomass (AGB) variance in mature Bornean forests. Edaphic factors were found in many sites and scale to have significant influence on floristic composition, biomass and net primary productivity (Newbery, et al., 1986, Vitousek and Sandford, 1986, Malhi, *et al.*, 2004). In Costa Rica palm tree spatial distribution was influenced by soil and topography (Clark, et al., 1995). Distributions of forest tree species have been linked to rainfall gradients and nutrient availability (Vitousek and Sandford, 1986, Baillie, et al., 1987, Newbery, et al., 1988, Wright, 1992, Swaine, 1996). Hall *et al* (1981) reported that rainfall, rock type, soil (mainly pH, richness in bases and calcium content) and occasional ground fires (in the driest regions) and altitude (in the wetter types) were the most significant factors affecting the natural forest floristic composition in Ghana. Tree mortality is one of the main components of the forest dynamic. Many factors such as frequency of heavy rainfall (Nelson, et al., 1994), slope (Robert, 2003), slope exposure and wind (Bellingham and Tanner, 2000), soil waterlogging (Madelaine, et al., 2007), soil fertility (Bellingham and Sparrow, 2009) and soil texture (Ashton, 1992) were found to affect the tree

mortality rate and therefore nutrient cycling. On the other hand, soil properties influenced the growth of recruits and seedlings (Ashton, 1992, Swaine, et al., 1997).

It is impressive that some of the lowest fertility soils support rain forests of massive structure and productivity (Proctor, et al., 1983). According to Baillie *et al.* (Baillie, *et al.*, 1987) and Ashton (Ashton, 1992), within lowland mixed forests in Borneo, the floristic composition is mainly depend to soil nutrients and topography because they determine water relations. According to van Schaik *et al.* (1985), variation in the trees growth strategies depends on soil fertility which results in higher tree longevity on poor soils, and hence in forest with fewer gaps and with more large trees, than on rich soils. Hall *et al.* (1981) reported the influence of soil fertility on tree seedlings for different plant functional types. Escudero et al. (1992) mentioned that pioneers tree would be more demander in soil nutrients because of their higher growth rate and turnover. However, the influence of soil properties on tree species and forest dynamics is not obvious. Aragão et al. (2009) reported no relationship between above and below-ground NPP and soil fertility in ten Amazonian forests.

According to Sollins (1998), important spatial and temporal noise would not allow identification of main drivers. This could be due to methodological problems, because some quantities such as the nutrient availability to the plants cannot be measured directly. An additional problem would be related to the difficulty to capture the spatial and temporal variability because experiments are costly and time consuming and are limited in term of time period and size of measurements. While Gourley-Fleury et al (submitted) and Maniatis et al (submitted) analyzed large areas using forest inventories, their studies cannot consider the forest dynamics and the size of the unit plot (often less than 0.3 ha) limits understanding of spatial variability (Chave, *et al.*, 2003). Few researches considered long time period permanent sample plots but see (Paracou in French Guiana (Gourlet Fleury, et al., 2004), Bobiri forest reserve in Ghana (Alder, 1993), M'Baiki in Central African Republic (Bedel, et al., 1998) and Barro Colorado Island in Panama (Condit, 1998)). Several permanent sample plot experiments were also implemented in Nigeria (Lowe, 1996), Ghana (Alder, 1995) and Uganda (Sheil, et al., 2000). They however fail to provide data that are adapted to fit the current needs such as NPP, C and biodiversity. Most of the researches on the dynamic of forest focused on biomass and nutrients (Floret, et al., 1993), carbon stocks (Kotto-Same, *et al.*, 1997, Glenday, 2006) or floristic composition and structure (Kahn, 1982) in post agricultural forest regeneration systems following chronosequences.

However, most of the studies fail when integrating the spatial and temporal variability because chronosequences and large scale studies do not consider the within plot floristic dynamics and within plot soil, topographic, water and light variations while local studies, mainly permanent sample plots, consider small scale areas without considering climate, biome and parent rock influences. As pointed out by Clark and Clark (2000), in spite of numerous plot-based studies and forest inventories, there are surprisingly few data on basal area and biomass that can be used to assess variation in these factors and their relation to edaphic conditions across mesoscale landscapes. Furthermore, the relationship between spatial patterns of floristic composition and structure in rain forests is little understood, and their relationships, in turn, to forest dynamics remains unknown. Very few attempts has yet been made to examine patterns of structural variation in detail particularly considering biomass (Chave, *et al.*, 2003).

Based on an intensive and extensive data collection in three types of forest in Ghana (wet evergreen, moist evergreen and moist semi-deciduous), this study tends to better understand the distribution of biodiversity and biomass. The objectives were (1) to provide the current status of biodiversity and carbon stocks in the different forests and (2) to analyse the relation between edaphic, climatic and anthropic factors in order to better understand the functioning of tropical rainforest in Ghana.

2. Materials and method

2.1 Study sites

The Bobiri, Boin River, and Boi Tano forest reserves were selected to represent the moist semi-deciduous, moist evergreen and wet evergreen forests according to the classification of Hawthorne (Hall and Swaine, 1981) (Figure 36). The three sites were under forest management by logging companies which facilitated their access.

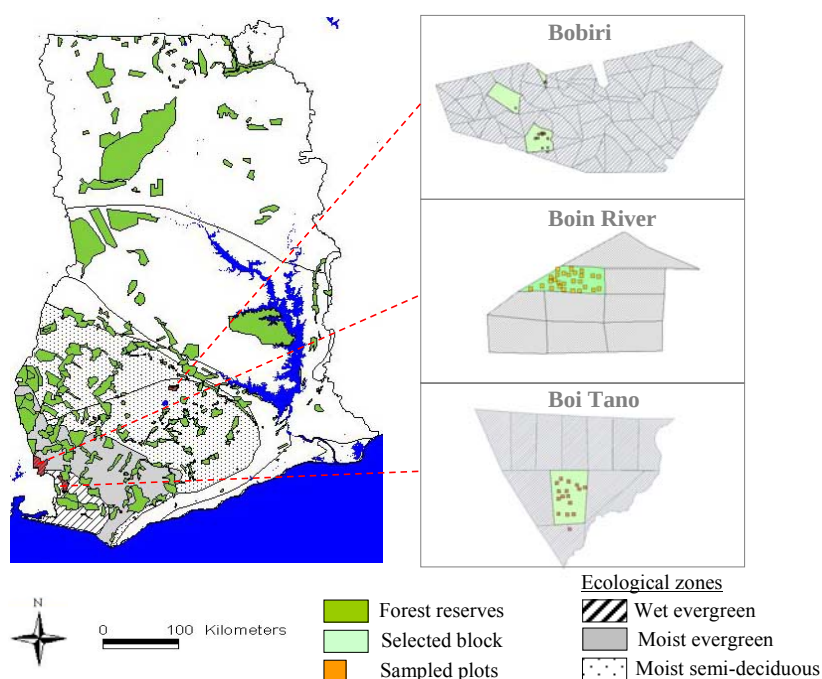


Figure 36: Forest site's location

Three forest blocks were selected in Bobiri, Boin River and Boi Tano forest reserves in moist-semi deciduous, moist evergreen and wet evergreen ecological zones respectively. In total 56 plots of one hectare were implemented.

The Bobiri forest falls within the South-east subtype of the moist semi deciduous forest (Table 1). The landscape is gently undulating. The shallow valleys bottoms along which the streams flow are flat and hydromorph and generally wet during rainy season and flooded for brief periods. The forest corresponds to the *Celtis-Triplochiton* association of Taylor's (1960) vegetation classification. The mean tree height is 49 m, and some trees reach 60 m height according to (Hall and Swaine, 1981). The Bobiri forest was used as an experimental area since the 40's to improve logging activities and

timber yields (Mooney, 1958). In 1945 a working plan based on a 20 years rotation cycle was established. The whole reserve was divided into five periodic blocks and various forest management systems were implemented (Conventional logging, Tropical Shelterwood System, Post Exploitation System, Taungya system and Diameter-limit Selection System). The various operations are described by Alder, (1993). It resulted in various types of forest structure, from secondary forest to natural pristine forest (Hall and Swaine, 1981).

The Boin River Forest Reserve is situated in the high forest zone and is described as a transition between the wet and moist evergreen forest type of Ghana (Hall and Swaine, 1976). The forest ecology is very similar to the moist semi-deciduous in appearance, the tallest trees are slightly shorter on average (43m). Deciduous species represent only a small proportion of the canopy (20%) and the application of the term evergreen is thus appropriate (Hall and Swaine, 1981). The landscape is hilly and undulating landscapes with no extensive lowlands but rather narrow river valleys interspersed with dissected hills. The forest corresponds to the *Lophira-Cynometra-Tarrieta* association of Taylor classification. The forest experienced conventional logging activities during the 50-60's.

The Boi Tano forest reserve corresponds to the wet-evergreen forest type (Hall and Swaine, 1976) and to the *Cynometra - Lophira - Tarrieta* association of Taylor's (1960) vegetation classification. The Forest Reserve lies in the lower Tano basin and consists of a series of hills. . The structure is compressed and the canopy average height is around 32 m (Hall and Swaine, 1981). Very few is known about the history of the Boi Tano Forest Reserve before its first concession in 1947 granted to African Timber and Plywood. There was timber exploitation before its selection and demarcation in 1967, but the area did not appear to have come under intensive selective logging and clearing for farming because of the low soil fertility and the hilly terrain. The first working plan was established in 1992 for the period 1990-2009 (Asiamah and Poku-Marboah, 1992).

2.2 Sampling design

The forest ecosystem was divided into nine compartments. Six aboveground ecosystem compartments or stratum were named: (S1) big trees (DBH>50cm), (S2) medium trees (20<DBH<50cm), (S3) small trees (DBH<20cm), (S4) liana, (S5) palm, and (S6) dead plants. The other three compartments were the (S7) litter, the (S8) roots and the (S9) soil. Different landscape units were identified as flat area and upper slope, middle slope and swampy areas. In order to facilitate access to the forest, the experiments were achieved in parallel with logging operations. The forest reserves were divided into forest blocks by the Forest Commission and the logging companies were allowed to exploit timber in one of the blocks. The selected blocks were 150, 120 and 173 ha in Bobiri, Boin River and Boi Tano respectively. The selected plots were centred on randomly selected trees to be felled by the logging company. Inventories were performed before and after tree felling. Two distinct sampling strategies were developed in order to analyse the variability (1) within the plots and (2) between plots and between forests. In that attempt, the variability of biomass was first analysed by achieving a full inventory in "variability plots" while comparison between plot and forest was achieved in "normal plots".

Table 22: Characteristics of three studied tropical forests

The rainfall was obtained from (FAO, 2005d). The elevation was obtained from resampled SRTM 250 (<http://srtm.csi.cgiar.org/>). The soil classification was obtained from the Harmonized Soil World Database (FAO/IIASA/ISRIC/ISSCAS/JRC, 2008).

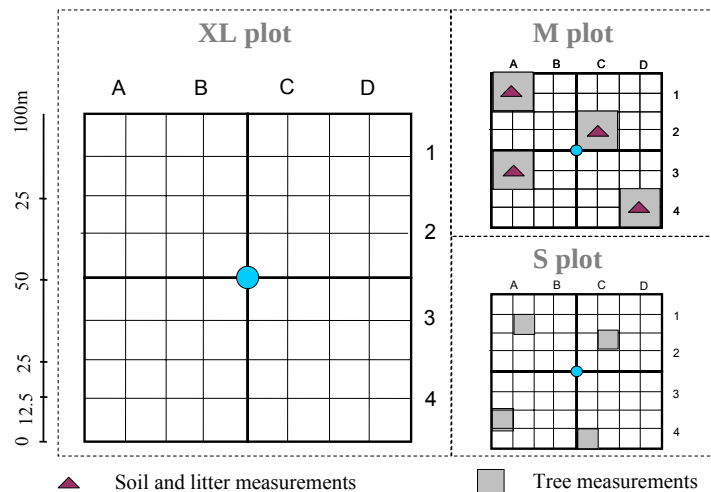
Study site (Lat, Long)	Boi Tano (5.41,-2.65)	Boin River (5.79,-2.88)	Bobiri (6.69, -1.34)
Ecological zones (Hawthorne,	Wet evergreen forest	Moist evergreen forest	Moist semi-deciduous forest
Elevation (m ASL)	Not much undulating: 64 -	Undulating: 183 - 279	Undulating: 183 - 252
Soil type (HWSD)	Xantic ferralsols (Fx): The	Orthic acrisols (Ao7ab). The soils	Orthic acrisols (Ao1ab). Soil is
Canopy cover	Close with average tree	Close with average tree cover of	Open / close with average tree
Climate	Bimodal rainfall distribution	Bimodal distribution with major	Bimodal distribution with about
Geology	Dahomeyan Granite series.	Upper Birimian type, with the	Dahomeyan Granite series. The
Variability plots (1 ha)	3	3	3
Normal plots (1 ha)	13	27	9
Compartment area (ha)	173	120	150
Forest area (ha)	12,171	30,503	5,051

➤ Variability plots

Three plots of one hectare were randomly implemented in each of the forests and were sub-divided into 100 plots of 100m² (namely variability plots). One hectare was considered as the minimum sample size to take into account the biomass and C stock variability within a tropical forest ecosystem (Chave, *et al.*, 2003). Designing and optimizing the sampling strategy require a good understanding of the biomass variability (Pearson et al, 2005). Biomass variability was analysed to identify optimum plot design. In Bobiri forest, the variability plots were located in selective logging (SL), tree shelterwood system, (TSS) and natural forest (NAT) in order to better represent the different management units.

➤ Normal plots

Nine, 27 and 13 plots of one hectare were implemented and a niche sampling strategy was designed to optimize the field measurement with accuracy and precision. The plots were divided into three



plots with different size namely XL (large), M (medium) and S (small) plots (Figure 37). While the big trees with DBH >50 cm were measured within the XL plots, the medium trees with DBH between 20 and 50 cm were measured within the M plots and the small trees and the liana with DBH less than 20 cm were measured within the S plots. The dead standing trees were measured on the XL plots. Litter and soil organic carbon were collected at the middle of each of the M plots (Figure 37).

Figure 37: Sampling design for the normal plots

Field measurements in normal plots were implemented following a niche sampling strategy where S3 (DBH<20cm), and S4 (liana), S5 (palm) were measured in four randomly sampled S plots (12.5 x 12.5m), S2 (20<DBH<50cm) was measured in four randomly selected M plots (25 x 25 m) and S1 (DBH>50cm) and S6 (dead trees) was measured in XL plots (100 x 100 m). Soil and litter samples were collected at the centre of the M plots.

2.3 Aboveground biomass

Trees DBH>2cm were inventoried. Tree species was identified using botanical handbooks (Hawthorne, 1990) and expertise from the logging companies team. The DBH was measured with a calliper and the tree aboveground biomass (AGBt) was estimated using the equation developed for Boi Tano forest reserve in chapter 5 which was considered as more representative of the forest types of Ghana than generalized equations (Chapter 4).

$$AGBt = 0.3 \times DBH^{2.3} \quad (1)$$

The liana aboveground biomass (AGBI) was estimated using the equation reported in Schnitzer *et al.* (2002).

$$AGBI = \exp(-1.484 + 2.657 \times \ln(DBH)) \quad (2)$$

Dead standing trees biomass and the dead biomass on the ground was estimated using the method developed by Pearson *et al.* (2005). For each of the categories, the biomass was estimated by subtracting the portion of biomass lost.

$$AGBd = AGB \times (1 - \%dead) \quad (3)$$

The biomass of palm trees was estimated using the equation reported by Brown (1997).

$$AGBp = 10 + 6.4 \times Ht \quad (4)$$

With Ht is total height (m) and n=25, r²=0.96. The height was measured with a Suunto. The herb layer and the epiphytes, which only represent a very small fraction of the biomass were not considered (Bernhard-Reversat, *et al.*, 1978).

2.4 Litter and belowground compartment

Soil samples were collected at 0-5, 5-10, 10-20 and 20-30 cm depth with a soil bucket auger (10 x10cm). Soil samples were sieved at 2 mm and oven-dried at 105 °C for 24 h. Samples were pooled and one analysis was made for each plot and/or soil layer. Soil pH was measured using a 1:2.5 soil/water or KCl solution. Total organic C was measured after dichromate oxidation and soil available P was measured after bicarbonate extraction. Exchangeable Cations were extracted with ammonium acetate at pH 7. The Effective Cation Exchange Capacity (ECEC) is calculated by summing the exchangeable cations determined from exchangeable bases and exchangeable acidity extraction method. Mineral particles of the clay, fine and coarse silt, and fine and coarse sand fractions were collected by mechanical analysis after the destruction of organic matter by H₂O₂ and dispersion in NH₄Cl. These methods are fully described in Anderson *et al.* (1993). Litter and other organic debris were collected using a 0.5 x 0.5 m quadrat. Litter was oven-drying at 70-80°C to a constant weight. The dried materials were sorted (leaves, small woody litter, reproductive structures and miscellaneous). All materials were expressed on an oven dry basis by re-drying sub-samples. The organic C was determined after dichromate oxidation. The root biomass was obtained using the root: shoot ratio presented in Pearson *et al.* (2005b) because it is more specific to the tropical regions than the general equation from Cairns (1997).

$$B_{Rtree} = \exp(-1.0587 + 0.8836 \times \ln(AGB)) \quad (6)$$

2.5 Carbon and biodiversity assessment

Conversion from biomass to C stock was achieved by multiplying biomass by the C content. Carbon content was measured for litter while it was assumed to correspond 47% for trees, palms and lianas (including roots) (IPCC, 2003). Aboveground and belowground carbon stocks were named AGC and BGC respectively in the text.

Several quantitative indices have been designed to provide information on the various aspects of plant diversity in landscapes. The Shannon index (SH) is used to measure diversity and is calculated by multiplying a species proportional abundance by the natural log of that number:

$$SH = -\sum p_i \times \ln(P_i) \quad (7)$$

where p_i is the proportion of individuals found in the species “i”. The plant functional type classification from Hawthorne (1995) was used to distinguish the different plant growth strategies.

3. Results

3.1 Floristic composition

Table 23 represents the most common families and tree species in the three forests. In total, 47 tree families and 365 tree species, from the 1360 species found in primary forest by Hall (Hall and Swaine, 1981), were identified while 4.5, 32 and 26% of tree species were not identified with scientific tree species name in Bobiri, Boin River and Boi Tano forest reserves respectively.

Most of trees in Bobiri forest belonged to *Sterculiaceae* (18%) while *Euphorbiaceae*, *Caesalpiniaceae* and *Meliaceae* represented 17, 10 and 10% of the tree population. The most common tree species was *Cleidion gabonicum* (13%) which was mainly found for DBH<20cm (14%). The most common tree species for 20<DBH<50cm and DBH>50cm were *Celtis zenkeri* (28%) and *Triplochiton sceroxylon* (21%) respectively. 85 different lianas species were identified with vernacular names. The biodiversity index SH ranged 0-3.13 within and 1.9 –2.2 between plots with average SH=2.53 ±0.02 (Figure 38). Higher biodiversity was found for small trees (2.19±0.02) > medium trees (0.85±0.02) > big trees (0.78±0.06) (<0.001).

The *Sterculiaceae* family was much more represented in Boin River forest with 41% of tree stems representing most of the small (30%) and medium trees (10%). The *Fabaceae*, *Ebenaceae* and *Lecythidiaceae* represented 12, 7 and 6% of the tree stems while the other families represented each less than 5%. The *Sterculiaceae* family was mainly marked by the presence of *Cola chlamydan* (88%). The *Fabaceae* family was exclusively represented by the presence of *Baphia nitida* and the *Ebenaceae* by *Diospyros sanza-min*. Most of the big trees belonged to *Caesalpiniaceae* family and mainly to *Dialium aubrevilliei* (51%). The biodiversity was significantly lower than in Bobiri forest with average SH=1.31 ±0.02 (<0.001) and ranged 0.3 – 2.6 within plots and 1.0-1.5 between plots.

In Boi Tano forest, the *Sterculiaceae* family represented 57% of the tree stems and were mostly found in the small trees (64%) while the *Caesalpiniaceae* represented 10% of tree stems but 17% of medium and 45% of big trees. 42% of small tree were *Scaphopetalum amoenum* while the other species represented less than 2% each. *S. amoenum* was very abundant in some plots while absent in others. *S. amoenum* was forming a dense understorey ticket by layering of its developing branches. Where *S. amoenum* was not found, *Microdesmis puberula* and *Coelocaryon oxycarpum* were the most common tree species.

Table 23: Floristic composition (most present families and species) SH corresponds to the Shannon index.

Bobiri					Boin River					Boi Tano				
Family	S1	S2	S3	Total		S1	S2	S3	Total		S1	S2	S3	Total
sterculiaceae	16	24	43	18	sterculiaceae	42	19	15	41	sterculiaceae	64	10	10	57
euphorbiaceae	19	3	0	17	graminae	13	3	1	12	Caesalpiniaceae	7	17	45	10
Caesalpiniaceae	11	5	2	10	ebenaceae	7	2	0	7	myrtaceae	4	8	3	4
meliaceae	9	15	7	10	lecythidiaceae	6	1	0	6	meliaceae	4	6	2	4
apocynaceae	10	4	0	9	Caesalpiniaceae	5	12	21	5	pandaceae	4	0	0	3
ulmaceae	7	26	18	9	pandaceae	5	0	0	4	guttiferae	2	15	6	3
pandaceae	7	0	0	6	meliaceae	4	14	14	4	graminae	3	0	0	3
Lecythidaceae	4	3	3	4	apocynaceae	5	3	0	4	euphorbiaceae	2	5	4	2
sapindaceae	3	4	2	3	anacardiaceae	3	1	0	3	anacardiaceae	2	1	0	2
graminae	2	0	0	2	olacaceae	2	5	1	2	apocynaceae	2	3	1	2
Others	12	17	24	12	Others	9	41	48	11	Others	8	34	29	11
Tree species	S1	S2	S3	Total		S1	S2	S3	Total		S1	S2	S3	Total
Cleidion gabonicum	14	0	0	13	Cola chlamydantha	25	0	0	25	Scaphopetalum	42	0	0	42
Funtumia elastica	8	4	0	7	Baphia nitida	8	0	0	9	Cynometra ananta	2	0	1	4
Celtis zenkeri	5	24	18	6	Diospyros sanza-	5	0	0	5	Coelocaryon	3	1	0	3
bafa mitiga	7	0	0	6	Napleonaea vogelii	4	0	0	4	microdesmis	3	0	0	3
microdesmis puberula	5	0	0	5	microdesmis	3	0	0	3	carapa procera	2	0	0	2
nesogordonia	4	7	11	4	tabernaemontana	2	0	0	2	Baphia nitida	2	0	0	2
Hymenostegia afzelii	4	2	0	4	Annickia polycarpa	2	0	0	2	Cola chlamydantha	2	0	0	2
bussea occidentalis	4	2	0	4	Dialium aubrevilliei	2	0	0	2	Annickia polycarpa	1	0	0	1
sterculia rhinopetala	4	5	5	4	Cola nitida	1	0	0	2	Napleonaea vogelii	1	0	0	1
trichilia priureana	4	3	0	3	turraeanthus	1	0	0	1	Gilbertiodendron	1	0	0	1
Others	33	54	66	35	Others	11	3	1	15	Others	10	5	3	18
SH	2.19	0.85	0.78	2.53		1.36	0.68	0.59	1.31		0.81	0.65	0.67	1.26
Dominant tree DBH>50cm	Triplochiton sceroxylon					Dialium aubrevilliei					Tarrieta utilis			

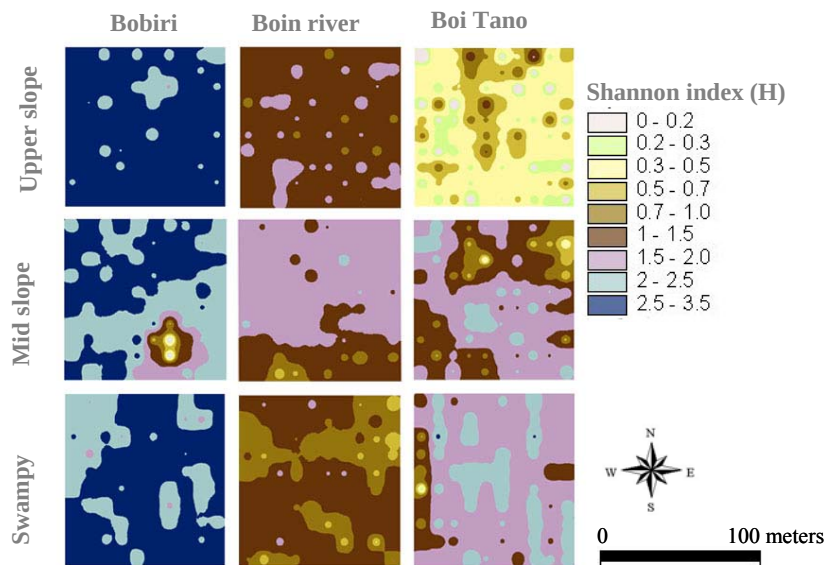


Figure 38: Spatial distribution of Shannon index in one hectare plots in three forest types and three landscape types in Ghana

Measurements were achieved every 10 meters and spatialization was achieved using a kriging procedure based on Euclidian distance.

Dacryodes klaineana was the most commonly found medium tree species (6%) while *Cynometra ananta* and *Tarrieta utilis* were the most commonly big tree species (28 and 12%). Only 7 types of liana were identified. Average biodiversity was lower than in Bobiri forest with average SH=1.26±0.02 (<0.001). Biodiversity ranged 0-2.6 within plots and 0.4 - 1.3 between plots.

While some common characteristics were found between forests, important differences were also found. Some families were well represented in Bobiri, Boin river and Boi Tano forests such as the *Sterculiaceae* (18, 41, and 4%), *Anacardiaceae* (0.2, and 3, and 2%), *Meliaceae* (10, 4 and 4%), and the *Pandaceae* (6, 4 and 3%) respectively. On the other hand, important proportion of small *S. amoenum* (*Sterculiaceae*) was present only in Boi Tano forest. In addition, the *Euphorbiaceae* represented 17% of the tree stems in Bobiri while only 1 and 2% in Boin River and Boi Tano forests respectively. The *Aracaceae* (palm trees) were found only in Bobiri forest reserve (14 stem ha⁻¹) and Boin River forest (24 stem ha⁻¹) while not in Boi Tano. Palm tree were however very abundant in swampy areas while absent in the rest of the areas. *Celtis Zenkeri* was found only in Bobiri forest while *Heritiera utilis* was found in Boin River and Boi Tano while not in Bobiri. Biodiversity variation was found to be the highest in Bobiri than in Boin River or Boi Tano forests.

When considering the plant functional types, the presence of Non Pioneer Light Demander (NPLD) trees was higher in Bobiri (1119 ±72 stem ha⁻¹) than in Boi Tano River (168±19 stem ha⁻¹) and Boin River (144 ±28 stem ha⁻¹) (<0.0001). On the other hand, more swampy trees were found in Boi tano and more shade bearer (SB) tree were found in Boin River (<0.0001). While there were no significant differences of NPLD tree density between plots in Boin River and Boi Tano, there were important

variations between plots in Bobiri with TSS: 1560 stems ha^{-1} > SL: 1010 stems ha^{-1} > NA: 797 stems ha^{-1} (<0.0001). Differences were also observed for Pioneer trees with NA and TS > SL (<0.005) while not for shade bearer. On the contrary, in Boin River, the proportion of Shade bearer trees was significantly different between plots (<0.0001). The landscape influenced significantly the distribution of plant functional types. Shade bearer trees were more abundant in upper slope than in swampy areas. In Boi Tano, shade bearer trees were mostly represented by *S. amoenum* in upper slope while NPLD trees were more abundant in swampy areas. The proportion of Pioneer trees was higher in sloppy areas but was not significantly influenced (>0.05). There were less swampy tree species in upper slope and slope areas than in swamp areas. Plant species richness was decreasing with tree size.

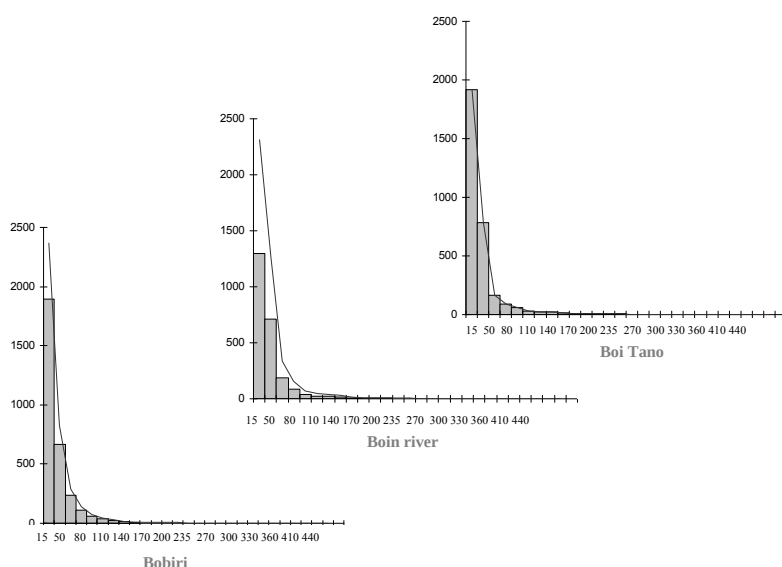


Figure 39: Tree distribution into girth classes of 30cm

3.2 Forest structure

Stem density was higher in Bobiri forest ($4,305 \pm 180$) than in Boin River ($3,610 \pm 132$) and Boi Tano forests ($3,563 \pm 170$). Significant differences were observed between plots in Bobiri with stem density TS: 5,634, >NA: 3,809 >SL: 3,468 (<0.0001). However, important proportion of stems in Bobiri was found to be liana (34%). The liana density was significantly different between forests with Bobiri: 34% > Boin River: 14% > Boi Tano: 9% (<0.001). The proportion of liana per tree was also higher in Bobiri: 0.5 > Boin River: 0.2, Boi Tano: 0.1. Significant differences was also found between plots of the same forest with the highest proportion of liana found 1644 liana ha^{-1} in TSS plot in Bobiri forest reserve and the lowest 207 liana ha^{-1} in Boi Tano. When considering only trees, the stem density was not significantly different between forests with tree density ranging 2,083 – 4,262 between plots and 100-8,900 stems ha^{-1} within plots and significant differences were found between plots in each of the three forests. Standing dead density was found 27 ± 7 stems ha^{-1} .

Most of the tree stems were found for the small diameters with tree with DBH < 10cm representing 88, 85 and 87% in Bobiri, Boin River and Boi Tano respectively (Figure 39). The number of tree stems decreased following a negative exponential and reached 24, 26 and 33 stems ha^{-1} for DBH > 50 cm,

and 4, 2 and 1 stems ha^{-1} for $\text{DBH} > 100\text{cm}$. While very big trees ($\text{DBH} > 125\text{cm}$) were found in Bobiri, they were not found in Boin River and Boi Tano. The Figure 40 represents the distribution of plant functional types with diameter. The figure shows that the frequency of pioneer and NPLD tree species is increasing with diameter while the frequency of shade bearer and swampy tree species is decreasing.

The proportion of plant functional types varies between forests. Most of the trees with $\text{DBH} > 50\text{cm}$ were Pioneer and Non Pioneer Light Demander in Bobiri and Boin River forest, while they were Shade Bearer in Boi Tano forest (*Cynometra ananta*: 73%). Only Pioneer and Non Pioneer Light Demander trees were found to reach 100 cm of DBH in Bobiri and Boi Tano. The most common trees with $\text{DBH} > 100\text{cm}$ were *Triplochiton sceroxylon* and *Ceiba pentandra*, *Cylicodiscus gabunensis* and *Ceiba pentandra*, *Piptadeniastrum africanum* and *Parkia bicolor* in Bobiri, Boin River and Boi Tano forest reserves respectively. Swampy trees were largely under-represented in tree $\text{DBH} > 50\text{cm}$ and represented an average of 0.4 stem ha^{-1} . Swampy tree species represented most of the tree population with $\text{DBH} < 20\text{cm}$ in Boi Tano (1,875 stems ha^{-1}) while less in Bobiri (310 stems ha^{-1}) and Boin River (313 stems ha^{-1}). In Boi Tano, shade bearer tree species were dominated by *S. amoenum*. When considering only trees $\text{DBH} > 50\text{cm}$, it appeared that NPLD trees were more abundant in upper slope in Boin River while in swampy areas in Boi Tano while no significantly influenced in Bobiri. Pioneer trees were generally more abundant in slope, upper slope areas and TSS in Boin River and Boi Tano and Bobiri respectively. Shade bearer trees were mostly found in upper slope, slope and SL in Boin River and Boi Tano and Bobiri respectively.

While there were no significant difference in term of basal area between forest types (average = $32.6 \pm 3.2 \text{ m}^2$), the basal area ranged 31-37, 26-44 and 26-35 $\text{m}^2 \text{ ha}^{-1}$ between plots in Bobiri, Boin River and Boi Tano respectively. The curves representing the tree density in relation with tree girth represented a strong sciaphilous tendency of the species (Figure 39). The most sciaphilous behaviour was found in Bobiri and Boi Tano and the most heliophilous in Boin River but this is not evident as important variations were found within each forest. When considering tree mortality, it was not proportionally influenced by diameter and was not significantly different between forests (< 0.05). 76% of the dead stems had $\text{DBH} < 20\text{cm}$ while only 1.6% had $\text{DBH} > 100\text{cm}$. On the other hand, dead tree represented 33% of the basal area of tree $\text{DBH} > 100\text{cm}$.

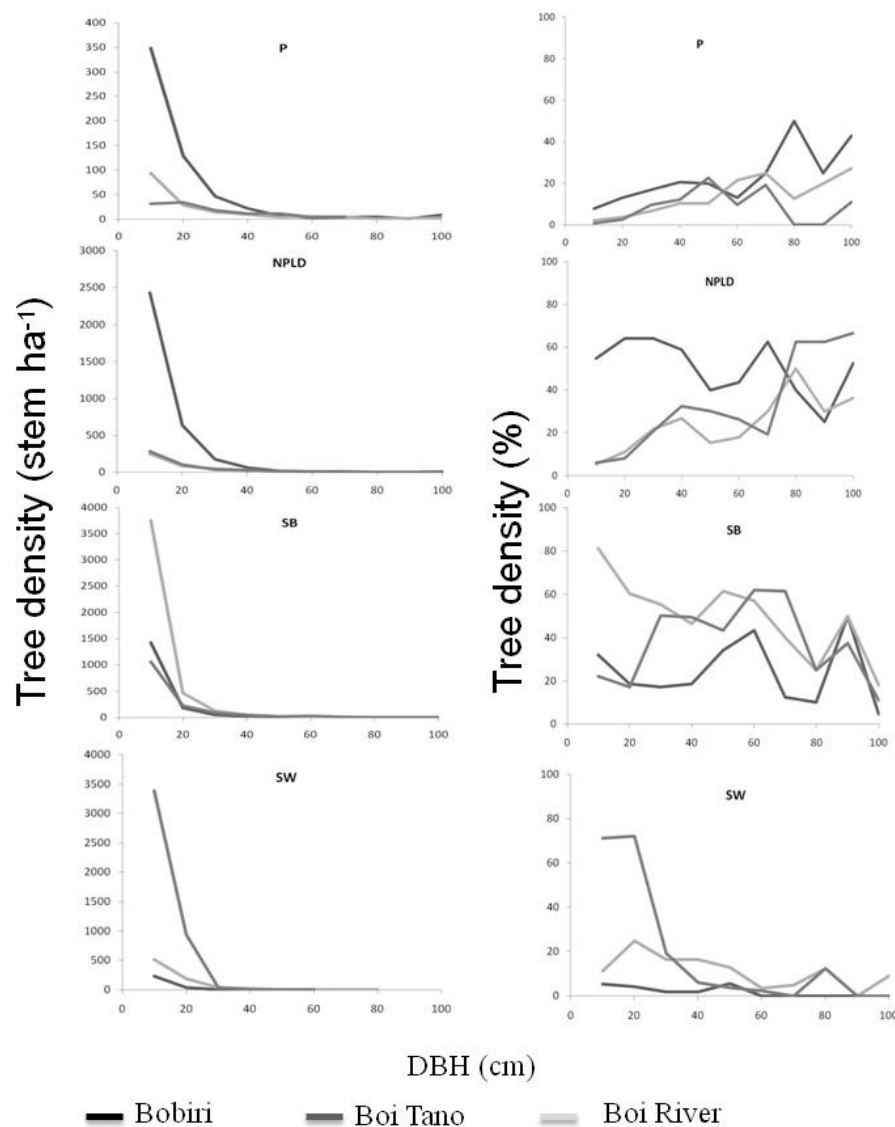


Figure 40: Distribution of plant functional type with diameter classes

3.3 Soil properties

Important differences of soil chemical properties were found between forests. Higher precipitation was correlated with more acid soil with pH in Bobiri: 5.83 ± 0.18 > Boi Tano: 3.87 ± 0.08 = Boi River: 3.71 ± 0.22 (< 0.001) (Table 24). Our results confirmed that pH which is a reasonably good indicator of soil fertility (Sollins, 1998). Chemical parameters (phosphorus, potassium, calcium, sodium, Total Exchangeable Bases) were found to significantly decrease with higher precipitation and pH. The cationic exchange capacity, the base saturation, was lower with more rainfalls (Boi tano, Boi river) while exchangeable acidity was found lower in Bobiri than the other forests. On the other hand, the C content was significantly higher on soils located on the upper Birimian type (BR: 6.1 ± 1.6 > BB: 1.9 ± 0.2 = BT: 1.6 ± 0.3). However important variability is found within the forests. For instance, within one hectare plot the C content ranged 3.12-24.7 in Boi River and 0.67 - 7.24 in Bobiri. The variation between plots varied with C content ranging 1.1 - 2.7 in Bobiri, 0.9-2.1 in Boi Tano and 2.6-9 in Boi River. Important variations were also found for the other soil properties such as the pH. In Bobiri the

pH ranged 3.5- 7.7 within one hectare and 5.1-7.1 between plots. Phosphorus was significantly higher in Bobiri (13.4 mequ/100g) than in the other forests (BR: 4.1, BT: 8.9) (<0.001).

The variation of chemical properties varied firstly with soil depth (Figure 41). All soil chemical parameters decreased with soil depth except the pH which was increasing with soil depth in Boin River and Boi Tano while the contrary was observed for Bobiri. In average the carbon concentration decreased by about 71% between 0 and 30 cm soil layers with significant difference between the forests. The decrease of chemical parameters was much less pronounced in Boi Tano and was not significant for Mg, Ca, CEC and TEB. Soil nutrients were influenced by landscape. Upper slope contained more clay, were more acid, contained less potassium, less base, more sodium and the cationic exchange capacity was higher. In term of agronomic purpose, those soils can be considered as low fertile or deficient with the limit for P between deficient and deficient around 15 ppm.

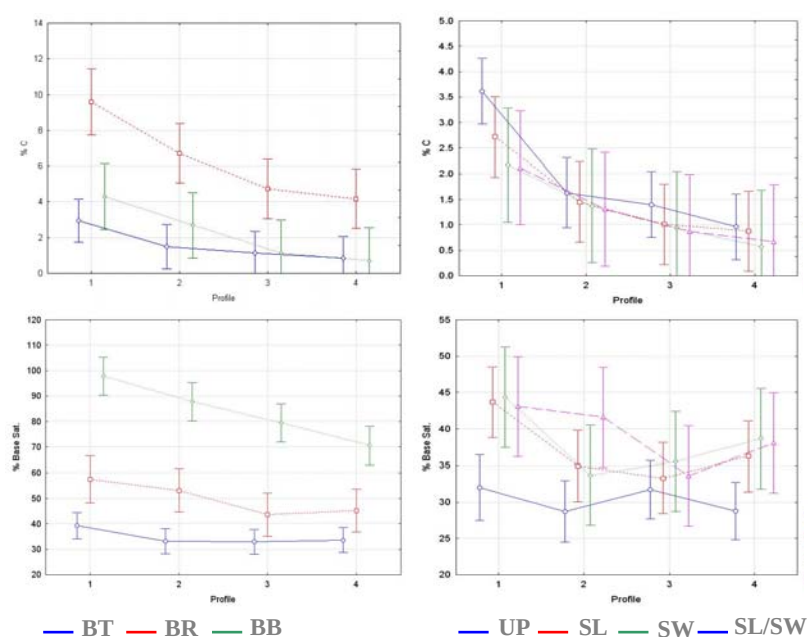


Figure 41: Soil organic carbon and base saturation variations with soil depth and topography

Table 24: Soil chemical properties ($\pm$ IC)

PH: hydroelectric potential, % C: carbon content, %OM: organic matter content, ppmP: phosphorus, ppmK: potassium, Ca calcium (me/100g), Mg: magnesium (me/100g), K: potassium, Na: sodium (me/100g), T.E.B. Total exchangeable bases (mmolc 100 g⁻¹), Ex.Acidity: exchangeable acidity (Al+H), ECEC: effective cation exchange capacity

	Bobiri forest reserve - moist semi-deciduous								Boi Tano Forest Reserve - wet evergreen								Boin River forest reserve - moist evergreen							
	Soil profile (cm)																							
Soil properties ($\pm$ CI)	0- 5 cm		5 - 10		10 - 20		20 -30		0- 5 cm		5 - 10		10 - 20		20 -30		0- 5 cm		5 - 10		10 - 20		20 -30	
PH	6.3	± 0.3	5.9	± 0.3	5.7	± 0.4	5.5	± 0.4	3.6	± 0.2	3.7	± 0.2	4.0	± 0.1	4.1	± 0.1	3.5	± 0.5	3.7	± 0.5	3.8	± 0.4	3.9	± 0.5
%C	3.8	± 0.5	2.0	± 0.4	1.1	± 0.1	0.7	± 0.1	2.9	± 0.7	1.5	± 0.2	1.1	± 0.2	0.8	± 0.1	9.6	± 5.3	6.7	± 2.8	4.7	± 2.3	4.2	± 2.2
%OM	6.4	± 0.8	3.5	± 0.6	1.8	± 0.2	1.2	± 0.1	5.1	± 1.3	2.6	± 0.4	2.0	± 0.4	1.5	± 0.2	16.5	± 9.2	11.6	± 4.8	8.1	± 3.9	7.2	± 3.8
ppmP	13.4	± 2.8	7.4	± 2.0	5.1	± 1.6	4.3	± 1.1	10.4	± 2.0	3.2	± 1.0	1.0	± 0.4	2.2	± 1.0	5.1	± 1.9	2.3	± 1.1	3.1	± 2.7	5.2	± 4.0
ppmK	187	36	109	16	95	15	83	15	94	19	68	10	62	10	57	9	143	57	103	42	77	34	68	26
Ca	14.2	± 2.5	7.4	± 2.1	5.0	± 1.2	3.5	± 0.8	1.2	± 0.2	0.8	± 0.1	0.7	± 0.1	0.7	± 0.1	16.7	± 12.0	9.5	± 6.6	6.2	± 5.3	4.3	± 3.3
Mg	3.9	± 0.6	2.1	± 0.4	1.3	± 0.3	1.1	± 0.2	0.5	± 0.1	0.3	± 0.0	0.3	± 0.1	0.3	± 0.0	5.8	± 4.0	3.5	± 2.1	2.4	± 1.6	2.0	± 1.6
K	0.7	± 0.1	0.4	± 0.1	0.3	± 0.1	0.3	± 0.0	0.2	± 0.0	0.1	± 0.0	0.1	± 0.0	0.1	± 0.0	0.6	± 0.4	0.6	± 0.3	0.4	± 0.2	0.3	± 0.1
Na	0.2	± 0.0	0.2	± 0.0	0.1	± 0.0	0.1	± 0.0	0.2	± 0.0	0.1	± 0.0	0.1	± 0.0	0.1	± 0.0	0.3	± 0.1	0.2	± 0.1	0.2	± 0.1	0.2	± 0.1
T.E.B.	63.6	± 86.9	10.1	± 2.5	6.8	± 1.5	4.9	± 0.9	2.0	± 0.3	1.4	± 0.1	1.2	± 0.2	1.2	± 0.1	23.3	± 16.0	13.8	± 9.0	9.1	± 7.0	6.7	± 4.9
Acidity	0.4	± 0.1	0.6	± 0.2	0.9	± 0.2	1.1	± 0.3	2.8	± 0.2	2.7	± 0.2	2.4	± 0.2	2.3	± 0.2	3.0	± 0.7	2.9	± 0.6	2.8	± 0.5	2.6	± 0.6
ECEC	19.9	± 3.2	10.7	± 2.4	7.7	± 1.4	6.1	± 0.8	4.8	± 0.4	4.3	± 0.6	3.6	± 0.3	3.5	± 0.2	7.3	± 0.8	7.7	± 3.6	5.1	± 0.7	5.0	± 0.9
%Base sat	97.0	± 1.8	90.2	± 3.9	84.3	± 5.0	78.2	± 6.3	39.4	± 3.5	33.2	± 3.1	33.0	± 2.6	33.7	± 2.9	57.5	± 12.1	53.2	± 16.3	43.6	± 12.6	45.3	± 13.1

3.4 Variation of biomass with habitat

Tree biomass and wood samples were collected in chapter 5 and allowed the development of allometric equations making the relation between the tree DBH and the different tree components. Most of the biomass corresponded to the trunk biomass (60%), the woody branch biomass (24%) and the rest 26%. The total biomass was not significantly different between forests with average $448 \pm 25 \text{ Mg ha}^{-1}$ (Figure 42).

A closer look at the different ecosystems compartments revealed that litter represented only 1.3% of the total biomass and roots 7.4% while AGB represented 91.3%. Litter content was significantly higher in Bobiri than in Boi Tano (BB: 2.7 ± 0.12 < BT: 6.0 ± 0.18). When considering only the aboveground compartment, 92, 3.6, 0.04 and 4.3% of biomass was contained in tree, dead standing tree, liana and palm trees. Important differences were found between forests. Palm trees biomass represented 0.72 and 1.14 Mg ha^{-1} in Bobiri and Boin River respectively. Liana biomass was not significantly different between the forests with an average $8.47 \pm 1.13 \text{ Mg ha}^{-1}$ revealing an important variation within forests. Liana biomass was found to vary 6.43-9.45 Mg ha^{-1} between forests and 5-14, 5-35 and 3-10 Mg ha^{-1} in Bobiri, Boin River and Boi Tano respectively. The tree biomass was higher in Bobiri ($364 \pm 34 \text{ Mg ha}^{-1}$) than in Boin River ($348 \pm 23 \text{ Mg ha}^{-1}$) and Boi Tano ($355 \pm 32 \text{ Mg ha}^{-1}$) but was not significantly different between forests because important variations were found within forests. Tree biomass ranged 280-460, 218-485 and 262-454 Mg ha^{-1} between plots in the different forests in Bobiri, Boin River and Boi Tano. The landscape significantly influenced tree biomass variability (Figure 43) and higher biomass was found in slope areas (392 ± 73 and $493 \pm 97 \text{ Mg ha}^{-1}$) than in upper slope (323 ± 53 and $282 \pm 61 \text{ Mg ha}^{-1}$) and swampy areas (262 ± 49 and $248 \pm 68 \text{ Mg ha}^{-1}$) in Boi Tano and Boin River respectively (<0.05). In a drier climate (Bobiri), tree biomass in swampy areas ($462 \pm 159 \text{ Mg ha}^{-1}$) was significantly higher than in slope ($354 \pm 73 \text{ Mg ha}^{-1}$) and upper slope areas ($228 \pm 77 \text{ Mg ha}^{-1}$). Higher tree biomass variations were found in swampy areas because of the presence of dead felled trees and sometime gaps in the forests. On the other hand, liana biomass was found to be significantly higher in upper slope (6.9 ± 1.4 and $35 \pm 8.3 \text{ Mg ha}^{-1}$) and swampy (7.2 ± 2.7 and $5.6 \pm 2.2 \text{ Mg ha}^{-1}$) areas than slope areas (4.4 ± 2.7 and $4.8 \pm 1.9 \text{ Mg ha}^{-1}$). Similar trend was observed in Bobiri but was not significant. Higher dead standing biomass was found in

swampy and upper slope areas than slope areas in all forests (<0.05).

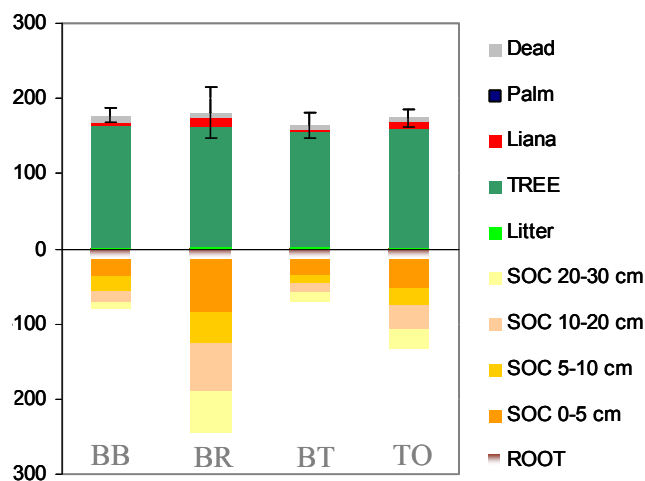


Figure 42: Distribution of carbon stocks in the different ecosystem compartments

3.5 Variation in biomass across the plots

Within plots of 1 ha, total biomass ranged 0 - 4,681 Mg ha⁻¹, and was mainly influenced by the presence of few big trees (Figure 43). Higher variations were found in Bobiri (SD=492, SD=500), than in Boin River (SD=385, SD=406) and in Boi Tano (SD=292, SD=308) for stratum 3 and total biomass. Stratum 3 represented 99% of AGB variability and represented 17% of it. When looking at the distribution at the biomass, it appeared that 16, 8, 14% of the biomass was found in stratum 1, and 20, 33 and 29 % in stratum 2 while trees with DBH>100cm were rare but represented 18, 15 and 6% of the total ecosystem biomass in Bobiri, Boi Tano and Boin River respectively. Biomass was found to be significantly different between different landscape units, stratum and forests. However, most of the biomass variability was captured by few big trees.

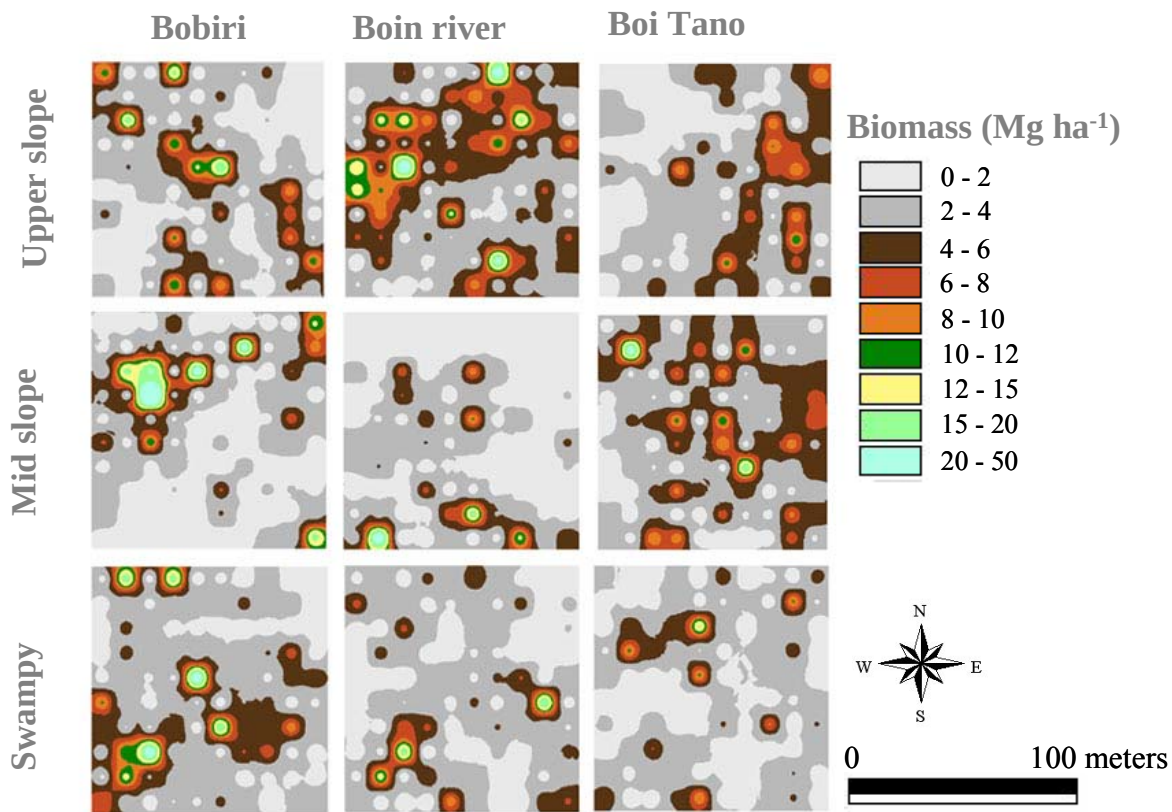


Figure 43: Spatial distribution of aboveground biomass in one hectare plots in three forest types and three landscape types in Ghana

3.6 Above and belowground carbon stocks

Average ecosystem C stock was 355 Mg C ha⁻¹ from which 51% is aboveground, 48% is belowground and 1% is contained in litter (Tab.5). 81% of BGC were soil organic carbon (SOC) and the rest was roots. 30% of the soil carbon stock was found for the 0-5cm soil layer. 51, 32 and 13 % of AGC were found in stratum 3, 2 and 1 while 1.57, 1.71 and 0.4% of the AGC were liana, dead wood and palm trees. However, important variations were found between and within forests. Carbon stocks were significantly higher in Boin River (427 Mg C ha⁻¹) ranging 348-505 Mg C ha⁻¹ within that forest (<0.0001). Variation of C stocks in Bobiri and Boi Tano were higher and were averaged 283±20 and 282±15 respectively. Higher SOC and litter C content in Boin River would mainly explain higher carbon stocks. However, litter carbon stock was higher (<0.0001) in Boi Tano, than in Boin River than in Bobiri (BT: 2.1>BR: 1.8>BB: 0.9). The ratio between above and belowground biomass was significantly lower in Boin River (0.74) than in Bobiri (2.12) and Boi Tano (2.09). When considering AGC, it was not significantly different between forests revealing no evident relation between above and BGC. Most of AGC were live trees while lianas represented only 1.6% of it but can represent in open canopy places up to 18% of AGC. About half of the AGC was contained in trees with DBH>50cm. Most of the C spatial variability was due to the frequency of tree with DBH>50cm. There were lower C stocks in big trees in swamps (65 Mg C ha⁻¹) than in slope (83 Mg C ha⁻¹), than in upper slope (89 Mg C ha⁻¹). This influenced the total AGC which resulted to be significantly higher in upper slope (206 Mg C ha⁻¹) than in swampy areas (160 Mg C ha⁻¹).

Table 25: Distribution of ecosystem carbon stocks (Mg C ha⁻¹ ±IC)

Compartments	Bobiri forest reserve		Boin River Forest reserve		Boi Tano forest reserve	
Soil Organic carbon						
0 - 5 cm	22.55	±4.36	61.38	±4.02	20.08	±3.02
5 - 10 cm	13.37	±3.18	42.55	±2.35	10.75	±1.14
10 - 20 cm	13.51	±1.93	59.84	±3.91	15.71	±1.58
20 - 30 cm	8.79	±1.24	52.99	±4.02	12.10	±1.40
Roots	13.15	±1.30	11.66	±0.83	11.86	±0.89
Litter	0.86	±0.14	1.81	-	2.08	±0.25
Liana	4.47	±0.88	2.01	±1.14	3.22	±0.51
Dead	1.44	±0.74	1.12	±0.19	7.90	±0.00
Palm	3.05	±2.34	0.18	±0.02	0.00	±0.00
DBH<20cm	37.19	±3.54	14.82	±2.97	30.81	±2.25
20<DBH<50cm	46.84	±5.54	61.96	±8.26	65.26	±5.09
DBH>50cm	98.33	±14.54	97.32	±9.16	81.55	±9.26
Total	263.55	±18.30	407.63	±12.27	261.33	±13.87

3.7 Factor influencing biodiversity and carbon stock distribution

I have seen above that topography influenced the distribution of biodiversity and C stocks in landscape. Up to 40% of the tree stems could be found as pioneer trees with average density of 280-300 tree ha⁻¹. I

observed that pioneer trees were particularly more abundant with higher P and cations (<0.005 , $F=9$, and <0.0001 , $F=34.4$). While Ashton (1992) reported the same thing I also noted the same thing for the base concentration (<0.0001 , $F=64.6$). On the other hand, I observed more Shade Bearer with low CEC (<0.01 , $F=8.9$) and less NPLD with less base (<0.001 , $F=41.7$). Canopy gap is also an important factor but its consideration requires the implementation of permanent sample plots. When analysing the leaf area index I observed that the higher leaf area index was related to lower pioneer tree density in the TSS plot while lower NPLD in the NA plot in Bobiri. On the other hand, the analysis of the leaf area index in one plot (NA) in Bobiri forest revealed that higher Leaf Area Index is synonym to higher biodiversity (<0.0001 , $n=100$, $F=41.9$). On the other hand, while higher biodiversity is not related to biomass (>0.05), I observed higher biodiversity with higher biomass for stratum 1 and 2 (<0.0001) while not for stratum 3. In addition, higher LAI was found to be correlated with higher biomass in stratum 1 and 2 while not for stratum 3. There were no relation between LAI and biomass and biodiversity for palms and liana. Moreover, LAI and H were partially related to biomass and the relation depended on the considered population. When considering the other plots in Bobiri, no significant relation was found. The relation was very site dependant and very influenced by the variation of canopy opening. In denser canopy forests, the relation between AGC, H and LAI was less or non significant.

4. Discussion

4.1 Floristic composition is influenced by soil, climate, topography and anthropic factors

The three forests were different in term of floristic composition and structure and various factors were influencing between and within forests variations. Bobiri forest was characterized by *Triplochiton scleroxylon*, Boin River by *Dialium aubrevilliei* and Boi Tano by *Cynometra ananta* and *Tarrietia utilis*. As reported by Hall (1981), and Khan (Kahn, 1982) moist deciduous forest was characterized by the presence of *B. nitida* and *M. puberla* were mainly found in the moist evergreen. The floristic composition gives an indication about the evolution status of the forest. The presence of *Triplochiton scleroxylon* and *Terminalia superba* in Bobiri forest was typical of a secondary forest according to Guillaumet (1967). The presence of liana would be an indicator of a secondary forest (Kahn, 1982), of canopy opening and treefall gaps (Schnitzer and Bongers, 2002) or richer soils (Janzen, 1974). I however attribute the higher frequency of lianas in Boin River and Bobiri to logging activities.

The Figure 44 reports the frequency of indicator tree species for climax and pre-climax forests. While climax tree species were present in small diameters in Bobiri and Boin River, they were mostly found for big diameters in Boi Tano. On the other hand, the pre-climax tree species were more frequent in Bobiri. According to Kahn (1982), Boi Tano can be considered at the climax phase while Boin River and Bobiri would be in the pre-climax phase. *Microdesmis puberla* which is a typical tree species found in climactic forests was mostly found in Boi Tano. The structure (Figure 39) of the forests also confirms this hypothesis. Figure 40 reports the higher frequency of pioneer trees in Bobiri that can be interpreted as a heliphilous behaviour (Bernhard-Reversat, *et al.*, 1978) while the higher frequency of small diameter

classes in Boi Tano correspond to a sciaphilous behaviour (Kahn, 1982). According to Ashton (1992), the higher frequency of Pioneer trees in Bobiri can be explained by the higher phosphorus and cation rich soils content. On the other hand, the presence of previous fires can be noted by the presence of facultative savanna trees such as *Anogeissus leiocarpus*, *Azizica africana* or oil palm such as *Elaeis guineensis* in Bobiri (Swaine, *et al.*, 1997). Moreover, the plant species indicate us that the forest would have been perturbed before by canopy opening and fire damages.

It is generally accepted that in a tropical rain forest the distribution of tree species is governed by physical soil factors and topography than by chemical factors such as pH. It is however difficult to know how (Sollins, 1998). The soil properties I measured were similar to those reported in the literature. Swaine, Agyeman *et al.* (1997) reported similar soil chemical properties for Draw River (wet evergreen) and Tinte Bepo (Moist Semi-Deciduous). I also observed increase TEB, CEC with lower rainfall as reported by Hall and Swaine (1981). While Sollins (1998) reported the most significant parameters in decreasing order of importance were: P availability, Al toxicity, drainage, water holding capacity, and availability of K, Ca and Mg it is difficult in our study to understand the trend because within and between the plots spatial variation was important and not considered in the previous studies. Soil influences species richness. I found lower biodiversity on poorer soils. In addition, as noted in our study, the presence of Caesalpiniaceae is higher where P is low (Newbery, *et al.*, 1986).

Veenendaal, Swaine *et al.* (1996) reported that soil in the wet evergreen forests were more acid (pH<4.87) than the soil from the moist semi-deciduous forest (pH>6.12). It also had lower concentrations of total N, P, K, Ca and Mg, particularly in topsoil.

This has impact on the nutrient availability and several studies analysed the potential for seedling regeneration according to the nutrient availability (Hawthorne, 1993, Swaine, *et al.*, 1997) reported that seedlings grown in wet evergreen forest soil showed reduced leaf foliar concentrations of P, Ca and Mg. Foliar nutrient concentrations, particularly of P and Mg were lower in species found in the wet evergreen forest. A closer look at the potential growth of seedling reported that in less fertile soils root growth rate was higher for pioneer (*L. alata*) than for NPLD.

Climate is a determinant of species distribution with higher species richness to be expected in wetter climates (Hall and Swaine, 1981). While poorer soils are found on wetter climate it becomes difficult to explain the low biodiversity found in Boi Tano. However, Wright (1992) reported that the relationship between species densities and soil fertility is highly variable between sites. The explanation for our study comes from Hall and Swaine (1981) who found two forests from the 155 forest plots they inventoried to be dominated by *S. amoenum* (Jenik, 1969). This type of forests, was also identified in Ivory Coast and were characterized by FAO (FAO, 1984) for the important water capacity retention. The abundance of *S. amoenum* in Boi Tano can be responsible for low biodiversity while the other wet forest of Ghana were found to contain more species richness (Hall and Swaine, 1981).

While I do not have any explanation about the presence of *S. amoenum* in some forests of Ghana, our knowledge about species composition is poor. Some species that were mentioned in our study were not mentioned by Hall (e.g. *C. Gabonum*). While Hall (1981) did an important inventory (155 plots), the

sample size was however limited, and may have not captured the spatial variation of species richness. While the total number of species may stabilize for a plot size of 3,000m² in Boin River and Boi Tano, the number of tree species continues to increase after 10,000m² (Figure 44).

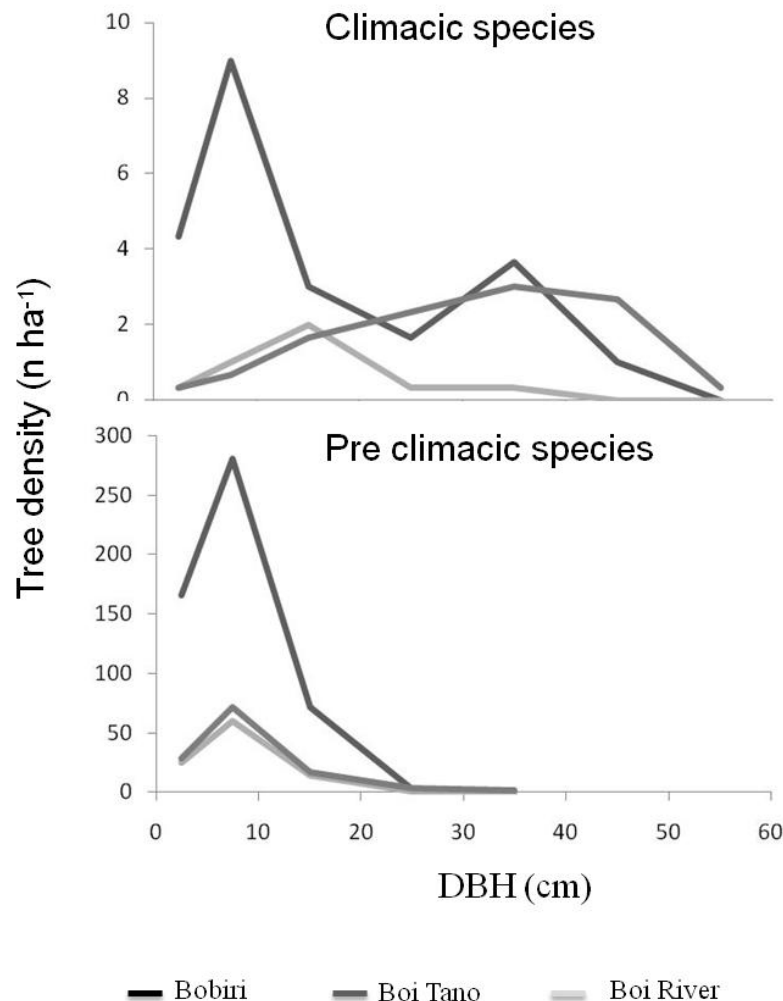


Figure 44: State of forest reconstitution of Bobiri, Boin River and Boi Tano forests

According to Kahn (1982), the presence of *Funtumia elastica*, *Fagara macrophylla* and *Albizia zygia* characterize the reconstitution phase, and *Piptadeniastrum africanum*, *Uopaca esculenta* and *Canarium scweinfurthii* characterize the climax phasis.

4.2 Variation of biomass and carbon stocks

About half of the carbon stock is located aboveground but vary according to soil type, topography, climate and previous natural and anthropic perturbations. (Anderson and Spencer, 1991) reported lower belowground carbon stocks while much higher litter ranging 6-74 while I reported 2 Mg ha⁻¹ in our study. Our study report also that tree biomass ranged 218-454 Mg ha⁻¹ in one hectare plots and 0-4,681 Mg ha⁻¹ in 100m² plots. This provides us two informations.

First, aboveground biomass varies by a factor more than two between forests. Maniatis (submitted) reported AGB ranging 24 - 483 Mg ha⁻¹ and Couralet (2009) 82 – 1,107 Mg ha⁻¹ which intervals were higher than in our study. On the other hand, Heather, Mackey et al. (2009) reported biomass 50-210 Mg ha⁻¹ in European forests, and up to 1,867 Mg of carbon per ha in Australian temperate moist Eucalyptus regnans forests. Moreover, forest biomass vary significantly between forests and the use of average biomass and carbon stocks such as in Gibbs (2006b) does not help in better understanding the biogeochemical cycles.

Secondly, within plot size has to be enough important to capture the biomass variability. Smaller is the size of the plots, higher is the number required to estimate the forest biomass (Figure 45). Within the 1-ha plots, the mean standard deviation was 414 Mg ha⁻¹, and the 95% confidence interval on the mean AGB was around 27 Mg ha⁻¹. For small subplot sizes (100 m²), the distribution of AGB estimates was strongly skewed to the left, but as subplot size increased, the sampling distribution was more symmetric. Based on Figure 45 and the forest reserve land area for Ghana, it results that 66, 113 and 1,399 plots of 1 ha are necessary to estimate AGC within ± 20, 10 and 5% of the mean at national scale. On the other hand, it is necessary to implement 54,721 plots of 100m² to estimate AGC within ±5%. Moreover, understanding the forest functioning depends also on the methods. Heather, Mackey et al. (2009) didn't considered the plot size. Without taking into consideration the plot size it will mean that the highest biomass of the world was found in Bobiri (4,681 Mg ha⁻¹ in a 100m² plots).

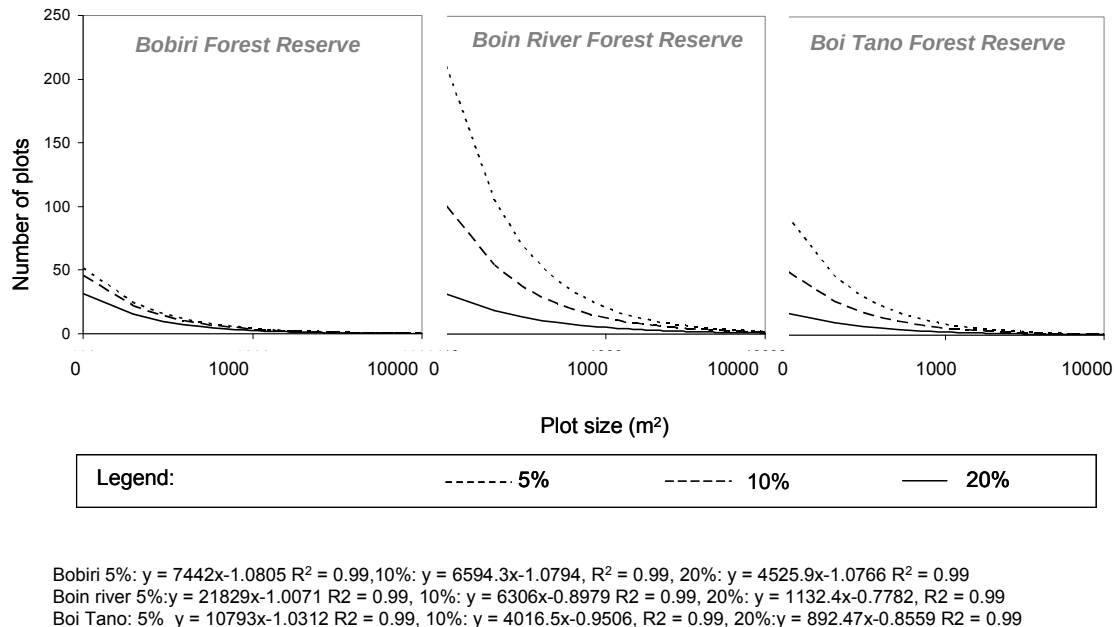


Figure 45: Influence of variability and plot size on the estimation of biomass

Despite the important within plot variation, the carbon stocks were higher in Boin River than in Bobiri and Boi Tano which is mainly explained by the higher carbon content in soil. Schistic soils are known to contain more soil organic carbon than granitic soils. Even if the forest was logged 50 years ago, the

carbon stocks are higher than in an unlogged forest such as Boi Tano. In Boi River, the lianas can contribute up to 30% of the aboveground biomass in some plots. While most of the forest inventories for logging companies do not consider the liana, this clearly limits their use for carbon stock estimation.

When considering the tree compartment, the basal area and the biomass were not significantly different. Dawkins (1959) and Hall and Swaine (1981) reported that density of trees and basal area do not differ appreciably between forest types, it thus seems reasonable to assume that variation in maximum tree height will be paralleled by variation in total biomass. The tree height was reported to be higher in Bobiri, than in Boi River and Boi Tano, and the tree density was not significantly different in our study. Hall (1981) reported that height increases with increasing rainfall until a maximum is reached in the 1250-1750 mm class. This variation is the results of the absence from the driest and wettest forests of the species which attain greater heights elsewhere, but this is not simple because *Ceiba pentandra* are shown to have the same trend in the various ecological zones. Decline in tree canopy height under the highest rainfall is possibly the result of poor nutrient status in highly leached soils of the wettest forests. In fact the lowest TEB occurred in the forest with rainfall. I would expect significant different biomass estimates between forests. It was not possible to measure the tree height because of the canopy density and it was not possible to see the top of the crowns. Moreover, I used an equation based on the diameter while not taking into account the different relation that would occur between diameter and height in the different forests. In this case, it is preferable to use site-specific allometric density, based on the diameter but which consider the forest structure or the soil properties such as TEB.

4.3 Toward a better understanding of tropical forest ecosystem functioning

Most of the studies in tropical rainforest analysed the effect of major perturbations such as fires (Hall and Swaine, 1981), selective logging (Swaine, *et al.*, 1997) and agriculture (Kahn, 1982, Floret, *et al.*, 1993) on the forest dynamics. However, very few studies analysed the variability found within the forests without directly considering the effect of perturbations. Our study is a first attempts to understand the functioning of the tropical rainforest in Ghana and considering the spatial variability of resources allocation. Our study is however limited by various considerations. While the equation I used was specific for tropical rainforest for tropical rainforest in Ghana, it significantly under-estimated the woody biomass of 7.3% in comparison with the equation provided by Alder (1982) that was developed based on 101 sample trees. While our study highlights the important spatial variability, our study is not able to capture the variability due to species composition or the landscape because the wood density was not collected for all the different tree species and the different topographic units.

On the other hand, soil water retention clearly influences the tree growth and the evapotranspiration but it is very difficult to measure it because it requires permanent experiments because of important annual variations. The water pathway is influenced by rainfall regime, evaporative conditions and canopy structure. Tree growth was not measured because it requires even longer term experiments. It is also difficult to consider the tree growth data from the permanent sample plots that were implemented by Alder (1993), because the original data are difficult to retrieve and they might not be suitable

because they consider only trees with DBH>20 cm while the small trees represented a significant population of the ecosystem in our study.

Soil influences the floristic composition, the biodiversity and the total carbon stocks. In order to better understand the biodiversity and carbon stock spatial distribution at national scale it would be possible to use soil maps. Sollins (1998) discuss this aspect and reported that existing soil classification systems do not provide enough information on any particular soil to help establish relations between its chemical properties and plant distribution. Soil-mapping techniques may reduce sampling needs by allowing stratification of plant sampling by broad soil types. The mapping must be done but has to consider the spatial resolution of the plant community variability. I believe that the soil maps will considerably help doing the stratification to better understand the linkage between soils and plant communities.

While Hall and Swaine (1981) says that the vertical structure of the forest shows much less characteristics variation than floristic composition, our idea is that the combination of both gives you an indication about the status of the forest, the growth strategies of the different plant groups according to the biotic and abiotic factors.

5. Conclusion

Climate, soil, topography influenced biodiversity and carbon stocks distribution within and between forests. While various aspects remain unexplained, this suggest further studies to better understand the functioning of tropical rainforests and their long term dynamics and particularly the development of experimental sites that consider the spatial variation within the forests. While most of the studies focus on small plots in various ecosystems very few sites were considered to analyse the spatial and temporal nutrient cycling.

Chapter 8

Analyzing the structure: towards harmonization of aboveground forest biomass estimates

This chapter is modified from the article: Henry, M., Manlay, R., Trotta, C. Couarlet, C., Beeckman, H., Asante, W., Chesnes, M. Martel, S., Gineste, M., Adu-Bredu.S., Gourley-Fleury, S., Peltier, R., Bernoux, M., Valentini, R. Saint-André, L. (2010) Volume and biomass conversion and expansion factors for tropical rainforest and agroforestry systems in Africa, I Forest – Biogeosciences & forestry, in preparation.

Abstract

Increasing concerns on biomass and carbon cycling allow countries to account their direct human-induced carbon emission and sequestration including those from forestry and other land use related activities. While several efforts were developed for temperate climatic regions, very few studies concern the development of biomass expansion and conversion factors in tropical regions. The focus of this research was to develop the first volume and biomass conversion factors for sub-Saharan African ecosystems, allowing the harmonization of volume and biomass measurements up to a common diameter. Tree stem distribution was modeled by a Beta law for all ecosystems. Amongst power, exponential and hyperbolic equations, the power model was the most suitable to model both volume and biomass conversion factors as a function of the minimum diameter recorded in the inventory. Such models were developed mostly for tropical rainforests but also for tropical moist and dry forests. As for tree stem distribution, an important variability was found in dry forests, agricultural land and plantations. Better consideration of soil, landscape, management types and age of the ecosystem would improve predictive models of these conversion factors, but in such they are a first improvement of the available tools in Africa.

Keywords: Greenhouse gas inventory, LULUCF, AFOLU, Climate change, Forest inventory, Kyoto protocol

1. Introduction

In the context of climate change, researches on the role of the carbon (C) cycle in forest ecosystems gained a lot of attention. In order to better understand the C cycle, important efforts are made to homogenize the data at global scale (GTOS, 2008). However, the role of the forests in Africa remains still poorly understood in comparison with the other continents. In the recent article of Lewis (2009), the authors point that African forests may store more C than other tropical forests. However, at continental scale the data uncertainty is important and most of the data concerning the African forests concerns the timber volume. In an effort to homogenize the biomass data and to estimate the C stocks of all the trees of forest ecosystems, it appeared that the studies on volume, biomass and C stocks in Africa report different diameter thresholds. Generally, forest inventories start with minimum diameter ranging 30-50cm for timber, and 5-10cm for woodfuel purposes. While the forest inventory of Cameroon and Mozambique used a minimum diameter of 10cm, the forest inventory of Zambia used a minimum diameter of 7cm. While Bernhard-Reversat, et al. (1978) measured the biomass of a tropical high forest of Ivory Coast using a minimum diameter of 14cm, Manlay (2002b) measured the biomass of tree formation in cultivated land in Senegal using a minimum diameter of 4cm.

Definition of the minimum diameter threshold of a forest inventory is generally limited by technical and logistic constraints and depends on the objectives of forest inventories. Recently, efforts to harmonize biomass data started being developed to better understand the role of terrestrial ecosystems in the carbon cycle. The FAO called to develop forest carbon measurements up to a diameter of 0cm. However, trees with diameter less than 2cm are often classified as regeneration. The IPCC does not provide any reference to a minimum diameter threshold.

Few attempts tried to propose models to harmonize volume and biomass up to a common diameter. Brown (1997), reported volume and biomass expansion factors to harmonize volume data up to a minimum diameter of 10cm and then convert it into biomass. The IPCC (2006a) reported biomass conversion and expansion factors to convert the volume into biomass based on classes of volume in the different ecological zones defined by the FAO (2001a). Somogyi et al. (2008) developed an allometric biomass and carbon factors database. While this database contains several types of expansion, conversion and combined factors by various tree species or species groups, this database concerns the Eurasian forests. Teobaldelli et al. (2009) produced several biomass expansion factors for conifers and broadleaved forests and considered stand age growing stocks and site index. Zianis et al. (2005) inventoried and classified an important quantity of allometric functions for temperate forests. While various efforts were developed for temperate forests, some studies contribute to the effort in tropical countries. At current status, no research proposes methods to homogenize the forest volume and biomass for various ranges of minimum diameter and different ecological zones in Africa.

The aim of this study is then fill part of this gap and to propose various volume and biomass conversion factors that allow estimating the total volume and biomass for different ecological zones and ecosystems types for forest inventories with minimum diameter ranging 2 - 30cm.

I state the following hypothesis: conversion factors should depend on the minimum diameter threshold and the forest structure. While natural forests generally follow a negative exponential, forest plantations follow a more normal distribution.

2. Material and methods

2.1 Case studies

The data collection concerns forest and tree inventories that were achieved for research purposes in Ghana, Democratic Republic of Congo, Kenya and Cameroon (Table 26). It includes inventories in natural forests, forest plantation and farmland in tropical rainforest, moist, dry and mountain systems. The researches led by Adu-Bredu et al. (2008) concerned two land use types (natural forest and teak plantation) in three different zones (wet evergreen , Dry Semi-Deciduous Forest and Savannah) in three locations of Ghana (Kakum, Ejura and Bawku). The researches led in chapter 7 concerned natural forests in three zones (wet evergreen, moist evergreen and moist semi-deciduous) and in three locations of Ghana (Boi Tano, Boin River and Bobiri forest reserves). The researches led by Henry et al. (2009) focused on farmland in western Kenya in two ecological zones (tropical dry forest and tropical moist deciduous forest) and in two locations (Vihiga and Siaya districts). The researches led by Couarlet et al. (unpublished) concerned Luki forest located in the tropical rainforest zone in the Democratic Republic of Congo. Data from Pointe-Noire, republic of Congo, were used to validate the growth and yield model E-Dendro developed by Saint-André et al. 2002. The ecological zone classification (FAO, 2001a) was used to classify the sites per ecological zones. The New Locate Climate Estimator software was used to derive climatic information (FAO, 2005d). While the forest inventories collected an important amount of data with minimum diameter of at least 2cm of DBH, soil characteristics were rarely considered.

2.2 Volume and biomass calculation

➤ Estimation of volume

The volume was estimated using the pan tropical biomass allometric equations from Chave et al. (2005).

For dry forest stand

$$Vi = \exp(-0.667 + 1.784 * \ln(D) + 0.207 * (\ln(D))^2 - 0.0281 * \ln(D))^3 \quad (1)$$

Moist forest stands:

$$Vi = \exp(-1.499 + 2.148 * \ln(D) + 0.207 * (\ln(D))^2 - 0.0281 * (\ln(D))^3) \quad (2)$$

Wet forest stands

$$Vi = \exp(-1.239 + 1.980 * \ln(D) + 0.207 * (\ln(D))^2 - 0.0281 * (\ln(D))^3) \quad (3)$$

➤ Estimation of biomass

Different biomass allometric equations were used according to the ecological zones and the management types. The biomass allometric equation from Chave (2005) was not used because specific wood densities were not available for all the tree species. In tropical rainforest I used the formula found in Pearson and Brown (2005). In Tropical mountain system and tropical dry forests of Kenya I used the allometric equation developed by Henry et al. (2009) because it was specifically developed for this region. For teak plantations I used the allometric equation found in Asomaning (2006). For eucalyptus plantations in Congo, I also used the dedicated equations for both tree volume (Gomat et al. 2009) and tree biomass (Saint-André et al. 2005). For the trees found in tropical dry forest in Ghana I used the equation found in Ponce-Hernandez (2004).

For tropical rainforest

$$AGB = \text{Exp}\left(-2.289 + 2.649 * \ln(DBH - 0.021 * \ln(DBH^2))\right) \quad (4)$$

For tropical mountain system

$$AGB = \text{Exp}(0.93 * \ln(DBH^2 * H) - 2.97) \quad (5)$$

For Teak plantation

$$AGB = 0.066 * DBH^{2.565} \quad (6)$$

For tropical dry forest

$$AGB = \text{Exp}(-1.996 + 2.32 * \ln(DBH)) \quad (7)$$

2.1 Analysis of the data

The number of tree stems was measured per DBH classes of 1cm. The plot areas vary from 0.005 to 1ha among the case studies. The plots where the number of diameter classes was more than 5 were only considered. The relation between DBH and the stem number (N) was modelled using the Beta model. The Beta model can be used to model any type of distribution.

$$N = \text{Constant} \times DBHr^{(\alpha-1)} \times (1 - DBHr)^{(\beta-1)} \quad (8)$$

Where DBHr is the relative DBH.

$$DBHr = \frac{(DBH - DBH \min)}{(DBH \max - DBH \min)} \quad (9)$$

The volume and the biomass conversion factors allow the conversion of volume and biomass for a certain minimum diameter (DMIN) to the total volume (Vtotal) or biomass (AGBtotal). The study considered only V_{DMIN} and AGB_{DMIN} that represented at least 10% of the total, assuming that tree inventories focus on more than 10% of the tree population.

$$VCF = \frac{V_{total}}{V_{DMIN}} \quad (10)$$

Table 26: Characteristic of the study sites

Country	Study site (Lat,	Ecological zone (FAO, 2001)	Mean rainfall (mm)	Soil type	Land cover
Ghana	Boi Tano (5.41,-	Tropical rainforest (wet	>1750	Oxysols	Managed forest (40years
	Boin River (5.79,-	Tropical rainforest (Moist	1750	Oxysol-ochrosol	Managed forest 40years
	Kakum (5.35, -	evergreen)	2000	-	Natural forest
	1.38)				Teak plantation
	Bobiri (6.69, -1.34)	Tropical rainforest (Moist	1500	Lateritic	Managed forest (40years
	Ejura (7.38, 1.37)	Tropical moist deciduous	1260	-	Natural forest
		forest (Dry Semi-Deciduous			Teak plantation
Democratic Kenya	Bawku (11.06, -	Tropical dry forest (Savannah)	1000	-	Natural forest
	0.24)				Teak plantation
	Luki forest (-5.6,	Tropical rainforest	1164	-	Managed forest (40 years
	Vihiga (0.30,	Tropical mountain system	1800	Acrisols, Ferralsols and Nitisols	Agroforestry (mixed
	Siaya (0.06, 34.29	Tropical dry forest	1400	Acrisols, Ferralsols and Nitisols	Agroforestry
Cameroon					Annual crop
					Permanent crop
	Sirlawé (10.12-	Tropical dry forest	800	Lixisol	Cultivated
Cameroon	14.97)				Fallow
	Mafa Kilda (9.20,	Tropical dry forest	900-1200	Lithosol	Cultivated
	13.5)				Moutain forest
Congo					Forest
	Pointe-Noire (-4.7,	Tropical rainforest	1200	-	Plantation

$$BCF = \frac{AGB_{total}}{AGB_{DMIN}} \quad (11)$$

Where V_{total} and AGB_{total} correspond to the total volume and biomass above 2cm. V_{DMIN} and AGB_{DMIN} correspond to the volume and the aboveground biomass for a certain minimum diameter ranging 2-30cm. When $Dmin=2$, $VCF=1$ and $BCF=1$

The relation between DBH and VCF and BCF was modelled using power, exponential and hyperbolic functions.

Power model

$$Y = a + b \left(\frac{(D_{MIN} - 2)}{10} \right)^c \quad (12)$$

Exponential model

$$Y = 1 + a \times (DMIN - 2) \times \exp(b * (DMIN - 2)) \quad (13)$$

Modified hyperbolic model

$$Y = 1 + a \times \left(\frac{\left(D_{MIN} - 2 - c \times b + \sqrt{\left((c \times b + D_{MIN} - 2)^2 \right) - 4 * b(D_{MIN} - 2)} \right)}{2} \right) \quad (14)$$

The model was tested using Non Linear Programming procedure of the SAS software (SAS® Institute Inc., Cary, NC, USA, 2004). Because the number of parameters are different between equations, the model comparison was achieved using Akaike Information Criterion (AIC) criteria which represents a good balance between model adjustment and number of parameters (Burnham and Anderson., 2002). Dummy variables were integrated to the models to allow comparison plot and site levels.

3. Results

3.1 Structure of the tree vegetation forms

The considered case studies are indicative and cannot be considered as representative of all the ecosystems of the same type found in sub-Saharan Africa. However, important differences of structure were observed and it is important to describe how they differ. Tree density was higher in forest ecosystems (1658±54), than in mountain forest (803±121), plantation (783±50) and farmland (198±25) (Figure 46). In forest ecosystems, average tree density ranged 1649-3148 stems ha⁻¹. While the highest tree density was found in the wet evergreen forest of Boi Tano (3148 ±557 stems ha⁻¹), the lowest was found in the tropical dry forest of Bawku (184 ±30). Tree stem density also varied within the different forests. In Luki forest, the tree density ranged 450-3,280 stems ha⁻¹ and the tree density could reach up to 4,262 stems ha⁻¹ in Boi tano forest and a difference up to 2800 stems ha⁻¹ between plots was found in Kakum forest. The highest variation of tree density was found in dry forest zone with density ranging 496-1,280.

As a consequence, important variability of the diameter distribution was found. Tree stems density varied between diameter classes, land use and ecological zones (Figure 46). When considering the tropical rainforest, most of the tree stems were found in the class 0-10 cm (67%) and decreased with diameter. Trees with diameter above 50 cm represented only 2% of the tree stem number. On the other hand, the number of small trees tended to decrease in drier climate. In agricultural land, the number of small trees was much lower but still represented the highest proportion (41.7%). In plantations, most of the tree stems were found in the class $10 \leq \text{DBH} < 20\text{cm}$ (83.1%) and trees with $\text{DBH} > 40\text{cm}$ were not found, mainly because these plantations were either young or dedicated to pulp wood (no need to get large diameters).

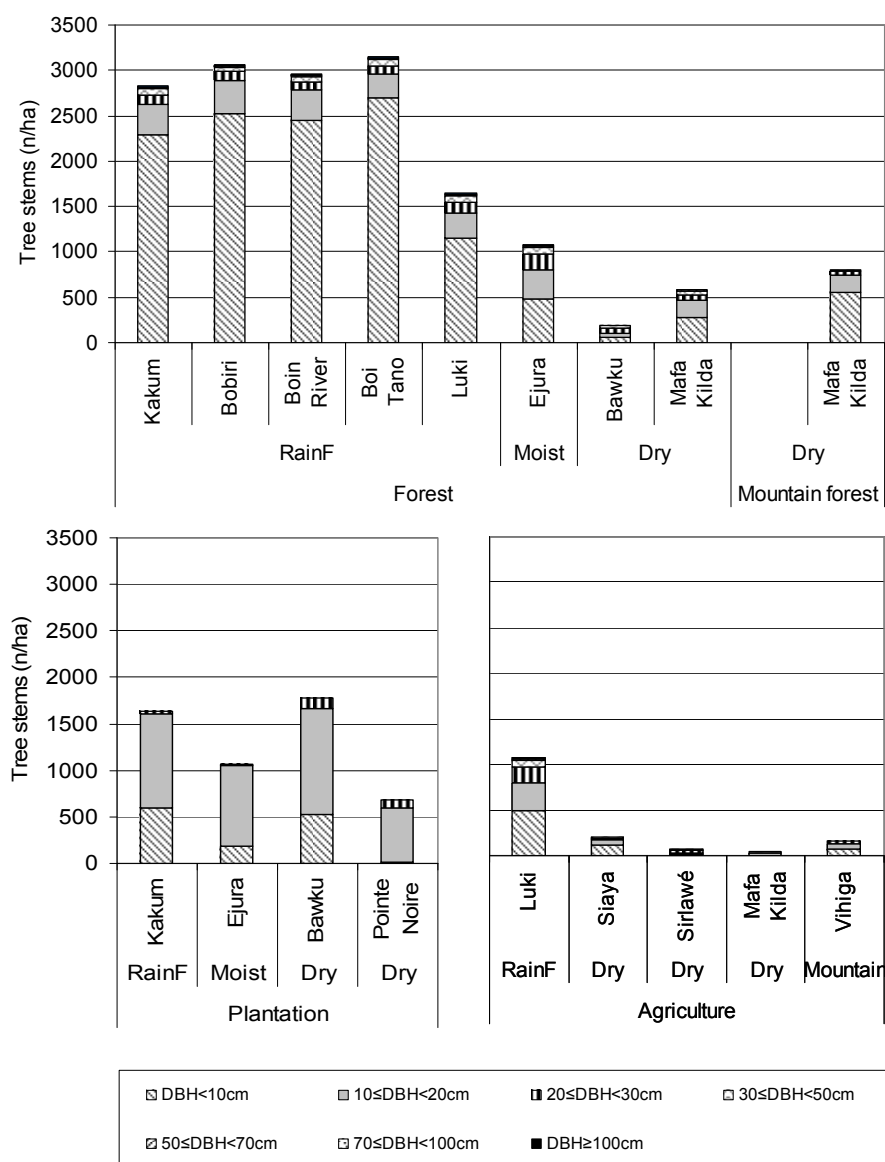
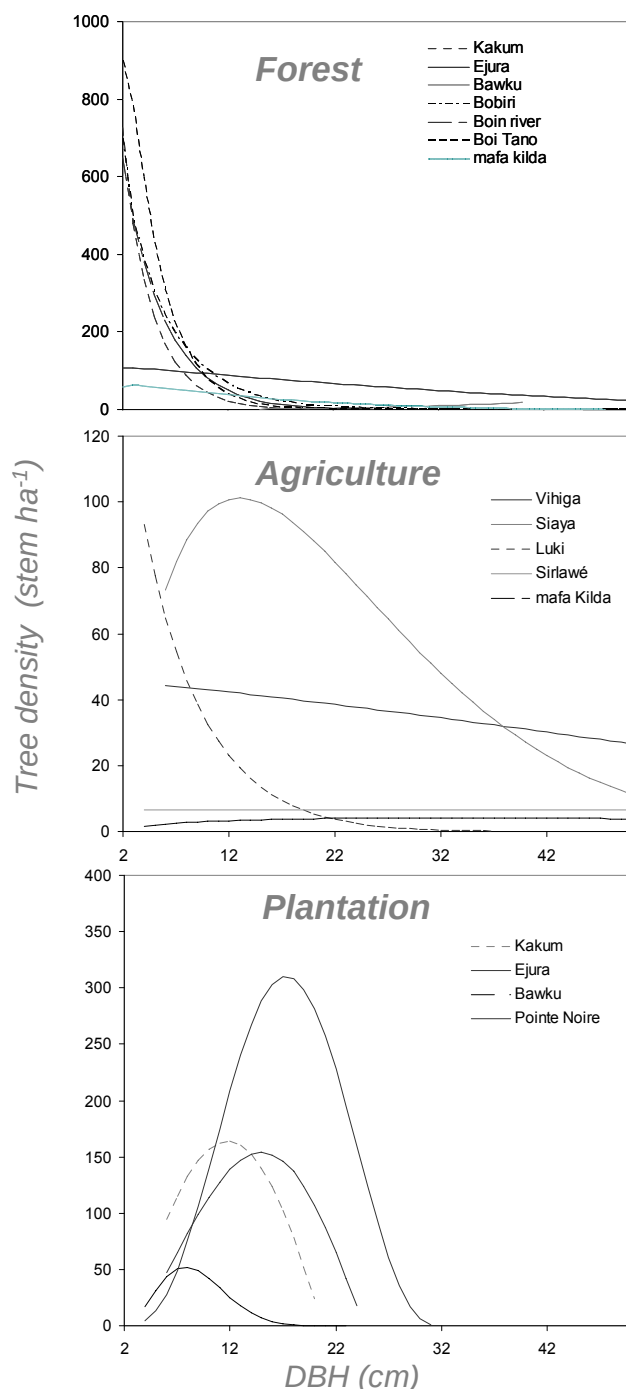


Figure 46: Distribution of diameter classes in various forests, agricultural land and plantations.

3.2 Modelling tree structure

The beta law was suitable to describe tree diameter distribution for almost all the sites and land uses (Table 27). Important difference was found between ecosystem types and sites (Figure 47).

For natural forest ecosystems, the model fitted well the decrease of the number of tree stems with diameter. The constant was positively and significantly correlated with increasing precipitation (ddl=6, $p<0.001$, $F=$) whereas the parameter beta was significantly negatively correlated with temperature (ddl=6, $p<0.01$, $F=25.4$) and the parameter alpha was negatively correlated with minimum temperature (ddl=6, $p>0.05$, $F=3.44$). While the beta parameters ranged 0.99-154 the alpha parameter varied ranged 0.93-1.39.



When considering farmland, the models revealed different relation between diameter and tree stem number. While the maximum tree stem number was observed at DBH 2cm in Vihiga, Luki and Sirlawé, the maximum was observed at 13, 15 and 33 cm in Siaya, Sirlawé and Mafa Kilda. In Sirlawé, variation of the tree number was low and ranged 5.6-6.5 stems ha⁻¹ while it ranged 0.2-101.1 stems ha⁻¹ in Siaya.

When considering plantation, the constant value was the highest in Pointe noire and the lowest in Bawku. Higher beta values were found in drier climate. Alpha value was higher in pointe noire with an increased number of trees with bigger diameters.

The comparison between plot and site-models revealed differences. While almost all the forests had better predicting models when considering plot models, models developed for site in Kakum, Ejura were better than plot models. While all the site models were more accurate than plot model in plantation, the contrary was observed in agricultural land.

Figure 47: Tree stems distribution models

Table 27: Tree stem distribution models

(* P(H0: Fobs > Fth = 0) < 0.05, ** P(H0: Fobs > Fth = 0) < 0.01, *** P(H0: Fobs > Fth = 0) < 0.001)

Ecological zones	Site	Mean Constant		Beta			Alpha			AIC site	AIC plot	sigma2	RHS	RMSE
		Mean	SD	Mean	SD		Mean	SD						
Natural forest														
Tropical rainforest	Boi Tano	1533	120.24	43.51	2.00	***	1.07	0.01	***	1609	1433	351	-800	64
	Boin river	547	22.27	32.57	0.88	***	0.97	0.00	***	1400	1363	83	-696	17
	Bobiri	417	40.21	35.74	2.35	***	0.93	0.01	***	1559	1406	234	-775	36
	Kakum	40	11.90	34.57	6.86	***	0.94	0.03	***	456	466	11	-224	10
	Luki	272	104.22	154.01	13.80	***	1.39	0.02	***	37138	24856	123	-	11
Tropical moist deciduous	Ejura	4	4	3.14	1.01	***	1.01	0.03	***	444	464	3	-218	2
Tropical dry forest	Bawku	1	0	0.99	0.95	***	0.96	0.02	***	86	21	1	-39	1
	Mafa	5	5	5.89	6.81	ns	1.05	0.07	***	453.09	501.09	2.05	-	2
Mountain forest														
Tropical dry forest	Mafa	44	30.50	18.77	4.10	***	1.18	0.07	***	1835	2019	10	-913	11
Agriculture														
Tropical rainforest	Luki	9	6.67	14.35	4.33	***	0.92	0.06	**	773.67	529.73	17	-378	6
Tropical dry forest	Mafa	5	4	2.47	0.01	**	1.49	0.01	***	404.37	500.37	1	-198	2
Tropical dry forest	Sirlawé	1	0	1.04	0.01	***	1.01	0.01	***	151.29	207.29	0	-72	1
Tropical dry forest	Siaya	99	48.88	9.05	1.71	***	1.83	0.16	***	2959.60	1579.79	16	-1964	3
Tropical mountain	Vihiga	3	0.68	1.80	0.25	***	1.01	0.03	***	576.80	184.07	1	-337	1
Plantation														
Tropical rainforest	Kakum	57	32	2.21	0.33	***	2.28	0.40	***	154	342	8	-73	3
Tropical moist deciduous	Ejura	77	52	2.32	0.38	***	2.72	0.47	***	132	274	7	-62	3
Tropical dry forest	Bawku	630	1312	7.76	1.39	***	3.40	0.89	***	90	102	4	-39	4
Tropical dry forest	Pointe	1877	878	3.90	0.28	***	4.03	0.35	***	2563	2763	62	-1318	14

3.3 Modelling volume and biomass

➤ Volume

The volume was not uniformly distributed among diameter classes (Figure 48). In natural forest ecosystems, the proportion of trees $DBH < 30\text{cm}$ was low in tropical rainforest but increased when precipitation decreased. When considering tropical rainforest the proportion of trees $DBH > 30\text{cm}$ ranged 76-83% and trees $DBH > 50\text{cm}$ ranged 52-57%. Moreover, most of the volume was found in trees $DBH > 50\text{cm}$ while trees with $DBH > 10\text{cm}$ represented 1-4% of the volume. When considering moist and dry forest, the proportion of trees from intermediate diameter $10 < DBH < 50\text{cm}$ represented 53-98% of the volume. When considering agricultural land, small trees $DBH < 10\text{cm}$ represented 0-5% of the volume. Most of the volume was found in intermediate classes of diameter $10 < DBH < 50\text{cm}$ and represented 32-74% of the total volume. In addition, because of the presence of big trees in certain agricultural systems such as Vihiga the classes $DBH > 100\text{cm}$ represented 32% of the total volume. When considering plantation, the intermediate classes of diameter $10 < DBH < 50\text{cm}$ represented 85-98% of the total volume. The big trees were absent and the small diameters were little represented.

➤ Volume and biomass conversion factor

Power models were the best in all sites and land-uses except in Siaya where the power model was not significant (Appendix VI). In all the sites and land-uses the VCF models were more powerful when considering the plots than the sites. When considering the forest ecosystems, the RMSE was increasing with decreasing precipitation. Variability of the distribution of volume among diameter classes was higher in drier ecological zones. When considering the plantation, it was more difficult to model the VCF and RMSE was more important than other land uses. The hyperbolic models had lower RMSE in Pointe Noire and power models had lower RMSE in Bawku. When considering farmland, I observed the same trend than for forest ecosystems. Higher variability was found in drier ecosystems. RMSE was important in sites such as Vihiga. Hyperbolic models had a trend to over or underestimate the small diameters and could lead to an overestimation in forest ecosystems up to 35%. The power models could lead to an overestimation of about 4% and expo model up to 3%. In average the power models were giving the best estimation of VCF with lowest RMSE and highest AIC.

When considering biomass conversion factors, power models were the most powerful in all the sites. Plot models had lower AIC than site models. In forest ecosystems and agricultural land, the RMSE was increasing with lower precipitation. Drier forest had higher biomass variability. In forest plantation, the variability of biomass distribution was important between sites and within plots.

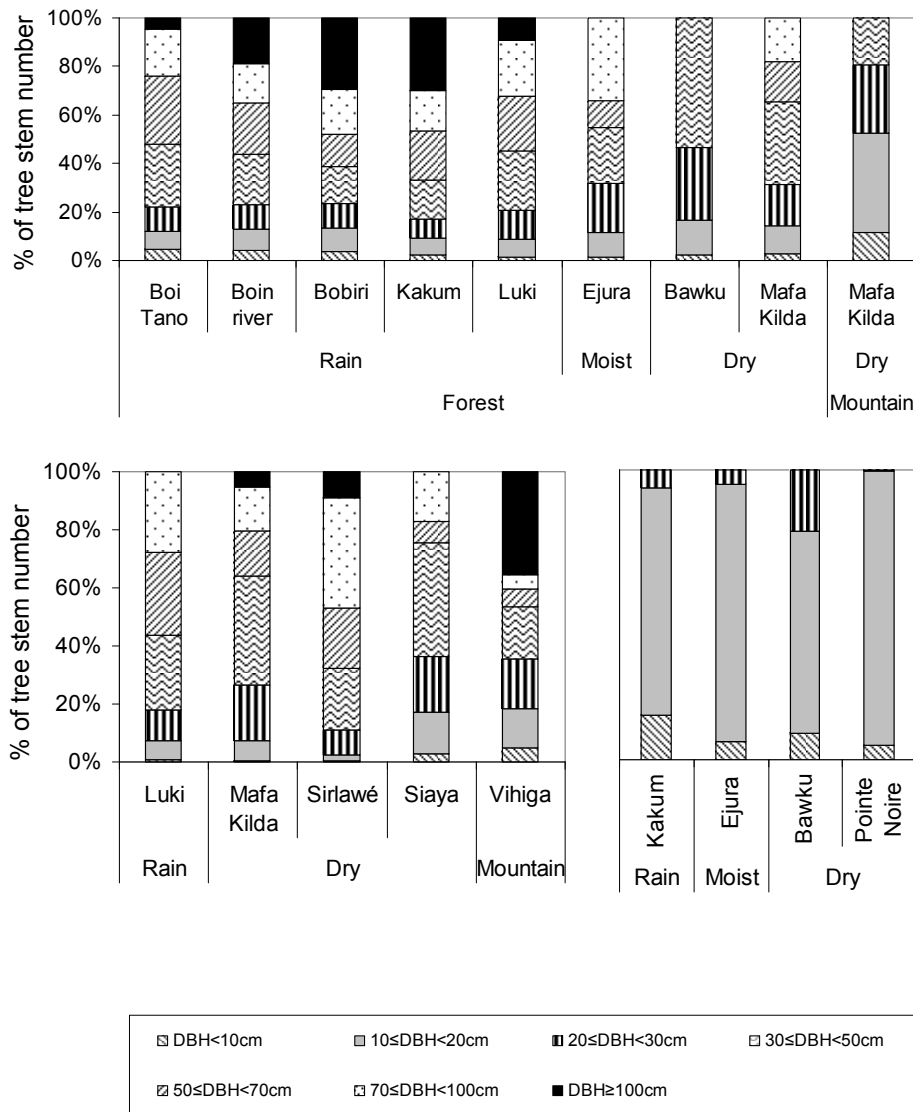


Figure 48: Volume distribution in various forests, agricultural land and plantations.

4. Discussion

4.1 Ecosystems structure

Within forest ecosystems, most of the tree stems fall into the small diameter classes while trees with DBH>50cm represent less than 3% of the total (Figure 46). This tendency is commonly found in the literature (Fournier and Sasson, 1983). They reported that the important number of small diameter trees corresponds to shade bearer trees while the light trees follow a Gaussian distribution. While big trees represent a small number of individuals they have an important role in forest functioning.

minimum efficient fructification diameter is of at least 40 cm of diameter for height common trees species in tropical rainforest of central Africa (Durrieu de Madron and Daumerie, 2004).

In this study, about 58% of the total volume is found in trees with $DBH > 50\text{cm}$ in tropical rainforest. They play a key role in mineral cycling as they capture most of the sun light and produce most of the organic matter (Hilton, 1987). On the other hand, smaller trees with $DBH < 10\text{cm}$ represent in average 66% of the tree stem number and less than 4% of the volume. They are very often not considered by forest inventories while they represent major part of plant biodiversity and play a key role of ecosystem functioning as they form forest regeneration. In addition, small trees are particularly sensible to events such as fires and logging activities. While Fournier (Fournier and Sasson, 1983) reported that 9.2% of the volume was found in the class $10 < DBH < 19\text{cm}$ in tropical rainforest, our study reported variation between 7 and 9% (Figure 48). He however reported important variations of forest structure between sites and authors.

4.2 Modeling ecosystem structure

Using beta model allowed us to model the distribution of tree stems in various ecosystem types (Figure 47). This is the first time that this attempt was made for tropical forests of sub-Saharan Africa. It appeared that the parameters of the beta model were significantly correlated with climatic parameters. Higher precipitation allows higher regeneration, plant stem density and higher constant. Increased temperature allows shifting from an exponential to a more linear tree stem structure and the beta parameter is lower. It is possible to model the structure of natural forests based on the climatic parameters (Figure 49). When considering the distribution of tree diameter in 56 sites of Africa, I observed the same trend than in our study. However, it also appeared that modelling is limited. In tropical rainforest the model tends to overestimate tree stem number of mangroves and tropical mountain forests with higher rainfalls. In other tropical rain, moist, dry forests and tropical shrub land, the model tends to underestimate tree stem number. Underestimation could reach up to 127% of the data found in the literature. Influence of landscape on tree structure was reported by Fournier and Sasson (1983) who reported higher precipitation and lower seasonal variability in mountain forests, allowing higher plant density and biomass.

On one hand, the model I developed is limited by the number of sites and climatic zones and it is furthermore not possible to extrapolate to different vegetation and climatic zones. On the other hand, using data from the literature is difficult to compare because the data are presented using different diameter intervals, diameter thresholds, different units, etc. While, many researches analyzed or reported the forest structure (E.g. Rollet, 1974), the minimum diameter is rarely below 10 cm and the quality is very variable. Further studies would consider additional sites particularly in the dry regions where higher variability was found. Particular attention has to be given to the trees with small and the big diameters in future forestry researches.

4.3 Factor in tree structure variability

Important variability was found within sites and various variables explain part of it. However, it was not possible to have information concerning landscape, soil types, age and history of management for all the different sites. Moreover, the discussion concerns only the factors that were considered in the different studies. It appeared in Boi Tano that the tree stem number was affected by landscape (Figure 50). Tree stem density was higher in slope than in swampy and upper slope landscape units. In Mafa Kilda, soil types affected the distribution of tree stem number. Higher tree density was found in sandy than in sandy clay and rocky soils. In Vihiga, management was affecting the ecosystem structure. Higher tree stem density was found in homegarden than in annual, permanent crops and pasture land. Impact of management and degradation and fires events on forest structure was reported by Swaine et al. (1997). In Pointe Noire, the age of the plantation was influencing the structure of the plantation. Older plantations had higher range of tree diameters.

4.4 Volume and biomass conversion factors

Comparison of models suggest that power models were the best predictive. While hyperbolic models didn't fitted well with small diameters, exponential models were close to power models and could be used as a proxy when power models are not significant (e.g. in Siaya). While plot models were more powerful than site models, it reveals variability within sites and between plots. This variability could be explained by the various factors presented before. However, the limited information about those factors does not allow giving volume and biomass conversion factors for different landscape or soil types etc. The analysis of volume and biomass conversion factors is a first attempt to produce tools to harmonize already existing inventories. The biomass and volume conversion factors given in this study (appendix VI and VII) could be used for similar ecosystems and ecological zones. While good relationships between diameter and tree stem density were observed in the different tropical rainforest sites, important variability was found in tropical dry forest and even more in plantation and agricultural land. Particular attention has to be taken into consideration when harmonizing the data found in managed ecosystems. The various forms of tree management that exist in sub-Saharan Africa increase the complexity of the issue. As for example, the tree structure in parklands varies between sylvo-pastoral, farming and fallow systems.

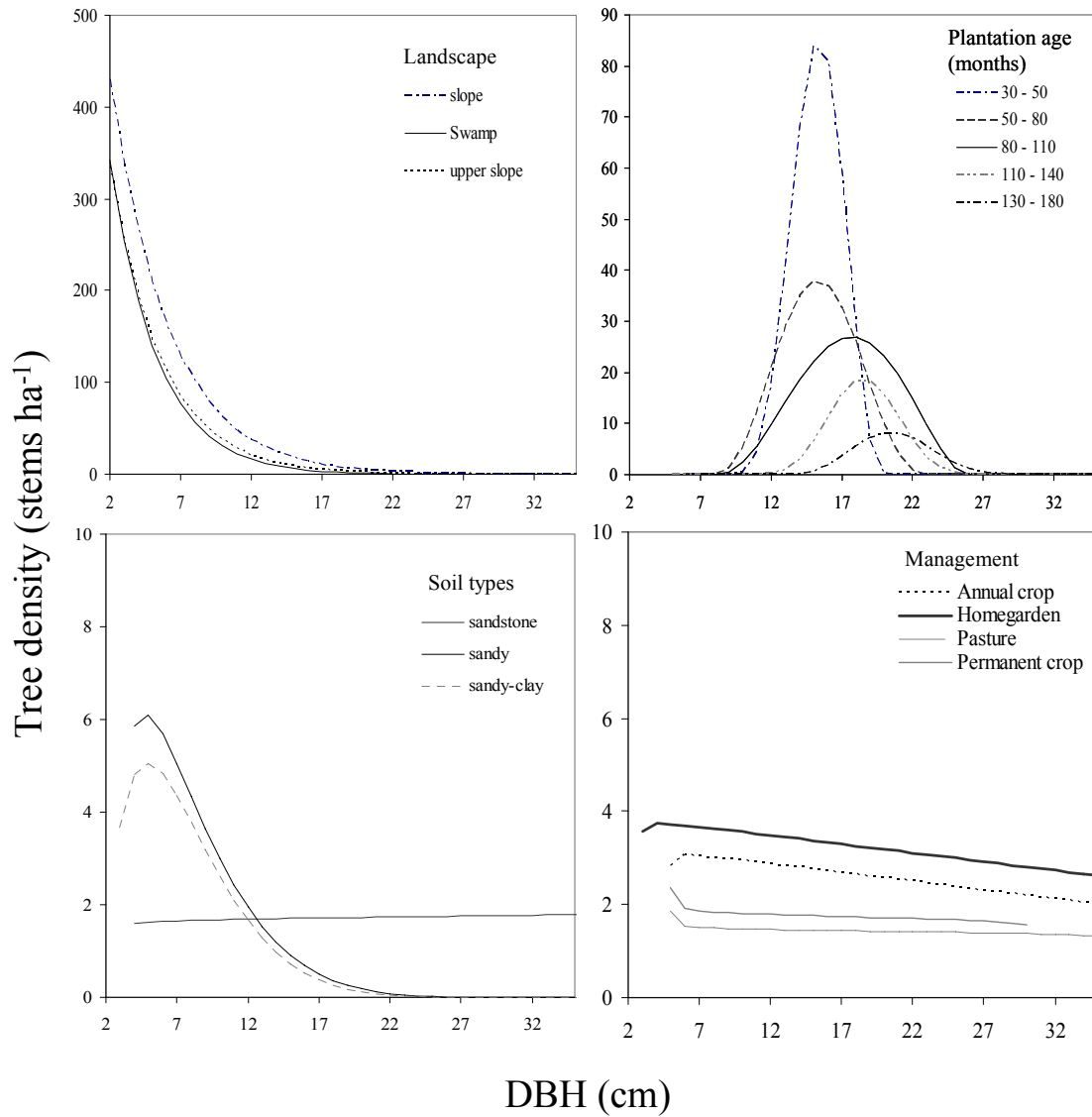


Figure 49: Modelled tree stem distribution in forest ecosystems for different precipitation

The minimum and average temperatures were considered as constant (27 and 23°C respectively). The constant was predicted based on the precipitation ($\text{Constant} = .1582x^2 - 26.234x + 1086.5$, $R^2=0.9614$). The beta parameter was predicted based on the mean monthly temperature ($\text{beta} = 5.181x^2 - 292.68x + 4144.7$, $R^2=0.90$). Alpha was predicted based on the minimum temperature ($\text{alpha} = 0.1047x^2 - 4.6053x + 51.577$, $R^2=0.68$).

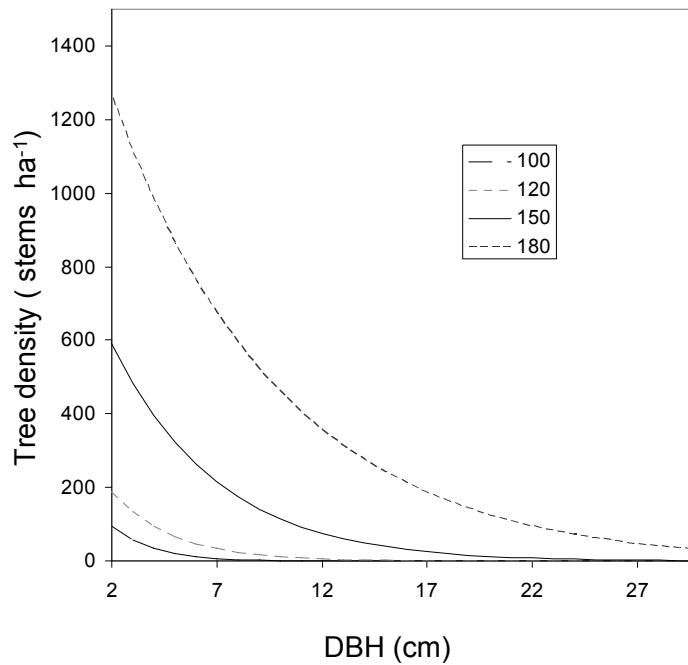


Figure 50: Influence of landscape, age, soil type and management on tree stem distribution

(A) Influence of landscape in Boi Tano Forest reserve (Ghana). (B) Influence of age in forest plantations in Pointe Noire (Congo). (C) Influence of soil types in dry forests in Mafa Kilda (Cameroon). (D) Influence of management type in agricultural land in Siaya (Kenya).

5. Conclusion

While most of the tree stem number is found in small diameter classes, most of the volume and the biomass are found in big diameter. Small and big trees play a crucial role in forest functioning and are often forgotten by forest inventories. Their consideration allows the modelling of the forest structure. In our study, the various models parameters were correlated with climatic variables. While the sampling was restricted to few forests in sub-Saharan Africa, better consideration of other climatic zones and main factors affecting the forest structure would allow scaling up to continental scale. This is the first time that volume and biomass conversion are developed for tropical ecosystems. This will allow foresters, researchers and developers to harmonize volume and biomass data up to a common diameter and allowing comparison. This is a preliminary step for all climatic and bio-geo-processing modelling operations.

While the two previous chapters focused on the scale of the ecosystem, the next chapter focuses on continental scale. The data from various studies, surveys, forest inventories were gathered and harmonized and integrated with models and land cover products in order to develop continental biomass and carbon estimates.

Chapter 9

Variability of carbon stocks at continental scale

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Abstract

Sub-Saharan Africa is the poorest continent in terms of data accessibility on biomass and carbon stocks. Even if the continent currently contributes to only 4% of global greenhouse gas emissions, it is expected to increase in the future. A better understanding, improvement and data provision on the carbon cycle is needed for the development and support of a global climate mitigation strategy, while helping countries to implement national actions. The aim of this study was to compile available biomass and carbon stock data at a continental scale in order to illustrate and describe the variability of carbon stocks found in sub-Saharan Africa. The objectives were to analyse, harmonise and integrate the available data into statistical models in order to derive continental estimates. The most important carbon variability was found in mountain ecosystems, while most of the acquired available data was for tropical lowland wet evergreen and deciduous forests. Important gaps were found for crop land uses and for subtropical ecological zones. Scaling up local field measurements to a regional and continental scale is limited by the information and definitions used in continental and global interpretations of the ecosystems. Using the GLOBCOVER product and various ecological classifications, we estimated that the total C in terrestrial ecosystems ranged from 133-150 PgC, while the aboveground C ranged from 58-76 PgC. Important variability resulted from ecological variations and management types but also from the methodology used to estimate the C stocks. This study points out that important gaps need to be solved to better understand the contribution of terrestrial ecosystems to the carbon cycle. Moreover, in order to develop a common strategy to mitigate climate change it is imperative to adopt common definitions and develop bridges between already existing ones.

Keywords: global change, harmonization, language, ecosystems, land cover, modelling

1. Introduction

Carbon dioxide (CO₂) is, by far, the largest contributor to the anthropogenically enhanced greenhouse effect (IPCC, 2007). The importance of CO₂ to the climate has provided the impetus for research on the global carbon cycle. One of the key drivers of greenhouse gas (GHG) emissions is land use change. It contributed 1.7 Gt to the total carbon (C) budget ($\pm 0.8 \text{ Gt C yr}^{-1}$) between 1980 and 1989 and is today the second major source of GHG emissions in the world (Houghton, 2003) and the major source in Africa (Williams, *et al.*, 2007). While Africa contributes a total of 17% to the terrestrial GHG balance, already 48% of its emissions originate from land use, land use change and forestry (Canadell, *et al.*, 2009). Mitigation actions in the Land Use, Land-Use Change and Forestry (LULUCF) sector were identified as win-win options worldwide (Schlamadinger, *et al.*, 2007) and in particular in Sub-Saharan Africa (Vagen, *et al.*, 2004). Sub-Saharan Africa is considered to be the most vulnerable region to climate change (IPCC, 2007d). Efficient carbon sequestration and emission reduction systems are needed in order to implement effective actions (Valentini, *et al.*, 2000). Currently, important gaps on available in-situ carbon measurements exist to assess the carbon stocks of Sub-Saharan Africa (Bombelli, *et al.*, 2009, Ciais, *et al.*, 2009a). This results in important differences of GHG emission estimates from the LULUCF sector and particularly those related to forest change (van der Werf, *et al.*, 2009). The recourse to geoprocessing and carbon cycling models is needed to close these gaps (Krinner, *et al.*, 2005) but model calibration is limited by data access and availability.

Currently, there is a crucial need to develop an inventory of the volume, biomass and carbon stocks data in sub-Saharan Africa and to identify gaps. In order to meet this target there is a crucial need to develop standards and methods for homogenization and provide harmonized databases. A harmonised inventory would support the development of carbon accounting and monitoring systems, support national initiatives for GHG national reporting and improve our knowledge and understanding of carbon cycling. It would considerably help data comparison and analysis of the variability allowing us to (i) gain a better understanding of the carbon spatial variability; (ii) improve our knowledge on the potential costs for implementing forest inventories and (iii) provide harmonized data on carbon stocks from field measurements will help modellers to calibrate their models.

The objectives of this study are (1) to provide a harmonized georeferenced database for aboveground carbon stocks for sub-Saharan Africa, (2) analyse the variability of biomass and carbon stocks in the various land cover, vegetations types and biome representations and (3) to use them in an integrated way with satellite imagery products to provide regional and national biomass and carbon estimates.

2. Background

Estimating continental aboveground carbon stocks in sub-Saharan Africa is based on ecological or biome classifications. I start by providing a brief overview of the relevant existing literature related to aboveground carbon stocks in sub-Saharan Africa.

2.1 Biome classifications

Various biome classification systems were developed to map the environmental resources of the continent (Table 28). White's vegetation map of Africa (1981) is based on the concept that physiognomic data, and in particular the cover and height of the vegetation, are fundamentally different from chorological data on patterns of species distribution. While it serves ecological purposes, other maps were developed to respond to other interests. FAO/IIASA's agroecological maps (2005a) were produced to assess the potential and restriction of agricultural production systems by monitoring biophysical factors such as climate, soils and landforms. The Forest Resources Assessment of the FAO developed an ecological classification (FAO, 2001a) to facilitate meaningful reporting on forest status and change. Biotic classifications were developed (Udvardy, 1975, WWF, 2000) in order to serve global and regional conservation priority-setting and planning efforts. Since climate research gained more attention, climate and vegetation maps were developed to better understand climate impacts and carbon cycling (Olson and Watts, 1982, Bailey, 1989, Leemans, 1992, Beck, et al., 2005). While Leemans (1992) correlated world plant formations with simple climatic data, Olson and Watts (1982) interpreted the role of vegetation in global CO₂ cycling and Bailey (1989) assumed that macroclimate is the most significant factor influencing distribution of life on Earth.

2.2 Remote sensing and Land cover classifications

Several case studies investigated the use of optical remote sensing and showed its potential to estimate biomass and carbon stocks (Defourny, 1990, Baccini, et al., 2008, Goetz, et al., 2009) allowing a global transparent and consistent approach. However, cloud cover and signal saturation in several vegetation types limit the use of remote sensing at regional and global scale (Imbernon, 2004). To date, most carbon estimates were developed using land cover products and assuming average biome carbon values for the vegetation classes (Gibbs, 2006b).

Extensive research has been undertaken on the development of land cover classifications. It has been recognized that they play an integral part in the improvement of climatic models, land cover modelling, biodiversity habitat and tropical forest monitoring and global carbon cycle change (Defourny et al. 2006). Since the early nineties there has been a continuing research effort to compile and improve global and continental land cover products from satellite imagery. The first global map was derived from Advanced Very High Resolution Radiometer (AVHRR) data (DeFries and Townshed, 1994) and still had a very coarse spatial resolution of 1°, which was later improved to 8 km (DeFries et al. 1998). Thanks to the efforts of IGBP, a 1km product followed, still using AVHRR data (Loveland et al, 2000). With the availability of advanced sensors, the basis was provided to generate the MODIS global land cover and GLC2000, both at 1km resolution, improving on the thematic detail and geometric accuracy of the previous maps (Friedl et al. 2002, Bartholomé and Belward, 2005).

Table 28: Available land classifications for Africa

Classification types	References	Description	Objective	Suitable for i.e.
Biome-ecological zone	Udvardy, M.D.F.(1975)	Definition of geographic units for conservation purposes considering: (a) the distribution of species and (b) the distribution of ecosystem units based on biogeographical entities.	To devise a satisfactory classification of the world's biotic areas for purposes of conservation	biogeographic life form analysis
Biome-ecological zone	White, F. (1981)	Based on the concept that physiognomic data, and in particular the cover and height of the vegetation, are fundamentally different from chorological data on patterns of species distribution.	To understand vegetation distribution.	botany, research
Biome-ecological zone	Olson, J.S., Watts, J.A., (1982)	Based on a compilation of patterns of pre-agricultural vegetation, modern aerial surveys and intensive biomass data from research sites, it represents the world's Major Ecosystem Complexes ranked by the amounts of carbon in live vegetation.	To interpret the role of vegetation in global CO2 cycling.	C stock estimates
Biome-ecological zone	Bailey, R.G.,(1989)	The theory behind the approach is that macroclimates are among the most significant factors affecting the distribution of life on Earth. The ecoregions were defined based on macroclimates.	To show the national forests of the United States fit within the global ecoregional scheme. The approach was then expanded to the world.	Analysis of biogeographic life forms
Biome-ecological zone	Leemans, R., (1990)	The Life Zones were identified based on biotemperature; mean annual precipitation; and a potential evapotranspiration ratio.	To correlate world plant formations with simple climatic data.	Tropical ecology
Land cover	Murai, S. Honda, Y.(1991)	This global vegetation map was derived from multi-temporal NOAA/Global Vegetation Index (GVI) data collected over a three-year period from 1985 to 1987.	To provide a tool for global vegetation change monitoring, particularly as relates to agriculture.	Agriculture
Biome-ecological zone	FAO (1999)	Characteristics and components of the FAO EZ classification include the use of the Köppen system (1931) as a basis for the delineation of forest zones.	To achieve meaningful reporting	Reporting
Land cover	Mayaux, P., Bartholome, E., (2003)	The data were based on SPOT-4 Vegetation sensor for the year 2000. The map of vegetation cover has been produced based upon the spectral response and the temporal profile of the vegetation cover.	To support research, aid and development programmes	Monitoring land use change
Climate zone	Beck, C., Grieser, J., et al.(2005)	Based on recent data sets from the Climatic Research Unit (CRU) and the Global Precipitation Climatology Centre (GPCC), a new digital Köppen-Geiger world map on climate classification.	Climate classifications are introduced in order to reflect the mean spatial climate characteristics.	Climate studies
Land cover	Gibbs, H.K., (2006)	Based on the work of Olson (1982), this is an update of the databases.	Improved estimates of carbon stocks	C cycle studies
Agro-ecological zone	FAO/IIASA (2008)	Thematic grid of Land Use Systems (LUS) and its attributes for Sub-Saharan Africa	Monitoring agriculture production	Agriculture, land degradation
Soil	FAO/UNESCO Soil Map of the World,	To provide a first evaluation of the world soil resources	To support agricultural activities	Agriculture

Studies have used these products already successfully to improve estimates of vegetation and natural exchanges of CO₂ (Gaston, et al. (1998); Gibbs (2006b) Laporte, et al. (1998). Recently, international efforts have led to the compilation of a new global land cover map at 300m resolution. The GlobCover product uses mainly Envisat MERIS fine resolution data and the land cover classes are compatible with the UN Land Cover Classification System (Defourny et al. 2006, Di Gregorio and Jansen 2000). Its potential to build continental or global carbon estimates has not been studied yet.

2.3 Existing carbon stock estimates and their variations

When considering biophysical data on carbon stocks, there is a general agreement that ecosystems are divided into the five components (figure 7) that were defined by the IPCC (2003). Important variations of woody biomass were reported for sub-Saharan Africa by Millington, Critchley et al. (1994). Walker, Pearson et al. (2008) reported 300 Mg ha⁻¹ for tropical humid forest while other authors reported 125.35 Mg C ha⁻¹ (Goetz, *et al.*, 2009), and 330 Mg C ha⁻¹ (Glenday, 2006). The error of bias estimates is suggested to be as high as ±20% to 60% (Brown, et al., 1995, Pfaff, et al., 2000). The variation of carbon stock data found in the literature could be due to different factors. First, the studies may have considered different sub-divisions of the tropical rainforest class. Secondly, most of the regional carbon assessments do not give the precision of the minimum diameter threshold which is considered and could introduce a bias in the estimation (Chapter8). Thirdly, different allometric equations were developed to estimate the carbon in different sites. The only way to control the reliability of those equations would be to achieve destructive measurements (Chapter 5). Important variations were also reported in southern America by Chave, Condit et al. (2003). They pointed out that reliable biomass estimates for large trees are important and that errors associated with large stems can lead to substantial estimation errors. Fourthly, the sampling size influences the distribution of AGB estimates. Extrapolating AGB estimates from point surveys to regional scale leads to proportionally increase of the bias in the estimate.

➤ Models

Carbon cycling models use various biophysical input parameters such as land cover or biome classes, the carbon content of classes and their associated emission factors from land use changes, and combine them into bookkeeping models (Houghton, 1999, Raupach, et al., 2007).

➤ Emission Factors

The last recent contribution from Goetz, Baccini et al. (2009) gives a picture of the state of carbon stocks in central Africa and the potential GHG emissions through deforestation. Only few African researches considered the aspect of emission factors. Some emission factors were produced for the agricultural sector (Takimoto, et al., 2008) and for selective logging (Chapter 10). However, relatively few data have been produced to date for forest degradation and deforestation, which are the most important contributors to the emissions from LULUCF sector (Bombelli, et al., 2009).

➤ Carbon sequestration and emission reduction potentials

Various authors reported that Sub-Saharan Africa represents an important potential for emission reduction and carbon sequestration from LULUCF sector. At local scale, various studies reported carbon sequestration and GHG emission reductions for forest, agroforest and agriculture sectors. In Western Kenya, Glenday (2006) identified the potential emission reductions from avoiding deforestation and the potential for carbon sequestration through improving forest management. In agricultural land, Tschakert (2004) assessed the potential for carbon sequestration in farmland of Senegal through optimum agricultural intensification. Bellassen, et al. (2009) did the same exercise modelling the impact of agricultural intensification at national scale. Montagnini and Nair (2004) and Albrecht and Serigne (2003) gave some estimates on carbon sequestration potential in various agroforestry systems in the world. Henry, et al. (2009) analysed the potential carbon sequestration and the afforestation and reforestation potential in agricultural systems of western Kenya.

Few studies have estimated carbon sequestration and GHG emission reduction potentials on a continental scale. While the first analyses were based on statistics, the availability of remote sensing techniques and satellite images has largely improved the estimates. Woomer, Palm et al. (1997) reported estimates for carbon sequestration through improved agricultural practices in Africa. Tiessen, Feller et al. (1998) did analysis of soil carbon sequestration in agricultural sector in semi-arid tropical regions in western Africa and North East Brazil. Ringius and Lasse (2002) developed soil carbon sequestration estimates based on the on the global harmonized soil map of the world (Batjes, 1995). Then, most of the estimates were developed from coarse vegetation maps obtained from satellite imageries. Vagen, Lal et al. (2004) estimated the potential for continental soil carbon sequestration in agricultural systems based on coarse resolution maps and estimates from Loveland, Reed et al. (2001). Gaston, et al. (1998) gave some of the first estimates on carbon emissions from deforestation. Zomer, Trabucco et al. (2008) developed global analysis of afforestation and reforestation potential and estimates of area that could be used for carbon sequestration projects. On the other hand, modellers develop geoprocessing models which are linked to the global environment (Ciais, *et al.*, 2009b) and give predictions on the GHG fluxes at continental and global scales.

3. Materials and methods

3.1 Data collection

The data collection was restricted to sub-Saharan Africa since it was identified as the most vulnerable to climate change and the least understood (Bombelli, *et al.*, 2009). I focused on gathering information on volume, wood density, biomass, and carbon stocks in aboveground vegetation components. In order to compile the available information, a literature survey was conducted in various libraries in the world (ICRAF, CIRAD, IRD, INRA, ENGREF, FORIG, FAO) and in forest, agriculture and ecology related journals. The data compilation included thesis, reports, conference proceedings and publications. No selection criteria were applied with regards to standard deviation, species, age, size, site conditions, or sampling method. However, all the data reported the variables in terms of area basis. From the database, I would like to highlight the meaningful contributions from the FAO for the inventory of Cameroon (FAO, 2004a) and Zambia (FAO, 2006d) and for the inventory of Mozambique (Marzoli, 2007). The data were georeferenced using the geographical location

(longitude, latitude, name of the location). When only the name of the location was available the geographical coordinates were obtained using administrative maps and © GoogleEarth (<http://earth.google.com>). In total, 7,774 data points were georeferenced while 475 data points were reported in the literature without any indication on their locality (Figure 51). Spatialization was achieved using ArcGIS 9.3 (ESRI, 2008).

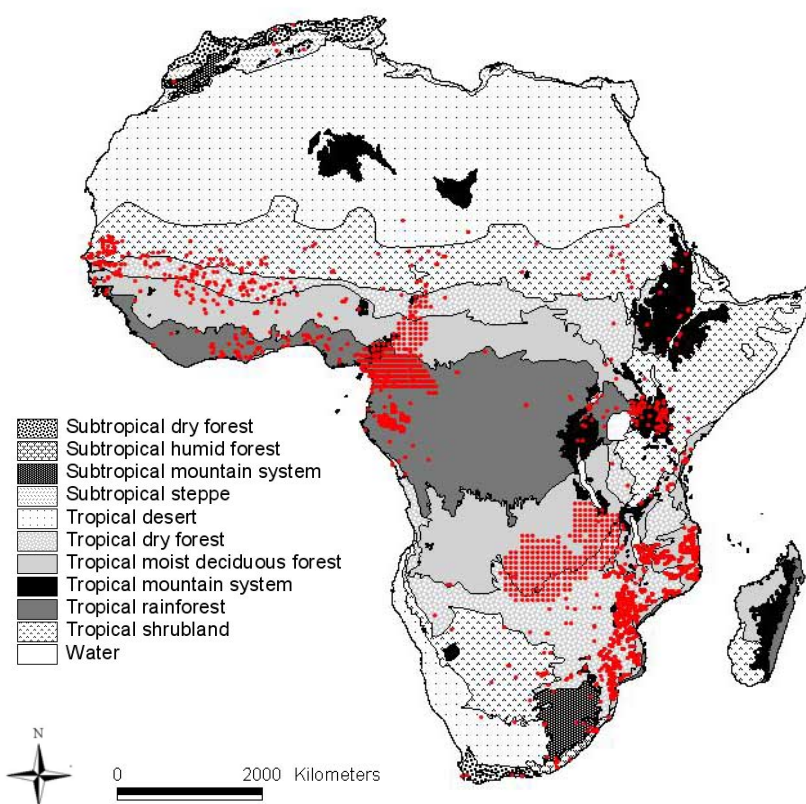


Figure 51: Geographical distribution of the field measurements

3.2 Data classification and harmonization

➤ Classification

The data were clustered in order to allow harmonization. Harmonization was achieved per clusters of homogenous data. The two main criteria used during the harmonization process were the ecological zones and the vegetation types. Clustering was based on quantitative (e.g. average rainfall, crown cover etc.) and qualitative data (e.g. closed grassland, degraded forest etc.). Site categorization was achieved using the ecological classification from FAO forestry resource assessment (FAO, 2001a) as it is the one recognized by the IPCC (2006a). However, the categorization was also achieved using other representation of biomes (Udvardy, 1975, White, 1981, Leemans, 1992) in order to allow their comparison. Table 28 summarized the different available biome classification maps and their purposes. Climatic parameters such as minimum, maximum and average temperature, evapotranspiration, wind, altitude and sun were extracted from the Local Climate Estimator FAO

software (FAO, 2005d). The resampled SRTM Digital Elevation Dataset to 250m resolutions was used to obtain the altitude (Jarvis, et al., 2004). Precipitation was obtained from CRU (Mitchell, et al., 2003). The tree cover was obtained from the MODIS tree cover at 500m resolution for the year 2001 (Hansen, *et al.*, 2002). The MODIS image was resampled to a 300m resolution matching the GLOBCOVER grid (Appendix VIII). In total, biome classification, altitude and climatic parameters were obtained for 6,525 of the data points while 1,724 of the data points fell out of the shapefile's boundaries or were not georeferenced.

➤ **Harmonization of the legend description**

The correspondence with land cover classification was achieved for 7,697 data points while the other concerned experimental sites (improved fallows, plantations) or concerned already existing meta-databases (without reference to the sampled area). Classification of vegetation meets constraints as the authors referred to different vegetation classification systems and description which were not homogenized. While some efforts are currently under development to implement a global land cover classification system (LCCS) (Di Gregorio and Jansen, 2005), the harmonization of vegetation classes remains challenging. However, I classified the data based on the main LCCS land classes (Table 29) which are further used to link with the GLOBCOVER land classes. The correspondence between the main classes and the GLOBCOVER legend is described in Appendix IX.

Table 29: Land cover classification (Globcover)

Plot ID	Land cover
1	broadleaved evergreen or semi-deciduous forest (> 5m)
2	broadleaved deciduous forest (>5m)
3	needle-leaved evergreen and deciduous forest (>5m) needle-leaved deciduous forest (>5m)
4	mixed broadleaved and needleleaved forest
5	broadleaved forest or shrubland permanently flooded, saline water
6	broadleaved or needle-leaved, evergreen or deciduous shrubland (<5m)
7	Grassland
8	Crop irrigated
9	Crop rainfed
10	Urban-artificial
11	Undefined forest
12	Undefined forest-shrub
13	Undefined herbaceous/shrub
14	Undefined natural vegetation
15	Bare soil
16	Water

➤ **Harmonization of tree biomass**

The data reported by the various authors does not represent the same tree populations. While the commercial forest inventories often start at 20-30cm diameters, firewood inventories start at 5-10cm and research plots can start from 2cm. In addition, while some authors reported volume (n=287) others reported biomass (n=7962). The objective of the harmonization is to make the data as possible comparable as possible whilst considering that they represent the same population. To

achieve this, the data were harmonized to represent volume and biomass with a threshold of 2 cm of DBH using the volume and biomass conversion factors reported in chapter 8. The volume and the biomass conversion factors allow the conversion of volume and biomass for a certain minimum diameter (DMIN) to the total volume (V_{total}) or biomass (AGB_{total}) (Table 30).

$$BCF = \frac{AGB_{total}}{AGB_{DMIN}} \quad (2)$$

Where V_{total} and AGB_{total} correspond to the total volume and biomass above 2cm. V_{Dmin} and AGB_{Dmin} correspond to the volume and the aboveground biomass for a certain minimum diameter ranging 2-30cm. When $Dmin=2$, $VCF=1$ and $BCF=1$.

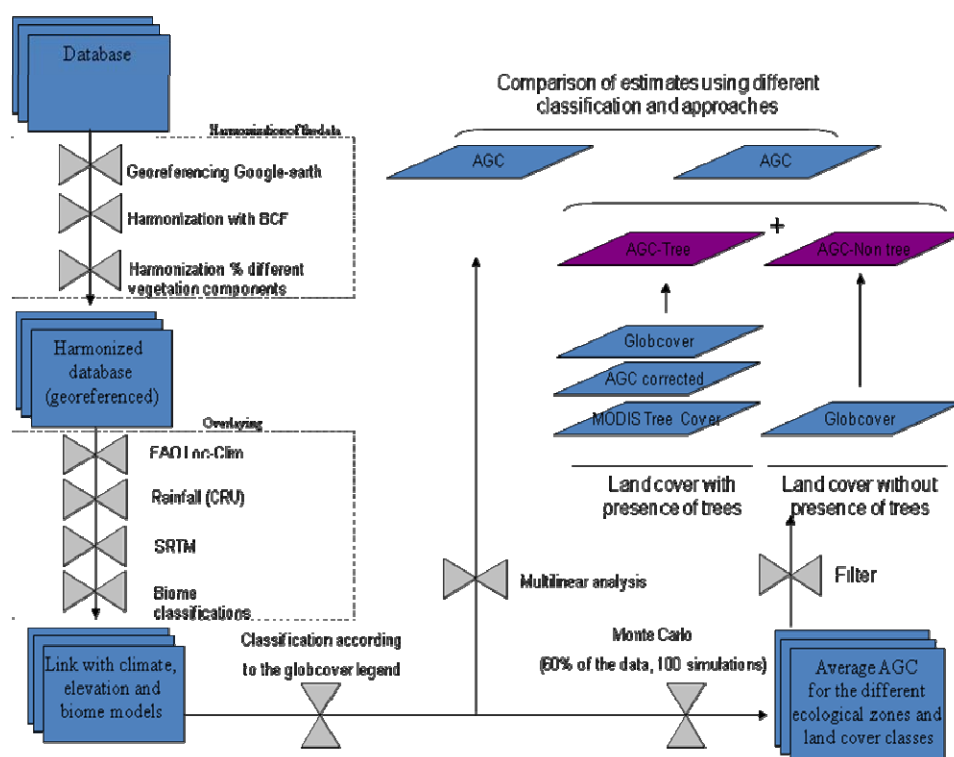


Figure 52: The procedure used to harmonize and integrate the data into modelling tools

Table 30: Belowground and aboveground carbon stocks in Africa using five different biome classifications

Country	FAO-GAUL	FAO-IIASA	SOC0-100cm	FAO	Mean	SD	Osion			Holdridge			Bailey			Udvardy		
	AREA (1000 km ²)	SOC0-30cm (Tg)		AGC (Tg)			AGC (Tg)	Mean	SD	AGC (Tg)	Mean	SD	AGC (Tg)	Mean	SD	AGC (Tg)	Mean	SD
Angola	1254	3157	5831	3033	24	±26	3201	26	±24	4592	37	±35	3784	30	±25	3496	28	±24
Botswana	580	662	1517	488	8	±18	341	6	±9	526	9	±13	341	6	±8	300	5	±7
Comoros	2	11	20	5	33	±20	15	88	±63	-	-	-	16	96	±65	-	-	-
Kenya	585	1599	3481	1050	18	±34	763	13	±23	952	16	±28	849	15	±36	959	16	±33
Lesotho	31	133	210	28	9	±12	46	15	±23	56	18	±23	74	24	±25	35	11	±13
Madagascar	594	2283	4565	2910	49	±76	2468	42	±49	2511	42	±49	1765	30	±36	2188	37	±46
Malawi	119	382	723	181	15	±20	198	17	±19	260	22	±27	254	21	±28	169	14	±16
Mayotte	0.39	1	2	2	43	±23	3	86	±53	-	-	-	4	98	±55	-	-	-
Mozambique	789	2253	4260	1870	24	±16	2479	31	±29	2750	35	±29	2736	35	±28	2424	31	±21
Namibia	828	961	1764	318	4	±11	236	3	±5	416	5	±9	221	3	±5	220	3	±8
Seychelles	0.19	0	0	0	5	±7	0	5	±11	-	-	-	0	23	±36	-	-	-
South Africa	1223	2538	4627	1683	14	±27	1264	10	±18	1544	13	±27	1895	16	±43	1461	12	±22
Swaziland	17	85	139	34	19	±20	43	25	±27	49	28	±26	45	26	±22	41	24	±20
Uganda	243	605	1141	775	32	±41	800	33	±36	782	32	±35	778	32	±29	657	27	±26
United Republic of	948	3702	6838	2590	27	±36	2444	26	±29	2796	30	±27	2669	28	±30	2516	27	±35
Zambia	756	3951	9868	1527	20	±13	1812	24	±21	2343	31	±23	2100	28	±20	1796	24	±17
Zimbabwe	392	755	1441	792	20	±16	785	20	±19	939	24	±20	761	19	±15	660	17	±13
Total Eastern and Southern Africa	8361	23077	46429	17287	21	±24	16897	28	±27	20515	24	±27	18294	31	±30	16923	20	±22
Algeria	2321	3453	5697	545	2	±21	202	1	±8	204	1	±8	254	1	±11	300	1	±12
Burkina Faso	275	694	1299	229	8	±8	273	10	±11	211	8	±8	250	9	±10	217	8	±8
Chad	1277	2682	4707	549	4	±8	617	5	±10	598	5	±9	598	5	±10	701	5	±15
Djibouti	22	26	22	3	1	±5	3	1	±2	5	2	±9	2	1	±2	4	2	±11
Egypt	984	1199	2053	12	0	±1	11	0	±1	56	1	±6	19	0	±1	141	1	±20
Eritrea	121	228	370	49	4	±10	44	4	±6	75	6	±36	40	3	±12	55	5	±16
Ethiopia	1136	3050	5610	2818	25	±39	2147	19	±26	2270	20	±28	2496	22	±44	3543	31	±57
Libyan Arab Jamahiriya	1621	2325	4287	20	0	±2	8	0	±1	18	0	±3	6	0	±1	20	0	±6
Mali	1257	2280	3885	419	3	±7	484	4	±8	441	4	±10	495	4	±11	398	3	±7
Mauritania	1043	1347	2028	50	0	±1	66	1	±2	57	1	±2	48	0	±2	52	0	±4
Morocco	407	1221	2199	371	9	±34	164	4	±15	237	6	±23	323	8	±36	258	6	±25
Niger	1189	1675	2745	101	1	±2	145	1	±2	152	1	±3	93	1	±2	97	1	±3
Somalia	637	912	1656	555	9	±20	339	5	±9	815	13	±54	311	5	±9	504	8	±21
Sudan	2495	5137	9810	2081	8	±18	1807	7	±15	2065	8	±17	2161	9	±24	2384	10	±25
Tunisia	155	426	624	105	7	±35	40	3	±11	48	3	±16	141	9	±51	63	4	±19
Western Sahara	269	518	832	0	5	±0	0	0	±0	0	0	±0	0	0	±0	0	0	±0
Total Northern Africa	15210	27172	47824	7908	88	212	6349	64	128	7252	78	232	7236	77	224	8735	86	249

Country	FAO-GAUL	FAO-IIASA	SOC0-100cm (Tg)	FAO	Osion		Holdridge		Bailey		Udvardy							
	AREA (1000 km2)	SOC0-30cm (Tg)		AGC (Tg)	Mean	SD	AGC (Tg)	Mean	SD	AGC (Tg)	Mean	SD	AGC (Tg)	Mean	SD	AGC (Tg)	Mean	SD
Benin	116	325	597	154	13	±8	190	16	±11	188	16	±11	207	18	±10	197	17	±11
Burundi	27	127	233	91	34	±41	70	26	±29	77	28	±26	74	27	±22	68	25	±21
Cameroon	469	2096	4431	4108	88	±78	4196	89	±78	4260	91	±77	2700	58	±39	3875	83	±71
RCA	624	1863	3358	2444	39	±42	2679	43	±46	3116	50	±43	2588	41	±25	2210	35	±21
Congo	344	2984	8101	3731	109	±68	3809	111	±74	3704	108	±70	2372	69	±36	3634	106	±66
Côte d'Ivoire	324	1009	1973	1301	40	±39	1289	40	±41	1373	42	±44	1087	34	±23	1346	42	±39
D.R.C	2343	9179	19150	24384	104	±77	23220	99	±73	25207	108	±109	16484	70	±36	21830	93	±67
Equatorial Guinea	27	145	236	404	149	±48	416	153	±49	418	154	±48	241	89	±30	413	152	±43
Gabon	266	1116	2400	3612	136	±56	3613	136	±61	3643	137	±58	2049	77	±30	3745	141	±55
Gambia	11	34	65	21	19	±22	28	26	±26	32	29	±52	31	28	±37	23	21	±19
Ghana	240	660	1204	685	29	±35	728	30	±36	829	34	±49	617	26	±22	763	32	±36
Guinea	247	901	1610	706	29	±28	857	35	±33	902	37	±32	876	36	±32	735	30	±20
Guinea-Bissau	34	118	219	143	42	±45	184	54	±51	184	54	±52	206	60	±69	143	42	±32
Liberia	96	438	730	1160	120	±50	1188	123	±56	1262	131	±61	721	75	±27	1177	122	±51
Nigeria	915	2497	4439	1748	19	±30	1878	21	±31	1824	20	±31	1725	19	±27	1844	20	±29
Rwanda	25	125	215	106	42	±57	89	35	±40	83	33	±34	79	31	±25	71	28	±22
Saint Helena	0.29	0	0	1	18	±7	0	1	±2	-	-	-	0	1	±1	0	0	±1
Sao Tome and Principe	1	6	11	12	126	±60	13	132	±67	-	-	-	13	136	±74	-	-	-
Senegal	198	486	883	217	11	±14	240	12	±18	232	12	±20	278	14	±24	205	10	±14
Sierra Leone	73	284	468	366	50	±38	437	60	±43	487	67	±47	382	52	±32	447	61	±41
Togo	57	160	276	83	14	±12	89	16	±13	91	16	±15	96	17	±11	100	17	±13
Total Western and Central	6439	24552	50600	45476	59	±41	45214	60	±42	47912	61	±46	32826	47	±30	42826	54	±34
Total Africa	30010	74802	144853	70670	31	±27	68461	33	±27	75680	32	±30	58356	29	±25	68484	29	±24

➤ Harmonization of ecosystem biomass

While some authors reported the total biomass of the ecosystem, some authors only reported the biomass for trees. Moreover, when authors reported the biomass in the different vegetation components (Figure 53), the proportion of biomass found in the different ecosystems was calculated. The biomass for the missing vegetation components was expressed as the proportion of tree biomass. Subsequently, the total biomass was calculated.

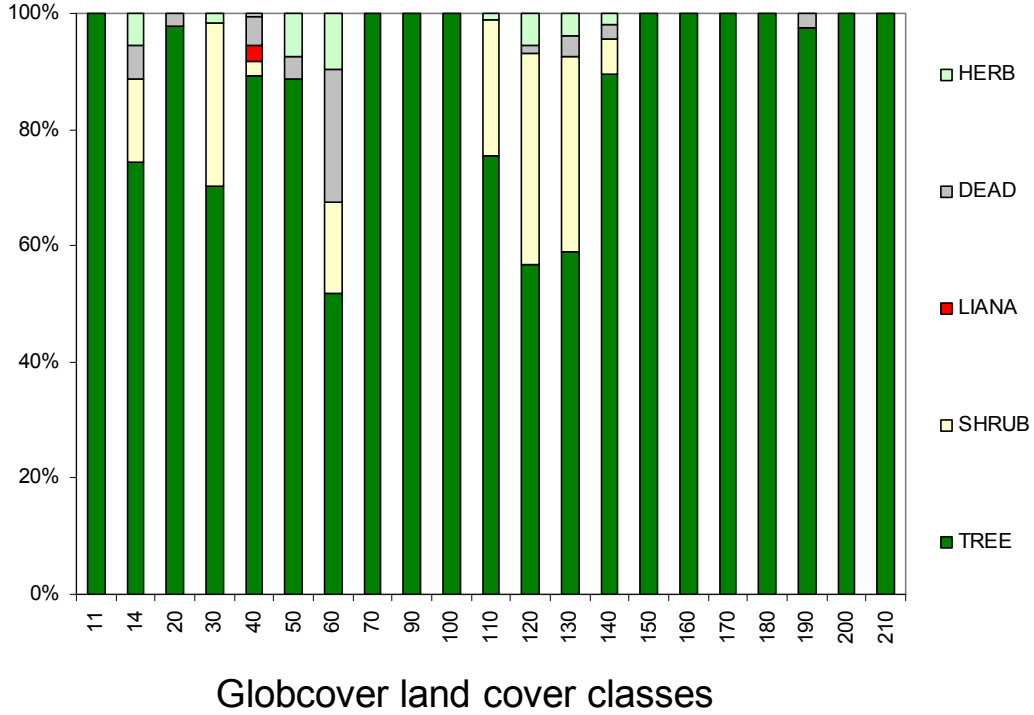


Figure 53: Distribution of aboveground in different compartments among land cover classes

The land globcover classes were:

$$AGB_j = AGB_{tree} \times \%agb_j \quad (3)$$

Where $\%agb_j$ is the proportion of biomass for the compartment j in relation to the tree biomass (Table 30).

The conversion from biomass to carbon stocks was achieved using an coefficient of 0.5 (IPCC, 2007). When the data reported total carbon stock, I assumed that the authors measured the total biomass.

$$AGC = AGB \times 0.5 \quad (4)$$

4. Data integration with land cover products

4.1 Assessing average biomass and carbon stocks per land cover classes

In order to scale up local field data to the continental scale, the GLOBCOVER product was used to represent the various land cover classes. This is the last global land cover product with the highest spatial resolution. The data were averaged per master classes using a Montecarlo procedure. 60% of the data were used to run 1000 simulations to estimate the average biomass per land cover and ecological zone classes (Figure 54). The highest variability was found for broadleaf evergreen forest of which the variance stabilized around 100 simulations. Furthermore, the average biomass and C stock was estimated based on 100 simulations.

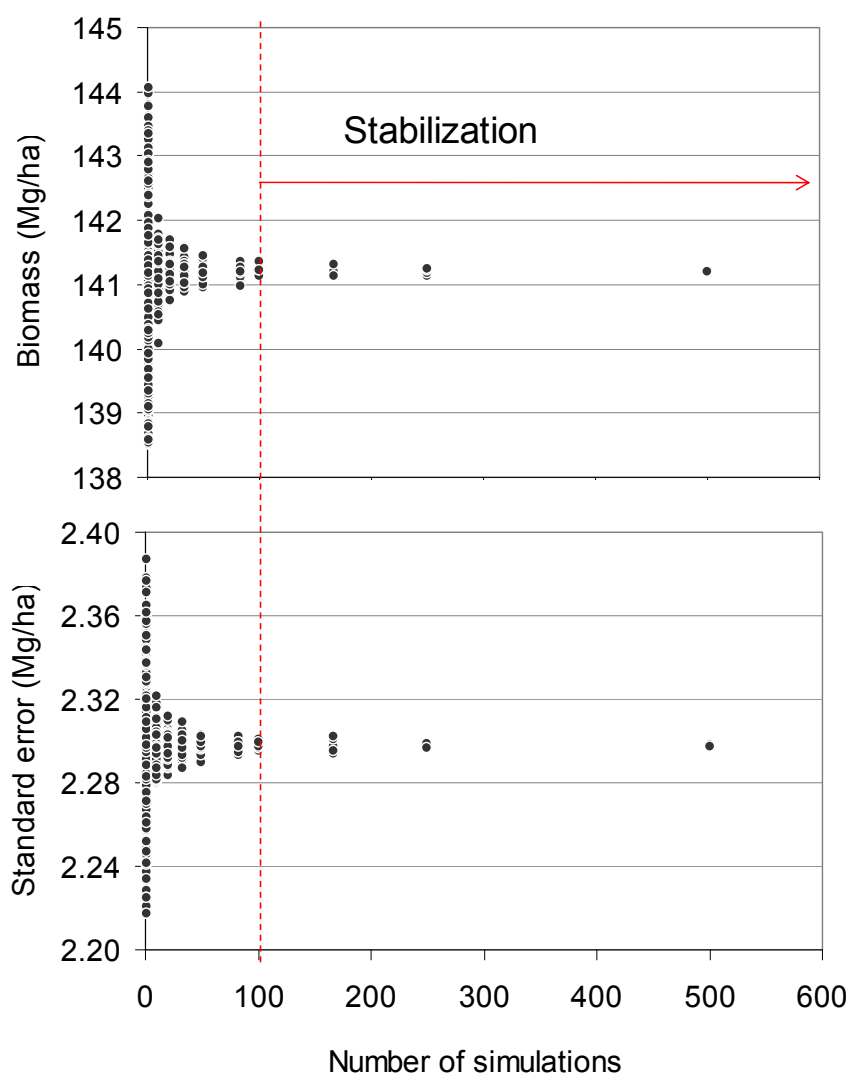


Figure 54: Relation between the number of simulations and the standard error and the average biomass

Since the data were measured for different plot size and different number of samples, they were weighted within each master class by the total area and sample plot that was measured.

The average AGC per master class and per biome was calculated:

$$\overline{AGC}_m = \sum AGCi \times \frac{ni \times SAi}{\sum ni \times SAi} \quad (5)$$

where AGC_m is the average C stock for a master class *m*, *i* corresponds to the aboveground C for a location *i*, *n* is the number of sample and SA is the sample area. The confidence interval was calculated:

$$IC = \sum n_i \times S_i \times (AGC_i - \overline{AGC}) \quad (6)$$

Since the MODIS tree cover 2001 is the best available global product to represent the distribution of tree, the tree cover was integrated with the land cover classification system to assess the biomass and the carbon stock of a pixel. This is based on the assumption that higher tree cover results in higher biomass.

4.2 Statistical analysis

The 6,525 data that fulfilled the conditions for georeferencing (located in all the shapefiles and grid layers), were combined with their respective sample sample, sampling area and the ecological zone. Spatial variability was studied at too different but complementary levels: the plot scale and the national scale; The underlying factors influencing the C stock might not be the same, or have the same importance, for the two different levels. Typically the climatic parameters must have a greater variability and thus influence at the national than local scale. The local scale variability was studied based on three case studies in agroforestry, agriculture and forestry systems in the moist forest, the dry forest and the rainforest ecological zones.

5. Variability of carbon stocks at local scale

5.1 Aboveground carbon stocks in agroforestry systems of western Kenya

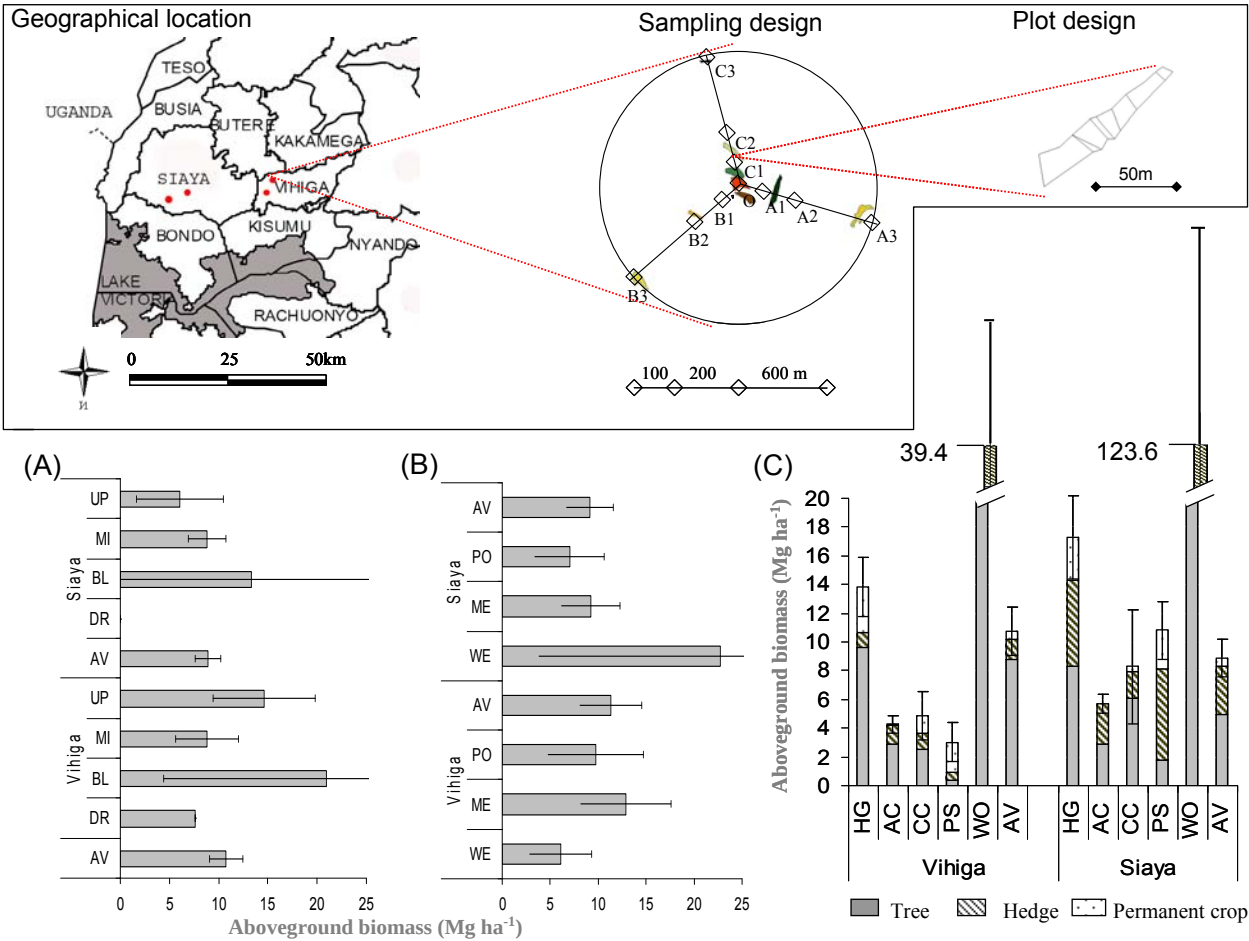
Western Kenya is located in East Africa and is characterized by undulating landscapes (Shepherd and Soule, 1998) with important tree cover which can be classified as agroforestry systems. The population density is one of the highest in Africa (300-1200 people per square km in Henry, et al. (2009) and the soils are particularly degraded due to unsustainable land management and continuous cropping systems (Tittonell, et al., 2005). Although some studies presented it as one of the most degraded landscape of East Africa (Place, et al., 2005), the region was identified by Holmgren, et al. (1994) as a case of “reforestation”.

Important landscape and spatial variations were observed by Henry, et al (2009) resulting in important variation of C stocks between field types, and regions. In two regions that were 50 km distant, Vihiga and Siaya districts, the tree biomass was managed differently according to the integration of the different farming and tree systems as a response to migration, social differentiation, and economic change, and the interplay between changing social and ecological conditions (Crowley and Carter, 2000).

On one hand, Vihiga district was characterized by intensive agroforestry systems (in terms of labour and investment on an area basis), making association between annual and permanent crops, vegetables, fruit, fodder and timber trees and livestock and household activities, the bottom lands were characterized by the presence of Eucalyptus woodlots. The biomass was higher in Vihiga than in Siaya, and were influenced by the landscape, socio-economic factors and cropping systems (Figure 55 a, b and c). In Vihiga the highest biomass was found in bottom land because they were mostly planted with Eucalyptus because those lands were the less appropriate for food and cash crop (slope, erosion, low fertility, difficult to secure from the thieves). Carbon stocks in upper slope were also important because of the presence of the homegardens and the important fruit, timber and fodder trees. In Siaya, the highest biomass was also found in bottom land but mainly because they were unmanaged land while the trees in the other cropland were mainly planted in hedgerow (Van Shaik, 1988). Higher biomass was found in medium farmers in Vihiga because they tended to diversify their farm as much as possible while wealthiest farmers were mostly cultivating tea. In Siaya, farmers were not cultivating trees and wealthy farmers tended to plant more trees in their compounds than poorer farmers in order to keep shade for their livestock. On the other hand, the poorest farmers tended to avoid planting trees that would enter into competition with food crops. This results in an important variability which depends on various factors including the climate, the market prices and the history of agrarian change.

Figure 55: Variability of biomass in agroforestry systems of Wetsern Kenya: adapted from Henry, et al. (2009).

- (A) Variation of C stocks according to the landscape: AV: average, DR: drainage, BL: bottom land, MI: midslope and UP: upslope
- (B) Variation of C stocks according to socio-economic factors: WE: wealthy farmer, ME: medium farmer, PO: poor farmer
- (C) Variation of C stocks according to the landscape units: HG: Homegarden, AC: Annual crop, CC: Cash crop, PS: Pasture, WO: Woodlot, AV: Average - Error bars represent the confidence interval.

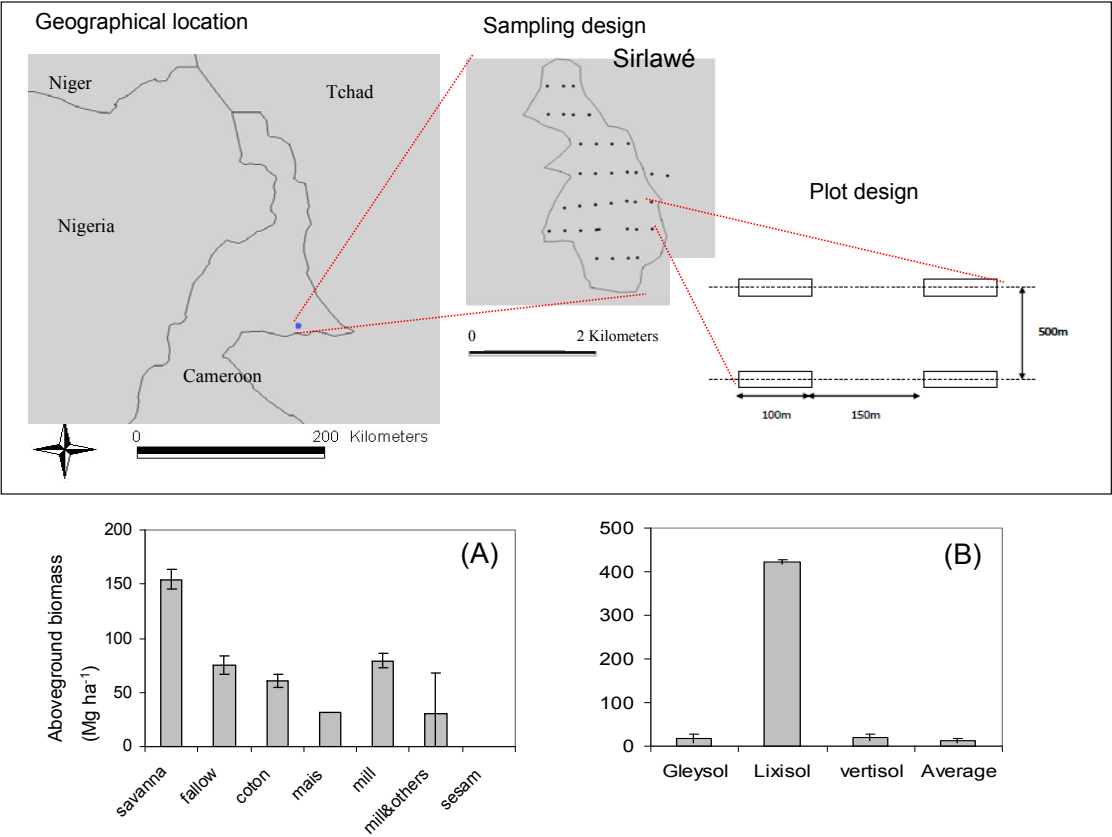


5.2 Aboveground carbon stocks in agricultural systems in the Sudanian savanna

Sudanian savanna is characterized by low tree density and short tree that are adapted to the dry conditions. The population density is particularly low (34 hab km² in Diop, Dufour et al (2004)) and most of agricultural activities are extensive rather than the intensive ones found in western Kenya. Agricultural activities are integrated into parklands with some few dominant tree species such as *Vitellaria paradoxa* or *Faidherbia albida*. When the tree cover becomes denser it is possible to consider the vegetation as forest land but it is difficult to make differentiation between shrubland, old fallows and forest unless the history of land use is known. A tree inventory was achieved in Sirlawé by Diop, Dufour et al. (2004) located in the Tupuri area in Northern Cameroon. They however reported the location as a highly densely populated area in comparison with the Sahelian region. The population density was reported by various authors as creating a demand in timber and fuelwood superior than the supply (Hiernaux and Gérard, 1999, Kaboré, 2005). As a result, many dry forests of the region are degraded which has an important impact on the carbon stock in the entire sahelian zone (Lufafa, et al., 2008). Various proposals were developed to improve forest management and particularly by encouraging sustainable pruning practices and tree regeneration (Smektala, et al., 2002, Peltier, et al., 2007).

In Sirlawé, the tree biomass resulted mainly driven by land uses and soil types. The highest biomass was found in the savanna ecosystem while the lowest was found in the sesam cropping system (Figure 56a). The mixture of millet and other crops had the largest variability. On the other hand, the soil types explained more variability. The highest biomass was found in lixisols while biomass on gleysol and vertisol areas was much lower (Figure 56b)

Figure 56: Variation of biomass in the sudanian savanna in northern Cameroon: adapted from Diop, Dufour et al. (2004).
Error bars represent the confidence interval.



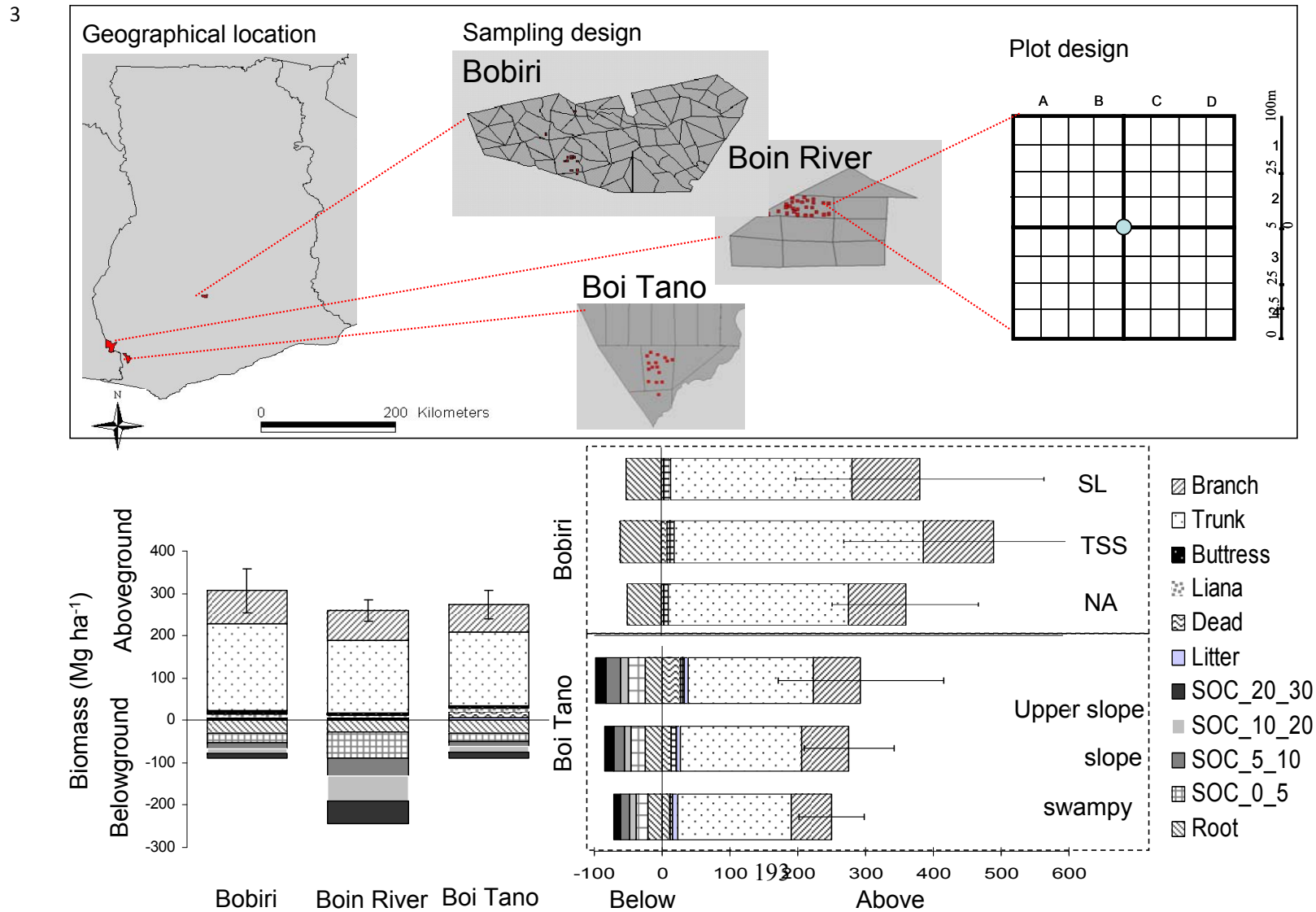
5.3 Carbon stocks in tropical rain forests of Ghana

The tropical rain forest of Ghana gained a lot of attention since 100 years since it is an important climate regulator for the cocoa plantations (Hawthorne and Abu Juam, 1995). Broadly, three main types of rainforest ecosystems can be found in the Guineo-Congolese basin. The tropical wet evergreen forest receive most of the rainfall and is principally located on soils characterized for their acidity and low nutrients content (Hall and Swaine, 1981). The moist evergreen and moist semi-deciduous forests are found in drier conditions but are taller and characterized by richer soils and the presence of bigger trees. However, 80% of the forest was lost during the last century despite the several policy attempts to improve the management of the forest (Asamoah Adam, et al., 2006). Most of the remaining forest is located within the national reserve and a significant proportion is under production management (Hawthorne, 1996). Three forest reserves were identified in three ecological zones and were analysed to illustrate the variability of biomass and carbon stocks within and between the forests (Chapter 7). The estimation of C stocks found in the forest gives an idea about the amount of C that has been released by its conversion to agricultural land. Measuring already logged forest gives an idea about the time period which is necessary for a forest to reconstitute its C stock.

While there were no significant differences in terms of aboveground C stocks between the forests, it resulted that the moist evergreen ecological zones had higher total C stocks because it was located in a soil rich in organic carbon (Figure 57a). When considering the impact of management types (Figure 57b), it resulted that the lower C stock was found in the natural forest, while the forest blocks that were logged 40 years ago had more biomass. While the difference between management types was not significantly different, the lower biomass in the natural forest can be explained by the fact that it was located in the most inaccessible and undesirable place for commercial logging. On the other hand, it seems that after a period of 40 years that the forest recovered the original C stocks. The proportion of dead standing tree was however higher in the Tree Shelterwood system (TSS) because many trees that were poisoned 40 years ago still remain as dead standing trees. When considering the influence of landscape in Boi Tano forest, upper slope areas had higher aboveground and belowground biomass than swampy areas. Swampy forests were smaller with soils dominated by the presence of sand while the slope and upper slope areas had clay soils with higher nutrient contents. Moreover, the C stocks in tropical rainforest of Ghana are mainly influenced by the soil types, the topography, the climate and the management type while the floristic composition was not considered in the C calculation.

1 **Figure 57: Variability of aboveground biomass and belowground carbon stocks in Ghana: adapted from chapter 7.**

2 Error bars represent the confidence interval.



6. Variability of biomass at national scale

6.1 Biomass variability in Zambia

Forests cover 66.4% of Zambia's total land area with another 8 percent being covered by other wooded land types which translates into approximately 49.97 and 6.1 million hectares respectively. In addition, an estimated 9.9 percent of the total land area is gazetted as forest reserves. The rate of deforestation is about 1% which is about 445,000ha per year (FAO, 2006c). The Integrated Land Use Assessments (ILUA) (Figure 58) revealed important variability within and between land use classes and ecological zones.

The highest aboveground biomass was found in mixed broadleaf and needleleaf forest according to the Globcover legend while in other natural land (raffia palms, bamboos) in the tropical moist deciduous forest. However, only one other natural land was measured and it is difficult that it would be representative of this class. The most common vegetation form with the highest carbon density was moist semi-evergreen forest according to the IULA classification. The lowest biomass was found in the shrubland and in the cropland systems except in the moist deciduous ecological zone where some croplands had even more biomass than in the evergreen and the semi-evergreen forest. Broadly, the lowest biomass was found in the drier region and the biomass allocation was different between the different land uses when using ILUA and Globcover classifications.

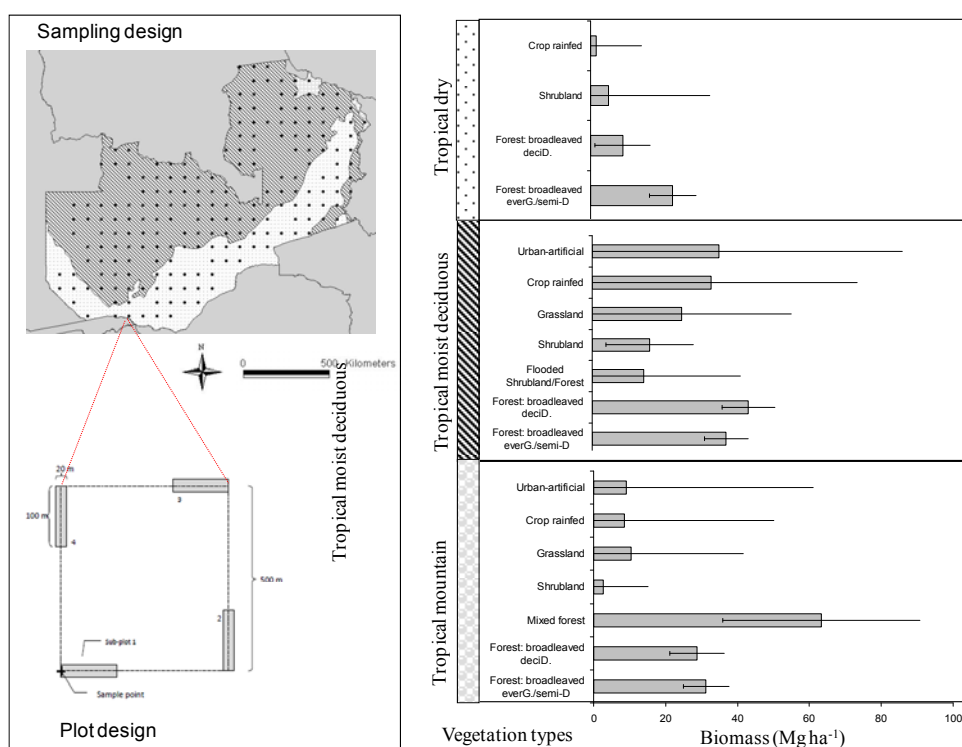


Figure 58: Variability of biomass in Zambia: adapted from the Integrated land use assessment FAO (2006d). Error bars represent the confidence interval.

6.2 Biomass variability in Cameroon

Forest cover 50% of Cameroon's total land area which corresponds to 23.86 and 0.08 million hectares of natural forest land and plantation respectively. Respectively, 24 and 8 % of the country forests were untouched and degraded during the national forest inventory led by the ministry of forest of Cameroon and the FAO (FAO, 2004a). Most of the forests were located in the tropical rainforest ecological zone while the smallest proportion was located in the tropical dry (northern savanna). The diversity of identified forest types was increasing with rainfall. While 18 vegetation classes were identified to contain vegetation in the tropical rainforest, only 8 and 4 were identified in the tropical dry forest and tropical shrubland respectively. The number of vegetation types was increasing with altitude to reach 16 vegetation types in the mountain ecological zone. When considering the broadleaved evergreen and semi-deciduous forest (Figure 59) the highest biomass was observed in the tropical rainforest zone while decreasing with drier climate. The highest biomass was found dense wet secondary evergreen forests while the lowest was found for young secondary gallery. The primary gallery forests had lower biomass than dense primary and secondary forests. While young dense secondary forests had higher biomass than forest galleries but lower than the other forests, there were not important differences between primary and secondary dense forest types. While unleaved natural forest were found in the northern Cameroon they were absent from the moist and rain forests. The tropical shrubland was not considered in the Figure 59 since no broadleaved forest was found there. However, the lowest biomass was found in the secondary forest gallery in the tropical shrubland zone. The biomass was even lower in annual cropland but varied a lot between ecological zones. It was found 84 Mg ha^{-1} in the tropical rainforest and 1 Mg ha^{-1} in the tropical shrubland zone.

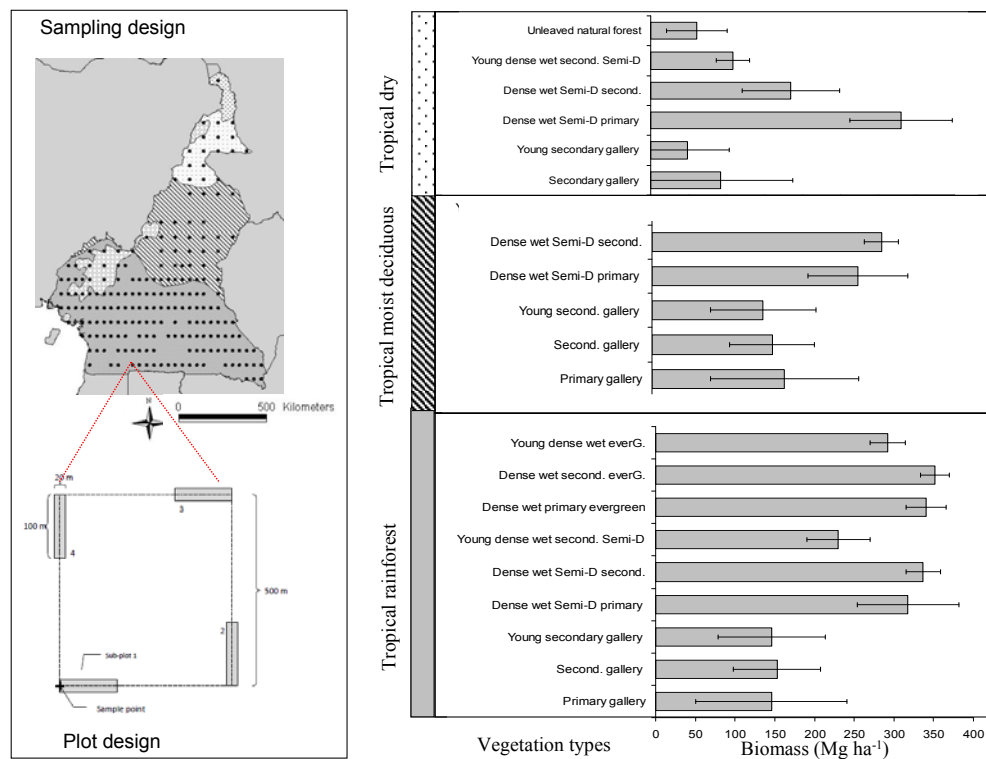


Figure 59: Variation of biomass in Cameroon: adapted from the national forest monitoring and assessment programme of the FAO (2004a). Error bars represent the confidence interval.

6.3 Biomass variability in Mozambique

Mozambique is one of the few countries in the Southern Africa region with still a considerable area of natural forest. The estimated total forest cover of the country is 40 million hectares (51% of the country), in which 22.5 million (56.2%) are dense forests and 16.4 million (40.9%) are open forests (Marzoli, 2007). Most of it (66%) falls in the dry tropical ecological zone (66%). However, the different forest area estimation initiatives in Mozambique provided dissimilar data, misleading discussions on forest changes. According to Saket (1994) the extent of forests was estimated of 19 million hectares while current estimate is 40 million hectares (Marzoli, 2007). Moreover, the rate of deforestation was estimated to range 0.2- 4.2% according to the different sources (EarthTrends, 2003, FAO, 2006c, Marzoli, 2007). Based on the national forest inventory (Marzoli, 2007), the highest biomass was reported in the broadleaved evergreen or semi-deciduous forests while this type of forest is restricted to a small number of samples and to tropical rainforest ecological zone. Except for this type of forest, there was not much variation between forest types in the different ecological zones. Important variation was found for flooded forests while broadleaved evergreen deciduous forests had the lowest confidence interval. There were not much difference between tropical dry forests and moist deciduous forests. When considering the land use classification used during the inventory, the highest average biomass and the highest amplitude of biomass was found in sub-littoral humid forests. The highest standard error was found for flooded areas revealing that higher biomass variation in humid areas. Mixed agriculture and forest vegetation had lower biomass than dense forest in all ecological zones. On the other hand, open forest does not have more biomass than mixed agriculture and forest vegetation.

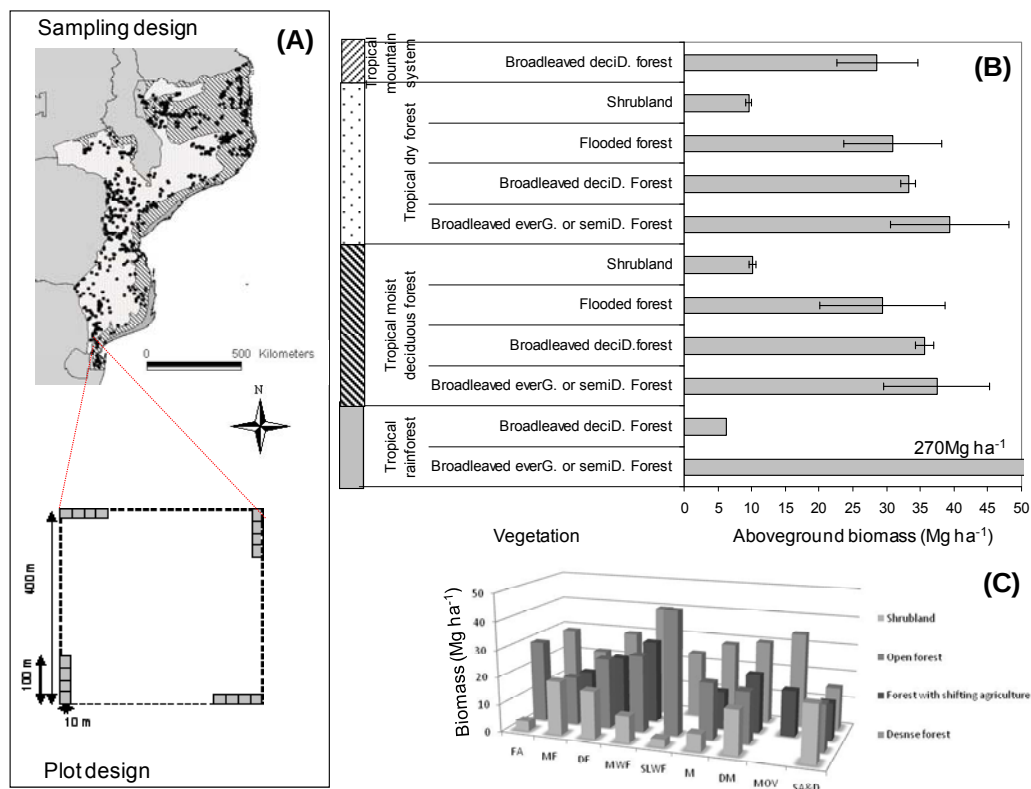


Figure 60: Variation of biomass in Mozambique: adapted from the national forest inventory (Marzoli, 2007). Error bars represent the confidence interval.

7. Variation of C stocks at continental scale

7.1 Carbon stocks in African countries

Total carbon stocks in Africa ranged from 133-150 Pg C (Table 29 30). The aboveground carbon stocks were found ranging 44 and 50%. The Democratic Republic of the Congo (DRC) is by far the largest carbon stock contributing between 28-33% of the continental carbon stock. On the other hand, it was not possible to calculate the carbon stocks of small countries because their land was not covered by the Globcover or were not represented by the ecological classification e.g. Mauritius, Europa Island, Cape Verde, etc... Equatorial Guinea represents about 1% of the DRC area but the highest average carbon density ($149\text{--}154 \text{ Mg ha}^{-1}$) which is mainly explained by an important dense humid forest cover. On the other hand, the vegetation types present in DRC are more diverse and also include vegetation with low carbon contents such as grassland and dry savannas. Some countries presented very low carbon density ($<2 \text{ Mg ha}^{-1}$) such as Algeria, Djibouti, Egypt, Libyan Arab Jamahiriya, Mauritania and Niger. Eight countries had carbon density higher than 50 Mg C ha^{-1} , while six had very low ($<3 \text{ Mg C ha}^{-1}$) and 14 had low C stock (between 3 and 10 Mg C ha^{-1}). Carbons stocks varied between vegetation types and influenced the continental C stocks. The highest carbon stock was found in dense closed broadleaved evergreen and semi deciduous forests and ranged between $155\text{--}174 \text{ Mg C ha}^{-1}$. On the other hand, Carbon stocks were considered as null in bare lands.

7.2 Influence of forest definition on C stocks

Since the countries use different forest definitions, using national reporting will obviously influence global carbon accounting based on the national estimation. Making comparison for national carbon stocks based on different definition is not correct. The Figure 61 represents the influence of the forest definition, here considered to depend on the tree cover, on the carbon stock estimation. Considering a lower tree cover threshold will increase the carbon stock estimation. When considering the national country reporting, a country like Ghana report his national carbon stocks using his own forest definition, based on a tree cover of 15% (614 Tg C in appendix XII). On the other hand, a country like Democratic Republic of the Congo (RDC) reports the forest carbon stocks with a single minimum tree crown cover value of 30 % (23,311 Tg C in appendix XII). When making a comparison between Ghana and DRC, the carbon stocks has to be standardized on the same definition (Ghana: 614 Tg C and DRC: 24,240 Tg C with a tree cover of 15% or 397 and 23,311 Tg C with a tree cover of 30%).

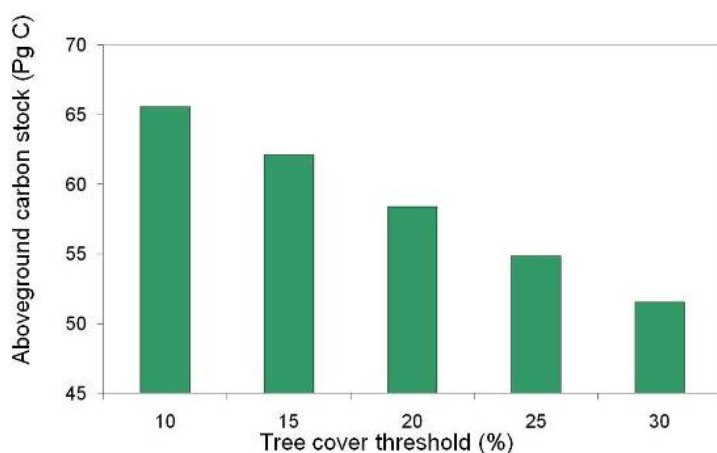


Figure 61: Influence of forest definition on aboveground carbon stock estimates

8. Discussion

Our results are about the magnitude of carbon stocks reported in Williams, Hanan et al. (2007) with carbon stocks in live plant ranging 58-76 and 50-105 Pg in our study and their study respectively. When considering only the forest ecosystems, Gaston, et al. (1998) reported aboveground carbon stocks ranging 31.5–43.4 PgC while I reported 52-66 PgC with minimum tree cover ranging 15-30%. However, they reported only tropical African countries and their forest definition considered woody formations with a minimum of 10% crown cover. When comparing the data the data from Gaston, Brown et al. (1998) that were reported for the year 1980, it appears that there are important differences which are not only due to deforestation rates and forest definition. In average our study overestimates the carbon stocks by 11 Mg ha⁻¹. While the increase of aboveground carbon stock observed in Rwanda (106 Tg in our study and 26 in their study), could be attributed to important afforestation; forest land increase by about 6.9% in Rwanda, it is difficult to explain the difference found in Burundi. The current rate of deforestation in Burundi is around 5.4% and our study reports 91 Tg C while they reported 27 Tg C. In our point of view our estimation is conservative since the maximum aboveground biomass was 174 Mg ha⁻¹ in closed broadleaved evergreen and/or semi-deciduous forest (appendix XI) while Baccini, Laporte et al. (2008) reported 251 and 216 Mg ha⁻¹ in Swamp and closed evergreen lowland forest and Gibbs reported carbon stocks in aboveground forest to range 120-250 Mg C ha⁻¹. Nobody from the 136 references used to assess the carbon stocks reported carbon stocks up to the 1836 Mg C ha⁻¹ reported by Heather, *et al.* (2009). It is important to note that all the meta-databases that were developed before never considered the harmonization for the biomass values considering the different vegetation forms and the minimum diameter threshold and the plot and number of samples. However, the methodology and the tools that were used to harmonize the data were limited in number and did not represent all the ecosystems. Further researches will have to consider additional ecosystems and vegetation forms in order to provide biomass conversion factors but also additional carbon stocks values particularly in the dry forest areas and central Africa.

9. Conclusion

Important variability of carbon stocks is found in Africa and results from complex interactions between climate, soils, topography and management. The methodology that was developed in our study allows for the harmonization and comparison of the data from different ecosystems and the use of different definitions. I report values of It is particularly important that further researches develop bridges between the field description data and the modelling process since most of the data descriptions are lost because continental product does not include this type of details. At the end, the carbon stock estimation and the comprehension of the vegetation is a compromise between the level of detail of the continental products and the time spent to implement field measurement.

The previous seven chapters focused on estimating the carbon stocks. They allow us to draw a picture of the state of knowledge and identify the missing gaps. However, carbon stocks are dynamics and largely influenced by anthropic activities. The next chapters deal with the impact of anthropic activities on carbon stocks and more particularly on the impact of selective logging on carbon stocks and the effect on enhancing carbon stocks in agroforestry systems. On the one hand, deforestation corresponds to the conversion of forest land to non-forest land. The carbon stock change can be easily estimated by making the difference of carbon stocks between the two land categories. On the other hand, forest degradation corresponds to forest land remaining as forest land. The carbon stock changes are moreover more difficult to measure and to monitor using remote sensing technique than for deforestation. Selective logging is one of the main drivers of forest degradation in SSA (Chapter 2) and its impact on the GHG balance was never considered before. Agroforestry systems are among the potential alternatives to revert the trend of forest degradation and deforestation but its potential is very poorly known. The next three chapters will deal with estimating the impact of selective logging and agroforestry systems on the carbon balance in order to identify potential options for forest C sequestration and emissions reduction.

Chapter 10

Estimating the impact of selective logging on aboveground carbon stocks in a wet evergreen forest of Ghana

This chapter is modified from the article: Henry, M., Adu-Bredu, S., Martel, S., Gineste, M., , Asante, W.A., Avitabile, V., Hamel, O., Eshun, J., Valentini, R. Bernoux, M., Saint-André, L. (2010), Impact of forest degradation caused by selective logging on carbon stocks in a wet evergreen forest of Ghana (2010), Ecological applications, submitted

Abstract

While land use change is considered to contribute to 20% of greenhouse gases (GHG) emissions, forest degradation is considered to be an important factor, as much as important or even more in the African continent. Selective logging is an important factor of forest degradation specifically in tropical forested countries such as Ghana but his contribution to the GHG balance is particularly poorly known and depends on various factors such as the original forest biomass, the harvesting intensity, the logging practices, the climate and the soil types. The aim of this study was to estimate the impact of selective logging on carbon (C) stocks and the GHG. The experiments were implemented in a 170 ha forest compartment of Boi Tano forest reserve, situated in the wet evergreen forest zone of Ghana. Sixteen plots of one ha were implemented, centred on trees to be felled and trees with diameter >2cm were measured and biomass estimated using a site-specific allometric equation. A post logging inventory was achieved to quantify the impact on the forest structure and the ground damaged areas.

1. 15 Mg C ha⁻¹ were lost with a logging intensity of 1.5 trees ha⁻¹ which is low in tropical humid Africa. The confidence interval at 95% was 14 Mg C ha⁻¹ and the variability in C stocks and emissions does not allow to measure significant emission reductions from reduced impact logging practices. This particularly limits the use of the C markets and funds to compensate logging companies to implement emission reduction strategies based only on the C accounting.
2. 745 Mg C were emitted from which fossil fuel combustion accounted 22%, burning waste 4%, decomposition 65% and decay 8%.
3. Based on an emission coefficient factor of 1.59 Mg C m⁻³ of log harvested I derived that 2.42 Tg C yr⁻¹ were emitted in Ghana and 88 in sub-Saharan Africa. Moreover, selective logging would contribute for 20-25% of the total emissions of sub-Saharan Africa.
4. There was a poor relation between the Landsat image spectral signatures and the measured biomass in plots of different size. It is not reliable to use a tracking method to report specific emission factors.
5. The GHG balance is poorly known since the future of wood residues inside forest is poorly known and particularly the contribution of this large input to the soil compartment and its stabilization in long term aggregates.
6. The future of the wood product is not known and mostly depends on the European use of timber products. The GHG balance of selective logging is then not only the responsibility of Ghanaians while it will be accounted for in their national accounting system.

Keywords: Tropical forest, Climate Change, Forest Management, Degradation, West Africa

1. Introduction

Land use change is considered to contribute to 20% of global greenhouse gases (GHG) emissions (IPCC, 2007a). In sub-Saharan Africa, forest degradation is considered to be the most important source of land-based emissions contributing to 0.77 Pg C y^{-1} (Bombelli, *et al.*, 2009). Forest degradation gained recently a lot of attention because reducing the emission from deforestation and forest degradation (REDD+) was integrated into the international negotiations on climate change (UNFCCC, 2007a). Selective logging is an important factor of forest degradation particularly in forested countries of tropical Africa where selective logging is the predominant timber harvesting practice (FAO, 2006c).

Logging activities were identified as a major proximate cause of forest degradation and deforestation (Angelsen and D., 1999) and increase the access for harvesting timber and non-timber forest products, firewood collection, increase the risk of fire propagation, hunting and the conversion of forest to agricultural systems (Lanly, 2003, Laurance, *et al.*, 2006). In a country like Ghana, where 80% of forest cover was lost during the last century, selective logging is as an important factor of forest degradation and deforestation (Dei-Amoah, 1993, Aguro, 1996, Agyeman, *et al.*, 1999b). The challenge of adequately integrate forest regeneration and logging activities into development policies and practices has plagued efforts to encourage sustainable harvesting (Asamoah Adam, *et al.*, 2006). However, the timber sector represents 1.15 million ha and the third economical sector of Ghana (ITTO, 2005) and focuses on harvesting few commercial species (Wong and Blackett, 1994) in an unsustainable way (ITTO, 2005).

Attempts to improve tree exploitation on a sustainable way tended to e.g. diversify the number of harvested tree species, improve directional tree falls, decrease transport (Ezzine de Blas and Ruiz Perez, 2008). Sustainable forest management has been identified as an option to decrease the impact of anthropic activities on the C stocks (Putz, *et al.*, 2008c, UNFCCC, 2008). However, the tree harvesting practices still depends on the timber market which drives the logging activities and practices, the amount and the species diversity of harvested timber logs (Adam, 2003, Karsenty and Gourlet-Fleury, 2006). Selective logging in Ghana is then an ecological, economical and social issue (Asamoah Adam, *et al.*, 2006).

Since climate change gained a lot of attention, many researches focused on estimating the impact of anthropic activities and particularly Land Use and Land Use Change (LULUCF) on C stocks. Various international progresses were achieved under the United Nations Framework on Climate Change (UNFCCC) to quantify and predict the relation between atmospheric fluxes and oceanic and terrestrial ecosystems and implement binding and voluntary actions in developed and developing countries. While developed countries are committed to reduce their emissions under the first commitment period of the Kyoto protocol, reducing emission from forest degradation (as part of the REDD+ mechanism) is likely to become eligible in developing country during the second commitment period (UNFCCC 4/CP.15). The SBSTA decision (SBSTA/CP.15) requests developing country Parties to use the most recent Intergovernmental Panel on Climate Change (IPCC) guidance and guidelines, as adopted or encouraged by the Conference of the Parties, as appropriate, as a basis for estimating anthropogenic forest-related greenhouse gas emissions by sources and removals by sinks, forest carbon stocks and forest area changes.

According to IPCC (2006a) there are two basic methods to estimate C stock changes. In the Gain-loss method the C stock changes are estimated by considering all relevant processes, and calculated as the difference between C gains (due to growth of trees) and carbon losses (due to harvests, fires, and other natural losses and disturbances). By contrast, in the Stock change method, the C stock changes are the difference of C stocks for a given forest area at two points in time.

While the impact of deforestation can be estimated by making the difference between forest and non-forest carbon stocks (stock difference) or applying a coefficient to changed area (gain-loss), the impact of forest degradation is more complex because it is considered as forest that remains as forest and does not induce a change in the land category as defined by the IPCC (2007). Healey, Blackard et al. (2009) proposed a method to systematically determine transport emissions from forest concessions using Landsat imageries in forest concession in the US. Landsat imageries represent the best compromise between freely accessible satellite imageries for spatial and spectral resolution. However, in tropical forests, the use of remote sensing techniques to detect logging operations is limited to spectral, temporal, spatial resolution and cloud cover (Imbernon, 2004) and few case studies show the feasibility to estimate biomass and C stock changes from forest degradation (Souza, et al., 2003). It is moreover difficult to implement a measurement system that will consider selective logging using the carbon difference approach. Current studies use the gain-loss methods and models to estimate the carbon balance after selective logging.

When considering the impact of selective logging on the C cycle, the dynamics are poorly known because it concerns a long term ecological process and tropical forest ecosystems are complex (Bernhard-Reversat, *et al.*, 1978, Bisong and Mfon, 2006). Most of the studies focuses on the sustainability of selective logging of few commercial species on an economic point of view (Verissimo, et al., 1995, Fredericksen and Pariona, 2002, Park, et al., 2005, Veloso de Freitas and Pinard, 2008). Various logging operations such as skid trails, logging bays, tree falls and roads (Hawthorne, 1993) affect the C cycle in different ways which differ in time and in the spatial distribution (Anderson and Spencer, 1991). The tree falls affect the surrounding biomass while the heavy machinery that is used for skidding compact the soil and increase leaching and nutrient losses (Fredericksen and Pariona, 2002). The dead biomass which results from the damages is then decomposed to organic matter. Canopy opening facilitates the regeneration of pioneer trees with lower wood gravity but faster growth (Hall and Swaine, 1981) and maintains species diversity (Schnitzer and Carson, 2001). The regeneration of forest follows different status of recovery according to the different soil types and topography (Kahn, 1982) and the different cohort of functional types, with pioneer trees growing first, then non pioneer light demander and then shade bearer (Hawthorne, 1995).

Different studies showed that identification of logging impacts is feasible at ground scale (Hawthorne, 1993, Broadbent, 2005). When considering carbon stocks estimation, Putz, Pieter A. Zuidema et al. (2008a) reported that conventional logging emitted over 100 Mg C ha⁻¹ in Malaysia. Pinard and Cropper (2000) used simulation models and estimated 116 Mg C ha⁻¹ losses in dipterocarp forest. Logging practices reduced aboveground carbon stocks by half (145 Mg C ha⁻¹) and a third (85 Mg C ha⁻¹) in conventional and intensive timber stand improvement treatments in Paracou in the French Guiana (Blanc, et al., 2009). According to the FAO/UNEP (1981), the removal of tree biomass by logging averaged 30 Mg C ha⁻¹ in an evergreen forest and 15 Mg C ha⁻¹ in a mixed forest. According to Anderson and Spencer (1991), a third of aboveground biomass resulted as residues after logging.

The lowest biomass removal was estimated 10 Mg C in central Africa by Brown, et al (2005). The important differences between estimates can result from – variation of forest biomass by biotic and abiotic factors - the biomass allometric equation (Chapter 4, 5 and 6) – different type of logging practices. Estimation of the variability of C stocks is complex even more when considering tropical forest ecosystems (Chave, *et al.*, 2003). Estimating the C stocks before logging require consistent forest inventories (Ponce-Hernandez, 2004) and adapted biomass allometric regressions (Chave, *et al.*, 2005, Mokany, *et al.*, 2006). Using unsuitable biomass allometric regression could lead to important errors (Kirby and Potvin, 2007).

This study indeed endeavoured to confirm the hypothesis that it is possible to develop a method to estimate the impact of logging using Landsat imageries. The second hypothesis is that previous carbon losses from logging activities were particularly low.

Based on destructive field measurements and tracking logging activities, our study tended to respond to the following objectives (i) estimation of forest biomass using a local developed biomass equation, (ii) estimation of impacted area, biomass and carbon losses (iii) estimation of GHG balance, and (iv) to test non destructive methods for estimation the impact of logging on C stocks. In that attempt, the first method is based on tracking logging activities and mapping carbon stocks while the second method is based on a relation between log volume and carbon losses.

2. Materials and methods

2.1 Study site

The Boi Tano forest reserve is located in the Enchi Forest District, in the Western Region of Ghana (Figure 62). It lies between latitudes 5°20' and 5°36' North and longitudes 2°34' and 2°50' West, and the total area is 122 km². The climate is characterised by a bimodal rainfall distribution and the annual precipitations are superior to 1750 mm (Hall and Swaine, 1981) and a mean temperature of 26.7 (FAO, 2005d). The landscape consists of a series of hills with altitudes varying between 64 m and 106 m above sea level (Chapter 7). The soils are mostly forest oxysols (Hawthorne and Abu Juam, 1995). The forest reserve falls within the wet-evergreen forest type (Hall and Swaine, 1976). The forest falls into the *Cynometra* - *Lophira* - *Terriatia* association of Taylor's (1960) vegetation classification and the tropical rainforest according to the FAO (2001a). Very little is known about the history of the Boi Tano Forest Reserve before its first concession in 1947 granted to African Timber and Plywood. There was timber exploitation before its selection and demarcation in 1967, but the area did not appear to have come under intensive selective logging and clearing for farming because of the low soil fertility and the hilly terrain. The first working plan was established in 1992 for the period 1990-2009 (Asiamah and Poku-Marboah, 1992). The Forest Reserve is currently under selective logging concession and the Samartex Timber Company (previously African Timber and Plywood) is the contractor.

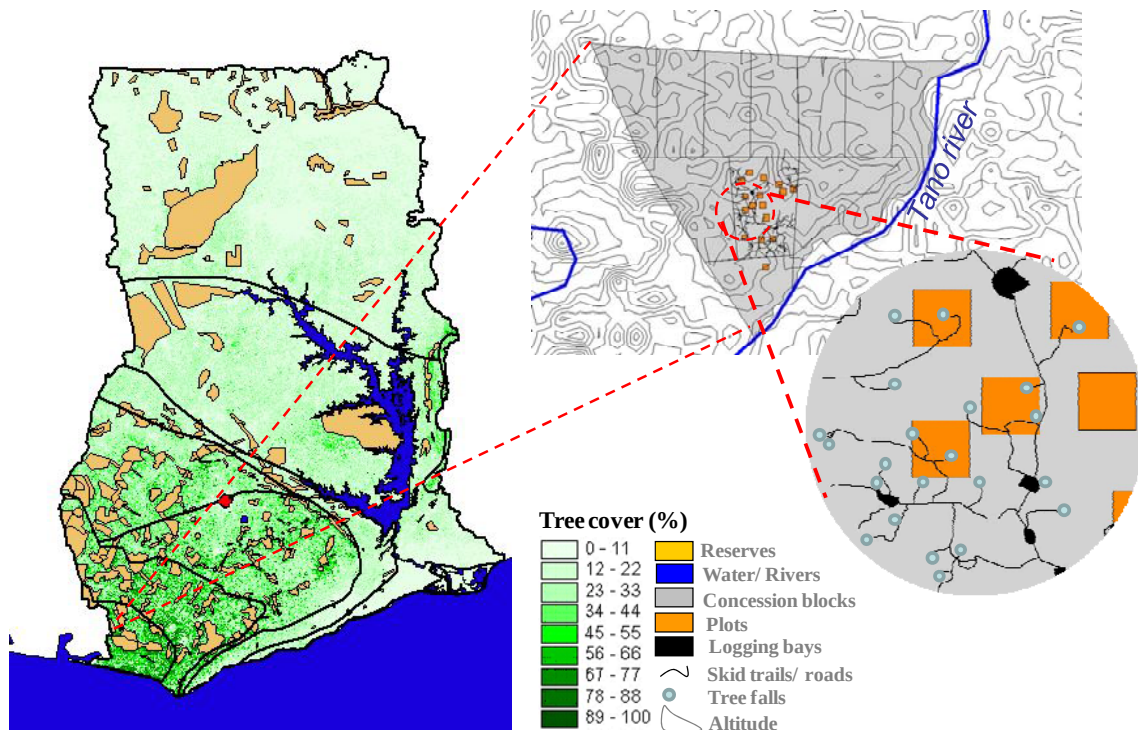


Figure 62: Map of the study area showing the location of the forest plots and the logging impacts.

2.2 Mapping logging activities

During the period August-November 2008, the logging company was operative in one of the 12 forest blocks (Figure 62). The logging impacts were identified as (TF) tree falls, (ST) skid trail, (R) roads and (LB) logging bays (Hawthorne, 1993) and were georeferenced using a Garmin GPS. The width of the road was measured every 100 meters and the width of the skid trails every 50 meters. The crown diameter and the diameter at breast height (DBH) of the felled trees were measured with a tape measure and a calliper. The corner of the logging bays were georeferenced and the ground areas for the different types of impact were calculated. Digital spatialisation was achieved with Arcview GIS 3.2 (ESRI, 1997). Roads and skid trail were represented as lines and logging bays and tree falls were represented as polygons (Figure 62). In order not to overestimate the area impacted by tree falls and skid trail (e.g. would overlap), the area that falls within the tree fall gap and skid trail were considered as skid trail impacted zone.

2.3 Inventorying aboveground biomass

Sixteen plots of one hectare were randomly implemented within a 170 ha forest compartment. All the plots were centred on a selected tree to be felled (Chapter 7). Three plots were selected to analyze the spatial variability of biomass between ecological zones. Those three “variability plots” were divided into 10x10m plots. Five vegetation classes were differentiated: (1) trees with

DBH<20cm, (2) trees of DBH between 20 and 50cm, (3) trees with DBH>50cm, (4) lianas and (5) dead plants. All the plants of a diameter at breast height (DBH) above 2 cm were inventoried and tree species identified and classified when it was possible per plant functional types (Hawthorne, 1995). A niche sampling strategy was used into the thirteen other plots. While all the trees above 50cm were inventoried inside one hectare plots, the trees with diameter between 50 and 20 cm were inventoried into four randomly selected subplots of 25x25 m whereas trees with DBH <20 cm were inventoried into four randomly selected subplots of 12.5x12.5 m. The tree aboveground biomass (AGBt) was estimated using site-specific and plant functional type specific allometric equations developed for Boi Tano forest reserve (Chapter 5).

$$\text{ALL: } AGBt = 0.3 \times DBH^{2.31} \quad (1)$$

$$\text{NPLD: } AGB_{npld} = 0.11 \times DBH^{2.58} \quad (2)$$

$$\text{P: } AGBp = DBH^{1.95} \quad (3)$$

$$\text{SB: } AGBsb = DBH^{1.99} \quad (4)$$

Where ALL concerns all the tree species, NPLD: the non pioneer light demander, P: pioneer, and SB: shade bearer. The generalized (ALL) equation was used when it was not possible to identify the plant functional type.

The liana aboveground biomass (AGBl) was estimated using the equation reported in Schnitzer *et al.* (2002).

$$AGBl = \exp(-1.484 + 2.657 \times \ln(DBH)) \quad (5)$$

Dead standing trees biomass (AGBd) and the dead biomass on the ground was estimated using the method developed by Pearson *et al.* (2005b). For each of the categories, the biomass was estimated by subtracting the portion of biomass lost. The proportion was estimated based on a qualitative observation.

$$AGBd = AGB \times (1 - \%dead) \quad (6)$$

The herb layer and the epiphytes, which only represent a very small fraction of the biomass were not considered (Bernhard-Reversat, *et al.*, 1978).

2.4 Aboveground carbon losses

The biomass loss (AGB_{loss}) was estimated assuming that all the aboveground biomass on the damaged area was removed when building the logging bays and the roads.

$$AGB_{loss} = A_g \times EF \quad (7)$$

Where A_g is the ground area where the vegetation is removed (m^2) and EF is the emission factor ($kg\ m^{-2}$).

When considering skid trails and tree falls, a post-logging forest inventory was achieved in one of the variability plot. The 10x10 meters sub-plots were categorized as skid trail, tree fall and intact and the impacted biomass was estimated using a stock difference method.

$$EF = AGB_{pre} - AGB_{post} \quad (8)$$

Where AGB_{pre} is the biomass before logging and AGB_{post} is the biomass after logging ($kg\ m^{-2}$).

The amount of residues left on the soil from harvested trees was measured for 17 trees and the relation between the DBH, and the impacted biomass was established (Figure 63a).

Conversion from biomass to C stock was achieved by multiplying biomass by the C content. Carbon content was measured for litter while it was assumed to correspond 47% for trees, palms and lianas (including roots) (IPCC, 2003). Aboveground carbon stock was named AGC in the text.

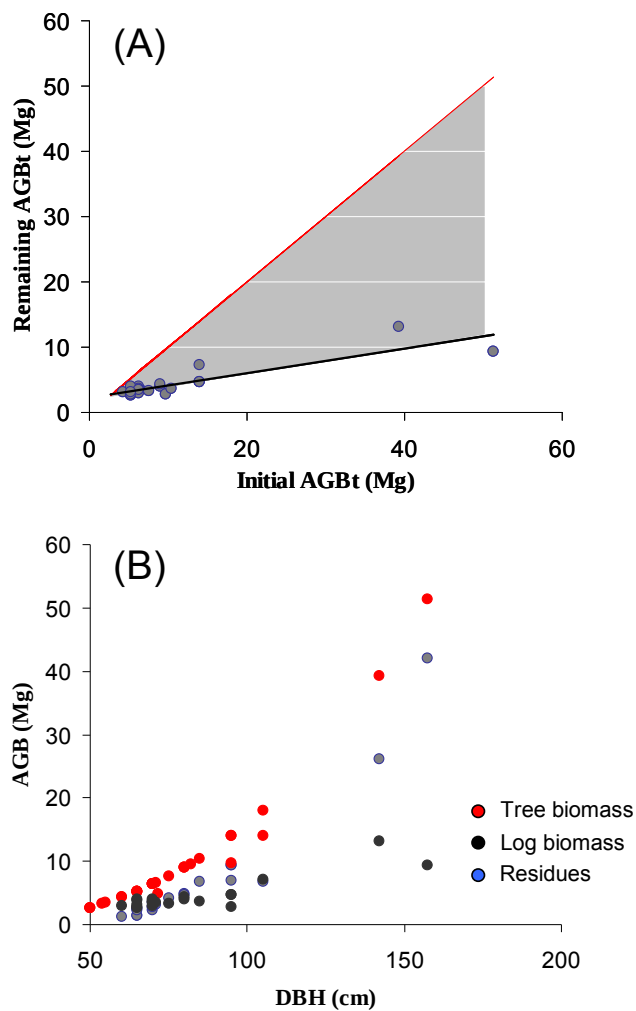


Figure 63: Relation between tree DBH, biomass, log volume and residues.

(A) Relationship between initial biomass and tree residues on the ground: $y = 0.1879x + 2.3157$, $R^2 = 0.77$, $n=21$, the grey area represents the residues from tree harvesting.

(B) Relationship between the DBH and biomass of the logs harvested: $y = 0.3595x - 22.898$

$R^2 = 0.90$, $n=21$.

2.5 Greenhouse gas balance of logging activities

The GHG balance considered only the loss and gain from the aboveground compartment since there are no default factors or scientific agreement on the soil dynamics after logging activities. I differentiated five main sources of GHG emissions. (1) Diesel consumption by the machinery (E_{ffc}), (2) Burning of solid wood waste by the factory (E_{waste}), (3) the decomposition of within forest wastes ($E_{decomposition}$), and (4) the oxidation of the timber products (E_{decay}). While the two first are emitted in a one year period after logging, dead wood remaining in the forest and the transformed wood products could be considered as a mid and long term C storage (Gitz, 2004). The forest regeneration (U_{growth}) starts immediately when logging activities leave the forest and can be considered as constant for the 40 years period after logging.

$$GHG_{balance} = U_{growth} - E_{ffc} - E_{decomposition} - E_{waste} - E_{decay} \quad (9)$$

➤ Diesel consumption (E_{ffc})

I estimated the emissions from the fossil fuel combustion by the machineries based on the diesel consumption data obtained by the factory and the default factors reported by the IPCC (IPCC, 2006b). Diesel combustion emits CO_2 , CH_4 and N_2O .

$$E_{ffc} = V_{diesel} \times MV \times NCV \times CEF \times FO \quad (10)$$

Where E_{ffc} is the carbon emission ($kg\ CO_2$), V_{diesel} is the volume of diesel consumption ($m^3\ yr^{-1}$), MV is the mass density of diesel ($850\ kg\ m^{-3}$), NCV is the selected net calorific value ($43.33\ TJ\ Gg$) and CEF is the carbon emission factor ($74,100\ kg\ CO_2\ TJ^{-1}$) and FO is the fraction of oxidised carbon of the energy source (0.99) (IPCC, 2007a).

When considering the emission of CH_4 and N_2O , the carbon emission factor was $4.15\ kg\ TJ^{-1}$ and $28.6\ kg\ TJ^{-1}$ respectively. The total emission of carbon from fossil fuel was calculated using conversion factors of 0.273 for CO_2 , 5.727 for CH_4 , 84.545 for N_2O (IPCC, 2006b).

➤ Burned wastes (E_{waste})

The proportion of wood which is burnt by the factory corresponds to the amount of waste or residues from the sawn timber (Aseidu, 2005).

$$E_{waste} = AGB_{harvested} \times E_t \quad (11)$$

Where $AGB_{harvested}$ is the wood which is harvested from the forest and E_t is the efficiency of transformation of 0.56 as reported by Aina, Adetogun et al. (2005).

➤ Decomposition (Edecomposition)

Some estimates of decomposition rates for sanitary landfills have been made (Micales and Skog, 1997), but how and where waste is dumped, and the associated decomposition rates are particularly uncertain for the developing countries (Anderson and Spencer, 1991, Brown and Schlamadinger, 1998). Moreover, I assumed that the residues left in the forest decay over time while not contributing to the soil compartment. The decomposition rate was calculated with the formula reported by Chambers, Higuchi et al. (2000), and an average temperature of 26.7C (FAO, 2005d).

$$K_d = 0.0157 \times \text{Exp}(0.0875 \times T) \quad (12)$$

Where K_d is the annual decomposition rate (%) and T is the time period (year).

$$E_{\text{decomposition}} = C_{\text{impact}} \times K_d \quad (13)$$

Where $E_{\text{decomposition}}$ is the C emitted from tree residues decomposition (Mg C yr^{-1}).

➤ Decay (Edecay)

The annual oxidation fractions were taken from (Winjum, et al., 1998). The oxidation fractions were selected for temperate forest regions because most wood products in Ghana are then exported.

$$E_{\text{decay}} = \text{AGB}_{\text{harvested}} \times \text{OF} \quad (13)$$

Where OF was considered to be 0.04 for industrial round wood.

➤ C uptake from vegetation growth (U_{growth})

Many factors affect the forest regrowth (water availability, irradiance, nutrient availability, tree functional group, etc.). Baker (2003) presented the tree diameter increment for different plant functional types, or forest types in the Amazon. However, no data were found on forest regrowth expressed in C for Ghanaian forests. Furthermore, I assumed that forest recovers the original C in 40 years, which is conservative when comparing to the data reported by (Kotto-Same, *et al.*, 1997). 40 years is the period of time which is considered by the forest commission of Ghana to recover the original timber capacity (Ghana Forestry Department, 1992). Chapter 5 reported no significant difference biomass between a natural forest and a 40years old logged forest in Bobiri forest in Ghana.

2.6 Testing methods

This study proposed the use of two methods to estimate the impact of selective logging on C stocks and the GHG balance. The first method hereafter named “tracking method”, proposes to develop a C stock map and to georeference the different types of impacts. This method allows considering spatial variation of biomass and would give more appropriate emission factors. The second method hereafter named “proxy method” proposes to give estimates based on the harvested volume rather than on the impacted area. Both methods are tested in order to compare their feasibility in the

context of the study. While the second method is based on the national statistics on log volume, the first one is based on mapping carbon stocks and tracking changes.

In order to develop a C stock map, the relation between the aboveground biomass measured in the field plots and the spectral response of Landsat data was investigated at different resolutions of the field data. The Landsat ETM+ image Path 195 Row 56 acquired on 02 February 2000 with spatial resolution of 28.5 m was used for this analysis (Figure 64). Atmospheric correction or radiometric calibration of the image was not necessary since the analysis was image-specific and not to be generalized over time or space (Song, et al., 2001). Landsat data were correlated with biomass density measured in 16 plots of 100 x 100 m, 75 plots of 20 x 20 m and 300 plots of 10 x 10 m. The plots with 20 x 20 m and 10 x 10 m size were subplots measured inside the 3 variability plots of 1 ha above-mentioned. Before the analysis, the data were aggregated to the same spatial scale according to the following procedure. For the plots larger than the image cell size, the spectral data located inside the plots were averaged for each band and then correlated with the plot biomass value, while in the opposite case the biomass density of all the plots with the centre located within each Landsat pixel were averaged and then correlated with the pixel value. After the latter aggregation, 37 and 52 average plot values were obtained from the 20 x 20 m and 10 x 10 m plots, respectively. Two different statistical models were tested to relate biomass and spectral data: a stepwise multivariate linear regression model and a regression tree-based model, Random Forest (Breiman, 2001). In both cases, all Landsat bands, except the thermal and panchromatic channels, were input to the models.

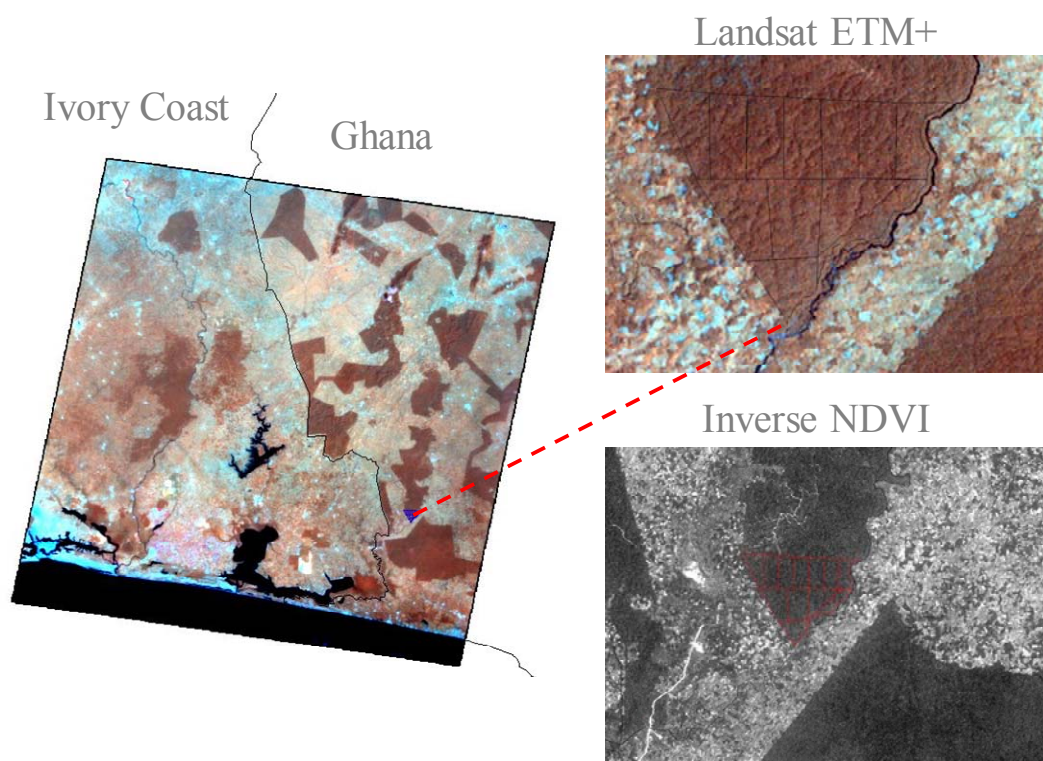


Figure 64: Analysis of Landsat images spectral response to biomass using different spectral signals combinations.

3. Results

3.1 Aboveground biomass

Aboveground biomass stock was $411 \pm 29 \text{ Mg ha}^{-1}$ which is lower than the average $448 \pm 25 \text{ Mg ha}^{-1}$ reported in Chapter 5 but higher than the $402 \pm 17 \text{ Mg ha}^{-1}$ reported for Boi Tano. Most of the biomass was contained in trees with $\text{DBH} > 50\text{cm}$ (41%), while 34, 19, 2 and 4% of biomass was found in tree DBH between 20 and 50, $\text{DBH} < 20$, liana and dead wood (Figure 65). When considering the stem density, on average it was $3395 \text{ stems ha}^{-1}$, and 82% of the trees were found having $\text{DBH} < 20\text{cm}$. On the other hand, trees with $\text{DBH} > 50$ represented 1% of the density but 47% of the variability. AGB variation within the 1 ha plot was high and ranged $31\text{--}3301 \text{ Mg ha}^{-1}$ which gives value lower than the 3734 Mg ha^{-1} reported by (Heather, *et al.*, 2009). Standard deviation of the 16 measured plots was in average 58.6 Mg ha^{-1} , and the 95% confidence interval on the mean AGB was around 28.7 Mg ha^{-1} . Based on the variability analysis, nine plots would be necessary to give a biomass estimate with a 5% precision (ref) while considering additional seven plots improved the precision of 1.2%. While I used site specific allometric equation, using other equations would have led to give significantly different biomass estimates. The equations from Chave reported aboveground biomass of 368 ± 29 and $373 \pm 29 \text{ Mg ha}^{-1}$ for wet evergreen and moist evergreen forest respectively, while the equation from Pearson (2007) reported $373 \pm 28 \text{ Mg ha}^{-1}$.

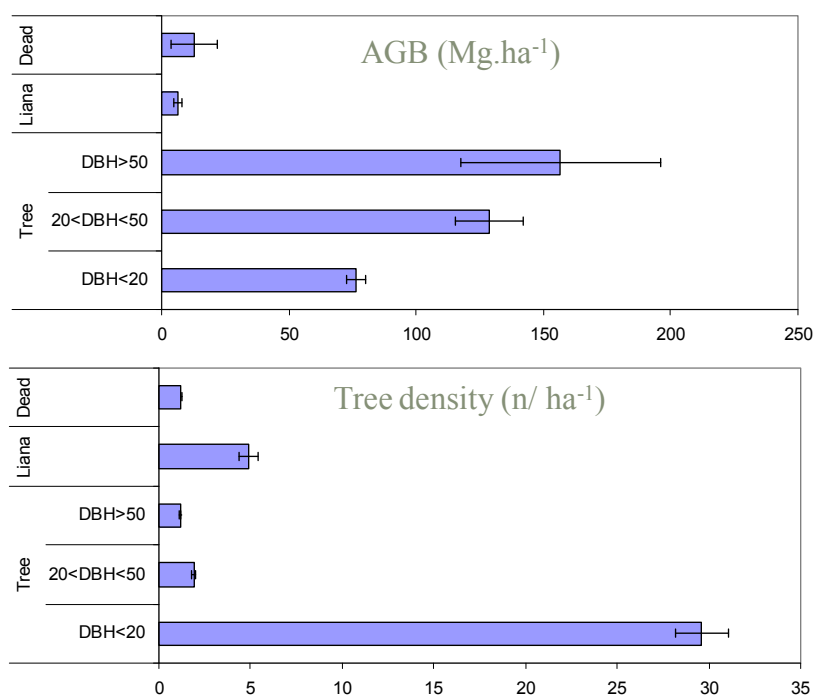


Figure 65: Distribution of aboveground biomass and tree density in the different ecosystem compartments.

3.2 Ground impacts

Selective logging operations focused on 258 trees and a total of 2086 m³ were harvested which corresponded to an average log volume of 8.5m³ per tree (Table 31). In average 1.5 trees per hectare were harvested. The tree falls impacted the surrounding trees and the impacted area increased with tree dimension and extracted volume (Figure 66). Based on the relationship between tree volume and impacted areas I estimated that 7 ha were damaged by tree falls and caused an impact of 0.07 ha per logged tree. In total, 17.83 ha were impacted by logging activities (10% of the total area) within the forest block from which 46% was attributed to skid trails and 39% to logging gaps (Table 32). 25% of the ground damages corresponded to tertiary skid trails that were used to collect less than three trees.

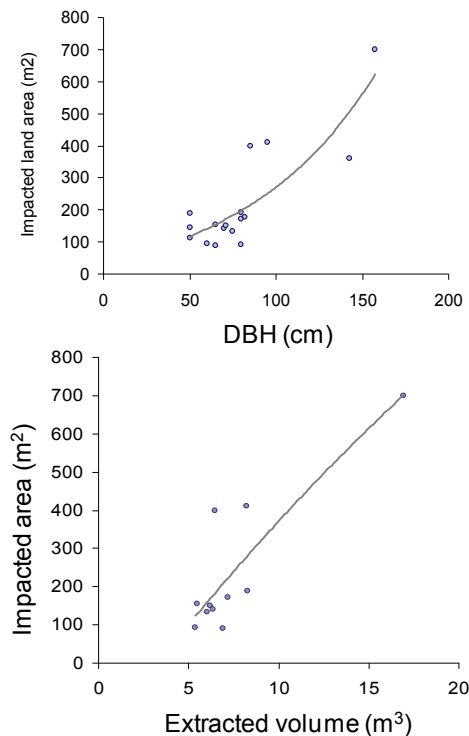


Figure 66: Relation between trees DBH, extracted volume and impacted area.

(A) $y = 0.0255 \cdot \text{DBH}^2 - 0.6551 \cdot \text{DBH} + 86.965$, $R^2 = 0.72$, $n=17$

(B) $y = -0.5468 \cdot \text{VOL}^2 + 62.244 \cdot \text{VOL} - 196.06$, $R^2 = 0.74$, $n=17$

3.3 Impacted biomass

The impact of the logging bays and roads on biomass corresponded to the total removal of the aboveground biomass which was on average 448 Mg ha⁻¹. When considering the total compartment area, the total impacted area by logging bays was 0.69 ha and the total road area was 2 ha which resulted in 309 and 896 Mg of biomass impacted by logging bays and roads respectively (Table 32). When considering the impact from skid trail and tree falls it is however more complex to assess. The post forest inventory in one of the variability plot revealed that 4% of the land area (414m²) was impacted by tree falls and it was considered as representative of the rest of the forest. In addition

the biomass loss was found to be 24 Mg ha^{-1} in that plot which gives an average 6% of the biomass that was impacted by tree fall. Moreover, the impacted biomass was 58 kg m^{-2} and was higher than the average 44 kg m^{-2} obviously because the bigger trees were logged (commercial trees). Without considering the biomass losses from the logged trees it resulted that the impacted biomass was 18 kg m^{-2} which was more than the biomass of trees with $\text{DBH} < 20 \text{ cm}$ (7 kg m^{-2}) but less than the biomass of trees with $\text{DBH} < 50 \text{ cm}$ (23 kg m^{-2}). Furthermore, I can conclude that 7 Mg ha^{-1} was impacted by tree falls (without considering the logged trees). This is also $1,176 \text{ Mg}$ at the scale of the block (considering the average biomass of the block). The amount of residues from harvested trees that is left in the forest (waste) depends on the size of the trees (Figure 63) and was on average 51% but ranged 25-82% of the original tree biomass.

When considering the impact of the skid trails I met the same issue for the tree falls. Only a limited part of the ecosystem population is impacted. Analysis of the variability plot showed that 9% of the plot area was impacted by skid trail which is about the same proportion than the block (9.4%). The impacted biomass was average 21 kg m^{-2} which corresponded to the tree biomass for $\text{DBH} < 50 \text{ cm}$ (23 kg m^{-2} in plot 15). In total, 4% of the plot biomass was impacted by skid trail and $1,683 \text{ Mg}$ at the scale of the block.

Overall, 309, 896, 1177 and 1682 Mg were impacted by logging bays, roads, tree falls and skid trails respectively. The impact from tree fall (18 kg m^{-2}) was impacting less biomass than skid trail (21 kg m^{-2}). Selective logging results in a total impact of 12 Mg ha^{-1} of biomass remaining inside the forest and 2 Mg ha^{-1} of exported biomass. The average emission factors would be 23.6 kg m^{-2} and the 33 kg logged trees. It resulted a total impacted ecosystem loss of 23 Mg C ha^{-1} from which 93% was remaining into the forest.

Table 31: Felled tree in compartment 4 in Boi Tano Forest reserve

Tree species	Common_name	Num of trees	Total volume (m³)	Log	Average volume (m3)	Wood density (g cm ⁻³)	Biomass/ tree (Mg)	Total biomass (Mg)	
Afzelia bella	Papaonua	1	5	2	5.37	0.67	3.60	3.60	
Amphimas pterocarpoides	Yaya	0	0	0	0.00	0.63	0.00	0.00	
Bombax brevicuspe	Bombax	1	8	2	8.06	0.4	3.22	3.22	
Copaifer salikounda	Entedua	5	42	9	8.32	0.5	4.16	20.80	
Ceiba pentandra	Ceiba	8	102	16	12.77	0.26	3.32	26.56	
Cynometra ananta	Ananta	1	3	2	2.93	0.74	2.17	2.17	
Daniellia thurifera	Sopi	4	43	8	10.82	0.45	4.87	19.48	
Entandrophragma angolense	Edinam	4	45	9	11.36	0.45	5.11	20.45	
Entandrophragma	Sapele	1	8	2	7.54	0.55	4.15	4.15	
Guarea spp	Guarea	2	0	0	0.00	0.52	0.00	0.00	
Heritiera utilis	Nyankom	165	954	293	5.78	0.56	3.24	534.26	
Khaya ivorensis	Mahogany	3	42	7	14.01	0.44	6.17	18.50	
Lophira alata	Kaku	1	0	0	0.00	0.87	0.00	0.00	
Lovoa trichhilioides	Walnut	11	121	24	10.97	0.45	4.93	54.28	
Nauclea diderichii	Kussia	7	83	14	11.88	0.63	7.49	52.40	
Piptadeniastrum africanum	Dahoma	21	168	36	8.01	0.56	4.48	94.17	
Pycnanthus angolensis	Otie	9	57	17	6.33	0.4	2.53	22.80	
Tieghemalla heckelii	Makore	14	405	48	28.93	0.55	15.91	222.79	
Total		17	258	2,086.45	489	8.50	0.54	4.19	1,099.60

Table 32: Impact of logging damages on ground area, biomass and carbon stocks

Type of damage	Surface impacted (ha)	%	Emission factor (kg m ⁻²)	Emission factor (kg tree ⁻¹)	AGB losses (Mg)	Average AGB losses (Mg ha ⁻¹)	Average AGC losses (Mg C)
Roads	2.00	1.16	44.80	3,473	896	5	2
Logging bays	0.69	0.40	44.80	1,198	309	2	1
Logging gaps	7.01	4.05	16.79	4,561	1,177	7	3
Skid trails							
primary	1.18	0.68	-	946	244	1	1
secondary	2.46	1.42	-	1,977	510	3	1
tertiary	4.49	2.59	20.70	3,600	929	5	3
Impacted biomass in the forest	17.83	10.31	-	15,755	4,065	24	11
Extracted tree	-	-	-	1,100	284	2	1
Total impact	35.65	20.62	23.60	33	8,413	49	23

3.4 The greenhouse gas balance

From the 258 harvested trees in Boi Tano forest, 489 logs were extracted which represented a total biomass of 1099 Mg and carbon of 517 Mg C (Table 32).

When considering that 51% of the biomass was remaining in forest as form of biomass residues, it resulted that 1.50 Mg C ha⁻¹ remained in the forest and 1.49 Mg C ha⁻¹ was extracted (Table 33). Considering the wood transformation efficiency of 56% in the sawmill, it resulted that 0.83 Mg C ha⁻¹ were emitted from burning the timber waste products during the first year. On the other hand, 1.4 Mg C ha⁻¹ is exported as medium and long term products. 624 l ha⁻¹ of diesel was consumed which corresponded to a total 4.31 Mg C ha⁻¹. While timber waste products and fossil fuels were emitted within the first year, the waste residues in the forest decomposed at an annual rate of 16%. The Figure 67 represents the annual emissions from the different sources of CO₂. After logging 2.1 Mg C ha⁻¹ of dead wood decomposed to reach 0.002 Mg C ha⁻¹ after 40 years. Decay emitted 10.3 Mg C yr⁻¹ which was about 0.06 Mg C ha⁻¹ yr⁻¹. When considering that the vegetation regrowth was sequestering the same amount of C that was lost from logging after a period of 40 years, 0.37 Mg C ha⁻¹ was uptaken by vegetation.

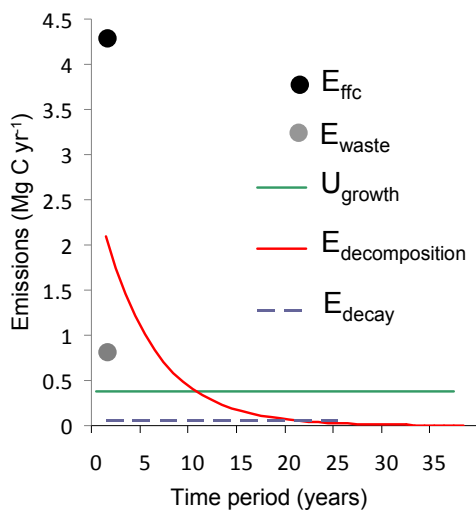


Figure 67: Impact of selective logging on emissions and sequestration of CO₂ within and outside forest.

Emissions arise from the fossil fuel, decay of unharvested biomass left in the forest, from processing wastes, and from the wood products. C sequestration results from plant growth.

Overall, 3,317 Mg C were emitted; 889 Mg C or 27% were emitted during the first year while 2,428 Mg C will be emitted in the considered period of 40 years. Moreover, 22% were emitted from fossil fuel combustion and 65% will be emitted from decomposition.

Table 33: Estimation of impacted biomass and carbon in Ghana and the Congo Basin

Sources	Total Emitted in 40 years period (Mg C)	per exploited surface (Mg C ha ⁻¹)	per volume (Mg C m ⁻³)	per harvested tree (Mg C tree ⁻¹)	Annual emissions
Fossil fuel	745	4.31	356.86	2.89	Emitted the first year
Burnt waste	144	0.83	0.07	0.56	Emitted the first year
Decomposition	2,171	12.55	1.04	8.41	16% emitted per year
Decay	257	1.49	0.12	1.00	4% emitted per year

3.5 Estimating GHG emissions from selective logging

The methodology presented above is limited to the scale of the experiment while it would be necessary to estimate the national emissions in the context of national GHG inventories and emission reduction strategies, and to estimate the GHG balance at global scale to better understand the carbon cycle. The following paragraphs analyse the potential of using the “tracking” or the “proxy” method.

➤ “tracking method”

Statistical analyses were performed to investigate the existence of an empirical relation between biomass density and Landsat spectral response for different field plot sizes. Both the linear (stepwise regression) and the non-linear (regression tree) models showed a poor correlation between the predicted and observed biomass at all spatial resolutions (Table 34). However, models performance improved with increasing plot size, with the Root Mean Square Error (RMSE) for the 1-ha plots decreasing to about 1/3 of the error for the 10 x 10 m plots. Smaller prediction errors at larger spatial resolutions are a consequence of the averaging of the satellite and field data, which decreases the variability of the parameter to be estimated, reduces the effect of plot and pixel geolocation errors, and increases the signal-to-noise ratio in the spectral data. In addition, the results for smaller plots were also affected by the aggregation procedure, which is not optimal when the plots are smaller than the pixel size: in such case each plot is related to the pixel where the plot centre lies but part of the plot area may be located outside the reference pixel. As a result of these effects, at 1 ha resolution a trend (although not significant at 95% confidence level) appears between predicted and observed biomass, while this trend is not evident at a pixel resolution (Figure 68).

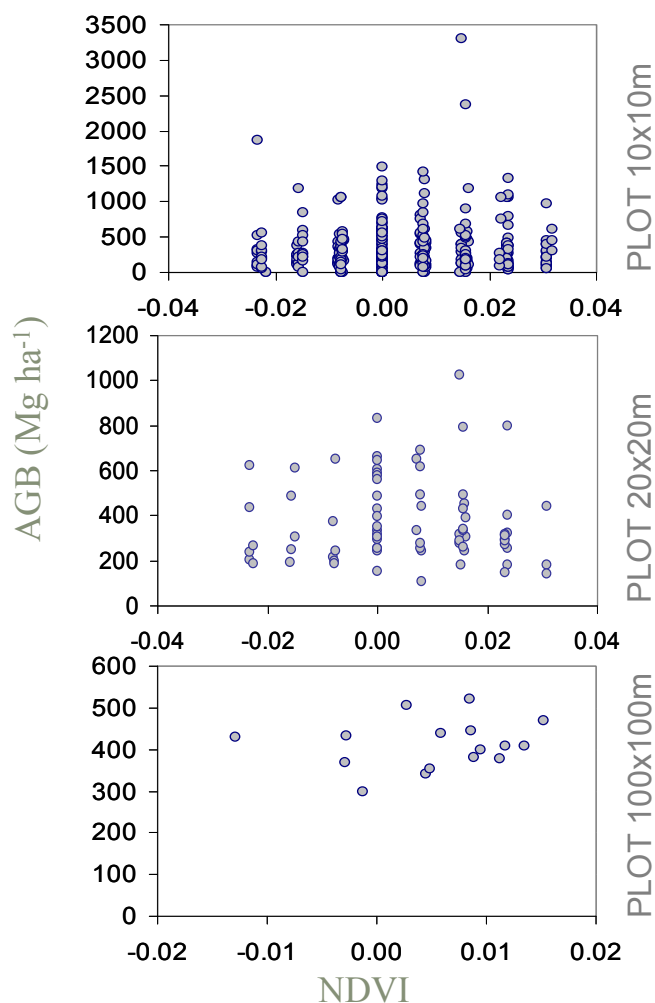


Figure 68: Analysis of the relation between the NDVI derived from Landsat ETM + imageries and the aboveground biomass for different plot sizes.

Table 34: Landsat spectral response for different field plot sizes - models results for different field plot sizes

	Stepwise Linear Regression					Regression Tree	
	N	Adj. R^2	RMSE	p-value	Variables used	R^2	RMSE
Plot 10x10	52	0.061	175.3	0.044	TM4	< 0	189.1
Plot 20x20	37	0.154	118.9	0.022	TM5, TM7	< 0	132.9
Plot 100x100	16	0.275	50.1	0.111	TM1, TM4, TM5, TM7	< 0	73.9

➤ “proxy method”

Using the default values from Table 33 it is possible to estimate the emissions that results at national scale. As an example, Ghana harvest a total of 1.2 millions of m³ that would result in 0.43 Tg C yr⁻¹ emissions during harvest, 0.08 Tg C yr⁻¹ during the transformation, 1.25 Tg C yr⁻¹ from decomposition in the forest, while the emissions from decay would be approximately of 0.15 10⁻³ Tg C yr⁻¹ but depend on the future wood products and the year after harvesting. However, the numbers reported by the FAO concerned legal harvesting while illegal harvesting was reported to be about 70% (Hansen and Treue, 2008). It resulted 1.91 Tg C yr⁻¹ from legal and 1.33 Tg C yr⁻¹ emissions from illegal activities. When considering the whole Congo basin, 22.23 Tg C yr⁻¹ were emitted from legal logging activities. It was not possible to derive the estimates based on the area under production because it was not reported for the countries of the Congo Basin by the FAO - FRA (FAO, 2006c). It was not possible to find the proportion of illegal logging in the literature. Considering the same proportion of illegal logging in the Congo Basin than in Ghana, it would result C emissions of 37.8 Tg C yr⁻¹.

4. Discussion

4.1 Selective logging contributes for a significant proportion of the African carbon budget

The coefficients I developed from Boi Tano forest experiment can be considered as representative of the rest of the tropical humid forests of Ghana, where almost all the timber is harvested because the carbon stocks were not significantly different between the moist semi-deciduous, the moist evergreen and the wet evergreen ecological zones (Chapter 7). In addition, White (1981) reported similar structure and biomass between the forests in the Guinean- Congolese and the Congolese basins. The biomass values I reported are comprised within the interval 112-1107 Mg ha⁻¹ from 164 plots in Congo (Couralet, et al., 2010) and 5-668 Mg ha⁻¹ from 2240 plots in Gabon (Maniatis, forthcoming).

Bombelli, et al. (2009) reported that selective logging contributed to 8 Tg C yr⁻¹ to the C balance in the Congo Basin. However, using a total coefficient of 19.17 Mg C ha⁻¹ instead of the 10.2 coefficient reported by Brown et al. (2005), it results that emission from selective logging would be about 15 Tg C yr⁻¹ in the Congo basin and 158 Tg C yr⁻¹ at continental scale (82 Tg C yr⁻¹ was reported by Bombelli, et al. 2009). Considering that 70 Tg C yr⁻¹ were exported from Africa as round wood from Africa, it results that 88 Tg C yr⁻¹ would be emitted from selective logging at continental scale. Similar result was reported by Asner (2005) for the Amazon (80 Tg C yr⁻¹). While nearly all the net release of carbon from land use in sub-Saharan Africa is attributed to deforestation (90% according to the data reported by William, 2007), the consideration of the impact of selective logging (absent in the study of Williams) would give a total net land use emission of about 448 Tg C yr⁻¹ from which 88 Tg C yr⁻¹ or 20% comes from emission from selective logging. In addition, considering the same rate of illegal logging from Ghana would even more increase the emissions and the logging activities would account for 25% of the emissions of the continent. In addition, the coefficient factors used in this study for logging bays, treefalls etc. In addition, the coefficient factors used in this study for logging bays, treefalls etc.(Table 32) can be considered as

conservative because the logging intensity was 1.5 trees per hectare while 2- 6 is commonly reported in Africa (Agyeman, et al., 1999a). Figure 69 represents the impacted ground area measured for different logging intensity. The ground area impacted in our study is about 50% lower than the ground area impact measured in other forest in Ghana and in Nigeria for the same harvested density. In Nigeria, about 50% the total area was reported as impacted (Agyeman, *et al.*, 1999a). When considering the other continents, the volume extracted was lower than the $9.4\text{m}^3\text{ ha}^{-1}$ reported by Pena-Claros, et al. (2008). The coefficient factors I reported are lower than the values reported in other tropical humid forests (FAO/UNEP, 1981, Pinard and Putz, 1997, Pinard and Cropper, 2000, Putz, et al., 2008b) .

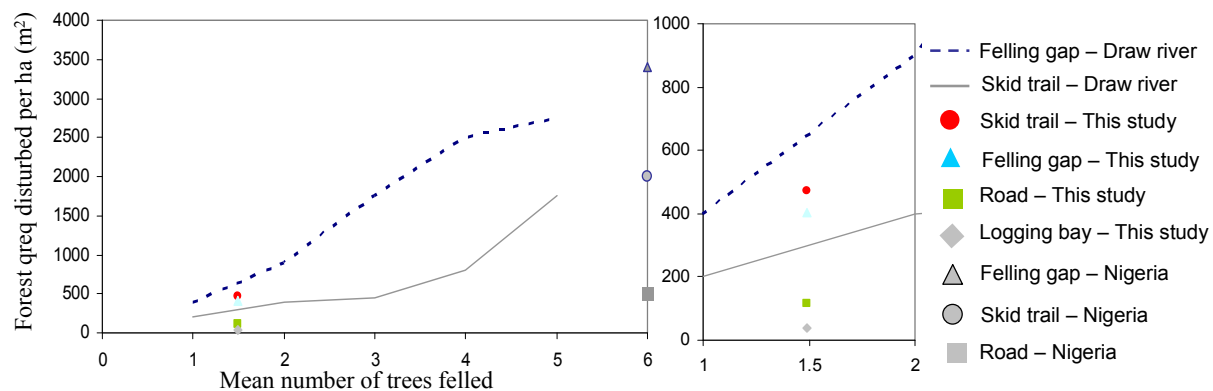


Figure 69: Influence of harvested tree number on damaged ground area in different sites of West Africa. The data from Nigeria and Draw river were reported by Agyeman *et al* (1999a).

4.2 Reducing impact from selective logging

Numerous studies have demonstrated that with appropriate harvest planning of log extraction paths, coupled with worker training in directional felling, 50% or more of this collateral damage can be avoided (Putz, *et al.*, 2008b). Based on our results, it would mean that 44 Tg C yr^{-1} can be reduced using improved selective logging practices while Francis E. Putz, Pieter A. Zuidema et al. (2008) found that 160 Tg C yr^{-1} would be retained for tropical forests. In a similar study in Amazonian Brazil, Keller, Asner et al. (2004) reported that the benefit of improved timber harvesting practices was estimated to be 7 Mg C ha^{-1} or 30% of the emissions.

Based on the results from this study 1.7 Mg C ha^{-1} would be reduced while the confidence interval for biomass estimates would be around 14 Mg C ha^{-1} . Moreover, carbon stocks and stock changes based on 16 plots will not give significant difference between reduced impact and conventional logging practices in forest such as Boi Tano. Reducing GHG emissions of selective logging would require the development of a methodology to quantify the emission reduction. However, this study underlines some limits when accounting emission reduction for i.e. implementation of sustainable forest management. Ascertaining significant difference between a selectively logged forest and a natural forest would require 57 ha plots for a 170 ha compartment with incertitude of 5%. In addition, if the C stock reduction through improved

selective logging is lower than for conventional logging it means that the difference with natural forest C stock will be lower and more than 57 plots would be necessary. Furthermore, it would not be feasible and cost-effective to quantify the GHG emission reduction of sustainable forest management in tropical evergreen forest of Ghana. In addition, only conservative project would be feasible to implement because it would be easier and more cost effective to ascertain the emission reduction.

Developing incentives based only on C emissions reduction within a C accounting and financial compensation system will not allow improving selective logging practices. In order to account the emissions from selective logging the proxy method I propose, based on the extracted volume, requires accurate national statistics that consider both legal and illegal activities. It is difficult to identify the proportion of the illegal activities that were performed with heavy machineries. The emission factors will have to be adapted to the impact of chainsaw activities which have less impact on the forest on a harvested tree basis. Developing actions to reduce the impact of selective logging require the assessment of the emissions and the “proxy” method I develop is the most practical and the most feasible one because it does not necessitate the implementation of a field monitoring system to track the skidding activities. However, tracking the displacement of skidders would be helpful to better identify and minimize transport, fuel consumption and impact on C stocks. Other options would be to implement sustainable and clean electric power generation station to provide electricity without burning the wastes. The improvement of waste transformation can also contribute for a significant part while improving the economic profitability of the industries and the quantity of long term wood products. Within the forest, increasing the harvesting efficiency by extracting more wood from each tree would decrease the amount of GHG emissions from decomposition. The additional extracted wood that would not suit for timber purpose could be used for carving. This could be achieved if the access to the forest is improved with better roads. On the other hand, logging activities encourage tree regeneration and plant growth, particularly for the remaining timber trees (Jonkers, 2000).

4.3 Improving the GHG balance calculation

While selective logging contributes for a significant part of the global C cycle, the GHG balance calculation is based on some assumptions that will have to be clarified by further researches. The impact of logging is based on the data, coefficients and equations used to estimate the biomass before and after logging. Using inappropriate models will tend to over or underestimate the biomass. E.g. using small plot size increase the variability of the estimates while precise estimates require higher number of sample measurements. The sample plot of 1 ha was found to be appropriate to measure the biomass of a tropical humid forest (Chave, 2005, Chapter 7), while smaller sample size will not consider the spatial variability and reach the stabilization of the variance (Picard, et al., 2004). In addition, the use of the tree biomass allometric equation is crucial as it can lead to important variability (Chapter 5). While this study used a site specific allometric equations, the selection of the allometric equation can influence the carbon balance (Chapter 4). When considering the C calculations after logging activities, there are important uncertainties about the future of the residues remaining inside forest and the future of wood products. While in our study we estimated that 51% of the biomass of harvested trees was remaining in the forest, Pearson and Brown (2005) reported 40%. In addition, Agyeman, Abu-Jam et al. (1999a)

reported for *Entandrophragma utile* an average extracted volume of 15m³ per tree while I measured 9.3m³. Moreover, the amount of remaining biomass is very dependent to the tree species (Table 32), the quality of the trees, their shape and the techniques used to log and extract the trees. The remaining dead wood in the forest then decompose with rates ranging 0.015 – 0.16 according to the sites and climate zones (Chambers, *et al.*, 2000). While Chambers, Higuchi *et al.* (2000) reported that no studies have considered the details of coarse-litter decomposition and the release of carbon in contrasting land use categories for tropical forests, 65% of the impacted C currently decompose. In addition, using the root:shoot ratio reported by Mokany, Raison *et al.* (2006), this is about 3 Mg C ha⁻¹ of dead root biomass which is remaining in the forest and was not considered by the study. Given the importance of ecosystem response to land use in determining net fluxes of carbon to the atmosphere (Canadell, *et al.*, 2007, Houghton, 2007, Ramankutty, *et al.*, 2007) additional studies on the dynamics of coarse litter and dead roots in disturbed ecosystems are needed.

Carbon pools decompose slowly and release CO₂ over a long timescale (Delaney, *et al.*, 1998, Foley, *et al.*, 2007) while a certain portion is transferred to the soil organic carbon pool through the mineralization process (Dewar, 1991). The authors do not report any study that estimate the proportion of dead organic materials which is going to the soil carbon pool in a tropical forest. Based on the mineralization coefficient of 32% reported by Sofo, Nuzzo *et al.* (2005) for Olive plantation after pruning, I hypothesize that 28 Tg C yr⁻¹ would be additionally stored in the soil. However, tropical soils are highly susceptible to degradation when physically disturbed and exposed to the sun and/or the direct impact of heavy tropical rains (Pulkki, 1997). Soil compaction by the heavy machinery (Kouamé, *et al.*, 2004) may retard root growth and restrict plant nutrient availability (Fredericksen and Pariona, 2002) and facilitate the erosion process. This influences germination and establishment of seedling of trees and climbers and the forest dynamics. Villela, Nascimento *et al.* (2006) did not reported a significant influence of logging on surface soils of the studied forest while Kindel *et al.* (1999) reported higher organic C nutrients in a 40 years old selectively logged forest than in the undisturbed forest and Gillman, Sinclair *et al.* (1985) reported that soil organic carbon decrease by 15% of soil organic carbon. In addition, the decay of extracted wood products is poorly known and depends on their use. Quantifying the decay of wood products at national scale could have important impact on the GHG balance calculation (Gitz, 2004).

Canopy opening facilitates the regrowth of the forest. While the logging influences species regeneration by facilitating the development of pioneer trees (Swaine, *et al.*, 1997), Hawthorne (1993) noted that the density of seedlings for a given species was highly patchy along skid trails, and argued that these patches indicated the presence of nearby parents in fruit at the time of logging. However, the regeneration strategies is particularly complex as the tree species use different strategies, e.g. some trees regenerate by sprouting (Kruger and Midgley, 2001), tree functional types grow differently according to their tolerance to light competition (Pena-Claros, *et al.*, 2008) and disturbed soils influence some tree species which are more adapted to soil compaction (Dickinson, *et al.*, 2000). The recovery of forest C stocks after a period of 40 years is generally accepted in Ghana and the measurements in chapter 7 confirm that there were no significant difference between 40 years old logged forest and natural forests. However, after a 40 years period the structure and the species composition are largely affected the spread of liana which reduce the accessibility and increase the risk of accident when logging the trees.

At last, logging activities, even when controlled, remains one of the most damaging interventions in the forests (Sist and Nascimento Ferreira, 2007). The contribution of selective logging to the GHG balance was largely underestimated for sub-Saharan Africa when the soil compartment is not considered. The intensity of harvest operations determines the impact on the C cycle, loss of biomass and soils (Keller et al. 2004) but also the forest regeneration and its future uses. The GHG estimates are however limited by the scientific contribution on estimation of soil mineralization after selective logging. It will determine a significant part of the estimates. In addition, the proportion of illegal activities is unknown and will determine part of the national potential for emission reduction strategies. I propose to encourage actions to facilitate the forest regeneration for valuable tree species and the valorisation of remaining timber waste in the forest.

5. Conclusion

Selective logging contributes to 20-25 % of the GHG emissions of sub-Saharan Africa, from which a large part (60%) is left in the forest to decompose. The proportion of the carbon in residues that reach the soil pool is poorly known and I encourage the implementation of long and medium term permanent experiments. The number of tree harvested is lower in Africa than in other tropical regions and the contribution of selective logging is lower. Financial Compensation of improved forest practices that reduce the C emissions is limited by the important C variability in the original forest in comparison with the C emission from logging activities. The best method to quantify the impact from logging requires the development of emission factors based on the volume harvested rather than the spatialization and the mapping of logging impacts and C stocks. Improved selective logging practices can be implemented to decrease the C emissions but also improve the regeneration of timber tree species, increase the biodiversity and reduce perturbation to the water cycle.

Various alternatives were identified to decrease the emissions or sequester carbon (Chapter 1). The CDM and the REDD+ are the two mechanisms that can be implemented in order to implement carbon forestry projects. However, while the previous chapters focused on measuring carbon stocks and carbon stock changes, the next two chapters deal with project implementation, economic benefits and national socio-economic, political and cultural constraints. The case study of Ghana was identified to be particularly interested as most of the research in this thesis provide good quality data and because Ghana is particularly advanced in term of forestry carbon projects in comparison with most of the SSA countries.

Chapter 11

Potential for country-level aboveground carbon sequestration and emission reductions through forestry activities– evidence from Ghana

This chapter is modified from the article: Henry. M, Bernoux, M., Tutu, D., Asante, W. , Kutsch, W.L. , Valentini. R., Saint-André, L. (2010), Potential for country-level aboveground carbon sequestration and emission reductions through forestry activities in sub-Saharan Africa – evidence from Ghana, Africa and the Carbon Cycle, in Bombelli A., Valentini R. (Eds.) - Africa and Carbon Cycle. World Soil Resources Reports No. 104. FAO, Rome, 115 – 130.

Abstract

In the context of climate change and researches on C cycle in sub-Saharan Africa, the estimation of the potential for carbon (C) sequestration and emission reductions using forestry is poorly known. Using the example of Ghana, this study aims to assess the C stocks in the various land cover types and ecoregions of the country and to estimate the potential C sequestration and emission reduction through afforestation and reforestation, forest restoration and conservation. Aboveground C stock in Ghana was found 1,158 Tg and most of it was in broadleaf forests (62%) and in the Eastern Guinean forest zone (81.56%). Soil C stock (SOC) was found to represent 40% of the total C stock when considering the 0-30cm soil layer. Most of the SOC was found in the Eastern Guinean forest zone (39%) and in Luvisols (44%). Forest restoration was found to have the highest C sequestration potential (6.7 Tg C yr⁻¹) than the other forestry activities. However, the estimation of C stocks and sequestration potential is mainly limited by the availability of data, the resolution and the calibration of the land cover products with a hypothetical area for degraded forests between 2,938 and 45,334 km². When considering the potential implementation of C forestry activities in sub-Saharan Africa, the main constraints reside in the lack of data to estimate C stocks and calibrate the remote sensing products, lack of capacity building to build national inventories, the complexity when developing projects which are adapted to the land tenure and management systems and the lack of funds to develop projects. While sub-Saharan Africa represents a significant potential to mitigate climate change, development of capacities to support and implement forestry projects is necessary.

Keywords: deforestation, forest degradation, restoration, MODIS, carbon cycle

1. Introduction

Climate change is now considered as the main environmental crisis and even the best case scenario is going to have major impacts on global weather patterns. Forests are a vital part of any global effort to address climate change. Forestry activities are seen as a potential alternative either to mitigate climate change because of its potential effects on emission reduction and carbon (C) sequestration or to play a role in adaptation scenarios (Guariguata et al. 2008). In the attempt to develop C sequestration forestry projects in developing countries, the Clean Development Mechanism for Afforestation and Reforestation (CDM A/R) activities was developed under the Kyoto protocol. While only one CDM A/R is currently operational at global scale, Reducing Emissions from Deforestation and forest Degradation (REDD+) is now becoming one of the main alternative to mitigate climate change - as deforestation is estimated to contribute for 17% of global greenhouse gas emissions (IPCC, 2007).

However, whereas forestry projects are seen as an important option to mitigate climate change, no CDM A/R project was developed on the African continent. There is great need to analyse the potentialities to develop forestry projects on the African continent. Population density especially in sub-Saharan Africa is increasing and ecosystem degradation has never been so important (UNEP, 2006).

Ghana is particularly interesting when analysing the potential for C forestry projects for various reasons. Ghana is representative of the different ecological zones found in West Africa (from dry savanna to wet evergreen forests). The population is highly dependent on forestry products which represent an important part of the economy (Falconer, 1994). Several ethnical groups compose the population of the country and they have different land tenure systems, natural resource management, practices etc. Several attempts tended to improve the governance of the country. Ghana is a pilot country for the Forest Law Enforcement Governance and Trade (FLEGT), the Forestry Carbon Partnership Facility (FCPF), and Ghana received a Millennium Challenge Corporation (MCC) grant in 2006.

The objectives of this study are to estimate the potential emission reduction and C sequestration through REDD+ and CDM implementation and identify the main constraints for project development. Analysing the REDD+ and CDM A/R potentials in Ghana helps understanding the potential of C forestry projects in Africa.

2. Calculation of C stocks and C sequestration

2.1 Study area

Ghana is almost centrally placed among the West African countries that lie along the shores of the Gulf of Guinea. It lies between latitudes 5° N and 11° N and between longitudes 1° E and 3° N. Ghana covers an area of about 23 million ha. About 80% of the forest cover disappeared in the last century at a deforestation rate of 65,000 hectares per annum (Opoku, et al., 2005). The net loss in cubic meter was ranged between -8,372 and -14,578 per year between 1970 and 1987 (Baytas and Rezvani, 1993). The annual rate of deforestation was said to have slowed in the 1980s to about 22,000 ha (FAO, 1988, &

IUCN, 1992) but the proportion of illegal logging is poorly known and the deforestation rate is supposed to be higher (Sarfo-Mensah, 2005). In 1992, it was estimated that only about 1.5 million ha of "intact closed forest" were remaining in Ghana. The country was a total net CO₂e remover over the inventory period of 1990-1996 even as its sinks rapidly decreased in size (EPA, 2000). This rapid decline in sinks has been attributed to deforestation, specifically a sharp increase in fuelwood consumption, timber harvesting, agricultural and settlement expansion, mining and low rates of reforestation (Osafo, 2005).

2.2 Map of carbon stocks

The map of carbon stocks was developed for the aboveground compartment by combining ecological zones and land cover classifications and ground field measurements found in the literature (Figure 70). Several ecological classifications were developed based on structural, floristic, functional characteristics (Hall and Swaine, 1981). However, most of them focused on forests and not all the ecosystems were represented, or considered an important variety of ecosystems types. In order to estimate the changes of C in the various ecosystem types Ghana was divided into five well-defined zones according to the WWF's Global 2000 terrestrial ecoregions from Olson et al. (2001): (1) Central African mangroves, (2) Eastern Guinean forests, (3) Guinean forest-savanna mosaic, (4) Guinean mangroves and (5) West Sudanian savanna. Within each region, 10 land cover types were considered. The land cover classification was obtained using the Moderate Resolution Imaging Spectroradiometer (MODIS) land cover (IGBP) and the MODIS plant functional type (PFT) classification categories (Friedl, et al., 2002). Despite the technical refinement to improve the accuracy of vegetation representation, there is still some misclassification. The vegetation class *cropland/natural vegetation mosaic* of the IGBP product was considered not to be enough reliable to estimate C stocks. In this study, the pixels that fell within this class were reclassified using the PFT product. A new land cover classification was obtained mixing the IGBP and the PFT products and averaging the images for the year 2002, 2003 and 2004. Two methods were used to estimate the land area under degraded forest (A_{deg}). The A_{deg} was estimated using two methods. The first method considered that the mosaic of vegetation/cropland corresponded to degraded forest. It is mentioned as RES1. The second method considered that degraded forest corresponded to the pixels that moved from natural vegetation to cropland. It is mentioned as RES2. Data on C density (Mg C ha⁻¹) were obtained from a metadatabase of C densities for sub-Saharan Africa (n=62). All the data were georeferenced and classified per land cover types. C density data were averaged for each land cover and ecological zones found in Ghana. The soil organic carbon (SOC) density were obtained from chapter 3.

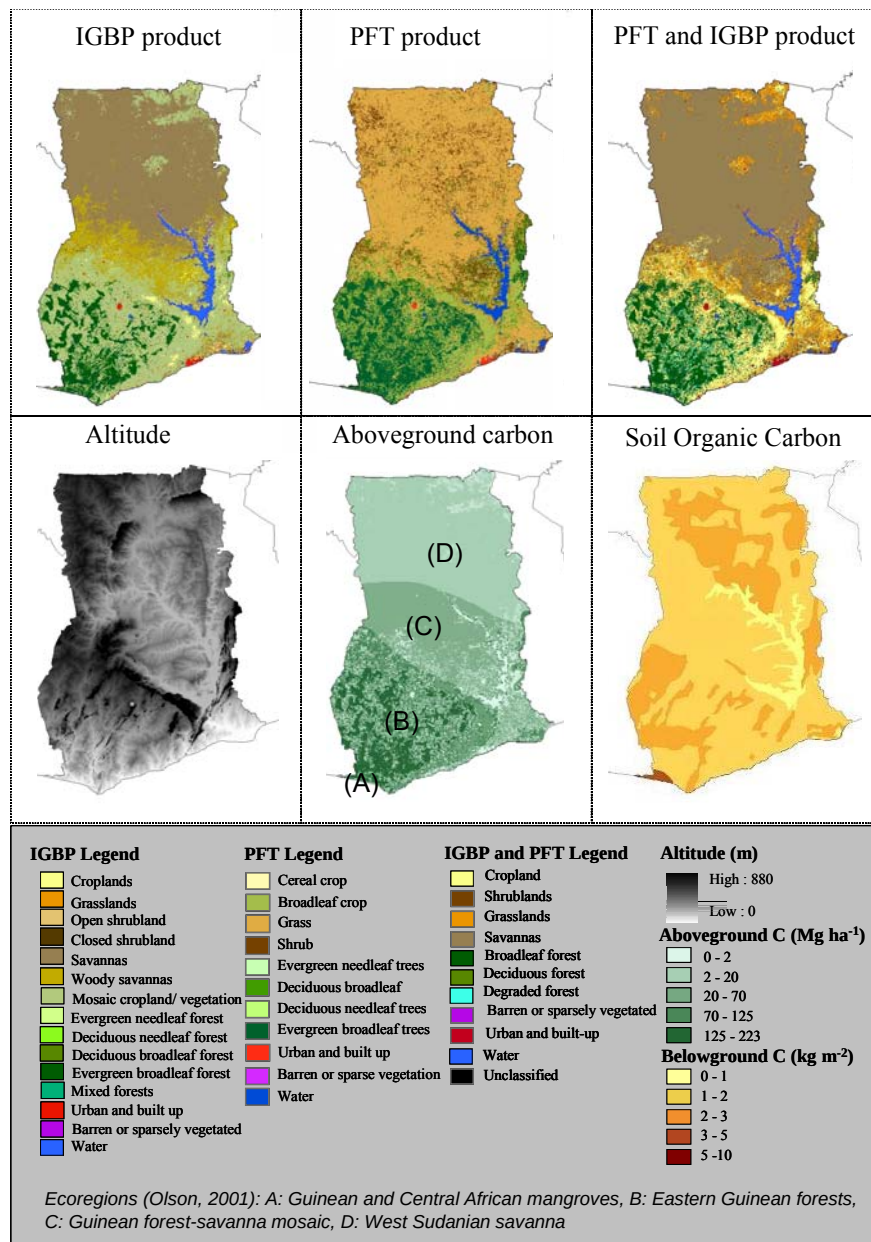


Figure 70: The different steps used to map above and belowground carbon stocks

The MODIS products *Land Cover* (IGBP) and *Plant Functional Type* (PFT) were provided by the geographic department of Boston University. The two products were integrated to make a more convenient and robust land cover map for estimating aboveground carbon stocks. The estimation of belowground carbon stocks was achieved

using the digital soil map of the world (Henry, et al. 2009). Above and belowground carbon stock estimations considered the altitude (Shuttle Radar Topography Mission version 4).

2.3 Land cover of Ghana

Most of Ghana corresponded to West Sudanian savanna (38%) while 33, 28 and 1% of land cover corresponds to Eastern Guinean forest, Guinean forest-savanna mosaic, and Central African and Guinean mangrove. Most of total land cover corresponded to savannas (51%) while 15, 13, 12 and 9 % corresponded to broadleaf forest, cropland, grassland and others land cover respectively. Savanna represented most of the vegetation into the West Sudanian savanna (88%), while broadleaf forest and cropland represented 43 and 28% of Eastern Guinean forest zone and grassland represented 34% of Central African mangrove zone. The total forest area of Ghana (degraded forest not included) was estimated 42,557 km² and represented 18% of the total country area. The potential area suitable for afforestation/reforestation activities represented 6,387 km² and 2.67% of the country area, and 4.4% of the grassland and savanna together. The forests under production were 7624 km² and represented 3% of the country area and 18% of the total forest area. When considering the estimation of degraded forest (RES1), degraded forest represented 45,334 km². When considering the estimation of degraded forest (RES2), degraded forest represented 2938 km². Furthermore, estimates of degraded forest area ranged 3.71-57.27% of the Eastern Guinean forests zone area.

2.4 Carbon stocks of Ghana

In total, 1,158 Tg was stored into the aboveground C stocks of Ghana. Most of aboveground C stock was located into the Eastern Guinean forests (945 Tg) while 147, 63 and 3 Tg C were stored into the Guinean forest-savanna mosaic, West Sudanian savanna, and the Central African and Guinean mangroves. Most of aboveground C stock was located into the broadleaf forest vegetation type (714 Tg), while 117, 37, 9, 14, 183, 75, and 10 Tg C were stored into the deciduous forest, degraded land, shrubland, grassland, savannas, cropland and wetland.

Semi-deciduous forests in Eastern Guinean forest zone represented the highest C density with 223 Mg ha⁻¹, while urban, water and barren or sparsely vegetated land had no C. C density varied between ecoregions and vegetation forms i.e. broadleaf forest had 223 Mg C ha⁻¹ in the Eastern Guinean Forests zone and 105 Mg C ha⁻¹ in Guinean forest savanna, degraded broadleaf forest had 125 Mg C ha⁻¹ in the Eastern Guinean Forest zone. Soil organic carbon (SOC) represented 759 Tg into the 0-30cm soil layer and 1,384 Tg into the 0-100cm). SOC differed between soil types. i.e. SOC ranged 1.8-8.1 kg m⁻² in Ferric Luvisols and in Arenosols respectively.

3. Baseline C stocks and potential for C sequestration country wide

The aboveground C sequestration and emission reduction potentials were estimated by assessing the difference of C stock between a reference level (assumed to be the current situations) and project scenarios. It was not possible to analyse the belowground C sequestration potential because it was not

possible to find in the literature soil organic carbon changes in the various land cover change and soil types found in Ghana. Here, I analysed three potential scenarios for the first 20 years project period of project implementation (Figure 71). The total amount of C sequestered was assumed to be the sum of the annual C sequestration.

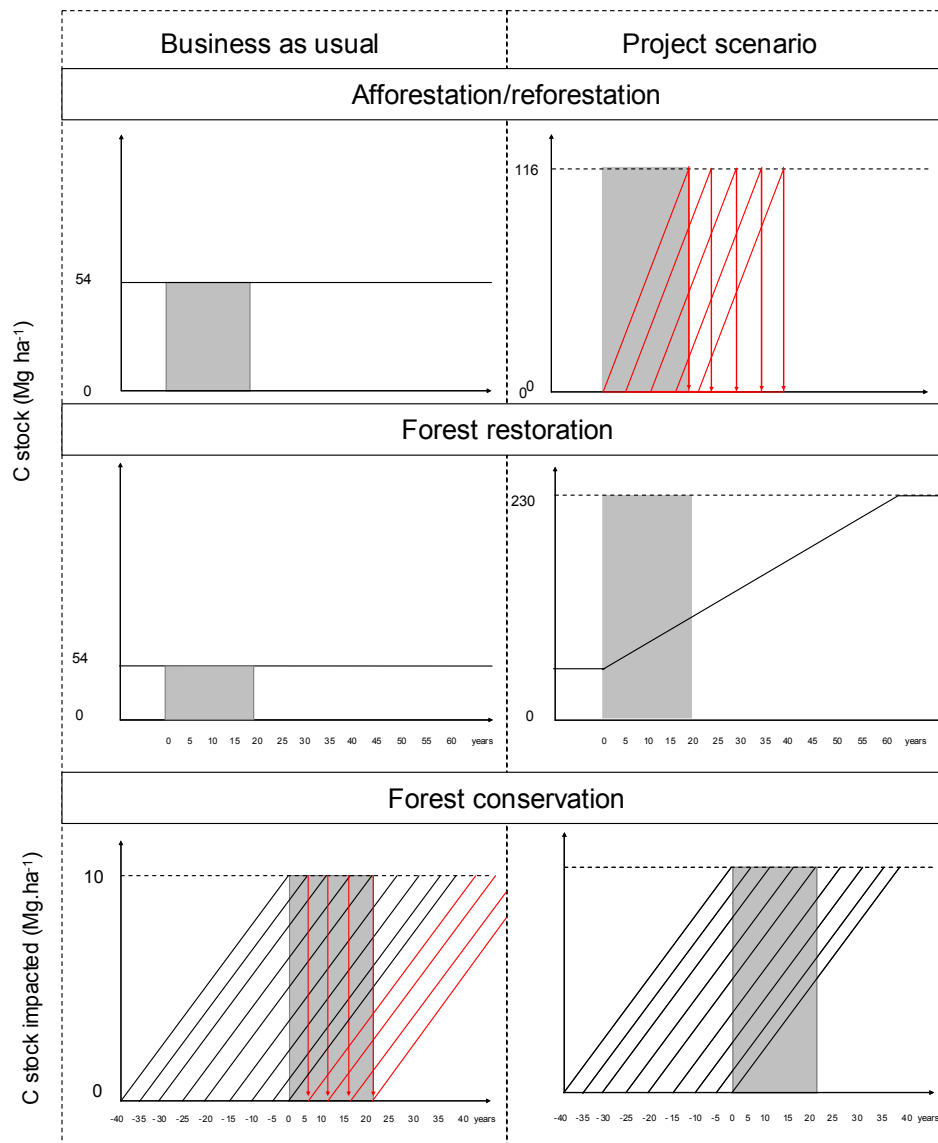


Figure 71: C sequestration and emission reduction project scenarios

The grey rectangles represent the project time period. The dark black lines represent the amount of C under business as usual (on the left) and the red lines represent the amount of C under project scenario (on the right). The red arrows represent the logging activities. While the total C stock is represented for afforestation and reforestation, and forest restoration scenario (up to 116 and 223 Mg ha^{-1}), the impacted amount of C by logging is represented under the forest conservation scenario. While the forest restoration is supposed to start into the whole country at the same time (only one line is represented), planting activities and logging activities are distributed equally during the project period (represented every 5 years in the diagram).

3.1 Assessing carbon sequestration and emission reduction potentials

➤ Aboveground C sequestration through afforestation and reforestation

The aboveground C sequestration potential through CDM A/R projects was estimated assuming that the suitable land for plantation identified by Zomer et al. (2008) was converted by teak plantation because they represent 80% of the plantation area of Ghana (Adu-Bredu, personal communication). C density of Teak plantation was assumed to be 116 Mg ha⁻¹ (Boateng, 2005) at the end of a 20 years rotation while the initial land use was assumed to be a short fallow with C density of 54.25 Mg ha⁻¹ (Kanmegne, 2004). The area converted to forest plantation was equally distributed over the 20 years project period (T_{pp}).

$$C_{seq} = \sum_{i=0}^{20} \left(\frac{A_{A/Ri} \times (C_{A/R} - C_B)}{T_{pp}} \right) \quad (1)$$

Where C_{seq} is the potential C sequestered (Mg ha⁻¹yr⁻¹), $A_{A/Ri}$ is the area converted to forest plantation every year i (ha), $C_{A/R}$ is the C density at the end of the rotation (Mg ha⁻¹), C_B is the initial C density (Mg ha⁻¹) and T_{pp} is the year period to reach $C_{A/R}$.

➤ C sequestration through forest restoration

The C sequestration through forest restoration was obtained assuming that all degraded forest are recovered after a 60 years period (Tr). Assessment was performed only for the Guinean forest zone because it was considered that identification of degraded forest was reliable only for this zone.

$$C_{res} = \frac{A_{Deg} \times (C_{NF} - C_{Deg})}{Tr} \quad (2)$$

Where C_{res} is the amount of C sequestered through forest restoration (Mg ha⁻¹yr⁻¹), A_{deg} is the total area of degraded forest, C_{NF} is the C density in natural forest, C_{deg} is the C density in degraded forest and Tr is the years period after which the amount of C is recovered (60 years). It is assumed that a 60 year period for forest recovery is conservative as according to Kotto-Same, et al. (1997), the same amount of natural forest C density would be reached after a 28 years period. C_{NF} and C_{Deg} were assumed to be 223 Mg ha⁻¹ and 125 Mg ha⁻¹ respectively (data obtained from the metadatabase).

➤ C sequestration through forest conservation

The C emission reduction from forest conservation is estimated assuming that all the forests under production would become protected. This means that there would be no more logging activities and that previous logged forest will continue to regenerate.

$$A_{pi} = \frac{A_p}{T_c} \quad (3)$$

Where A_{pi} is the forest area under production activities during the year i ($ha\ yr^{-1}$), A_p is the total area under forest production in Ghana (ha) and T_c is the production cycle period (40 years).

$$C_R = \frac{C_E}{40} \quad (4)$$

Where C_{Ri} is the annual regeneration of C ($Mg\ ha^{-1}\ yr^{-1}$), C_E is the impacted amount of C by logging ($10.2\ Mg\ ha^{-1}$) and T_c is the production cycle period (Gineste, et al., 2008).

The amount of C impacted by logging activities corresponds to the quantity of C which is damaged by the logging operations. From this amount, a part is extracted (logs) and a part is left into the forest and is then decomposed.

$$C_{ER} = \sum_{i=0}^{20} A_{pi} \times (C_E - C_R) \quad (5)$$

Where C_{ER} is the C emission reduction during the project period (Mg), A_{pi} is the annual area of forest under production ($ha\ yr^{-1}$) and C_E is the C emission factor under selective logging ($10.01\ Mg\ ha^{-1}$) (Gineste, et al., 2008).

MODIS images analysis and C stock map were achieved using ArcGis 9.2. Surface calculation was corrected using a Shuttle Radar Topography Mission (SRTM) version 4 at 90m spatial resolution obtained from <http://srtm.csi.cgiar.org/>.

3.2 C sequestration and C emission reduction potentials

Implementation of CDM A/R project on all the suitable lands identified by Zomer et al.(2008) (total available area=6 387 km^2 or 2.67% of the country area) would potentially sequester $61.75\ Mg\ C\ ha^{-1}$ and $3.1\ Mg\ C\ ha^{-1}\ yr^{-1}$ in the aboveground compartment (when considering that this amount could be reached after a 20 years period). When considering an equally distribution of plantation during the 20 years project, it resulted that, in total, 20.7 Tg C would be stored through CDM A/R project at national scale.

Under scenario RES1, leaving degraded forests to restore during a 20 years period would represent a potential C sequestration of 148 Tg C with an annual C uptake of $6.7\ Tg\ C\ yr^{-1}$. Under scenario RES2 , forest restoration sequestered 9.60 Tg of C after 20 years with an annual C uptake of $0.48\ Tg\ C\ yr^{-1}$.

Selective logging decreased forest C density of $10.01\ Mg\ C\ ha^{-1}$. After logging, regeneration of C density was estimated to be $0.25\ Mg\ C\ ha^{-1}\ yr^{-1}$. As forest is regenerating on the whole production forest area while exploitation is achieved on only 50% of the forest area during a 20 years project, forest exploitation would emit a total of 0 $Mg\ C\ ha^{-1}\ yr^{-1}$. Under forest protection, 2.81 Tg C would be additionally sequestered during a 20 years period forest protection scenario.

The different options revealed different aboveground C sequestration potentials (Figure 72). While forest restoration (RES1) presented the highest C sequestration potential (148 Tg) it also presented the highest C uptake per ha (98 Mg C ha⁻¹) and the highest potential suitable land area (19% of the country area). On the other hand, forest conservation presented the lowest C sequestration potential (2.81 Tg) and presented the lowest average C sequestration potential (7 Mg C ha⁻¹) but also the lowest suitable land area (3% of the country). Afforestation/reforestation scenario presented the second C sequestration potential (21 Tg), and it presented the second C uptake (62 Mg ha⁻¹). When considering the scenario RES2, forest restoration had the second C sequestration potential (9.6 Tg), while the C uptake was the same than for RES1 but the suitable land area was much lower (1.23% of the country).

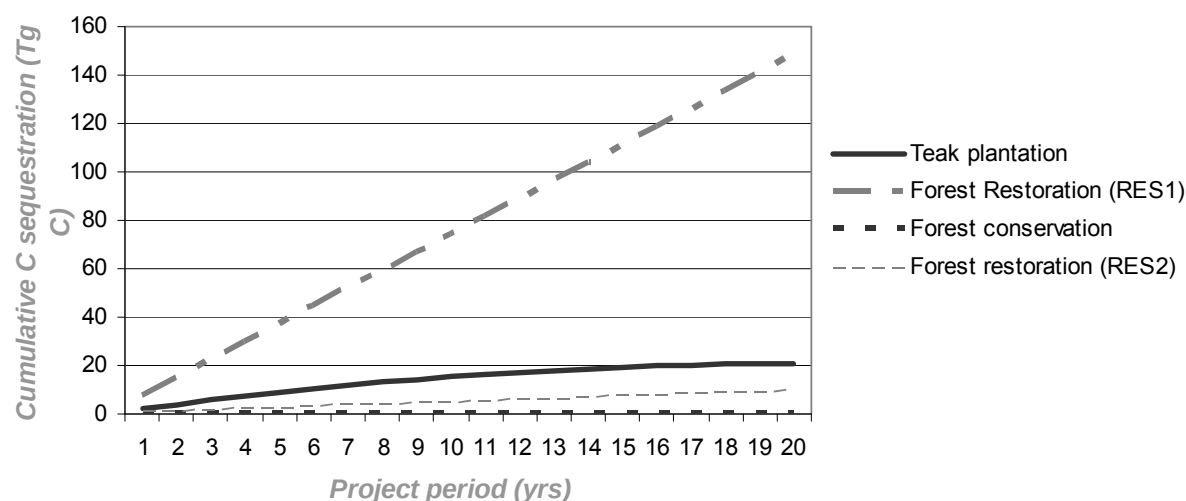


Figure 72 C sequestration and emission reduction potentials under three project scenarios

4. Constraints to the implementation of C forestry projects

4.1 Identification of land cover

Using MODIS images is useful for a national land cover accounting when most of land cover analysis in Ghana focused only at regional and local scale i.e. (Braimoh, 2006, Tan, et al., 2008, Tutu, 2008). However, the land cover estimates obtained in this study differ from other national forest inventories. The FAO (2005c) and Agyarko (2001) reported that in 2000 and 2005 the forest area was about 5.5 and 9.2 million ha while 4.3 million ha was estimated in this study. Estimation of forest area differs between different authors because of use of different forest definitions and technical means to evaluate the forest area. There is great need to develop national land cover accounting system that uses the definition of forest communicated by the DNA to the UNFCCC in the attempt to evaluate the national C stocks and land use change. However, while a definition of forest exists, forest degradation does not have definition under UNFCCC. Furthermore, there is no standardized method to identify and assess forest degradation. It results that the estimation of forest degradation differs between authors. Using two different methods of identification of degraded forest gives area ranging 4-57% of the Eastern Guinean Forest zone.

4.2 Estimation of C stocks

C stock estimates are of main importance when analysing the potential for terrestrial ecosystems to uptake CO₂. The data provided by this study are the first C estimate at national scale that considers various land cover types and ecological zones in an African country. Previous estimates considered only the forest ecosystems. Aboveground C stocks of forest ecosystems of Ghana were estimated 363 Tg and 831 Tg of C according to the FAO (2005c) and this study respectively. The difference is mainly explained by differences in C estimates and the methods of identification of land cover types. While C stock estimates of this study are based on averaging C stocks reported by the literature, the C stock estimates from FAO are obtained from the average stem volume, average wood density of Africa, general biomass expansion factor specific for timber production, permanent protection and open forest area and a general C conversion factor. C stock estimates of forest based on FAO data were 108, 100 and 49 Mg C ha⁻¹ for timber production, permanent protection and open forest while 210, 105, 46 and 47 Mg C ha⁻¹ were contained in Eastern Guinean forest, Guinean forest savanna, west sudanian savanna and mangrove, respectively (Figure 73). FAO C estimate for broadleaf forest in the Eastern Guinean forest zone is about two times lower than the C stocks obtained in this study. This study overestimates the C stocks compared to the FAO reports. On the other hand, forests areas in the FAO document were reported by the Ghanaian Forest Commission and were respectively 12,552, 3,525 and 39,092 km² for timber production, permanent protection and open forests, respectively. In this study, those three different forest types were not considered, but ecological zones were taken into account. There is great need to improve C stock estimates that are specific for the ecological zones, the vegetation types and the management types.

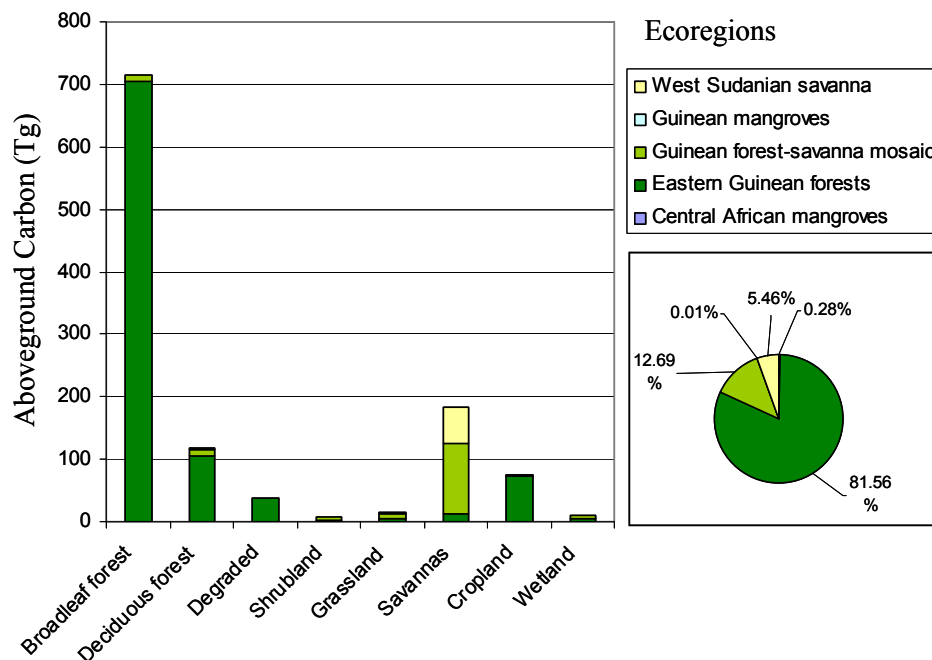


Figure 73: Distribution of aboveground carbon in the ecoregions of Ghana

4.3 C sequestration

This study is a first try to estimate the national potential C sequestration and emission reduction for an African country. While the countries are currently negotiating the modalities for the implementation of REDD+, there is a great need to provide scientific data that would help them to negotiate and better consider the potential of their ecosystem to mitigate climate change. However, different ways to estimate C stocks and potential C sequestration area could result in different estimates of C sequestration.

In this study, the C potential estimates are rough and needs to be improved. The estimates focus only on the aboveground C while 54% of the total C stock is contained into the soil compartment and no data were available for litter, dead wood and the roots. On the other hand, this study considers only teak plantation while other plantation and agroforestry systems are developed in Ghana and would sequester different amounts of C: for example, rubber plantation would sequester 80 Mg C ha⁻¹ (Wauters, et al., 2008) instead of 116 Mg ha⁻¹ for teak at the end of the rotation.

The potential area suitable for afforestation and reforestation activities was based on the study of Zomer (2008) and corresponded only to 4.3% of the total area of grassland and savanna together. The potential area calculated by Zomer was estimated using socio-ecological characteristics including current land use, population levels and ecosystem characteristics. I suppose that the aridity criteria have decreased the potential area for afforestation as plantations were considered only on optimal bioclimatic conditions defined as having a minimum threshold as aridity index > 0.65. However, the biophysical potential for afforestation/reforestation in Ghana might be higher than the one estimated in this study.

When estimating the potential area for restoration activities it ranged 3.7-57.1% of the Eastern Guinean forest area and the C sequestration potential ranged 9.6-148.1 Tg C for a 20 years project period. The amount of C sequestration through forest restoration is particularly difficult to estimate as the forms of degradation differ according to the geographical location and the anthropic activities. In addition it is difficult to differentiate the various forms of degradation using remote sensing (Lambin, 1999). The use of satellite imageries is limited by the presence of clouds, the spatial, temporal and spectral resolutions, particularly when considering national scale.

The potential area suitable for conservation activities concerned only the forests under production. However, this does not include the forests outside the productive area which are illegally logged. Current estimates indicate that illegal chainsaw activities alone account for about 1.7 million cubic meters of timber harvested in the country while legal activities harvest 1.1 million cubic meters (Birikorang, et al., 2001). It means that the potential emission reduction by stopping illegal logging would be of about 4.34 Tg C for a 20 years period. However, illegal logging have less impact on the C stocks as in many case illegal logging is referred to chainsaw operations without building road or skid trail. At current status, no study exist on the impact of illegal logging on C stocks.

The estimates of impact of selective logging given in this study consider only the ground impact and do not consider the fuel consumption of the logging operator and the permanence of C into the extracted round wood. While a part of the round wood is used to produce firewood or electricity, an other part is used to build houses or furniture. Improving the estimates would consist in estimating the part of the C in the wood which is released to the atmosphere directly and the part which is stored for a mid or a long term period.

4.4 Limitations of the accounting methods

The biophysical potential for C sequestration in Ghana is important. In addition, the economy of Ghana is stable in comparison with other African countries. However, implementation of C forestry activities faces several constraints.

Development of forestry activities in Ghana is limited by problems of: (1) land tenure, (2) financial capacity, (3) climate and plant disease, (4) social management, and (5) capacity building. Those constraints limit the adaptation, the adoption and the feasibility of the projects.

Land tenure could be considered as one main constraint as most of the land in Ghana belongs to the stools and is leased to the farmers or private enterprise by the government. When considering the process of decision making of foresters, farmers and private enterprise would invest into agroforestry or forest plantation systems only when they will secure the land property. Food security is an important problem in Ghana and it would be difficult to develop forestry activities on the land used for food production purpose. Planting forest has financial and labour costs and the capital availability is limited. Moreover, the investor (farmer or private enterprise) would have to recover the money invested. In addition, forestry activities are limited by plant disease i.e. increasing the tree cover into cocoa farms may increase the humidity and the spread of pod rot disease (*Phytophthora megakarya*). In this case the only alternative for the farmer is to increase the use of fungicide and the financial investment into chemical products. Since the diversion of forestry law application in the 60's, farmers fear logging operators. During the 60-70's, forestry operators destroyed a large part of forest outside the reserve while the farmers used to keep trees within their farm as an agroforestry systems. When most of the forests outside reserves were exploited, many logging operators decided to exploit the trees within the farms and in most of the case never compensated the farmers for the damaged occurred in their farms. The damages were particular important, particularly in cocoa farms (Tropenbos International, 2004). The farmers have to be convinced by the positive externalities of planting trees so they will maintain the trees within their farms.

The constraints faced by developers of forest activities in Ghana are in most of the case present in the countries of sub-Saharan Africa. However, in most of the countries the problem of access to the funds, food security, and land tenure conflicts, are even more important. i.e. The political situation of Ivory Coast favoured mis-management of the forest ecosystem, its degradation and illegal activities (i.e. the forest of Sangoué). The country faced an important decrease of the foreign development funds and private sector investment. Developing C forestry activities faces the general constraints of forestry project development and the specific constraints for CDM and REDD+ projects.

5. Conclusion

The study shows that most of the aboveground C sequestration potential of Ghana would be through restoration of degraded forest outside the national forest reserves. CDM A/R would represent half of this potential while the potential for forest conservation would be smaller. However, the estimation of forest area is uncertain and vary according to the methods and definitions. The definition of forest degradation will determine the potential for C sequestration through forest restoration in Ghana. When developing the modalities for international mechanism such as the REDD+, there is a great need to analyse its feasibility and to make it enough flexible to adapt to the regional, national and local constraints.

Forest restoration is not recognized under the UNFCCC and is not eligible under the CDM or the REDD+ mechanism. However, enhancement of forest carbon stocks is eligible under REDD+ and can be considered as part of the forest restoration activities. The next chapter will deal with enhancement of forest carbon stocks. Using the example of the cocoa agroforests in Ghana, the next chapter analyses the potential for carbon sequestration and considers the national context, constraints and opportunities to implement the REDD+ mechanism.

Chapter 12

Enhancing forest carbon stocks in agroforestry systems: the case of cocoa in Ghana

This chapter is modified from the article: M. Henry, D. Huberman, Zefc, G., R. Valentini, M. Bernoux (2010) Enhancing forest carbon stocks in agroforestry systems: the case of cocoa in Ghana, Ecological economics, submitted

Abstract

In the context of the climate change convention, various options are proposed to developing countries to implement voluntary actions which may affect the forest sector. The emergence of REDD+ is particularly relevant to tropical forest countries such as Ghana. In search of a better balance between agricultural development and fight against deforestation, economic development and poverty alleviation, agroforestry seems an interesting compromise if it meets the eligibility criteria for REDD+. The objective of this study was to analyze the potential introduction of cocoa agroforestry systems in Ghana as part of REDD+. From a biophysical and economic analysis, the study analyzed different scenarios and revealed that the intensification of already existing cocoa plantations was the most suitable option. The national carbon gain could reach 1.93 Tg C yr⁻¹ and 68 millions of dollars. On the one hand, the economic benefits of carbon sequestration to farmers were more important than in the other scenarios. On the other hand, it is technically more feasible to intensify existing systems than to expand them or conserve the forests. The intensification of cocoa systems, however, must be accompanied by other innovations that may encompass a broader range of the population and thereby reduce the risk of conflicts, which largely contributed to the erosion of national forest resources.

Keywords: REDD+, cash crop, carbon payment, landscape, livelihood, payments for environmental services, tropical forest

1. Introduction

1.1 The agroforestry potential

Every year, thirteen million hectares are deforested (FAO, 2010), contributing to about 25% of human induced greenhouse gas emissions (GHG) (IPCC, 2007b). Beyond the critical effects that this trend has on the climate, it also has important impacts on biodiversity loss, soil erosion, and local livelihoods. Agricultural activities have often been identified as one of the main drivers of deforestation in tropical countries (Geist and Lambin, 2002, Lanly, 2003). In many instances, ongoing competition between agricultural and forest conservation interests has also resulted in increasing poverty, illegal activities, and has jeopardized local level capacity to sustainably manage their resources (Upreti, 1983, Nagothu, 2001). A major problem is the enforcement of restrictive forest policies which deny access and use of natural resources to local communities who depend on forests for their livelihoods (Peskett, et al., 2008). In Ghana, the exclusion of local fringe communities has often increased hostility between the forest service and local people and has thus contributed to the degradation of the forests (Amanor, 1996). In the context of an increasingly unsustainable agricultural sector (Drechsel, et al., 2001), climate change and biodiversity loss (UNEP, 2006), the equilibrium between sustainable farming activities and sustainable forest management has yet to be identified.

The challenges of adequately integrating conservation and agricultural objectives into rural development policies and practices have long plagued international efforts to encourage sustainable development. Inevitably, there are trade-offs to consider between the conversion of land to economic activities such as agriculture, and the conservation of ecosystem and the services they provide to society. However, it has been proposed that an ecosystem (or landscape) approach to conservation can serve as a useful means of ensuring that these trade-offs are properly assessed in light of competing interests and that optimal management decisions can be reached through bottom-up and participatory governance processes within a given landscape (Sayer and Maginnis, 2005, Shepherd, 2008).

A central component of the so-called ecosystem approach is the integration of conservation objectives into productive landscapes. On the ground, this translates to the development of mixed productions systems in which a variety of goods and services are being produced in accordance with broader sustainability concerns. Mixed land-use systems such as agro-forestry, eco-agriculture (Scherr and McNeely, 2003), or integrated silvo-pastoralism (Pagiola, et al., 2004) offer some examples of how such an approach can be put into practice.

A significant advantage of these land-uses is that they offer a wider variety of ecosystem services than simple monoculture systems. Shaded cocoa agroforestry systems, for instance, provide a variety of commodities beyond cocoa (fruits, medicine, timber) while also sequestering carbon, conserving biodiversity (Leakey, 1999), enhancing soil quality and fertility (Nair, et al., 2009), and enhancing hydrological cycling (Gockowski, et al., 2009). By encouraging economic activity, agroforestry also offers significant potential in terms of alleviating poverty and supporting rural development (Place, et al., 2005). Agroforestry systems were also identified as a promising option for mitigating climate change in sub-Saharan Africa through carbon (C) sequestration in soil and biomass (Woomer, et al., 1997). In addition, agroforestry systems tend to decrease the pressure of local fringe communities on forest products and could thus contribute to reducing deforestation and forest degradation.

Agroforestry is currently being discussed as a potential form of land-use that would be eligible for compensation under an international regime for reducing emissions from deforestation and forest degradation, recognizing the role of conservation, sustainable forest management and the enhancement of forest C stocks as means of mitigating climate change (REDD+). In such a scenario, the C sequestration and associated emission reductions from agroforestry systems could be accounted for, thereby generating carbon credits as additional sources of revenue for farmers.

Already, standards for certifying C sequestration projects in the voluntary carbon market have integrated agricultural land-uses into their methodologies (VCS AFOLU standard). With these markets growing rapidly (Hamilton, et al., 2009), it seems useful to assess how new incentives for climate change mitigation could be used to support both biodiversity conservation as well as agricultural production and farmers livelihoods. By looking more closely at agroforestry systems in a country which is currently taking steps to access REDD+ and carbon financing opportunities - Ghana -, it is hoped that more clarity can be brought on the potential that integrated land-use systems such as agroforestry might have in terms of delivering positive economic, social, and environmental results.

The aim of this article is to analyze the potential for enhancing forest C stocks in cocoa agroforests in Ghana. The objectives are (i) to identify how agroforestry can address deforestation and forest degradation, (ii) to quantify the biophysical and economic potential for C sequestration in cocoa agroforestry systems and (iii) to identify how cocoa agroforests could be integrated into an international regime for climate change mitigation.

1.2 Agroforestry in the context of REDD+

Agriculture and deforestation are inextricably linked, especially in Africa. It is estimated that about 70% of agricultural emissions could be mitigated through activities in developing countries (Smith, et al., 2007). While some promote the implementation of forest conservation actions within the forestry sector (Bruner, et al., 2001), others argue that the solution for mitigating forest degradation and deforestation lies outside the forestry sector and particularly within the agricultural sector (Riedacker, 2009). However, the agricultural sector is still largely overlooked in the international climate change policy agenda, and the extent to which different agricultural activities such as agroforestry can be successfully integrated into mitigation policies and projects remains unclear.

To date, several mechanisms have been developed to support forestry-based C sequestration, particularly in developing countries. The Clean Development Mechanism (CDM) is one of the so-called flexibility mechanisms that is implemented through the United Nations Framework Convention on Climate Change (UNFCCC) to support mitigation projects in developing countries. Currently, afforestation and reforestation are the only eligible forms of forestry projects, but have yet to develop in most African countries (Marot, 2003). However, the CDM has raised significant criticisms, relating primarily to low sustainability outcomes, lack of additionality, and restricted geographical scope (Karsenty, 2009). For instance, to date there is only one afforestation/reforestation CDM project in Africa.

While recent climate change negotiations at the 15th conference of the parties failed to make progress in terms of agreeing on future targets for GHG reductions, they nevertheless confirmed the growing consensus on the need to develop appropriate policies and measures to support forest-based mitigation. The discussions on REDD+ were seen as being particularly encouraging in this regard. Significant resources have already been pledged to the task, and the focus is now on ensuring that national-level REDD+ programmes are successfully established and implemented. While the debate

initially focused on means of reducing emissions by avoiding deforestation, the broader REDD+ approach to mitigating forest-based GHG emissions has highlighted the importance of considering a wider range of activities that fall within the national definition of forests, potentially including agroforestry.

The fifteenth session of the COP adopted a decision on methodological guidance for activities relating to REDD+. (UNFCCC 4/CP.15), which requests developing countries to use the most recent guidelines of the Intergovernmental Panel on Climate Change (IPCC) as guidance. The relevant REDD+ activities are covered by the following three categories in the IPCC good practices guidance (GPG) for Land Use and Land Use Change and Forestry (LULUCF): (i) forest land converted to other land, which includes deforestation, (ii) forest land remaining forest land, which includes forest degradation, forest conservation, sustainable forest management and enhancement of C stocks; and (iii) other land converted to forest land, which includes enhancement of forest C stocks. While (i) and (iii) corresponded to land use change activities, forest cover change under (ii) remains under the definition of forest land. Agroforestry systems can potentially be accounted under REDD+ as forest cover change remaining as forest land or as other land converted to forest land. However, agroforestry can only be considered under REDD+ if it falls or will fall within the definition of forests, as communicated by the country under the UNFCCC.

2. Ghana and climate change

2.1 The GHG balance of Ghana

Although Africa contributes to less than 4% of global GHG emissions (Canadell, et al., 2009), it is expected that the rate of deforestation and forest degradation will grow in the coming years (Chapter 2). According to a national communication from the UNFCCC, Ghana still acts as a carbon sink, with a net removal estimated at some $-1.45 \text{ Tg C yr}^{-1}$. Eighty-five percent of GHG emissions come from the LULUCF sector, and the rapid decline in emissions removal is mainly attributed to deforestation (EPA, 2000). If deforestation is not reduced, there is a great chance that Ghana will flip from being a net sequester to a net emitter of GHG, if it has not happened already.

The greatest potential for reducing the nation's GHG emissions and expanding its C sinks lies in the LULUCF sector (Ghana NatComm, 2000). When analyzing the potential emissions reductions and C sequestration from forestry activities, chapter 11 reported that forest conservation could only preserve 3 Tg C annually, and concerns only 3% of the total area of the country (Table 35). On the other hand, afforestation and reforestation activities could sequester 21 Tg C and forest restoration up to 148 Tg C. These figures suggest that the greatest potential for enhancing Ghana's contribution to climate change mitigation can be achieved through activities aiming to restore the country's degraded forests.

Table 35: C sequestration potentials for Ghana (Chapter 3)

Activities	C sequestration potential (Tg)	Tg C yr ⁻¹	% of total land area	
Restoration of forest	148	7.4	19	
Forest conservation	3	0.15	3	
Afforestation/ reforestation	21	1.05	2.7	

2.2 State of deforestation and forest degradation in Ghana

At the beginning of the 1900's, one-third of Ghana's land area was covered by natural tropical forest (Wagner and Cobbinah, 1993). According to Dogbevi (2008), about 80% of Ghana's tropical forest has since disappeared (1.6 million in 2007). Deforestation in Ghana reached a peak between the 1950s and the 1970s, during which time about a third of the country's forest disappeared (Hall and Swaine, 1981). Then, the annual rate of deforestation slowed in the 1980s to an annual loss of about 220 km² yr⁻¹ (FAO, 1988) and 120 km² yr⁻¹ between 1990 and 2000 (FAO, 2006c). Currently, the mean annual rate of deforestation in Ghana is estimated at about 2% and is one of the highest rates in the world, largely exceeding the regional deforestation rate of Africa (0.8%) (FAO, 2006c). Deforestation rates have changed over time (Figure 74) and are the result of complex interactions between social, cultural, political and economic factors. It should also be noted that these estimates are largely influenced by often imperfect methodologies for assessing different forms of forest degradation and forest transition (Achard, *et al.*, 2007, DeFries, *et al.*, 2007a) and the forest definition (FAO, 2006a).

It is believed that most of the forests in Ghana are currently degraded, with only 16 % of the total area estimated to be experiencing slight or no disturbance (Treue, 2001, Abebrese, 2002, Agyeman, *et al.*, 2003). Moreover, it has been estimated that only 19.6% of forests in reserves have a crown cover of more than 75% FAO (2002). Overall, this means that more than 90% of Ghana's forests have been exploited since the 1940s (Asibey and Owusu, 1982). The different forms of forest degradation are difficult to categorize, as various land use change transitions involving different important spatial and temporal variation of the forest cover make forest area and C stock estimations difficult to carry out. However, a closer look at some of the underlying and proximate drivers of forest cover change can provide further insights into the complex dynamics of the Ghanaian forest landscape.

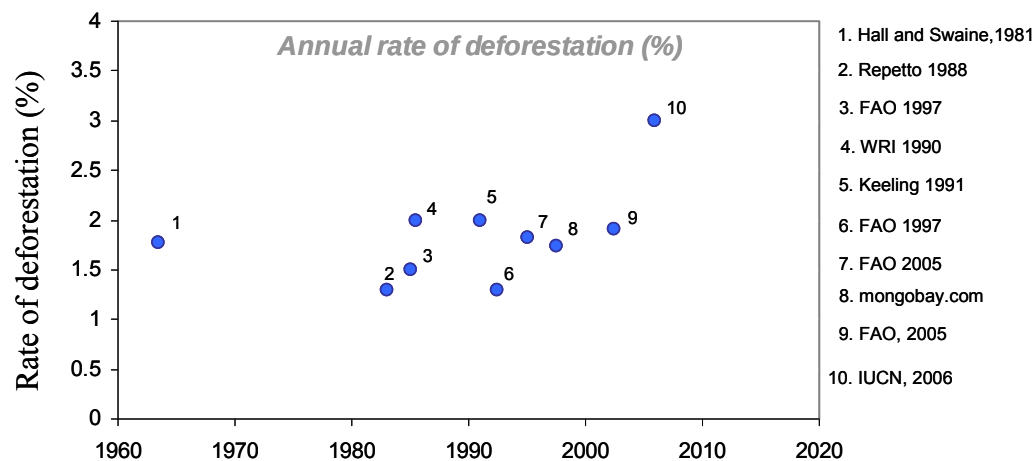


Figure 74: Annual rates of deforestation of Ghana

2.3 The proximate and underlying factors of deforestation and forest degradation

It is crucial to understand the different factors that lead to deforestation and forest degradation processes in order to implement feasible, adapted, and efficient policy responses. Five principal proximate causes of deforestation were identified: (1) Agriculture, (2) Timber exploitation, (3) Fires, (4) Fuelwood and (5) Mining.

(1) Agriculture is the main land use and driver of deforestation in Ghana (62.9%) (Appiah, et al., 2007) with short-cycle systems responsible for about 70% of deforestation (Agyarko, 2001).

(2) Timber exploitation concerns 75% of Ghanaian forests (Asamoah Adam, et al., 2006) and the significant logging activities are now concentrating in existing forest reserves, while off-reserve forests are mainly patches of forests in the form of scattered trees on agricultural fields (Hawthorne 1996).

(3) Fires mainly occur during periods of lower rainfall and are the immediate cause of most forest degradation in the moist semi-deciduous forest zones (Hawthorne, 1993). Forest fires are further encouraged by several factors such as the accumulation of residues from logging activities and weed invasion from agricultural abandonment (IIED, 1994a).

(4) Fuelwood collection represents the main source of energy for over 75% of Ghana's population (Agyarko, 2001). The increasing fuelwood deficit was estimated to be 11.6 million m³ in the year 2000 (FAO, 2005c) and represents the main driver of forest loss in the transitional and northern savannah zones.

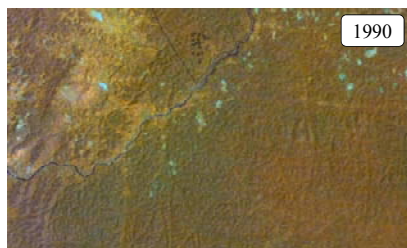
(5) Ghana is Africa's second largest gold producer and two million acres of forest land are lost annually to mining in Ghana (Anane, 2003).

Five underlying factors were identified to influence the proximate causes of deforestation: (1) Forest policy, (2) Land and forest tenure, (3) Poverty (4) Illegal logging and (5) Market prices.

(1) The forest policies of delivering forest concessions (Asamoah Adam, et al., 2006), e.g. to deliver the necessary timber to European countries after World War II, the increased foreign investments and the revamping of the timber industry have encouraged a heavy exploitation of the country's forests. The government started considering forest damages during the 90's and introduced new forest practices and the Forest and Wildlife Policy (IIED, 1994a). However, this is yet to be manifested in practice (Tropenbos International, 2005).

(2) Land and tree tenure affect the management of trees within and outside forest concessions and farmlands. Currently, traditional authorities own the land on behalf of the people. However, all rights for the management and development of natural resources were transferred to the President (Amanor, 1996) on behalf of the traditional authorities. Therefore, farmers are not owners of their land and trees within their farms. As timber shortages increased, timber operators are used to logging commercial trees within farms, without or with little compensation to farmers for the damages caused by logging on their crops. Furthermore, farmers have tended to destroy trees in order to minimize the damages of tree exploitations on their farms. Overall, the exclusion of local people from forest resources has often encouraged illegal practices.

(3) Illegal logging is believed to reach alarming dimensions and proportions in Ghana, and many, including the government, identify it as one of the key causes of deforestation (Tropenbos International, 2004). It has been estimated that out of the 3.7 M m³ of timber which is harvested annually from Ghanaian forests, 70% is estimated to be illegally cut (Hansen and Treue, 2008). Illegal timber harvesting has been encouraged by a context of poverty where illegal activities often offer better returns to farmers.



(4) Thirty percent of the population of Ghana lives below the poverty line (UNDP, 2007). Poverty incidence is highest among the forest fringe population, which constitute about 70% of all Ghanaians and for whom forests provide some 38% of their total household income (Glastra, 1999, Appiah, *et al.*, 2007). Poverty is also directly dependent on market prices, especially for important export commodities such as cocoa.



(5) The liberalization of Ghana's economy has significantly impacted the status of natural resources (Barbier, 2008). For instance, the increasing price of cocoa during the 60's led to an important conversion of forest to cocoa systems and the falling cocoa prices in the 80's led to the collapse of the cocoa economy and the subsequent abandonment of cocoa farms.

Picture 1: forest cover changes between 1990 and 2003 detected with Landsat ETM+ images

3. Cocoa agroforestry: an alternative to mitigate deforestation and forest degradation?

3.1 Agroforestry and climate change

Agroforestry systems have been perceived as representing an option to simultaneously improve biodiversity, soil fertility, medium to long term C sequestration, socio-ecological resilience and livelihoods (Sanchez, et al., 1997, Leakey, 1999, Young, 2005, González-Estrada, et al., 2008, Henry, *et al.*, 2009). Several authors have also presented agroforestry as an option to reduce or prevent desertification (Baumer, 1990, Schroeder, 1994). However, agroforestry as a means of reducing tropical deforestation has received little attention in the literature. Its contribution to the reduction of forest degradation and deforestation depends largely on local circumstances (Angelsen and Kaimowitz, 2004). Several researches have reported that technological change often leads to more, rather than less, deforestation (Angelsen, et al., 2001, Tomich, et al., 2001) and this may also apply to agroforestry if it increases the profitability of land use, unless there are other factors such as labour, capital, or market constraints that limit agricultural expansion into forest areas.

Cocoa systems in particular have been reported to contribute to deforestation in Nigeria (Oke and Odebiyi, 2007) and in Ghana (Ruf, 2001). On the other hand, C storage in agroforestry systems was reported to significantly contribute to climate change mitigation and adaptation (Unruh, et al., 1993, Albrecht and Serigne 2003). While most agricultural practices are based on slash and burn activities in tropical humid zones, which in turn lead to important losses in terms of biomass and soil fertility (Juo and Manu, 1996), agroforestry is seen as an interesting alternative particularly in degraded environments. Agroforestry systems therefore stand a larger chance to effectively sequester C in the long-term than annual cropping systems, adding aboveground C storage capacity through a broader diversity of living forms, including fruit or timber trees on-farm and/or perennial crops, plus potential ‘fertilizer’ and ‘fodder’ trees (Henry, *et al.*, 2009).

3.2 Cocoa agroforestry systems in Ghana

Cocoa is the main cash crop in Ghana. Its farming started at the beginning of the 20th century and currently represents the most important agroforestry system in the country, covering about 17,500 km² (FAOSTAT). Cocoa is a natural under-storey plant and is usually established by under-planting selectively thinned natural forests (Ruf and H. Zadi, 1998). It is often planted in association with economically attractive trees such as oil palm, avocado and citrus to provide shade in addition to providing food and cash for the farm household. Many medicinal plants are also found in shaded cocoa systems (Gockowski, et al., 2009).

Despite the many positive attributes of shaded systems, unshaded agroforestry systems are currently the most commonly practiced forms of cocoa farming in Ghana (Asare, 2005). While shaded agroforestry systems are perceived as being more environmentally-friendly, most farmers are reluctant to exploit timber trees within their farms and often choose to destroy them so as to avoid encroachment on their estates (Obiri, et al., 2007). It has been found that shade levels tend to decrease as farmers seek to maximize their production through intensification and specialization (Gockowski, *et al.*, 2009). Unshaded cocoa farms have the advantage of producing pods earlier, although this has also been found to be unsustainable because of the higher levels of inputs of insecticides and fertilizers required (Rice and Greenberg, 2000).

Several initiatives have attempted to promote cocoa agroforestry systems in Ghana as a buffer zone around protected areas (Zenelrneyer and Maddison 2004) and to increase the diversity of forest trees in farms by promoting the plantation of timber tree species (Tropenbos International - Ghana, 2007). Despite their potential to support local livelihoods, increase carbon storage capacity, and preserve biodiversity, efforts to promote cocoa agroforestry have yet to receive broad buy-in from Ghanaian farmers.

3.3 Carbon storage in cocoa agroforests

Several studies have reported on the C storage capacity in cocoa agroforests (Figure 75). They have revealed an important variation in C stocks that reflect differences between ecological zones, management practices and age. In Africa, Woomer et al. (1997) estimated cocoa agroforests to store some 82 Mg C ha⁻¹ in above-ground biomass, representing 40% of C stored in humid forests. Similar results were reported by Kanmegne (2004) and Eyoho Ewane et al. (2009). In these plantations, 53% of the C was stored in the cocoa tree, and other associated trees stored 47%. In older plantations in southern Cameroon, cocoa forests stored up to 141 Mg C ha⁻¹ (Kotto-Same, et al., 1997) and 243 Mg C ha⁻¹ (Sonwa, et al., 2009). In Ghana, Asase et al., (2010) differentiated un-shaded and shaded agroforests which contained 104 and 39 Mg C ha⁻¹ respectively in aboveground biomass. While this study estimated that forests contained 155 Mg C ha⁻¹, forest conversion to traditional (unshaded) cocoa systems was assumed to emit 116 Mg C ha⁻¹, while conversion from unshaded to shaded systems could sequester an additional 65 Mg C ha⁻¹.

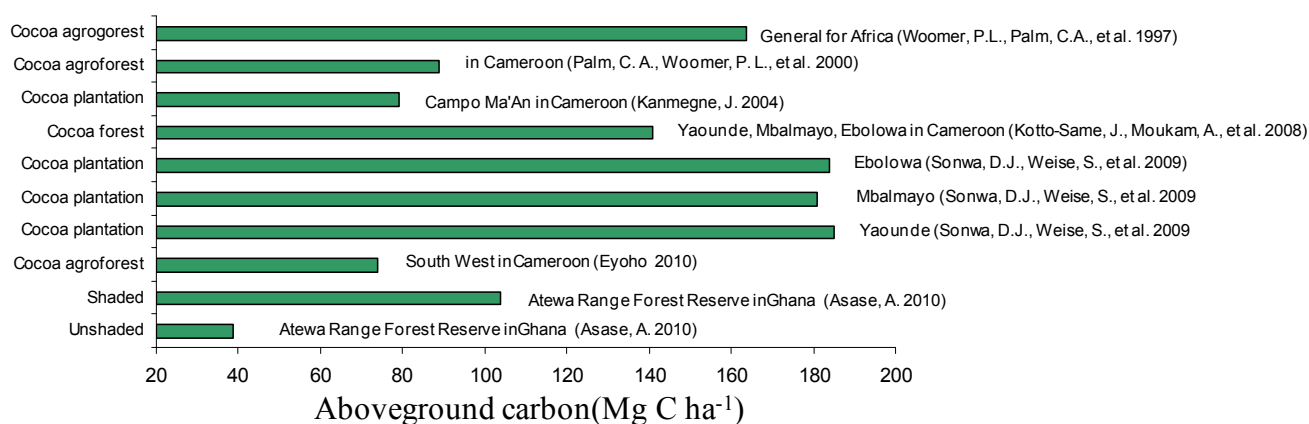


Figure 75: Aboveground carbon stocks in cocoa agroforest in sub-Saharan Africa

In Ghana, most of the forests are already degraded and the enhancement of forest carbon stocks is seen as the most promising means of mitigating GHG emissions through REDD+. Further, cocoa agroforestry systems could become eligible under REDD+ as it would fall within the current Ghanaian definition of forest "A piece of land with a minimum area of 0.1 hectares, with a minimum tree crown cover of 15% or with existing tree species having the potential of attaining more than 15% crown cover, with trees which have the potential or have reached a minimum height of 2.0 meters at maturity in situ".

In the tropical humid forests, forests with tree cover less than 30% can be considered as degraded while cocoa tree cover exceeds 30% (Asare, 2005) and is generally found at around 70% in Cameroon (Palm, et al., 2000). It therefore seems as though incentives channeled through a REDD+ regime could serve as a means of supporting the expansion the cocoa sector through the conversion of degraded forests into

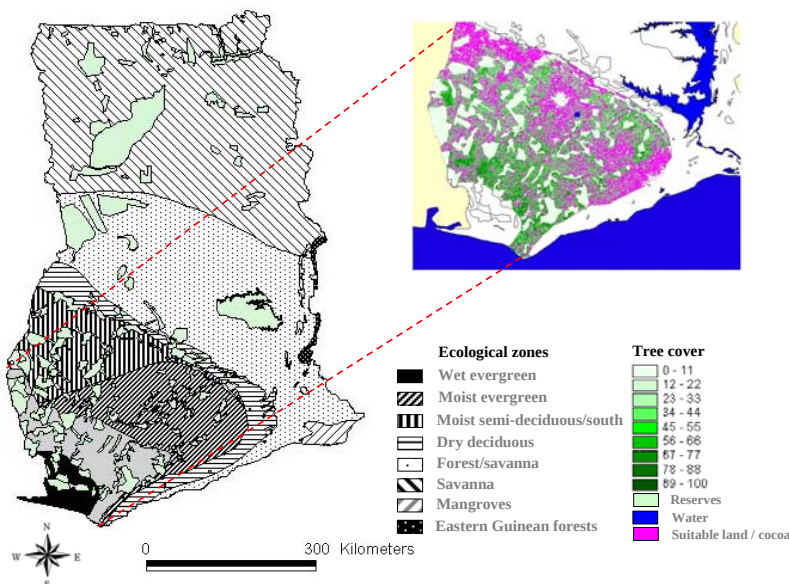
sustainably managed agroforestry systems. However, such a scenario is currently not supported by current trends in the country's cocoa sector, which is still dominated by unshaded systems. One possible explanation for this situation is that it is very difficult to encourage individuals to adopt practices or technologies that save resources when these are not perceived as scarce, such as forest land in an open frontier situation. The adoption of cocoa agroforests by farmers mainly depends on a variety of feasibility, profitability, and acceptability criteria, as identified by Franzel (1999). However, as market prices tend to have a significant effect on farming practices, it seems useful to shed some more light on the potential that markets for carbon could play in terms of further encouraging the development of sustainable agroforestry systems in Ghana.

4. Analysis

Our analysis focuses on the potential adoption of cocoa agroforestry adoption under a REDD+ programme in Ghana. I first analyze the feasibility for C sequestration and emission reduction under four hypothetical scenarios. Then, I explore the economic profitability of the different scenarios. After, I analyze the potential acceptability considering the context of Ghana. At last, I discuss the consideration of cocoa agroforestry within possible REDD+ architecture.

4.1 Carbon sequestration potential in cocoa agroforestry systems

In an effort to assess the C sequestration potential of different forms of development and expansion of the cocoa industry in Ghana, four scenarios were envisioned. The first scenario (SC1) assumed that forests with a tree cover ranging between 15-30% corresponded to significantly degraded forests which were converted to shaded cocoa agroforestry systems. The extent and location of the land that is suitable for the expansion of cocoa in Ghana is shown in Figure 76. The second scenario (SC2) proposed the conversion of the same surface of degraded forests to unshaded cocoa plantations. These first two scenarios correspond to an extension of the cultivation area for cocoa.



The third scenario (SC3) envisaged an intensification of existing cocoa production, which would take the form of a conversion of already existing unshaded plantations to shaded agroforests. This scenario did not involve any increase of the surface area devoted to cocoa farming. The fourth scenario (SC4) envisaged a 'no development' situation, whereby agricultural expansion was halted and the remaining forests outside of forest reserves were conserved.

Figure 76: Potential land for extension of cocoa agroforestry systems in Ghana

4.2 Assumptions

In each case, the C sequestration and emission reduction potential were calculated based on a period of 20 years. Also, it was assumed that 63% of cocoa farms were currently shaded (Asare, 2005), and that the average farm size was 2.3 ha, corresponding to a total of 644,000 cocoa cultivating farmers (FAOSTAT, 2010). Considering 37% of the cocoa agroforest as unshaded system is a conservative estimate. The C stocks in the various vegetation forms were obtained from C stock maps of Africa (Chapter 9) and the different forest forms were identified using the MODIS tree cover products (Hansen, et al., 2002).

The analysis assumed that the total area suitable for extending cocoa plantations were degraded forests with crown cover percentages ranging from just 15 to 30% (Anim-Kwapong and Frimpong, 2002). This assumption was supported by Asare's (2005) observation that cocoa systems in Ghana have a crown cover which is superior to 30%.

Based on the C stock map developed in chapter 9, it was assumed that, on average, 88 and 56 Mg C ha⁻¹ are stored in forests and very degraded forests (15<TC<30%) respectively while 21 Mg C ha⁻¹ are being stored outside of forests. In total, forest reserves store 77 Tg C while forests outside reserves store 107 Tg C. Moreover, forests outside reserves represent 58% of the C stocks and 80% of the forest area. It was estimated that the conversion from forest to non-forest led to emissions of about 68 Mg C ha⁻¹ per year. Based on the average rate of deforestation of 1.9% reported by FAO (2006), it was assumed that the total amount of emissions from deforestation in the country's moist ecological zone was equivalent to 1.75 Tg C yr⁻¹.

5. Results

5.1 Carbon stocks, carbon sequestration and emission reductions

These data were used to run simulations models for the different scenarios (Appendix II). It thus resulted that 17,670 km² were found to be suitable for the extension of cocoa cultivation (see Figure 76), as was the case for SC1 and SC2. This corresponds to a doubling of the existing extent of cocoa agroforestry in the region. As can be seen in table 2, two of the scenarios involved an increase in total C stock (SC1: +48 and SC3: +65 Mg C ha⁻¹), while SC2 – the conversion of degraded forests to unshaded cocoa plantations, resulted in a net decrease in carbon emissions (-0.84 Mg C ha⁻¹) and SC4 – the conservation of forests, resulted in an emission reduction (+68 Mg C ha⁻¹).

At the national scale, the conversion of degraded forests to shaded cocoa plantations (SC1) would result in a gain of +4.26 Tg C yr⁻¹, the largest total gain across all four scenarios envisaged, while the conversion to unshaded plantations (SC2) provoked a loss of -1.49 Tg C yr⁻¹. When looking at a per hectare carbon sequestration potential, it was found that the conversion of unshaded to shaded systems offered even greater gains than under SC1, with a total per hectare gain which is approximately 135% larger. However, since only 5950 km² were considered, the total yearly gains are smaller under SC3. The per hectare gains (or, more appropriately, avoided losses) under a 'conservation' scenario (SC4) were the largest of the four scenarios envisaged. However, since the surface considered was also the smallest, the total amount of C sequestered yearly was smaller than both SC1 and SC3 at 1.76 Tg C.

5.2 Profitability of cocoa agroforests under REDD+

As the potential adoption of carbon-intensive agroforestry systems by farmers is largely dependent on the financial compensation associated with the necessary behavioral change, the analysis was extended to consider some economic data. The economic benefits of cocoa farming were estimated under the four proposed scenarios (Appendix XIII). The analysis considered three main variables: the revenue from cocoa farming, the revenue from carbon credits and the transactions costs related to project implementation, monitoring and verification.

The cocoa price used in the analysis is the one reported by the Ministry of Finance & Economic Planning of Ghana (2005). Average inputs were estimated to cost 7 and 8 \$ ha⁻¹ in unshaded and shaded cocoa agroforests, respectively (Obiri, et al., 2007). Based on an average cocoa price of 0.84 \$ kg⁻¹, it was estimated that, at the national scale, unshaded and shaded cocoa agroforestry generated an average income of 269 \$ ha⁻¹ and 506 \$ ha⁻¹ respectively. It should be noted that, in this case, 'unshaded' systems correspond to traditional farming systems. This choice was made as it was felt that it corresponded more precisely to a context whereby REDD+ policies and measures would be specifically tailored to target such areas, as opposed to large unshaded industrial plantations which are likely to have a higher carbon content than traditional farms as a result of intensified production.

Table 36: Carbon sequestration and economic profitability for four scenarios in the cocoa belt of Ghana

Scenarios	SC1	SC2	SC3	SC4
Total area (km ²)	17670	17670	5950	5378
Number of farmer (x1000)	636	636	219	-
Initial carbon stock (Mg C ha ⁻¹)	56	56	39	88
Carbon sequestration (Mg C ha ⁻¹)	48	-17	65	68
Mg C ha ⁻¹ yr ⁻¹	2.41	-0.84	3.25	3.39
Tg C yr ⁻¹	4.26	-1.49	1.93	1.76
Transaction costs (million \$)				
Average	9.9 (0.2 - 28.6)	-	4.4 (0.2 - 9.6)	4 (0.2 - 8.7)
Country income (million \$)				
Average	87 (81-92)	-	68 (64-71)	61 (58-64)
Farmer income (\$ ha ⁻¹ yr ⁻¹)				
Average	557 (553 - 559)	269	620 (614 - 626)	542 (540 - 543)
Carbon revenue (\$ ha ⁻¹ yr ⁻¹)				
Average	50.7 (47 - 53.3)	-	114.3 (108 - 119.7)	35.7 (33.8 - 37.4)

Based on a market price of \$10 per ton of carbon, it was found that, at the national scale, the conversion of degraded forests to shaded agroforestry systems (SC1) would generate the highest national carbon income ranging 81 - 92 M\$ yr⁻¹. This is significantly larger than under SC3, which would generate an average of 68M\$ yr⁻¹, as well as under SC4, which would generate 61M\$ yr⁻¹. The extension of unshaded cocoa would not generate revenue because it results in a negative carbon balance.

When considering the national transaction costs, I analyzed the numbers reported by Olsen and Bishop (2009) (Table 36). Average annual transaction costs were estimated between 4.41 and 9.85 millions \$, but ranged 0.23 - 28.63 M\$ under SC1, 0.18-9.64 under SC2, and 0.16-8.71 under SC4.

When considering the benefits to farmers, under SC1, it was found that the conversion to shaded agroforestry systems would yield, on average, 556 \$ ha⁻¹ yr⁻¹ from cocoa and 51\$ ha⁻¹ yr⁻¹ from the delivery of carbon credits (Table 36). Under SC2, which envisaged the conversion of degraded forests to unshaded plantations, cocoa agroforests would provide an average of 269 \$ ha⁻¹ yr⁻¹ while no revenue from carbon credits would be received. Under SC3, farming revenue would be about 620 \$ ha⁻¹ yr⁻¹ and the carbon revenue would reach 114 \$ ha⁻¹ yr⁻¹. At last, SC4 would generate 36\$ ha⁻¹ yr⁻¹ from carbon credits when considering the same number of farmers than in SC3.

Overall, at the national scale, the extension of shaded cocoa agroforests provides the highest national carbon revenue. At the level of individual farmers, the highest per hectare cocoa revenue is obtained under a scenario of intensified cocoa production (SC3), representing an increase of about 18% of the farming income, while extension of shaded cocoa farms (SC1) represented an increase of about 9% of farmer income – half as much. Under SC2 the carbon revenue was null. Finally, under the fourth scenario (SC4), the farmer revenue was estimated to be about 35\$ ha⁻¹ yr⁻¹ representing only 6.5% of a farmer's income from cocoa.

These numbers are significant, but they are still relatively modest when compared, for instance, to current amounts of funding that Ghana receives from foreign aid (1293 M\$ yr⁻¹ in 2008 – OCDE). It should be noted that the carbon revenue that could be derived from the extensification of cocoa agroforestry systems (SC1) is not likely to be sufficient to compensate for the up-front investments needed for the conversion of degraded forests to cocoa agroforests as most of the farmers are poor and cannot invest in the medium to long term. The conversion from unshaded to shaded holds greater potential in terms of using carbon revenues to leverage changes in farming prices as the gains are more significant on a per hectare basis. However, our analysis did not consider the costs of converting the land from unshaded to shaded systems.

6 Discussion

6.1 There is a potential for C sequestration in existing cocoa farms

As demonstrated by the results presented above, the promotion of shaded cocoa agroforestry systems presents the advantage to sequestering important amounts of C in comparison with degraded forests (Table 36). In addition, agroforestry systems present higher C sequestration potential than afforestation and reforestation (Table 35), as well as forest conservation. Intensifying already existing agroforestry systems presents higher C sequestration potential than strict forest conservation.

Although its influence on deforestation rates was not considered, agroforestry could also help alleviate pressure on forests by attracting labor. When considering economic aspects, the highest revenue at the national scale would be obtained under a scenario of expanded cocoa agroforestry systems, as there is an important amount of suitable land. On the other hand, the revenue to farmers would be higher under a scenario of intensified agroforestry systems, as the both the carbon as well as the cocoa-related benefits are highest on a per hectare basis.

While the cost of planting new cocoa farms will undoubtedly exceed the potential benefits from carbon credits, the activities would be limited to the shading of already existing cocoa farms. It has been found, however, that shading tends to decrease as farmers seek to maximize their cocoa production (Gockowski, *et al.*, 2009). In some instances – notably in large farms with scarce labor, shade is used as a means of ensuring a more stable production of cocoa (Gockowski, *et al.*, 2009). Our analysis, however, considered that shaded systems have a significantly larger economic potential than unshaded systems (\$506/ha/year as opposed to \$269), as only traditional (small-scale) production systems were considered.

Based on our analysis, it appears as though carbon revenues can provide an added incentive for leveraging the funds needed to maintain and intensify cocoa farms, but not necessarily to convert degraded forests into cocoa agroforests. While it may be difficult for the Ghanaian government to provide the necessary capital for converting degraded forests into cocoa farms, an increase of 19% in farmer income can provide a significant incentive to convince farmers to keep trees within their farms. This further strengthens the economic case for encouraging the conversion of existing unshaded plantations into shaded agroforestry systems. However, before accepting this type of change in practices, farmers have to be effectively informed, trained, and convinced.

6.2 Integrating agroforestry into the REDD+

As previously stated, most of the potential for Ghana to mitigate climate change is through the LULUCF sector. To date, the CDM has not produced the expected outcomes. The development of C forestry projects through the CDM will not be common in Africa so long as the rules do not consider the specificities on land and tree tenure and the available capacities and facilitated access to the funds and markets. Thus, the possibility of using REDD+ as a means of allowing African countries such as Ghana to access carbon finance opportunities stands out as a particularly attractive opportunity. However, the activities can be considered within the REDD+ only if they meet the criteria that are identified under the UNFCCC. Moreover, I identify two types of constraints: (1) the criteria under the UNFCCC, and (2) the institutional and legislative context of Ghana.

- (1) Financial compensation will be based on a system of monitoring, reporting, and verification (MRV). However, important variations of C stocks in cocoa agroforests were found in Africa (Figure 76) and the MRV of C stocks and C changes in cocoa farms faces problems of limited data accessibility and difficulty in the identification through remote sensing (Imbernon, 2004).
- (2) The Ghanaian government recognizes that the forest sector needs governance reform rather than just technical assistance (VPA, 2009). Governance initiatives need to adequately address national development, sustainable livelihoods, and poverty alleviation (Owusu, *et al.*, 1989, Kotey, *et al.*, 1998). REDD+ policies and measures have to be implemented in parallel with ongoing efforts to improve Forest Law Enforcement, Governance and Trade (FLEGT) (FERN, 2007). Efficient financial compensations will have to avoid the capture of the funds by a minority of elites.

7 Conclusion

The results of our analysis suggest that, when considering revenues from cocoa as well as from carbon, in the highest economic returns from cocoa agroforestry systems in Ghana can be achieved through the development of in situ forest restoration actions (i.e. conversion from unshaded to shaded systems) rather than through strict forest conservation, sustainable forest management and/or afforestation and reforestation. These findings suggest that the extension of a national REDD+ programme in Ghana to include cocoa agroforestry could potentially enhance the overall cost effectiveness of the scheme.

As we have seen, there are many economic, social, and environmental benefits associated with the sustainable development of agroforestry. Developing cocoa agroforestry systems is believed to be an attractive means of mitigating climate change while supporting the livelihoods of local populations (Leakey, 2001, Schreckenberg, et al., 2006). From a social perspective, it has been found that the diversification of economic activities has positive effects on gender equality, as the non-cocoa products (e.g. fruits, medicine) provided in these systems tend to be managed by women (Gockowski, *et al.*, 2009). On the environmental front, the multitude of ecosystem services delivered by agroforestry systems presents strong advantages beyond carbon sequestration. Higher biodiversity and higher ecosystem stability and resilience are found in agroforestry systems compared to other agricultural systems particularly in the context of a changing environment (climate variation, plant disease etc.) (Schroth, et al., 2000). From an economic perspective, the diversification of income generation activities and integrated forest crop and agricultural cropping systems can help secure rural income and a substantial reduction of new forest area clearance in some areas (Appiah, 2001, Geist and Lambin, 2002, Russell and Franzel, 2004, Appiah, *et al.*, 2007). In addition, agroforestry usually consists in fixed investments that are more regular and reliable than in monoculture systems (Gockowski, *et al.*, 2009) and supports land security (Angelsen and Kaimowitz, 2004).

Most fundamentally, these mixed-use systems are able to integrate different activities into a coherent ecosystem management strategy, thereby offering an opportunity to overcome competing interests while generating employment. Set within a broader landscape approach to conservation, it is hoped that agroforestry can support biodiversity while achieving positive returns on investment. However, the feasibility and viability of such systems is largely dependent on fluctuations in market prices. The simple fact that such mixed land-use systems are able to simultaneously tap into different markets (i.e. carbon and cocoa), thereby reducing vulnerability through economic diversification, is in itself a strong argument for supporting their development.

Although the economic benefits from carbon credits could represent up to 19% of the total farmer's income, the farmers are still likely to remain heavily dependent on market prices for cocoa. The sustainable development of agroforestry in Ghana is likely to remain largely dependent on a secured international market price for cocoa, but also by encouraging farming diversification and developing capacity to develop new agroforestry systems without encroaching on the remaining forests.

Yet, there are still significant challenges currently hindering the implementation of C forestry activities in Ghana. The lack of clearly defined tree and land property rights represents a major hurdle in terms of associating the incentives with the appropriate actors unless the land and tree tenure systems are clarified, it is unlikely that farmers will cultivate shaded systems and invest more labor in their farm. The lack of transparency in decision-making processes further exacerbates these challenges, especially in situations where the benefits can be captured by corrupted officials or self-serving elites. It is also important to acknowledge that not all the farmers in the forest fringe communities cultivate cocoa and

enhancing carbon in existing cocoa farms will concern only a part of the population, while excluding the others farms. Broad stakeholder participation and access to credit and information are essential for the equitable and sustainable implementation of REDD+ policies. Increased participation is particularly important in terms of maximizing local knowledge and capacity to support the implementation of REDD+.

In recent years, the Ghana forest service tried to develop Taungya plantation systems, where farmers were encouraged to cultivate trees within their farms. However, this initiative failed, mainly because farmers had no rights to the trees, and no influence on whether or when they were felled (Ageyman, Marfo et al. 2003). Without adequate land tenure and forest tenure systems that fully consider the various relation between local fringe-communities and the forests, reinforcement of the regulation system could lead to conflict and enhance illegal activities and forest degradation and deforestation. Moreover, other alternatives have to be developed in parallel to cocoa agroforests to increase the participation of the local communities and to avoid conflicts.

Despite these significant challenges, it is hoped that ongoing efforts to internalize the value of carbon sequestration in biomass can offer a promising means of further encouraging the development of sustainable agroforestry projects through an integrated management of a variety of ecosystem goods and services. While Ghana is only just beginning to gain access to financial resources that are being mobilized through carbon markets and funds (e.g. through REDD+), the prospect for using this opportunity to encourage a broader recognition of the many positive attributes provided by sustainable shaded cocoa systems appears to be encouraging. So long as such developments are able to support, and not undermine, rural development, notably by creating jobs and diversifying income sources in a participatory and equitable manner, the resulting economic and environmental benefits are likely to pay significant dividends.

Chapter 13

General discussion and conclusions

There is still much to do and to learn in order to provide the “arsenal” of tools and financial capacities to allow sub-Saharan African countries to develop a carbon (C) accounting system of the same level than developed countries- allowing their effective participation in a global system centered on carbon - that can be represented by the ideal Carbon City described in the first chapter.

It is clear that the possession of Science and technologies allows greatest ability and flexibility for a country to implement actions for greenhouse gas (GHG) emission reduction that are to their advantage. As for exemple, the Chapter 4 shows the ability to use the allometric equations for calculating GHG balance in an advantageous way. Certainly, the climate arena is based on a more equal basis than the other conventions because it is backed by a scientific body which is represented internationally and which principles would correspond to the common principle in the idealized carbon city. However, production of scientific data remains highly dependent on the political orientations of the nations and therefore their interests. The results presented in this thesis tend to contribute to a more equitable climate arena and to better understand the contribution of terrestrial ecosystems to the C cycle.

Besides the fact that sub-Saharan African countries have limited scientific data (Chapter 2, 6 and 9) and means for the estimation of the biophysical capacity of interaction with the global environment, the ecosystems of the continent are complex, rich in biodiversity and human activities have learned how to appreciate their multifunctionality and have developed a multitude of practices. The result is a wide range of vegetation forms and management practices which complexifies further analysis of the ecosystems functioning (Chapter 7, 8 and 9). This complexity is represented for example by the many forms of language used to define species, different practices and different forms of vegetation (Chapter 6 and 9). To cite only one example, management of forest has had to adapt to ecological diversity and to harvest few commercial species (between 3 and 6 stems per hectare generally) while clearcuts are common practices in Asia and South America (Chapter 2 and 10).

Forests are multifunctional and are recognized by a wide range of interests. However, only carbon is considered as a priority (Chapter 1 and 2). On the one hand, the climate arena justifies and recognizes actions on a carbon base. Certainly, socio-economic factors are crucial for understanding the interactions between the societies and the forests, but it is a secondary consideration because they are not part of a global consensus. The repository in which we operate is dominated by the measurement of C fluxes in order to determine whether or not we are acting in the right direction, that is to say maintaining viable conditions to our lives and those of other organisms. On the other hand, carbon measurements are only a fraction of the necessary information that are necessary to improve the management of natural ressources. Complementary analysis has to be adapted to the situations in order to consider the national/ sub-national context on policy, land tenure, local livelihoods and local practices that interact with the natrual ressources. As for exemple, the chapters 11 and 12 report the impact of tree tenure and forest policy on the tree management systems of Ghana. At current state, one of the main constraint for the intensification of agroforestry systems in Ghana is the farmer perception of the

role of trees in their farm. For many years, the farmers have been used to destroying the trees within their farms in order to avoid the damages from timber logging practices. Improving the C stock estimates without considering the socio-economic aspects will not allow the implementation of efficient policy actions that are adapted to local contexts. It is obvious that many other aspects than carbon stocks have to be considered to improve the management of natural resources.

However, this thesis has focused more on the estimation of C stocks in SSA than on the developing issues. It is urgent to provide C stock data in order to identify the biophysical potential and to better understand the C cycle. On the other hand, developing issues have been analyzed for decades. However, the analysis of the link between development and C issues still has to be developed. Very few studies link the C measurements and socio-economic aspects which limits the reliability of the options that are proposed by the political sphere in the climate arena. Chapters 11 and 12 tend to identify national options to mitigate forest degradation and deforestation in Ghana. However, this kind of studies has to be refined and more widely spread in order to test the feasibility of the various options that are proposed within the climate arena.

The great variability of carbon stocks affects the accuracy of measurements and thus trust between potential donor and project developers. MRV has been established for building such a trust. It still faces many constraints. In the case of forestry operations for example, it is possible that the improvement of silvicultural practices reduces the impact on C stocks. However, we must consider that the significant variability of forest C stocks do not allow to make statistically valid measurements of emission reduction through improved selective logging practices in SSA (Chapter 10). In addition, improved forestry practices, as recommended by the ITTO, proposes the diversification of commercial tree species and therefore the exploitation of species that have lower commercial value. It should therefore be cut down more trees to enable the logging company to obtain an equivalent economic return and obviously generate higher impact on carbon stocks. Moreover, it is very difficult to find synergies between biodiversity and carbon issues in the case of selective logging. This difficulty becomes higher when considering the time scale for carbon and biodiversity processes. The time scale that is necessary for a forest to regenerate or reach the climatic status is much higher than the time period considered by project activities. In addition, little is known about the dynamics of tropical forests which limits our understanding on the ecosystem processes. The modelling tools are largely limited by the available data for their calibration. It should be noted that for example, Okoumé forests (*Aucoumea klaineana*) seem to have been the result of human occupation in the past.

If the consideration of the degradation of forests in the climate convention has been widely supported by countries such as the COMIFAC (*Commission des forêts d'Afrique centrale*) and France, the monitoring and the verification of the impact of forest degradation at the scale of the Congo Basin is technically and economically unfeasible. In the case of forestry operations, the use of satellite images is limited by the presence of cloud cover and a very weak relationship between the spectral signals and biomass (Chapter 2 and 10). While it is possible to acquire satellite imagery at very high resolution, it is however important to weight the cost of image acquisition and analysis with the potential monetary compensation through REDD+. The estimation of the impact of logging on the GHG can be done using the method outlined in Chapter 10. It is easier to estimate the impact of logging activities based on the

extracted volume. However, the countries would be responsible to measuring with accuracy the extracted legal and illegal volume from the forest. When considering the other types of forest degradation, they are poorly recognized in the field, very little literature and estimates exist which make the use of remote sensing illusive because it cannot be connected with ground data measurements (Chapter 2 and 11).

When considering the potential options to reduce emissions and sequester carbon, the Chapter 11 uses the MODIS satellite images and the data of carbon stocks reported in Chapter 9 and shows strong potential for carbon sequestration through forest restoration activities. Although this term is not used and identified in the climate convention, forest restoration, or the conversion of a degraded forest to secondary dense forest, would have the greatest potential to sequester carbon while reducing potential GHG emissions in Ghana. The potential for forest conservation is limited because the majority of forests outside reserves have already been converted to agricultural land. The potential for afforestation and reforestation is limited by the land availability and the tree tenure issues (Chapter 11 and 12). Under the climate convention, REDD+, which has covered only the reduction of emissions, has considered enhancement of forest carbon stocks allowing the consideration of agroforestry systems. According to Chapter 12 the increase of farmer income by 19% through the intensification of existing agroforestry systems would represent a significant economic benefit. However, the cultural barriers inherited by more than 40 years of destructive practices primarily related to the development of agriculture and forestry policies have to be considered. The issues of governance and innovation adoption by local fringe communities have to be considered with attention. As pointed out by chapter 1 and chapter 12, the use of the forest in a REDD+ objective, if it is not made in an equitable way among forest actors, can lead to the reverse objective and lead to massive forest destruction. Also, the introduction of measures for carbon sequestration or emission reductions must be made in parallel with adapted agriculture and forestry policies.

The various chapters have revealed significant gaps in the estimation of carbon stocks. The establishment of a coordinated effort is needed to enhance and harmonize what is already existing. However, it should develop methods that are adapted to the needs and the means. E.g. tree allometric equations have to be adapted to what is feasible to measure in the field (Chapter 5 and 6). Some methodological shortcuts can be identified. It is possible to develop allometric equations per ecological zones, but they have to consider the various vegetation forms and management types and ecological zone classification has to be adapted to biomass variable. As for example, chapter 5 reveals the difficulty in identifying the default allometric equation using inappropriate ecological zones. The use of allometric equation per plant functional types is also an interesting option (chapter 5), but this alternative is partially limited by the identification of plant functional groups.

Besides, the problems of estimating tree biomass and the passage from the tree estimate to the plot, and then from the forest to the biome, are stained with many errors and dark shortcuts. In the past, no study has attempted to harmonize the different types of inventories we can meet in sub-Saharan Africa. Chapter 8 is a novelty. Certainly, it concerns only a few sites and the representativeness of the models is limited, especially for forest plantations. The methodologies and tools we have used allow improving data comparison but still remain incomplete. Indeed, ecological zones, forest types and management

types are far more diverse than the few examples that were studied in Chapter 8. This requires a wider range of experiments to establish harmonization tools across the continent.

Finally, the potential involvement of sub-Saharan countries in the climate regime, and mostly the development of forestry projects, is conditioned by its ability to establish measures and systems for estimating C stocks. The measurement of carbon stocks must meet the criteria established by the Convention. This is the basis of the contracts countries are making together. While the carbocentrism has allowed the emergence of a new international regime and probably a long-sought plan drills, it remains that the quantification of carbon and statistical tools available limits the consideration of the many activities in developing countries and more specifically in sub-Saharan Africa. Agricultural activity is one of the key driver of deforestation and forest degradation in sub-Saharan Africa. The issue of considering the potential of agricultural activities in developing countries to the C cycle and the GHG mitigation target will have to be seriously addressed in the future.

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List of acronyms

AGB	Aboveground biomass
AGC	Aboveground carbon stocks
AIC	Akaike Information Criterion
ANOVA	Analysis of variance
BCF	Biomass Conversion Factor
BCEF	Biomass Conversion and expansion factor
BD	Bulk density
BEF	Biomass expansion factor
BGB	Belowground biomass
Ca	Calcium
CD	Crown diameter
CDM	Clean Development Mechanism
CEF	Carbon emission factor
CO ₂	Carbon dioxide
CO ₂	Carbon
CO ₂ e	Carbon dioxide equivalent
COMIFAC	Commission des Forêts d'Afrique Centrale
DBH	Diameter at Breast Height
DNA	Designated National Authorities
ECEC	Cation exchange capacity
ETM+	Enhanced Thematic Mapper Plus
FAO	The Food and Agriculture Organization of the United Nations
FCPF	Forestry Carbon Partnership Facility
FLEGT	Forest Law, Enforcement and Trade
GPG	Good Practice Guidance
GPG-LULUCF	Good Practice Guidance for Land Use, Land-Use Change and Forestry
GS	Guild status
GTOS	Global Terrestrial Observation System
H	Height
Ha	Hectare
HWSD	Harmonized World Soil Database
IC	Confidence interval
IPCC	Intergovernmental Panel on Climate Change
ISRIC	World Soil Information
ITTO	International Timber Trade Organization
IUCN	World Conservation Union
kg	kilogram
MCC	Millennium Challenge Corporation
MODIS	Moderate Resolution Imaging Spectroradiometer
N	Nitrogen
Na	Potassium
NAT	Natural forest block
NPLD	Non Pioneer Light Demander
PgC	Pentagram of carbon
P	Pioneer

pH	Potential for hydrogen ion concentration
ppm	Part per million
REDD+	Reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries
RES1	Method consisting in assuming that degraded forest The first method considered that the mosaic of vegetation/cropland corresponded to degraded forest. It
RES2	The second method considered that degraded forest corresponded to the pixels that moved from natural vegetation to cropland
RMSE	Root Mean Square Error
SB	Shade Bearer
SC1	First scenario: expansion of shaded cocoa agroforests
SC2	Second scenario: expansion of unshaded cocoa agroforests
SC3	Third scenario: intensification of existing cocoa agroforests
SC4	Fourth scenario: forest conservation
SD	Standard deviation
SE	Standard error
SH	Shannon index
SL	Selective logging block
SO1	Social status expressed as the ration between CD to H
SO2	Social status expressed asd the ration between H to DBH\
SOC	Soil Organic Carbon
TEB	Total Exchange Basis
TgC	Teragram of carbon
TM	Thematic Mapper
TSS	Tree Shelterwood system
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework on Cliamte Change
VCF	Volume Conversion Factor
WD	Wood density

List of figures

Figure 1: state of progress	29
Figure 2: study sites per chapter	30
Figure 3 : The carbon cycle	4
Figure 4 : Forest carbon stock per region	12
Figure 5: Schematic representation of the importance of quantifying forest carbon in the climate arena. The red dot represents the measurement of carbon.	14
Figure 6: Conceptual framework	17
Figure 7: The carbon pools.....	19
Figure 8: Integrated approach to estimate soil and biomass carbon at national, regional and continental scales.....	20
Figure 9: Sources and sinks of carbon from forest area and cover change in tropical humid ecological zone of sub-Saharan Africa.	27
Figure 10: Assessing C stocks of sub-Saharan Africa	29
Figure 11: Biomass variability in a wet-evergreen forest reserve in Ghana	36
Figure 12: Soil carbon stock distribution in Africa for the 0–30 cm soil layer using the HWSD database..	47
Figure 13: Global and African soil carbon stocks estimates based on the digital soil Map of the World and the Harmonized World Soil Database.....	48
Figure 14: Diameter distribution in four forest types in Ghana and Cameroon.....	60
Figure 15: Hypothetical forest change scenarios.....	61
Figure 16: Impact of allometric equations on carbon change assessment in dry ecological zone.....	66
Figure 17: Schematic of partition procedure for mass determination of the trees	77
Figure 18: Influence of radial distance from the earth and volume on wood density	83
Figure 19: branch biomass allometric equations.....	84
Figure 20: Distribution of biomass in the different tree components.....	85
Figure 21: Comparison with allometric equations found in the literature.....	87

Figure 22: Variation of wood densities	90
Figure 23: Relation between tree circumference and tree height in various ecological zones of Africa	93
Figure 24. Representation of the different tree components referred to in this study.....	99
Figure 25. Geographic distribution of available volume and biomass allometric equations according to the Global ecological zoning for the global forest resources assessment (FAO, 2001a).	100
Figure 26. Quality control assessment.....	102
Figure 27. Distribution of allometric equations in the FAO ecological zones.....	103
Figure 28. Evolution of the number of references during the period 1950-2009	111
Figure 29: Variations in wood density (kg dm ⁻³) in tropical sub-Saharan Africa by plant functional types using classification made in Ghana by Hawthorne (1995).....	112
Figure 30. Tree biomass (kg by tree) equations in different ecological zones of sub-Saharan Africa.....	113
Figure 31: Volume of tree species in various forest types.....	115
Figure 32: Stand biomass in various locations of Senegal at different time periods.....	117
Figure 33: Tree volume and biomass of four tree species in various geographic locations.	119
Figure 34: Aboveground biomass estimation for individual tree stem using tier method for tree species.	121
Figure 35. Aboveground tree biomass estimation for individual tree stem using tier methods for three ecological zones.....	122
Figure 36: Forest site's location	135
Figure 37: Sampling design for the normal plots.....	138
Figure 38: Spatial distribution of Shannon index in one hectare plots in three forest types and three landscape types in Ghana	142
Figure 39: Tree distribution into girth classes of 30cm	143
Figure 40: Distribution of plant functional type with diameter classes.....	145
Figure 41: Soil organic carbon and base saturation variations with soil depth and topography	146
Figure 42: Distribution of carbon stocks in the different ecosystem compartments.....	148

Figure 43: Spatial distribution of aboveground biomass in one hectare plots in three forest types and three landscape types in Ghana	149
Figure 44: State of forest reconstitution of Bobiri, Boin River and Boi Tano forests	153
Figure 45: Influence of variability and plot size on the estimation of biomass	154
Figure 46: Distribution of diameter classes in various forests, agricultural land and plantations.	164
Figure 47: Tree stems distribution models	165
Figure 48: Volume distribution in various forests, agricultural land and plantations.	168
Figure 49: Modelled tree stem distribution in forest ecosystems for different precipitation	171
Figure 50: Influence of landscape, age, soil type and management on tree stem distribution	172
Figure 51: Geographical distribution of the field measurements.....	180
Figure 52: The procedure used to harmonize and integrate the data into modelling tools	182
Figure 53: Distribution of aboveground in different compartments among land cover classes.....	185
Figure 54: Relation between the number of simulations and the standard error and the average biomass	186
Figure 55: Variability of biomass in agroforestry systems of Wetsern Kenya: adapted from Henry, et al. (2009).	189
Figure 56: Variation of biomass in the sudanian savanna in northern Cameroon: adapted from Diop, Dufour et al. (2004).	191
Figure 57: Variability of aboveground biomass and belowground carbon stocks in Ghana: adapted from chapter 7.	193
Figure 58: Variability of biomass in Zambia: adapted from the Integrated land use assessment FAO (2006d). Error bars represent the confidence interval.	194
Figure 59: Variation of biomass in Cameroon: adapted from the national forest monitoring and assessment programme of the FAO (2004a). Error bars represent the confidence interval.	195
Figure 60: Variation of biomass in Mozambique: adapted from the national forest inventory (Marzoli, 2007).	196
Figure 61: Influence of forest definition on aboveground carbon stock estimates	197
Figure 62: Map of the study area showing the location of the forest plots and the logging impacts.....	206
Figure 63: Relation between tree DBH, biomass, log volume and residues.....	208

Figure 64: Analysis of Landsat images spectral response to biomass using different spectral signals combinations.	211
Figure 65: Distribution of aboveground biomass and tree density in the different ecosystem compartments.....	212
Figure 66: Relation between trees DBH, extracted volume and impacted area.	213
Figure 67: Impact of selective logging on emissions and sequestration of CO ₂ within and outside forest.	217
Figure 68: Analysis of the relation between the NDVI derived from Landsat ETM + imageries and the aboveground biomass for different plot sizes.	219
Figure 69: Influence of harvested tree number on damaged ground area in different sites of West Africa. The data from Nigeria and Draw river were reported by Agyeman <i>et al</i> (1999a).....	221
Figure 70: The different steps used to map above and belowground carbon stocks	229
Figure 71: C sequestration and emission reduction project scenarios.....	231
Figure 72 C sequestration and emission reduction potentials under three project scenarios	234
Figure 73: Distribution of aboveground carbon in the ecoregions of Ghana	235
Figure 74: Annual rates of deforestation of Ghana	245
Figure 75: Aboveground carbon stocks in cocoa agroforest in sub-Saharan Africa	248
Figure 76: Potential land for extension of cocoa agroforestry systems in Ghana	249

List of Tables

Table 1: Mitigation activities potentially included under REDD+	32
Table 2: Main sensors of different spatial resolution for monitoring forest cover change.....	33
Table 3: The organic soil databass and digital data used to make soil carbon maps.	45
Table 4: Inventory of soil carbon pools for the different countries of Africa using the HWSD database. .	49
Table 5: Soil C stocks and mean C content for African ecoregions using the HWSD database.	51
Table 6: Continental carbon stock estimate based on different digital map and soil properties databases	51
Table 7: Soil properties variability in group of soils adapted from Batjes (1996).....	53
Table 8: Continental carbon stock estimates based on various soil properties databases and the DMSW spatial database	54
Table 9: Comparison of SOC estimates at national scale.....	55
Table 10: selected tree aboveground biomass allometric equations:.....	62
Table 11: variation of carbon stock change using different allometric equations (Mg C ha^{-1}).....	64
Table 12: Characteristics of the selected trees	74
Table 13: Selected models for estimating tree biomass.....	79
Table 14: Selected models for estimating biomass of tree components	80
Table 15: Wood densities of the different tree species included into the analysis of the wood density. .	82
Table 16: Comparison with other tree biomass allometric equations found in the literature	86
Table 17 - : Selected models for the analysis of the wood density	91
Table 18. Quality of data and allometric equation's gap	105
Table 19. Number of volume allometric equations per tree species and countries in sub-Saharan Africa.	107
Table 20. Number of biomass allometric equations per tree species and countries of sub-Saharan Africa.	108

Table 21. Number of volume and biomass allometric equations per tree compartments and countries of sub-Saharan Africa	109
Table 22: Characteristics of three studied tropical forests.....	137
Table 23: Floristic composition (most present families and species) SH corresponds to the Shannon index.....	141
Table 24: Soil chemical properties ($\pm$ IC)	147
Table 25: Distribution of ecosystem carbon stocks ($\text{Mg C ha}^{-1} \pm \text{IC}$)	150
Table 26: Characteristic of the study sites.....	162
Table 27: Tree stem distribution models.....	166
Table 28: Available land classifications for Africa	177
Table 29: Land cover classification (Globcover).....	181
Table 30: Belowground and aboveground carbon stocks in Africa using five different biome classifications	183
Table 31: Felled tree in compartment 4 in Boi Tano Forest reserve	215
Table 32: Impact of logging damages on ground area, biomass and carbon stocks	216
Table 33: Estimation of impacted biomass and carbon in Ghana and the Congo Basin	218
Table 34: Landsat spectral response for different field plot sizes - models results for different field plot sizes.....	219
Table 35: C sequestration potentials for Ghana (Chapter 3).....	244
Table 36: Carbon sequestration and economic profitability for four scenarios in the cocoa belt of Ghana	251

List of Appendixes

Appendix I: Assessing emission reductions at continental scale

Estimation of the C emissions from LULUCF, total emissions, removals and the net emissions is based on the UNFCCC national communication to the UNFCCC. The data for Sao Tome and Principe, Uganda, Sierra Leone, Guinea-Bissau and Comoros were not taken into account because the data were considered as none reliable. Assessment of forest area is based on the Globcover product with a definition of forest based on a tree cover above 15%. Assessment of the forest C stock is based on the data from IPCC (2003) except for tropical desert and subtropical humid forests. In this case the data from the CDIAC (Gibbs, 2006b) were used. Assessment of soil organic carbon was achieved using the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISSCAS/JRC, 2008). The rate of deforestation was obtained from the 2005 FRA report (FAO, 2006c). The rate of forest degradation and the extent of selective logging was obtained from Nasi et al. (2006).

Appendix II: The various wood density models used in the analysis

Where int is the intercept, PFT is the plant functional type, SP is the tree species, Hr is the relative height, dim is the tree dimension (m³), dist is the pith to bark distance (cm) and location is stump, trunk or branch.

Appendix III: Wood density data found in the literature

AppendixIV: Allometric equations predicting individual tree and stand volume in sub-Saharan Africa.

The calibration range of the variable X is presented in bracket. When no calibration range was mentioned in the article, it was calculated. * and ** means that one and two thresholds were calculated from this study respectively. The maximum DBH was considered to be 200 cm. The calibration range of the variable W, Z, U and V were not mentioned in this table. The value of the column “Interval of possibility” corresponds to the percentage of value comprised within the interval of possibility. Three quality levels were identified: quality 1 (the interval of possibility is lower than 90%), quality 2 (the equation is comprised within the interval of possibility without indication about the sampling and correlation) and quality 3 (n, r² and the calibration range were mentioned and the interval of possibility was higher than 90%). Acronyms used: As: stem cross-sectional area at DBH, BA: basal area, BD: basal diameter, C: circumference, C (10,180): circumference at 10 cm and 180 cm, CA: crown area, Cb: basal circumference, CD: crown diameter, CH: crown height, CV: canopy volume, D20 – 30: diameter at 20 and 30 cm height, DBH: diameter at breast height, H: height, Log: natural logarithm, Log10: logarithm in basis 10, SQRT: square root, wd: wood density and yr: age. adj means adjusted squared correlation coefficient.

Appendix V: Allometric equations predicting individual tree and stand biomass in sub-Saharan Africa.

When no specific location is mentioned the name of the country is considered except in the case of general allometric equations (E.g. Chave, 2005 and Brown, 1997). The calibration range of the variable X is presented in bracket. When no calibration range was mentioned in

the article, it was calculated. * and ** means that one and two thresholds were calculated from this study respectively. The maximum DBH was considered to be 200 cm. The calibration range of the variable W, Z, U and V were not mentioned in this table. The value of the column “Interval of possibility” corresponds to the percentage of value comprised within the interval of possibility. Three quality levels were identified: quality 1 (the interval of possibility is lower than 90%), quality 2 (the equation is comprised within the interval of possibility without indication about the sampling and correlation) and quality 3 (n, r² and the calibration range were mentioned and the interval of possibility was higher than 90%).

Appendix VI: Volume conversion functions

Appendix VII: Biomass conversion functions

Appendix VIII: The Globcover legend

Appendix IX: Calculation of AGC using Globcover legend, MODIS tree cover and field data

The carbon stock value is calculated for each pixel based on the MODIS tree cover and the ratio between carbon stocks and the mean tree cover found for each land cover types in each ecological zone. The average carbon stocks for each land cover types was calculated based on the average carbon stock in each master classes weighted by the average tree cover reported in the GLOBCOVER legend. The master classes were: MAS1: broadleaved evergreen or semi-deciduous forest, MAS2: broadleaved deciduous forest, MAS3: needle-leaved evergreen and deciduous forest,

MAS4: mixed broadleaved and needleleaved forest, MAS5: broadleaved forest or shrubland permanently flooded, MAS6: broadleaved or needle-leaved, evergreen or deciduous shrubland, MAS7: grassland, MAS8: Crop irrigated, MAS9: Crop rainfed, MAS10: Urban-artificial, MAS11: Undefined forest, MAS12: Undefined forest-shrub, MAS13: Undefined herbaceous/shrub, MAS14: Undefined natural vegetation, MAS15: Bare, MAS16: Water. AVTC is the average tree cover, and AvCC is the average crown cover in the Globcover product.

Appendix X: Distribution of land cover classes in sub-Saharan Africa

Appendix XI: Aboveground carbon stocks in vegetation types of Africa

Appendix XII: Influence of tree cover on forest definition and aboveground carbon stocks

Appendix XIII: biophysical and socio-economic parameters for analysing carbon sequestration potentials through cocoa agroforestry systems in Ghana

Appendix I: Assessing emission reductions at continental scale

Country	UNFCCC national				Forest						Deforestation				Degradation		Selective logging	
	Emissions from LULUCF (Tg yr-1)	Total emissions (Tg yr-1)	Removals (Tg yr-1)	Net emission (Tg yr-1)	Definitive UNFCCC C	Area GLOBEC OVER (1000)	SOC (Tg)	ABC IPCC (Tg)			Rate FRA 2005	C loss (Tg yr-1)			Rate (Nasi, 2006)	C loss (Tg yr ⁻¹)	Area (1000 ha)	C loss (Tg yr ⁻¹)
Angola	-	-	-	-	-	68449	2194	5546	(1400	- 9693)	-0.2	-11.09	-(2.80	-19.39)				
Botswana	2.54	3.73	11.56	7.83	-	2540	42	74	(30	- 119)	-1	-0.74	-(0.30	-1.19)				
Comoros	-	-	-	-	-	89	8	10	(1	- 19)	-7.4	-0.75	-(0.10	-1.40)				
Kenya	-	-	-	-	30 - 0.1 -	14580	553	509	(108	- 910)	-0.3	-1.53	-(0.33	-2.73)				
Lesotho	1.47	1.72	0.83	-0.89	30 - 0.1 -	874	42	9	(6	- 12)	2.7	0.24	(0.17	0.32)				
Madagascar	123.80	124.43	183.26	58.83	30 - 1 - 5	22390	1058	1335	(266	- 2404)	-0.3	-4.01	-(0.80	-7.21)				
Malawi	5.96	7.17	0.28	-6.89	30 - 0.1 -	3735	178	230	(66	- 394)	-0.9	-2.07	-(0.59	-3.55)				
Mozambique	8.38	11.70	0.36	-11.34	-	45921	1604	2715	(865	- 4566)	-0.3	-8.15	-(2.60	-13.70)				
Namibia	1.37	1.91	1.74	-0.17	-	2171	38	67	(30	- 104)	-0.9	-0.60	-(0.27	-0.93)				
South Africa	0.35	0.26	0.00	-0.26	30 - 0.05 -	25414	631	648	(331	- 966)	0	0.00	(0.00	0.00)				
Swaziland	1.17	1.58	1.68	0.10	30 - 0.1 -	1009	55	24	(13	- 36)	0.9	0.22	(0.12	0.32)				
Uganda	-	-	-	-	30 - 1 - 5 -	4528	174	339	(80	- 598)	-2.2	-7.46	-(1.77	-13.15)				
United Republic of Zambia	24.74	28.75	1.02	-27.73	30 - 0.1 -	40817	2063	2206	(652	- 3760)	-1.1	-24.27	-(7.17	-41.36)				
Zimbabwe	-	-	-	-	-	36938	2577	2423	(590	- 4256)	-1	-24.72	-(6.88	-42.56)				
Zimbabwe	-	-	-	-	-	7377	190	197	(118	- 277)	-1.7	-3.37	-(2.03	-4.71)				
Total Eastern	170	181	201	19	4	276831	11408	16335	(4557	- 28113)	-0.7	-88	-	-151.24)				
Burkina Faso	3.11	3.46	1.97	-1.49	-	2270	70	98	(40	- 155)	-0.3	-0.29	-(0.12	-0.46)				
Chad	7.95	8.29	18.20	9.90	-	12057	403	447	(215	- 679)	-0.7	-3.13	-(1.51	-4.75)				
Djibouti	0.57	0.66	0.67	0.01	-	18	0.27	0.41	(0	- 1)	0	0.00	(0.00	0.00)				
Eritrea	1.20	2.42	0.29	-2.12	-	1255	33	27	(9	- 45)	-0.3	-0.08	-(0.03	-0.13)				
Ethiopia	15.73	18.45	7.53	-10.92	20 - 0.05 -	26939	795	687	(187	- 1187)	-1.1	-7.56	-(2.06	-13.06)				
Mali	10.25	10.56	10.44	-0.12	30 - 1 - 2	5468	188	220	(81	- 360)	-0.8	-1.76	-(0.65	-2.88)				
Niger	2.17	2.45	0.00	-2.45	30 - 4 - 0 -	1618	33	59	(10	- 109)	-1	-0.59	-(0.10	-1.09)				
Somalia	-	-	-	-	30 - 0.1 -	12937	223	457	(68	- 846)	-1	-4.57	-(0.68	-8.46)				
Sudan	22.66	25.30	3.59	-21.71	-	45429	1553	2152	(725	- 3579)	-0.8	-17.18	-(5.73	-28.63)				
Total Northern	64	72	43	-29	4	107990	3297	4148	(1337	- 6960)	-0.7	-35.17	-	-59.47)				

Country	UNFCCC national				Forest						Deforestation				Degradation		Selective logging	
	Emission s from LULUCF	Total emissio ns (Tg)	Remov als (Tg yr-1)	Net emission (Tg yr-1)	Definiti on UNFCC	Area GLOBC OVER	SOC (Tg)	ABC IPCC (Tg)			Rate FRA 2005	C loss (Tg yr-1)			Rate (Nasi, 2006)	C loss (Tg yr ⁻¹)	Area (1000 ha)	C loss (Tg yr ⁻¹)
Benin	-	-	-	-	-	3564	123	204	(53	- 355)	-2.5	-5.11	-(1.32	-8.89)				
Burundi	0.33	0.60	0.82	0.22	-	1311	81	15	(8	- 23)	-5.2	-0.79	-(0.40	-1.18)				
Cameroon	12.67	14.24	1.70	-12.54	-	31127	1804	2996	(297	- 5696)	-1	-29.96	-(2.97	-56.96)	-0.02	-0.61	4348	1.11
Central African Congo	-	-	-	-	-	45627	1660	2965	(603	- 5326)	-0.1	-2.96	-(0.60	-5.33)	-0.02	-0.89	2994	0.76
Côte d'Ivoire	3.87	4.17	22.76	18.59	-	22478	2879	2869	(185	- 5553)	-0.1	-2.87	-(0.19	-5.55)	-0.01	-0.22	7115	1.81
D.R. of the Equatorial	21.89	28.48	26.09	-2.40	-	15375	556	1192	(177	- 2207)	0.1	1.19	(0.18	2.21)		0.00		
Gabon	127.74	130.78	163.09	32.32	30 - 0.5 - 2 2 2	168169	8402	19211	(1854	- 36569)	-0.2	-38.42	-(3.71	-73.14)	-0.15	-24.72	9680	2.47
Gambia	-	-	-	-	-	2298	150	294	(15	- 574)	-0.9	-2.65	-(0.14	-5.16)	0.52	1.17	55	0.01
Ghana	0.68	2.51	137.36	134.84	-	21185	1086	2757	(143	- 5372)	n.s.	n.s.	ns		-0.09	-1.87	6368	1.62
Guinea	8.66	9.74	22.02	12.28	-	192	8	19	(5	- 32)	0.4	0.07	(0.02	0.13)				
Guinea-Bissau	3.36	5.55	6.99	1.44	15 -0.1 -2 2 2	9464	340	708	(141	- 1275)	-2	-14.16	-(2.83	-25.50)				
Liberia	23.90	27.15	27.71	0.56	-	12308	559	874	(169	- 1579)	-0.5	-4.37	-(0.85	-7.89)				
Nigeria	-	-	-	-	-	1753	76	167	(30	- 305)	-0.5	-0.84	-(0.15	-1.52)				
Rwanda	47.21	90.18	10.03	-80.15	-	5702	315	745	(39	- 1451)	-1.8	-13.41	-(0.71	-26.12)				
Sao Tome and Principe	0.38	2.64	2.05	-0.59	-	21048	822	1623	(244	- 3003)	-3.3	-53.57	-(8.04	-99.10)				
Senegal	0.38	2.64	2.05	-0.59	-	888	62	4	(5	- 2)	6.9	0.24	(0.35	0.14)				
Sierra Leone	-	-	-	-	-	73	5	10	(1	- 19)	0	0.00	(0.00	0.00)				
Togo	6.40	8.25	7.05	-1.21	-	3291	115	135	(46	- 225)	-0.5	-0.68	-(0.23	-1.12)				
	-	-	-	-	-	3047	150	299	(33	- 565)	-0.7	-2.09	-(0.23	-3.95)				
Total Congo	6.52	7.01	0.00	-7.01	-	1805	63	108	(27	- 188)	-4.5	-4.85	-(1.22	-8.48)				
Total Western Africa	144.96	151.69	324.91	173.22	1	290885	15981	31093	(3096	- 59089)	-0.46	-77	-(7.60	-146.14)	0	-27	30560	7.79
	264	331	428	96	2	370706	19257	37196	(4074	- 70318)	-0.5	-175	-	-327.44)				
	497	584	671	87	10	755527	33962	57679	(9967	- 105391)	-0.62	-299	-(22.22	-538.15)				

Appendix II: The various wood density models used in the analysis

Model	Fixed effect	Random effects	k	AIC	Δ AIC
1	PFT SP(PFT) dist dim PFT*dim	int dist location dist*location	17	784	0
2	PFT SP(PFT) dist dim PFT*dist PFT*dim	int dist location dist*location	19	787	-3
3	PFT SP(PFT) dim PFT*dim	int dist location dist*location	16	787	-3
4	PFT SP(PFT) dist dim PFT*dim dim*dist	int dist location dist*location	18	787	-3
5	PFT SP(PFT) dim PFT*dim	int dist location dist*location	16	787	-3
6	PFT SP(PFT) SOC1 dist SOC1*PFT	int dist location dist*location	17	790	-6
7	PFT SP(PFT) dist dim PFT*dist PFT*dim	int dist location dist*location	20	790	-6
8	PFT SP(PFT) SOC2 dist	int dist location dist*location	15	792	-9
9	PFT SP(PFT) SOC2 dist SOC2*PFT	int dist location dist*location	17	793	-9
10	PFT SP(PFT) SOC1 SOC2 SOC1*SOC2	int dist location dist*location	16	794	-10
11	PFT SP(PFT) SOC1 dist	int dist location dist*location	15	795	-11
12	PFT SP(PFT) SOC1 dist	int dist location dist*location	15	795	-11
13	PFT SP(PFT) dist	int dist location dist*location	14	796	-12
14	PFT SP(PFT) SOC2 dist SOC2*dist	int dist location dist*location	16	796	-12
15	PFT SP(PFT) SOC2	int dist location dist*location	14	796	-12
16	PFT SP(PFT) dist	int dist location dist*location	14	796	-12
17	PFT SP(PFT) SOC2 dist	int dist location dist*location	15	796	-12
18	PFT SP(PFT) dist dim	int dist location dist*location	15	796	-12
19	PFT SP(PFT) dist loc dist*loc PFT*LOC	int dist location dist*location	26	797	-13
20	PFT SP(PFT) SOC1	int dist location dist*location	14	798	-14
21	PFT SP(PFT) SOC1 SOC2	int dist location dist*location	15	798	-15
22	PFT SP(PFT) dist PFT*dist	int dist location dist*location	16	798	-15
23	PFT SP(PFT) SOC1	int dist location dist*location	14	799	-15
24	PFT SP(PFT) SOC1 dist SOC1*dist	int dist location dist*location	16	799	-15
25	PFT SP(PFT) dist dist*PFT	int dist location dist*location	16	799	-15
26	PFT SP(PFT) dist Hr	int dist location dist*location	15	799	-15
27	PFT SP(PFT) SOC1 dist SOC1*dist	int dist location dist*location	16	799	-15
28	PFT SP(PFT) dim	int dist location dist*location	14	799	-16
29	PFT SP(PFT) LOC LOC*PFT	int dist location dist*location	23	799	-16
30	PFT SP(PFT) SOC2 dist SOC2*dist	int dist location dist*location	16	800	-16
31	PFT SP(PFT)	int dist location dist*location	13	800	-16
32	PFT SP(PFT) dist loc dist*loc	int dist location dist*location	18	800	-16
33	PFT SP(PFT) SOC2	int dist location dist*location	14	800	-16
34	PFT SP(PFT) dist Hr	int dist location dist*location	15	801	-17
35	PFT SP(PFT) Dist dim PFT*Dist Dist*dim	int dist location dist*location	18	802	-18
36	PFT SP(PFT) LOC	int dist location dist*location	15	802	-18
37	PFT SP(PFT) dist Hr dist*HR	int dist location dist*location	17	803	-19
38	PFT SP(PFT) dist Hr PFT*Hr	int dist location dist*location	17	803	-19
39	PFT SP(PFT) Hr	int dist location dist*location	14	803	-20
40	PFT SP(PFT) dist Hr dist*HR	int dist location dist*location	17	804	-21
41	PFT SP(PFT) dist Hr PFT*Hr	int dist location dist*location	17	805	-21
42	PFT SP(PFT) Dist dim PFT*dim	int dist location dist*location	17	808	-24
43	PFT SP(PFT) Hr Hr*PFT	int dist location dist*location	16	808	-24
44	PFT SP(PFT) Hr Hr*SP(PFT)	int dist location dist*location	24	808	-24
45	PFT SP(PFT) Dist PFT*dist	int dist location dist*location	16	815	-31
46	PFT SP(PFT)dist dim PFT*dist*dim	int dist location dist*location	19	820	-36
47	PFT LOC PFT*LOC	int dist location dist*location	13	846	-62

Model	Fixed effect	Random effects	k	AIC	Δ AIC
48	PFT SOC1 SOC2 SOC1*SOC2	int dist location dist*location	6	849	-65
49	PFT SOC1 dist SOC1*PFT	int dist location dist*location	7	853	-70
50	PFT Dist	int dist location dist*location	4	855	-71
51	PFT SOC1 dist	int dist location dist*location	5	855	-72
52	PFT SOC1 dist	int dist location dist*location	5	855	-72
53	PFT dim PFT*dim	int dist location dist*location	6	856	-72
54	PFT SOC2 dist	int dist location dist*location	5	856	-72
55	PFT SOC2 dist	int dist location dist*location	5	856	-72
56	PFT SOC2 dist SOC2*PFT	int dist location dist*location	7	856	-72
57	PFT Dist dim	int dist location dist*location	5	856	-72
58	PFT Dist LOC	int dist location dist*location	6	856	-72
59	PFT	int dist location dist*location	3	857	-73
60	PFT SOC1	int dist location dist*location	4	857	-73
61	PFT dist LOC dist*LOC	int dist location dist*location	8	857	-73
62	PFT SOC1	int dist location dist*location	4	858	-74
63	PFT Dist PFT*dist	int dist location dist*location	6	858	-74
64	PFT dist dim dist*dim	int dist location dist*location	6	858	-74
65	PFT SOC1 SOC2	int dist location dist*location	5	858	-74
66	PFT dim	int dist location dist*location	4	858	-74
67	PFT SOC2	int dist location dist*location	4	858	-74
68	PFT SOC2	int dist location dist*location	4	858	-74
69	PFT LOC	int dist location dist*location	4	858	-74
70	PFT Dist Hr	int dist location dist*location	5	858	-75
71	PFT SOC2 dist SOC2*dist	int dist location dist*location	6	859	-75
72	PFT SOC2 dist SOC2*dist	int dist location dist*location	6	859	-75
73	PFT SOC2 dist SOC2*dist	int dist location dist*location	6	859	-75
74	PFT SOC1 dist SOC1*dist	int dist location dist*location	6	859	-75
75	PFT SOC1 dist SOC1*dist	int dist location dist*location	6	860	-76
76	PFT SOC1 dist SOC1*dist	int dist location dist*location	6	860	-76
77	PFT Hr	int dist location dist*location	4	861	-77
78	PFT dist Hr dist*Hr	int dist location dist*location	6	862	-78
79	PFT SP(PFT) dist loc dist*loc	int dist location	18	865	-82
80	PFT SP(PFT) dist	int dist location	14	871	-87
81	PFT SP(PFT) dist dim	int dist location	15	872	-88
82	PFT SP(PFT) dist Hr	int dist location	15	874	-90
83	PFT SP(PFT) dist loc	int dist location	16	874	-90
84	PFT SP(PFT) dist Hr	int dist hr location	15	875	-91
85	PFT SP(PFT) dist dim dist*dim	int dist location	16	875	-91
86	Hr dist dim	int dist location dist*location	4	880	-96
87	PFT dist VOL PFT*VOL	int dist location	7	906	-122
88	PFT dist VOL	int dist location	5	908	-124
89	PFT dist VOL PFT*VOL PFT*DIST	int dist location	9	908	-124
90	PFT dist PFT*DIST	int dist location	6	909	-125
91	PFT dist VOL DIST*VOL	int dist location	6	911	-127
92	PFT dist VOL PFT*VOL PFT*dist dist*VOL	int dist location	10	911	-127
93	PFT SP(PFT) dist Hr	int dist hr	15	1089	-305
94	PFT SP(PFT) dist Hr	int dist	15	1313	-529
95	PFT SP(PFT) dist loc	int dist	16	1316	-532
96	PFT SP(PFT) dist dist*PFT dist*SP(PFT)	int dist	26	1319	-535
97	PFT SP(PFT) dist dist*PFT	int dist	16	1321	-537
98	PFT SP(PFT) dist	int dist	14	1322	-538
99	PFT SP(PFT) dist dim	int dist	15	1322	-538
100	PFT SP(PFT)	int dist	13	1325	-541

Model	Fixed effect	Random effects	k	AIC	Δ AIC
101	PFT SP(PFT) dist dim dist*dim	int dist	16	1326	-542
102	PFT SP(PFT) dist dist*PFT dist*SP(PFT)	int	26	1330	-546
103	PFT SP(PFT) dist	int	14	1332	-548
104	PFT SP(PFT) dist dist*PFT	int	16	1332	-548
105	PFT SP(PFT)	int	13	1349	-565
106	PFT dist	int dist	4	1360	-576
107	PFT	int dist	3	1362	-578
108	PFT dist	int	4	1370	-586
109	PFT	int	3	1385	-601
110	int	int	1	1409	-626
111	PFT SP(PFT) Dist SP(PFT)* dist	int dist location dist*location	24	not working	
112	PFT SP(PFT) dim SP(PFT)*dim	int dist location dist*location	24	not working	
113	PFT SP(PFT) dist Hr	int dist hr	15	not working	
114	PFT SP(PFT) Height Height*SP(PFT)	int dist location dist*location	24	not working	

Appendix III: Wood density data found in the literature.

Botanical name	References	Mean wood
<i>Azelia bella</i>	Sallenave, P. 1955	0.64
<i>Cecropia peltata</i>	Brown, S. 1997	0.32
<i>Ceiba pentandra</i>	A.T.I.B.S. 1975	0.26
	Brown, S. 1997	0.26
	Centre Technique Forestier Tropical, 1989	0.29
	Compendium, F. 2009	0.30
	Flynn Jr., J.H. and Holder, C.D. 2001	0.25
	Gyimah-Buadi, N., 1999	0.24
	Hidayat, S. and Simpson, W.T. 1994	0.35
	Howard, L.A. 1951. 1951	0.26
	Kryn, J.M., and Fobes, E.W. 1959	0.28
	Kukachka, B.F. 1970	0.25
	Reyes, G. Brown, S. Chapman, J. Lugo, A.E 1992	0.26
	Sallenave, P. 1955	0.28
	Sylla, M. L. and N. Picard 2007	0.26
	Tree Talk. 2005	0.28
<i>Garcinia</i>	Brown, S. 1997	0.78
	Howard, L.A. 1951.	0.82
	Reyes, G. Brown, S. Chapman, J. Lugo, A.E 1992	0.78
<i>Guarea cedrata</i>	A.T.I.B.S. 1975	0.56
	Brown, S. 1997	0.56
	Centre Technique Forestier Tropical, 1989	0.77
	Howard, L.A. 1951. 1951	0.48
	ICRAF 2009	0.47
	Kryn, J.M., and Fobes, E.W. 1959	0.51
	Kukachka, B.F. 1970	0.48
	Lavers, G.M. 1983	0.47
	Reyes, G. Brown, S. Chapman, J. Lugo, A.E 1992	0.48
	Sallenave, P. 1955	0.52
	Tree Talk. 2005	0.50
<i>Nauclea</i>	A.T.I.B.S. 1975	0.69
	Brown, S. 1997	0.32
	Compendium, F. 2009	0.68
	Gutierrez Oliva, A. and Plaza Pulgar, F. 1967	0.69
	Howard, L.A. 1951	0.63
	Kryn, J.M., and Fobes, E.W. 1959	0.64
	Kukachka, B.F. 1970	0.67
	Reyes, G. Brown, S. Chapman, J. Lugo, A.E 1992	0.63
	Rijsdijk, J.F. and Laming, P.B. 1994	0.66
	Sallenave, P. 1955	0.68
	Tree Talk. 2005	0.65

Botanical name	References	Mean wood
<i>Nesogordonia</i>	A.T.I.B.S. 1975	0.66
	Brown, S. 1997	0.48
	Howard, L.A. 1951. 1951	0.65
	ICRAF 2009	0.57
	Kryn, J.M., and Fobes, E.W. 1959	0.65
	Reyes, G. Brown, S. Chapman, J. Lugo, A.E 1992	0.65
	Rijsdijk, J.F. and Laming, P.B. 1994	0.63
	Sallenave, P. 1955	0.65
<i>Piptadeniastrum</i>	Tree Talk. 2005	0.65
	A.T.I.B.S. 1975	0.60
	Brown, S. 1997	0.56
	Howard, L.A. 1951. 1951	0.56
	Kryn, J.M., and Fobes, E.W. 1959	0.65
	Lavers, G.M. 1983	0.57
	Reyes, G. Brown, S. Chapman, J. Lugo, A.E 1992	0.56
	Sallenave, P. 1955	0.61
<i>Strombosia</i>	Soerjanegara and Lemmens, R.H.M.J. 1994	0.55
	Tree Talk. 2005	0.59
<i>Heritiera utilis</i>	Brown, S. 1997	0.74
	Reyes, G. Brown, S. Chapman, J. Lugo, A.E 1992	0.80
<i>Tieghemella</i>	Reyes, G. Brown, S. Chapman, J. Lugo, A.E 1992	0.54
<i>Tieghemella</i>	Brown, S. 1997	0.55
	Chudnoff, M. 1973	0.51
	Flynn Jr., J.H. and Holder, C.D. 2001	0.55
	Howard, L.A. 1951.	0.58
	ICRAF 2009	0.52
	Kryn, J.M., and Fobes, E.W. 1959	0.53
	Kukachka, B.F. 1970	0.54
	Lavers, G.M. 1983	0.54
	Reyes, G. Brown, S. Chapman, J. Lugo, A.E 1992	0.55
	Sallenave, P. 1955	0.58

Appendix IV: Allometric equations predicting individual tree and stand volume in sub-Saharan Africa

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
Individual tree in tropical rainforest (classification per tree species)							
1	<i>Acacia auriculiformis</i> in Lama in Benin (1065)	$\log_{10}Y(m3) = 1.37 + (2.65 * \log_{10}(X))$	DBH in m (0.01, 1.69)**	T+GB+TB3+B+S	190, 0.96	100	2 Fonton, N. H., Kakai, R. G., et al. (2002)
2	<i>Afzelia africana</i> in Nigeria	$Y(m3) = 0.0075 + 0.000049 * (X^{(2.091)}) * (Z^{(0.8871)})$	DBH in cm, Hme in m (1, 200)**	T	80	98	2 Akindele, S.O. (2005)
3	<i>Afzelia bipindensis</i> in Gabon	$Y(m3) = 0.6 + 10.8 * (X^{(2)})$	DBH in m (0.01, 0.4)*	T	-	0	1 Bilé Allogho, J. (1999)
4	<i>Afzelia pachyloba</i> in Gabon	$Y(m3) = 9.72 * (X^{(2.46)})$	DBH in m (0.01, 0.4)*	T	-	100	2 Bilé Allogho, J. (1999)
5	<i>Albizzia ferruginea</i> in Nigeria	$Y(m3) = 0.0983 + 0.000002 * (X^{(2.4307)}) * (Z^{(1.5607)})$	DBH in cm, Hme in m (1, 200)**	T	25	95	2 Akindele, S.O. (2005)
6	<i>Albizzia zygia</i> in Nigeria	$Y(m3) = 0.001 + 0.000073 * (X^{(1.9472)}) * (Z^{(0.9638)})$	DBH in cm, Hme in m (1, 200)**	T	35	99	2 Akindele, S.O. (2005)
7	<i>Alstonia boonei</i> in Nigeria	$Y(m3) = -0.1488 + 0.000683 * (X^{(1.636)}) * (Z^{(0.5998)})$	DBH in cm, Hme in m (13, 200)**	T	39	100	2 Akindele, S.O. (2005)
8	<i>Amphimas pterocarpoides</i> in Nigeria	$Y(m3) = -0.1372 + 0.000501 * (X^{(1.5873)}) * (Z^{(0.7744)})$	DBH in cm, Hme in m (13, 200)**	T	23	100	2 Akindele, S.O. (2005)
9	<i>Antiaris africana</i> in Gabon	$Y(m3) = 9.72 * (X^{(2.46)})$	DBH in m (0.01, 0.4)*	T	-	100	2 Bilé Allogho, J. (1999)
10	- in Côte d'Ivoire	$Y(m3) = -0.580 + 10.378 * (X^{(2)})$	DBH in m (0.24, 1.69)**	T	-	100	2 CTFT (1967)
11	- in Bossématié in Côte d'Ivoire (1325)	$Y(m3) = 12.81 * (X^{(2)}) - 3.31 * X + 0.35$	DBH in m (0.13, 1.69)**	T	-	100	2 Pieper, Y., and Laumans, P. (1992)
12	<i>Antiaris toxicaria</i> in Nigeria	$Y(m3) = 0.0434 + 0.000031 * (X^{(1.9463)}) * (Z^{(1.2133)})$	DBH in cm, Hme in m (1, 200)**	T	49	96	2 Akindele, S.O. (2005)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations					
13	Antrocaryon klaineana in Gabon	$Y(m3) = 9.28 * (X^{2.07})$	DBH in m (0.01, 0.4)*	T	-	80	1 Bilé Allogho, J. (1999)
14	- in Nigeria	$Y(m3) = -0.072 + 0.000337 * (X^{(1.4886)}) * (Z^{(0.9625)})$	DBH in cm, Hme in m (11, 200)**	T	7	100	2 Akindele, S.O. (2005)
15	Aucoumea klaineana in Gabon	$Y(m3) = 10 * (X^2)$	DBH in m (0.01, 1.69)**	T	-	95	2 Mapaga, D., Ingueza, D., et al. (2002)
16	- in Fernan-Vaz in Gabon (1953)	$Y(m3) = -0.146424 + 9.16325 * (X^2)$	DBH in m (0.13, 1.69)**	T	-	100	2 CTFT (1979)
17	- in Mvoum in Gabon (2157)	$Y(m3) = -0.1 + 11 * (X^2)$	DBH in m (0.1, 1.69)**	T	-	100	2 Mapaga, D., Ingueza, D., et al. (2002)
18	Autranella congolensis in Gabon	$Y(m3) = 9.72 * (X^{2.46})$	DBH in m (0.01, 0.4)*	T	-	100	2 Bilé Allogho, J. (1999)
19	- in RCA	$Y(m3) = 12.16 * (X^{(1.91)})$	DBH in m (0.01, 1.69)**	T	-	74	1 CTFT (1964)
20	Baillonella toxisperma in Mbalmayo in Cameroon (1628)	$Y(m3) = 0.000139 * (X^{2.362})$	DBH in cm (1, 80)*	T	-	100	2 Mapaga, D., Ingueza, D., et al. (2002)
21	- idem	$Y(m3) = 1.062 + 7.689 * (X^2)$	DBH in m (0.5, 1.2)	T	-	100	2 Mapaga, D., Ingueza, D., et al. (2002)
22	- in Gabon	$Y(m3) = 11.59 * (X^{1.94})$	DBH in m (0.01, 0.7)*	T	-	51	1 Bilé Allogho, J. (1999)
23	Berlinia bracteosa in Gabon	$Y(m3) = 9.72 * (X^{2.46})$	DBH in m (0.01, 0.4)*	T	-	100	2 Bilé Allogho, J. (1999)
24	Berlinia confusa in Gabon	$Y(m3) = 9.28 * (X^{2.07})$	DBH in m (0.01, 0.7)*	T	-	84	1 Bilé Allogho, J. (1999)
25	Blighia sapida in Nigeria	$Y(m3) = 0.0967 + 0.000016 * (X^{(2.2774)}) * (Z^{(1.0182)})$	DBH in cm, Hme in m (1, 200)**	T	20	93	2 Akindele, S.O. (2005)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
26	Bombax buonopozense in Nigeria	$Y(m3) = -0.0339 + 0.000107 * (X^{(2.1219)}) * (Z^{(0.5608)})$	DBH in cm, Hme in m (10, 200)**	T	18	100	2 Akindele, S.O. (2005)
27	Brachystegia eurycoma in Nigeria	$Y(m3) = -0.0666 + 0.000208 * (X^{(1.7482)}) * (Z^{(0.8732)})$	DBH in cm, Hme in m (11, 200)**	T	27	100	2 Akindele, S.O. (2005)
28	Brachystegia kennedyi in Nigeria	$Y(m3) = -0.2308 + 0.001043 * (X^{(1.5817)}) * (Z^{(0.5632)})$	DBH in cm, Hme in m (15, 200)**	T	11	100	2 Akindele, S.O. (2005)
29	Brachystegia nigerica in Nigeria	$Y(m3) = -0.0785 + 0.000154 * (X^{(1.7479)}) * (Z^{(1.019)})$	DBH in cm, Hme in m (11, 200)**	T	21	100	2 Akindele, S.O. (2005)
30	Canarium schweinfurthii in Gabon	$Y(m3) = 9.72 * (X^{2.46})$	DBH in m (0.01, 0.6)*	T	-	100	2 Bilé Allogho, J. (1999)
31	- in Nigeria	$Y(m3) = -0.1538 + 0.000487 * (X^{(1.5191)}) * (Z^{(0.8941)})$	DBH in cm, Hme in m (13, 200)**	T	12	100	2 Akindele, S.O. (2005)
32	Carapa procera in Nigeria	$Y(m3) = -0.0729 + 0.000189 * (X^{(1.9179)}) * (Z^{(0.6436)})$	DBH in cm, Hme in m (12, 200)**	T	30	100	2 Akindele, S.O. (2005)
33	Cedrelopsis grevei in RCA	$Y(m3) = 11.48 * (X^{(1.95)})$	DBH in m (0.01, 1.69)**	T	-	77	1 CTFT (1964)
34	Ceiba pentandra in Gabon	$Y(m3) = 9.72 * (X^{2.46})$	DBH in m (0.01, 0.4)*	T	-	100	2 Bilé Allogho, J. (1999)
35	- in Bossématié in Côte d'Ivoire (1325)	$Y(m3) = 12.5 * (X^2) - 2.9 * X + 0.28$	DBH in m (0.12, 1.69)**	T	-	100	2 Pieper, Y., and Laumans, P. (1992)
36	- in Nigeria	$Y(m3) = 0.0286 + 0.000047 * (X^{(1.9788)}) * (Z^{(1.0475)})$	DBH in cm, Hme in m (1, 200)**	T	31	98	2 Akindele, S.O. (2005)
37	Celtis briei in Gabon	$Y(m3) = 9.72 * (X^{2.46})$	DBH in m (0.01, 0.4)*	T	-	100	2 Bilé Allogho, J. (1999)
38	Celtis zenkeri in Nigeria	$Y(m3) = 0.0224 + 0.000078 * (X^{(1.695)}) * (Z^{(1.2034)})$	DBH in cm, Hme in m (1, 200)**	T	75	96	2 Akindele, S.O. (2005)
39	Chlorophora excelsa in Guinea-Bisseau	$Y(m3) = 9.7 * (X^2) - X + 0.11$	DBH in m (0.05, 1.69)**	T	-	95	2 CTFT (1986)
40	- in Côte d'Ivoire	$Y(m3) = -1.05 + 10.078 * (X^2)$	DBH in m (0.33, 1.69)**	T	-	100	2 CTFT (1967)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations					
			Variables X (min, max), W, Z, U and V				
41	- idem	$Y(m3) = 0.037 + 9.07 \cdot (X^2)$	DBH in m (0.01, 1.69)**	T	-	91	2 CTFT (1967)
42	- in RCA	$Y(m3) = 11.95 \cdot (X^{2.22})$	DBH in m (0.01, 1.69)**	T	-	95	2 CTFT (1964)
43	Chrysobalanus icaco in Nigeria	$Y(m3) = -0.002 + 0.001032 \cdot (X^{1.064}) \cdot (Z^{1.1164})$	DBH in cm, Hme in m (1, 200)**	T	20	95	2 Akindele, S.O. (2005)
44	Chrysophyllum sp in Guinea-Bisseau	$Y(m3) = 13.3 \cdot (X^2) - 3.2 \cdot X + 0.27$	DBH in m (0.12, 1.69)**	T	-	100	2 CTFT (1986)
45	Coelocaryon klaineana in Gabon	$Y(m3) = 11.24 \cdot (X^{1.96})$	DBH in m (0.01, 0.4)*	T	-	40	1 Bilé Allogho, J. (1999)
46	Coelocaryon preussii in Nigeria	$Y(m3) = -0.038 + 0.000264 \cdot (X^{1.3081}) \cdot (Z^{1.2792})$	DBH in cm, Hme in m (8, 200)**	T	36	100	2 Akindele, S.O. (2005)
47	Copaifera mildbraedii in Gabon	$Y(m3) = 9.28 \cdot (X^{2.07})$	DBH in m (0.01, 0.4)*	T	-	68	1 Bilé Allogho, J. (1999)
48	- in Nigeria	$Y(m3) = 0.1092 + 0.000092 \cdot (X^{1.3779}) \cdot (Z^{1.4803})$	DBH in cm, Hme in m (1, 200)**	T	17	93	2 Akindele, S.O. (2005)
49	Cordia millenii in Nigeria	$Y(m3) = 0.0189 + 0.000041 \cdot (X^{2.0049}) \cdot (Z^{1.0888})$	DBH in cm, Hme in m (1, 200)**	T	64	98	2 Akindele, S.O. (2005)
50	Cylicodiscus gabonensis in Nigeria	$Y(m3) = 0.0102 + 0.000166 \cdot (X^{1.79}) \cdot (Z^{0.822})$	DBH in cm, Hme in m (1, 200)**	T	15	96	2 Akindele, S.O. (2005)
51	Dacryodes buettneri in Gabon	$Y(m3) = 9.2 \cdot (X^{1.9})$	DBH in m (0.01, 0.7)*	T	-	79	1 Bilé Allogho, J. (1999)
52	Dacryodes igaganga in Gabon	$Y(m3) = 11.24 \cdot X^{1.96}$	DBH in m (0.01, 0.4)*	T	-	53	1 Bilé Allogho, J. (1999)
53	Dacryodes normandii in Gabon	$Y(m3) = 9.72 \cdot (X^{2.46})$	DBH in m (0.01, 0.4)*	T	-	100	2 Bilé Allogho, J. (1999)
54	- in Fernan-Vaz in Gabon (1953)	$Y(m3) = 0.43094 + 8.2619 \cdot (X^2)$	DBH in m (0.01, 1.69)**	T	-	85	1 CTFT (1979)
55	Daniellia klainei in Gabon	$Y(m3) = 9.72 \cdot (X^{2.46})$	DBH in m (0.01, 0.6)*	T	-	100	2 Bilé Allogho, J. (1999)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
56	Daniellia ogea in Guinea-Bisseau	$Y(m3) = 9.3 \cdot (X^2) + 5.3 \cdot X - 0.6$	DBH in m (0.1, 1.69)**	T	-	87	1 CTFT (1986)
57	- in Nigeria	$Y(m3) = -0.0501 + 0.000389 \cdot (X^{1.3084}) \cdot (Z^{1.184})$	DBH in cm, Hme in m (8, 200)**	T	30	100	2 Akindele, S.O. (2005)
58	Daniellia soyauxii in Gabon	$Y(m3) = 9.72 \cdot (X^{2.46})$	DBH in m (0.01, 0.4)*	T	-	100	2 Bilé Allogho, J. (1999)
59	Desbordesia glaucescens in Gabon	$Y(m3) = 9.72 \cdot (X^{2.46})$	DBH in m (0.01, 0.4)*	T	-	100	2 Bilé Allogho, J. (1999)
60	Detarium macrocarpum in Gabon	$Y(m3) = 9.72 \cdot (X^{2.46})$	DBH in m (0.01, 0.4)*	T	-	100	2 Bilé Allogho, J. (1999)
61	Detarium senegalensis in Nigeria	$Y(m3) = 0.0214 + 0.000054 \cdot (X^{1.9785}) \cdot (Z^{1.1273})$	DBH in cm, Hme in m (1, 200)**	T	74	96	2 Akindele, S.O. (2005)
62	Dialium guineense in Nigeria	$Y(m3) = -0.0553 + 0.00056 \cdot (X^{1.3336}) \cdot (Z^{0.9561})$	DBH in cm, Hme in m (9, 200)**	T	12	100	2 Akindele, S.O. (2005)
63	Didelotia africana in Gabon	$Y(m3) = 9.28 \cdot (X^{2.07})$	DBH in m (0.01, 0.4)*	T	-	63	1 Bilé Allogho, J. (1999)
64	Diospyros mespiliformis in Nigeria	$Y(m3) = -0.0779 + 0.000329 \cdot (X^{1.5498}) \cdot (Z^{0.9614})$	DBH in cm, Hme in m (11, 200)**	T	29	100	2 Akindele, S.O. (2005)
65	Diospyros sanza-minika in Gabon	$Y(m3) = 9.28 \cdot (X^{2.07})$	DBH in m (0.01, 0.4)*	T	-	58	1 Bilé Allogho, J. (1999)
66	Distemonanthus benthamianus in Guinea-Bisseau	$Y(m3) = 9.06 \cdot (X^2) - 0.02$	DBH in m (0.05, 1.69)**	T	-	100	2 CTFT (1986)
67	- in Bossématié in Côte d'Ivoire (1325)	$Y(m3) = 9.06 \cdot (X^2) - 0.02$	DBH in m (0.05, 1.69)**	T	-	100	2 Pieper, Y., and Laumans, P. (1992)
68	- in Nigeria	$Y(m3) = -0.0221 + 0.000107 \cdot (X^{1.9082}) \cdot (Z^{0.8747})$	DBH in cm, Hme in m (8, 200)**	T	26	100	2 Akindele, S.O. (2005)
69	Entandrophragma angolensis in Gabon	$Y(m3) = 10.82 \cdot (X^{1.89})$	DBH in m (0.01, 0.8)*	T	-	78	1 Bilé Allogho, J. (1999)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
70	- in Guinea-Bissau	$Y(m3) = 10.25 * (X^2)$	DBH in m (0.01, 1.69)**	T	-	93	2 CTFT (1986)
71	- in Côte d'Ivoire	$Y(m3) = -1.022 + 12.041 * (X^2)$	DBH in m (0.3, 1.69)**	T	-	100	2 CTFT (1967)
72	- in RCA	$Y(m3) = 11.82 * (X^{(2.13)})$	DBH in m (0.01, 1.69)**	T	-	95	2 CTFT (1964)
73	Entandrophragma candollei in Gabon	$Y(m3) = 10.82 * (X^{1.89})$	DBH in m (0.01, 0.8)*	T	-	70	1 Bilé Allogho, J. (1999)
74	- in Côte d'Ivoire	$Y(m3) = 1.966 + 9.542 * (X^2)$	DBH in m (0.01, 1.69)**	T	-	72	1 CTFT (1967)
75	Entandrophragma congeonse in Gabon	$Y(m3) = 10.82 * (X^{1.89})$	DBH in m (0.01, 0.8)*	T	-	68	1 Bilé Allogho, J. (1999)
76	Entandrophragma cylindricum in Api in Cameroon (1485)	$Y(m3) = 2.003 - 1.094 * X + 11.89 * (X^2)$	DBH in m (0.8, 1.69)*	T	-	100	2 Palla, F., Louppe, D., et al. (2002)
77	in Mbalamayo in Cameroon (1628)	$Y(m3) = 0.00046 * (X^{2.1485})$	DBH in cm (1, 80)*	T	-	93	2 Palla, F., Louppe, D., et al. (2002)
78	in Mayombe in Congo (1424)	$Y(m3) = -0.631 + 13.173 * (X^2)$	DBH in m (0.22, 1.69)**	T	-	100	2 Palla, F., Louppe, D., et al. (2002)
79	in Gabon	$Y(m3) = 10.82 * (X^{1.89})$	DBH in m (0.01, 0.8)*	T	-	70	1 Bilé Allogho, J. (1999)
80	in Côte d'Ivoire	$Y(m3) = 0.590 + 12.180 * (X^2)$	DBH in m (0.01, 1.69)**	T	-	78	1 CTFT (1967)
81	in Mopri in Côte d'Ivoire (1272)	$Y(m3) = 12.3 * (X^2) + 0.04$	DBH in m (0.01, 1.69)**	T	-	88	1 Palla, F., Louppe, D., et al. (2002)
82	in Nigeria	$Y(m3) = 0.0176 + 0.000008 * (X^{(2.2857)}) * (Z^{(1.2502)})$	DBH in cm, Hme in m (1, 200)**	T	8	97	2 Akindele, S.O. (2005)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
83	in RCA	$Y(m3) = 11.44 \cdot (X^{2.27})$	DBH in m (0.01, 1.69)**	T	-	98	2 CTFT (1964)
84	in M'Baiki in RCA (1671)	$Y(m3) = 9.68 \cdot (X^2) + 0.2 \cdot X$	DBH in m (0.01, 1.69)**	T+B	-	91	2 Palla, F., Louppe, D., et al. (2002)
85	Entandrophragma utile in Gabon	$Y(m3) = 10.82 \cdot (X^{1.89})$	DBH in m (0.01, 0.8)*	T	-	73	1 Bilé Allogho, J. (1999)
86	in Guinea-Bisseau	$Y(m3) = 10.01 \cdot (X^2) - 0.06$	DBH in m (0.08, 1.69)**	T	-	100	2 CTFT (1986)
87	in Côte d'Ivoire	$Y(m3) = 0.848 + 10.365 \cdot (X^2)$	DBH in m (0.01, 1.69)**	T	-	79	1 CTFT (1967)
88	in RCA	$Y(m3) = 13.06 \cdot (X^{2.05})$	DBH in m (0.01, 1.69)**	T	-	88	1 CTFT (1964)
89	Eribroma oblongum in Gabon	$Y(m3) = 9.72 \cdot (X^{2.46})$	DBH in m (0.01, 0.4)*	T	-	100	2 Bilé Allogho, J. (1999)
90	in Nigeria	$Y(m3) = 0.0252 + 0.000036 \cdot (X^{1.8522}) \cdot (Z^{1.2872})$	DBH in cm, Hme in m (1, 200)**	T	54	96	2 Akindele, S.O. (2005)
91	Erythrophleum ivorensis in Gabon	$Y(m3) = 9.72 \cdot (X^{2.46})$	DBH in m (0.01, 0.6)*	T	-	100	2 Bilé Allogho, J. (1999)
92	Erythrophleum suaveolens in Nigeria	$Y(m3) = -0.0119 + 0.000428 \cdot (X^{1.3979}) \cdot (Z^{1.0433})$	DBH in cm, Hme in m (4, 200)**	T	34	98	2 Akindele, S.O. (2005)
93	Fagara heitzii in Gabon	$Y(m3) = 9.72 \cdot (X^{2.46})$	DBH in m (0.01, 0.4)*	T	-	100	2 Bilé Allogho, J. (1999)
94	Funtumia africana in Nigeria	$Y(m3) = 0.2594 + 0.000000012 \cdot (X^{2.9144}) \cdot (Z^{2.5063})$	DBH in cm, Hme in m (1, 200)**	T	6	76	1 Akindele, S.O. (2005)
95	Funtumia elastica in Nigeria	$Y(m3) = 0.0076 + 0.000057 \cdot (X^{1.9577}) \cdot (Z^{1.0165})$	DBH in cm, Hme in m (1, 200)**	T	55	98	2 Akindele, S.O. (2005)
96	Gambeya africana in Gabon	$Y(m3) = 9.72 \cdot (X^{2.46})$	DBH in m (0.01, 0.4)*	T	-	100	2 Bilé Allogho, J. (1999)
97	Gambeya lacourtiana in Gabon	$Y(m3) = 9.2 \cdot X^{1.9}$	DBH in m (0.01, 0.4)*	T	-	48	1 Bilé Allogho, J. (1999)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
98	Gambeya perpulchra in Gabon	$Y(m3) = 9.28 * (X^{2.07})$	DBH in m (0.01, 0.4)*	T	-	73	1 Bilé Allogho, J. (1999)
99	Gilbertiodendron dewevrei in Gabon	$Y(m3) = 9.72 * (X^{2.46})$	DBH in m (0.01, 0.4)*	T	-	100	2 Bilé Allogho, J. (1999)
100	Gmelina arborea in Omo in Nigeria (2293)	$Y(m3) = 0.00007141 * (X^{(1.8562)}) * (Z^{(0.98123)})$	DBH in cm, H in m (7, 200)*	T+B	60	100	2 FORMECU (1991)
101	in Onigambari in Nigeria (1316)	$Y(m3) = 0.0206 + 0.00004 * (X^2) * Z$	DBH in cm, Ht in m (1, 200)**	T+B	75, 0.98	97	Akinnifesi, F. and 2 Akinsanmi, F. (1995)
102	idem	$Y(m3) = 0.0394 + 0.0005 * (X^2)$	BD in cm (1.33, 225.33)**	T+B	75, 0.86	94	Akinnifesi, F. and 2 Akinsanmi, F. (1995)
103	idem	$Y(m3) = -0.0345 + 0.0008 * (X^2)$	DBH in cm (7, 200)**	T+B	75, 0.94	100	Akinnifesi, F. and 2 Akinsanmi, F. (1995)
104	Gossweilerodendron balsamiferum in Gabon	$Y(m3) = 11.7 * (X^{2.16})$	DBH in m (0.01, 0.6)*	T	-	88	1 Bilé Allogho, J. (1999)
105	in Nigeria	$Y(m3) = 0.2512 + 0.00000084 * (X^{(2.4695)}) * (Z^{(1.7271)})$	DBH in cm, Hme in m (1, 200)**	T	9	92	2 Akindele, S.O. (2005)
106	Guarea cedrata in Gabon	$Y(m3) = 9.72 * (X^{(2.46)})$	DBH in m (0.01, 0.4)*	T	-	100	2 Bilé Allogho, J. (1999)
107	in Côte d'Ivoire	$Y(m3) = -0.478 + 12.942 * (X^2)$	DBH in m (0.2, 1.69)**	T	-	100	2 CTFT (1967)
108	in Nigeria	$Y(m3) = 0.1184 + 0.000002 * (X^{(2.4381)}) * (Z^{(1.554)})$	DBH in cm, Hme in m (1, 200)**	T	30	94	2 Akindele, S.O. (2005)
109	Guarea thompsonii in Gabon	$Y(m3) = 9.72 * (X^{2.46})$	DBH in m (0.01, 0.4)*	T	-	100	2 Bilé Allogho, J. (1999)
110	in Nigeria	$Y(m3) = -0.6121 + 0.036142 * (X^{(0.7003)}) * (Z^{(0.4544)})$	DBH in cm, Hme in m (14, 200)**	T	12	100	2 Akindele, S.O. (2005)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
111	Guibourtia demeusei in Fernan-Vaz in Gabon (1953)	$Y(m3) = -0.24434 + 8.397 \cdot (X^2)$	DBH in m (0.18, 1.69)**	T	-	100	2 CTFT (1979)
112	Guibourtia ehie in Gabon	$Y(m3) = 9.72 \cdot (X^{2.46})$	DBH in m (0.01, 0.4)*	T	-	100	2 Bilé Allogho, J. (1999)
113	Guibourtia tessmannii in Gabon	$Y(m3) = 1.05 + 10.08 \cdot (X^2)$	DBH in m (0.01, 0.7)*	T	-	30	1 Bilé Allogho, J. (1999)
114	Hallea ciliata in Fernan-Vaz in Gabon (1953)	$Y(m3) = -0.38493 + 9.9592 \cdot (X^2)$	DBH in m (0.2, 1.69)**	T	-	100	2 CTFT (1979)
115	in Guinea-Bisseau	$Y(m3) = 14.03 \cdot (X^2) - 3.6 \cdot X + 0.34$	DBH in m (0.13, 1.69)**	T	-	100	2 CTFT (1986)
116	Hannoa klaineana in Nigeria	$Y(m3) = 0.085 + 0.000014 \cdot (X^{(1.7008)}) \cdot (Z^{(1.7901)})$	DBH in cm, Hme in m (1, 200)**	T	5	96	2 Akindele, S.O. (2005)
117	Heritiera utilis in Yapo in Côte d'Ivoire (1434)	$Y(cm3) = 1.95 \cdot X^{(2.7)}$	C in cm (3.14, 530.93)**	T	114	100	2 Martinot-Lagarde, P. (1961)
118	idem	$Y(cm3) = 42.9 \cdot X^{(2.7)}$	DBH in cm (1, 200)**	T	114	100	2 Martinot-Lagarde, P. (1961)
119	Holoptelea grandis in Nigeria	$Y(m3) = 0.2908 + 0.000002 \cdot (X^{(1.1882)}) \cdot (Z^{(3.0336)})$	DBH in cm, Hme in m (1, 200)**	T	5	91	2 Akindele, S.O. (2005)
120	Hylodendron gabunense in Nigeria	$Y(m3) = 0.0773 + 0.000021 \cdot (X^{(1.9464)}) \cdot (Z^{(1.3307)})$	DBH in cm, Hme in m (1, 200)**	T	47	93	2 Akindele, S.O. (2005)
121	Irvingia gabonensis in Nigeria	$Y(m3) = -0.0467 + 0.000123 \cdot (X^{(1.8552)}) \cdot (Z^{(0.9061)})$	DBH in cm, Hme in m (10, 200)**	T	22	100	2 Akindele, S.O. (2005)
122	Khaya grandifoliola in Nigeria	$Y(m3) = -2.0966 + 0.372804 \cdot (X^{(0.5351)}) \cdot (Z^{(0.0824)})$	DBH in cm, Hme in m (18, 200)**	T	6	100	2 Akindele, S.O. (2005)
123	Khaya ivorensis in Gabon	$Y(m3) = 10.82 \cdot (X^{(1.89)})$	DBH in m (0.01, 0.8)*	T	-	79	1 Bilé Allogho, J. (1999)
124	in Côte d'Ivoire	$Y(m3) = -1.531 + 12.047 \cdot (X^2)$	DBH in m (0.36, 1.69)**	T	-	100	2 CTFT (1967)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
125	in Bossématié in Côte d'Ivoire (1325)	$Y(m3) = 12.91 \cdot (X^2) - 3.07 \cdot X + 0.27$	DBH in m (0.12, 1.69)**	T	-	100	2 Pieper, Y., and Laumans, P. (1992)
126	in Nigeria	$Y(m3) = -0.0391 + 0.000107 \cdot (X^{(1.6115)}) \cdot (Z^{(1.2689)})$	DBH in cm, Hme in m (9, 200)**	T	23	100	2 Akindele, S.O. (2005)
127	Lannea welwitschii in Nigeria	$Y(m3) = 0.0808 + 0.000009 \cdot (X^{(2.2765)}) \cdot (Z^{(1.2)})$	DBH in cm, Hme in m (1, 200)**	T	29	95	2 Akindele, S.O. (2005)
128	Lophira alata in Cameroon	$Y(m3) = 0.00619 \cdot (X^{(1.690)})$	DBH in cm (1, 200)**	T	-	53	1 Palla, F., Louppe, D., et al. (2002)
129	in Gabon	$Y(m3) = 9.72 \cdot (X^{(2.46)})$	DBH in m (0.01, 0.7)*	T	-	100	2 Bilé Allogho, J. (1999)
130	in Côte d'Ivoire	$Y(m3) = 0.437 + 11.210 \cdot (X^2)$	DBH in m (0.01, 1.69)**	T	-	68	1 CTFT (1967)
131	idem	$Y(m3) = 13 \cdot (X^2) - 0.7 \cdot X$	DBH in m (0.06, 1.69)**	T	-	77	1 Palla, F., Louppe, D., et al. (2002)
132	in Nigeria	$Y(m3) = -0.0091 + 0.000127 \cdot (X^{(1.9816)}) \cdot (Z^{(0.7462)})$	DBH in cm, Hme in m (5, 200)**	T	20	100	2 Akindele, S.O. (2005)
133	Lovoa trichilioides in Gabon	$Y(m3) = 0.48 + 10.2 \cdot (X^2)$	DBH in m (0.01, 0.7)*	T	-	63	1 Bilé Allogho, J. (1999)
134	in Côte d'Ivoire	$Y(m3) = 0.252 + 12.942 \cdot (X^2)$	DBH in m (0.01, 1.69)**	T	-	85	1 CTFT (1967)
135	in Nigeria	$Y(m3) = 0.0469 + 0.000023 \cdot (X^{(1.9187)}) \cdot (Z^{(1.3645)})$	DBH in cm, Hme in m (1, 200)**	T	24	96	2 Akindele, S.O. (2005)
136	in RCA	$Y(m3) = 12.43 \cdot (X^{(2.43)})$	DBH in m (0.01, 1.69)**	T	-	100	2 CTFT (1964)
137	Mammea africana in Gabon	$Y(m3) = 9.72 \cdot (X^{2.46})$	DBH in m (0.01, 0.4)*	T	-	100	2 Bilé Allogho, J. (1999)
138	in Guinea-Bissau	$Y(m3) = 10.98 \cdot (X^2)$	DBH in m (0.01, 1.69)**	T	-	86	1 CTFT (1986)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations					
			Variables X (min, max), W, Z, U and V				
139	Manilkara obovata in Nigeria	$Y(m3) = -0.0688 + 0.000218 * (X^{(1.6895)}) * (Z^{(0.9203)})$	DBH in cm, Hme in m (11, 200)**	T	62	100	2 Akindele, S.O. (2005)
140	Mansonia altissima in Guinea-Bisseau	$Y(m3) = 11.62 * (X^2) - 0.05$	DBH in m (0.07, 1.69)**	T	-	100	2 CTFT (1986)
141	in Côte d'Ivoire	$Y(m3) = -0.524 + 13.127 * (X^2)$	DBH in m (0.2, 1.69)**	T	-	100	2 CTFT (1967)
142	in Bossématié in Côte d'Ivoire (1325)	$Y(m3) = 11.62 * (X^2) - 0.05$	DBH in m (0.07, 1.69)**	T	-	100	2 Pieper, Y., and Laumans, P. (1992)
143	in Nigeria	$Y(m3) = 0.0212 + 0.00005 * (X^{(2.0284)}) * (Z^{(0.9383)})$	DBH in cm, Hme in m (1, 200)**	T	59	96	2 Akindele, S.O. (2005)
144	Milicia excelsa in Gabon	$Y(m3) = 1.05 + 10.08 * (X^2)$	DBH in m (0.01, 0.7)*	T	-	43	1 Bilé Allogho, J. (1999)
145	in Nigeria	$Y(m3) = 0.0733 + 0.000013 * (X^{(2.0596)}) * (Z^{(1.4004)})$	DBH in cm, Hme in m (1, 200)**	T	9	95	2 Akindele, S.O. (2005)
146	Milletia stuhlmannii in Gabon	$Y(m3) = 9.72 * (X^{2.46})$	DBH in m (0.01, 0.4)*	T	-	100	2 Bilé Allogho, J. (1999)
147	Mitragyna ciliata in Gabon	$Y(m3) = 1.24 + 13.33 * (X^2)$	DBH in m (0.01, 0.4)*	T	-	3	1 Bilé Allogho, J. (1999)
148	Mitragyna ledermannii in Nigeria	$Y(m3) = 0.0892 + 0.000015 * (X^{(2.1194)}) * (Z^{(1.2398)})$	DBH in cm, Hme in m (1, 200)**	T	31	94	2 Akindele, S.O. (2005)
149	Mitragyna stipulosa in Nigeria	$Y(m3) = 0.1479 + 0.000029 * (X^{(1.3729)}) * (Z^{(1.9167)})$	DBH in cm, Hme in m (1, 200)**	T	9	93	2 Akindele, S.O. (2005)
150	Monopetalanthus coriaceus in Gabon	$Y(m3) = 9.28 * (X^{2.07})$	DBH in m (0.01, 0.7)*	T	-	89	1 Bilé Allogho, J. (1999)
151	Monopetalanthus durandii in Gabon	$Y(m3) = 9.28 * (X^{2.07})$	DBH in m (0.01, 0.7)*	T	-	89	1 Bilé Allogho, J. (1999)
152	Monopetalanthus heitzii in Gabon	$Y(m3) = 9.72 * (X^{2.46})$	DBH in m (0.01, 0.7)*	T	-	100	2 Bilé Allogho, J. (1999)
153	Monopetalanthus letestui in Gabon	$Y(m3) = 9.28 * (X^{2.07})$	DBH in m (0.01, 0.7)*	T	-	87	1 Bilé Allogho, J. (1999)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
154	Monopetalanthus microphyllus in Gabon	$Y(m3) = 9.28 * (X^{2.07})$	DBH in m (0.01, 0.4)*	T	-	73	1 Bilé Allogho, J. (1999)
155	Monopetalanthus pellegrini in Gabon	$Y(m3) = 9.28 * (X^{2.07})$	DBH in m (0.01, 0.7)*	T	-	90	1 Bilé Allogho, J. (1999)
156	Monopetalanthus sp in Gabon	$Y(m3) = 9.28 * (X^{2.07})$	DBH in m (0.01, 0.4)*	T	-	73	1 Bilé Allogho, J. (1999)
157	Nauclea diderichii in Gabon	$Y(m3) = 9.72 * (X^{2.46})$	DBH in m (0.01, 0.4)*	T	-	100	2 Bilé Allogho, J. (1999)
158	in Guinea-Bisseau	$Y(m3) = 13.43 * (X^2) - 1.55 * X + 0.06$	DBH in m (0.06, 1.69)**	T	-	100	2 CTFT (1986)
159	in Côte d'Ivoire	$Y(m3) = -1.240 + 13.334 * (X^2)$	DBH in m (0.31, 1.69)**	T	-	100	2 CTFT (1967)
160	in Nigeria	$Y(m3) = 0.1678 + 0.000005 * (X^{1.98}) * (Z^{1.8463})$	DBH in cm, Hme in m (1, 200)**	T	13	31	1 Akindele, S.O. (2005)
161	Nesogordonia papaverifera in Gabon	$Y(m3) = 0.04 + 9.07 * (X^2)$	DBH in m (0.01, 0.4)*	T	-	53	1 Bilé Allogho, J. (1999)
162	in Côte d'Ivoire	$Y(m3) = -0.329 + 11.665 * (X^2)$	DBH in m (0.17, 1.69)**	T	-	100	2 CTFT (1967)
163	in Bossématié in Côte d'Ivoire (1325)	$Y(m3) = 13.9 * (X^2) - 2.2 * X + 0.16$	DBH in m (0.08, 1.69)**	T	-	98	2 Pieper, Y., and Laumans, P. (1992)
164	in Nigeria	$Y(m3) = -0.6346 + 0.003726 * (X^{1.3977}) * (Z^{0.4029})$	DBH in cm, Hme in m (20, 200)**	T	5	100	2 Akindele, S.O. (2005)
165	Nesogordonia sp in Gabon	$Y(m3) = 9.72 * (X^{2.46})$	DBH in m (0.01, 0.4)*	T	-	100	2 Bilé Allogho, J. (1999)
166	Ongokea gore in Gabon	$Y(m3) = 9.72 * (X^{2.46})$	DBH in m (0.01, 0.4)*	T	-	100	2 Bilé Allogho, J. (1999)
167	Oxystigma oxyphyllum in Gabon	$Y(m3) = 9.72 * (X^{2.46})$	DBH in m (0.01, 0.4)*	T	-	100	2 Bilé Allogho, J. (1999)
168	Paraberlinia bifoliolata in Gabon	$Y(m3) = 9.28 * (X^{2.07})$	DBH in m (0.01, 0.6)*	T	-	77	1 Bilé Allogho, J. (1999)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
169	Pentaclethra macrophylla in Nigeria	$Y(m3) = -0.1424 + 0.001426 * (X^{(1.2539)}) * (Z^{(0.823)})$	DBH in cm, Hme in m (11, 200)**	T	15	100	2 Akindele, S.O. (2005)
170	Pentadesma butyracea in Nigeria	$Y(m3) = 0.0944 + 0.000013 * (X^{(2.0961)}) * (Z^{(1.3257)})$	DBH in cm, Hme in m (1, 200)**	T	48	93	2 Akindele, S.O. (2005)
171	Petersianthus macrocarpus in Gabon	$Y(m3) = 0.33 + 11.66 * (X^2)$	DBH in m (0.01, 0.4)*	T	-	3	1 Bilé Allogho, J. (1999)
172	in Nigeria	$Y(m3) = -0.116 + 0.000276 * (X^{(1.7476)}) * (Z^{(0.7508)})$	DBH in cm, Hme in m (13, 200)**	T	28	100	2 Akindele, S.O. (2005)
173	Pinus caribaea in Uganda	$Y(m3) = 0.00001638 * (X^{(1.9497)}) * (Z^{(1.2006)})$	DBH in cm, Hd in m (1, 200)**	T+GB+TB5+S	594, 0.96	100	Alder, D., Drichi, P., et al. (2003)
174	Piptadeniastrum africanum in Gabon	$Y(m3) = 9.72 * (X^{2.46})$	DBH in m (0.01, 0.4)*	T	-	100	2 Bilé Allogho, J. (1999)
175	in Nigeria	$Y(m3) = -0.1873 + 0.000908 * (X^{(1.5394)}) * (Z^{(0.6294)})$	DBH in cm, Hme in m (14, 200)**	T	34	100	2 Akindele, S.O. (2005)
176	Poga oleosa in Nigeria	$Y(m3) = -0.0577 + 0.000147 * (X^{(1.7572)}) * (Z^{(0.994)})$	DBH in cm, Hme in m (10, 200)**	T	17	100	2 Akindele, S.O. (2005)
177	Pterocarpus osun in Nigeria	$Y(m3) = 0.0326 + 0.000061 * (X^{(1.9204)}) * (Z^{(1.0331)})$	DBH in cm, Hme in m (1, 200)**	T	33	95	2 Akindele, S.O. (2005)
178	Pterocarpus santalinoides in Nigeria	$Y(m3) = 0.1281 + 0.0000000047 * (X^{(1.978)}) * (Z^{(4.7225)})$	DBH in cm, Hme in m (1, 200)**	T	13	18	1 Akindele, S.O. (2005)
179	Pterocarpus soyauxii in Gabon	$Y(m3) = 9.72 * (X^{2.46})$	DBH in m (0.01, 0.7)*	T	-	100	2 Bilé Allogho, J. (1999)
180	Pterygota macrocarpa in Bossématié in Côte d'Ivoire (1325)	$Y(m3) = 17 * (X^2) - 3.4 * X + 0.3$	DBH in m (0.1, 1.69)**	T	-	99	Pieper, Y., and Laumans, P. (1992)
181	in Nigeria	$Y(m3) = 0.0238 + 0.000041 * (X^{(2.0923)}) * (Z^{(0.9443)})$	DBH in cm, Hme in m (1, 200)**	T	32	97	2 Akindele, S.O. (2005)
182	Pycnanthus gymnorhiza in Guinea-Bissau	$Y(m3) = 10 * (X^2) - 0.25 * X - 0.05$	DBH in m (0.09, 1.69)**	T	-	100	2 CTFT (1986)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations					
183	in Côte d'Ivoire	$Y(m3) = 1.17 + 8.099 * (X^2)$	DBH in m (0.01, 1.69)**	T	-	77	1 CTFT (1967)
184	in Bossématié in Côte d'Ivoire (1325)	$Y(m3) = 10 * (X^2) - 0.25 * X - 0.05$	DBH in m (0.09, 1.69)**	T	-	100	2 Pieper, Y., and Laumans, P. (1992)
185	Pycnanthus angolensis in Gabon	$Y(m3) = 9.72 * (X^{2.46})$	DBH in m (0.01, 0.6)*	T	-	100	2 Bilé Allogho, J. (1999)
186	in Nigeria	$Y(m3) = -0.1088 + 0.000185 * (X^{(1.8474)}) * (Z^{(0.8031)})$	DBH in cm, Hme in m (13, 200)**	T	31	100	2 Akindele, S.O. (2005)
187	Rhodognaphalon brevicuspe in Gabon	$Y(m3) = 9.72 * (X^{(2.46)})$	DBH in m (0.01, 0.4)*	T	-	100	2 Bilé Allogho, J. (1999)
188	in Bossématié in Côte d'Ivoire (1325)	$Y(m3) = 12 * (X^2) - 0.05$	DBH in m (0.07, 1.69)**	T	-	94	2 Pieper, Y., and Laumans, P. (1992)
189	Ricinodendron heudelotii in Nigeria	$Y(m3) = 0.0064 + 0.000099 * (X^{(1.9762)}) * (Z^{(0.762)})$	DBH in cm, Hme in m (1, 200)**	T	34	98	2 Akindele, S.O. (2005)
190	Scottellia coriacea in Nigeria	$Y(m3) = -0.0997 + 0.000354 * (X^{(1.66)}) * (Z^{(0.7596)})$	DBH in cm, Hme in m (12, 200)**	T	23	100	2 Akindele, S.O. (2005)
191	Scottellia sp in Bossématié in Côte d'Ivoire (1325)	$Y(m3) = 11.25 * (X^2) - 0.08$	DBH in m (0.09, 1.69)**	T	-	100	2 Pieper, Y., and Laumans, P. (1992)
192	Sindoropsis letestui in Gabon	$Y(m3) = 9.28 * (X^{2.07})$	DBH in m (0.01, 0.7)*	T	-	83	1 Bilé Allogho, J. (1999)
193	Staudtia stipitata in Gabon	$Y(m3) = 9.72 * (X^{2.46})$	DBH in m (0.01, 0.4)*	T	-	100	2 Bilé Allogho, J. (1999)
194	in Fernan-Vaz in Gabon (1953)	$Y(m3) = -0.353040 + 10.8736 * (X^2)$	DBH in m (0.19, 1.69)**	T	-	100	2 CTFT (1979)
195	in Nigeria	$Y(m3) = -0.0869 + 0.00014 * (X^{(1.8223)}) * (Z^{(0.8974)})$	DBH in cm, Hme in m (13, 200)**	T	18	100	2 Akindele, S.O. (2005)
196	Stemonocoleus micranthus in Nigeria	$Y(m3) = -0.0346 + 0.000349 * (X^{(1.6717)}) * (Z^{(0.7359)})$	DBH in cm, Hme in m (8, 200)**	T	20	100	2 Akindele, S.O. (2005)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations					
			Variables X (min, max), W, Z, U and V				
197	<i>Sterculia Oblongata</i> in Gabon	$Y(m3) = 10 \cdot (X^2)$	DBH in m (0.01, 0.7)*	T	-	76	1 Bilé Allogho, J. (1999)
198	<i>Sterculia rhinopetala</i> in Nigeria	$Y(m3) = 0.0307 + 0.000037 \cdot (X^{(2.0726)}) \cdot (Z^{(1.017)})$	DBH in cm, Hme in m (1, 200)**	T	72	96	2 Akindele, S.O. (2005)
199	<i>Sterculia tragacantha</i> in Nigeria	$Y(m3) = 0.1335 + 0.000002 \cdot (X^{(2.7221)}) \cdot (Z^{(1.0965)})$	DBH in cm, Hme in m (1, 200)**	T	18	93	2 Akindele, S.O. (2005)
200	<i>Strombosia pustulata</i> in Nigeria	$Y(m3) = 0.0031 + 0.000083 \cdot (X^{(1.8401)}) \cdot (Z^{(1.0424)})$	DBH in cm, Hme in m (1, 200)**	T	113	98	2 Akindele, S.O. (2005)
201	<i>Swartzia fistuloides</i> in Gabon	$Y(m3) = 9.72 \cdot (X^{2.46})$	DBH in m (0.01, 0.4)*	T	-	100	2 Bilé Allogho, J. (1999)
202	<i>Symphonia globulifera</i> in Nigeria	$Y(m3) = -0.009 + 0.000205 \cdot (X^{(1.4431)}) \cdot (Z^{(1.2301)})$	DBH in cm, Hme in m (4, 200)**	T	142	100	2 Akindele, S.O. (2005)
203	<i>Tarrietia densiflora</i> in Gabon	$Y(m3) = 1.11 + 13.23 \cdot (X^2)$	DBH in m (0.01, 0.4)*	T	-	0	1 Bilé Allogho, J. (1999)
204	<i>Tarrietia utilis</i> in Côte d'Ivoire	$Y(m3) = -1.110 + 13.226 \cdot (X^2)$	DBH in m (0.29, 1.69)**	T	-	100	2 CTFT (1967)
205	<i>Tectona grandis</i> in Côte d'Ivoire	$Y(m3) = 0.03077 \cdot (X^2) \cdot Z + 0.01827 \cdot X \cdot (Z^{0.05}) - 0.0186$	C in m, H in m (0.25, 5.31)**	T+GB+B+S	-	100	2 Dereix, C., and Maitre, H.F. (1979)
206	idem	$Y(m3) = 1.1957 \cdot (X^2) - 0.3933 \cdot X + 0.0456$	C in m (0.16, 5.31)**	T+GB+B+S	-	100	2 Dereix, C., and Maitre, H.F. (1979)
207	idem	$Y(m3) = 0.03077 \cdot (X^2) \cdot Z + 0.01827 \cdot X \cdot (Z^{0.05})$	C in m, H in m (0.03, 5.31)**	T+GB+B+S	-	99	2 CTFT (1990)
208	<i>Terminalia ivorensis</i> in Mbalmayo in Cameroon (2445)	$Y(m3) = 5.04 \cdot X$	As in m2 (0, 2.24)**	T+GB+TB+B+S	13, 0.95	100	2 Norgrove, L. and Hauser, S. (2002)
209	idem	$Y(m3) = 7.49 \cdot X$	As in m2 (0, 2.24)**	T+GB+TB+B+S	11, 0.93	99	2 Norgrove, L. and Hauser, S. (2002)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
210	idem	$Y(m3) = (5.46 \cdot \log(X)) + 36.16$	Ht in cm (175.1, 3221.45)**	T+GB+TB+B+S	24, 0.9	32	1 Norgrove, L. and Hauser, S. (2002)
211	in Guinea-Bisseau	$Y(m3) = 10.4 \cdot (X^2) - 0.05$	DBH in m (0.07, 1.69)**	T	-	100	2 CTFT (1986)
212	in Côte d'Ivoire	$Y(m3) = -1.230 + 11.334 \cdot (X^2)$	DBH in m (0.33, 1.69)**	T	-	100	2 CTFT (1967)
213	in Nigeria	$Y(m3) = -0.1616 + 0.000242 \cdot (X^{(1.772)}) \cdot (Z^{(0.8073)})$	DBH in cm, Hme in m (15, 200)**	T	31	100	2 Akindele, S.O. (2005)
214	Terminalia superba in Mayombe in Congo (1424)	$Y(cm3) = 4.196268 \cdot (X^2) \cdot Z + 26954.8 - 0.002050 \cdot (X^4)$	C180 in cm, H in m (2.27, 226.89)**	T	-	95	2 Groulez, J. and Wood, P.J. (1984)
215	idem	$Y(dm3) = -55.4 + 0.0746 \cdot (X^2)$	C180 in cm (29.5, 383.45)**	T+GB+B+S	-	100	2 Groulez, J. and Wood, P.J. (1984)
216	idem	$Y(cm3) = 88.86137 \cdot (X^2) - 71831.8 - 0.00119822 \cdot (x^4)$	C180 in cm (29.5, 190.59)**	T	-	100	2 Groulez, J. and Wood, P.J. (1984)
217	idem	$Y(cm3) = -119233 + 108.961 \cdot (X^2) - 0.00093 \cdot (X^4)$	C in cm (34.56, 238.76)**	T	-	100	2 Groulez, J. and Wood, P.J. (1984)
218	idem	$Y(cm3) = -208.0477 \cdot X \cdot \text{SQRT}(z) + 400663 - 49954.6 \cdot z + 1545.5 \cdot (z^2) + 5.7716 \cdot (X^2) \cdot z - 0.130701 \cdot (X^2) \cdot (z^2) - 0.00118288 \cdot (X^4)$	C in cm, H in m (34.56, 153.94)**	T	-	100	2 Groulez, J. and Wood, P.J. (1984)
219	idem	$Y(m3) = 220.7 - 147.28 \cdot X + 35.33 \cdot (X^2) - 1.3 \cdot (X^3)$	Yr in Yr	T+GB+B+S	21, 0.99	NA	3 Groulez, J. and Wood, P.J. (1984)
220	in Gabon	$Y(m3) = 10.34 \cdot (X^{2.22})$	DBH in m (0.01, 0.6)*	T	-	95	2 Bilé Allogho, J. (1999)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
221	in Mekambo in Gabon (1583)	$Y(m3) = 0.19 + 10.46 \cdot (X^2)$	DBH in m (0.01, 1.69)**	T	-	91	2 Groulez, J. and Wood, P.J. (1984)
222	in Oyem in Gabon (1784)	$Y(m3) = 0.14 + 9.64 \cdot (X^2)$	DBH in m (0.01, 1.69)**	T	-	92	2 Groulez, J. and Wood, P.J. (1984)
223	in Ghana	$Y(dm3) = \text{Exp}(-9.022 + 1.904 \cdot \log(X) + 0.765 \cdot \log(Z))$	DBH in cm, H in m (1, 200)**	T+B+S	-	100	2 Forster, H. (1994)
224	idem	$Y(dm3) = -0.416 + 6.288 \cdot (X^2)$	DBH in m (7, 7)*	T+GB+B+S	-	100	2 Forster, H. (1994)
225	idem	$Y(dm3) = -0.149 + 1.0758 \cdot X + 0.2016 \cdot (X^2) \cdot Z$	DBH in m, H in m (7, 7)*	T+B+S	-	100	2 Forster, H. (1994)
226	idem	$Y(dm3) = -8.7752 + 0.0273118 \cdot (X^2) \cdot Z$	DBH in cm, H in m (7, 200)**	T	-	100	2 Forster, H. (1994)
227	idem	$Y(dm3) = -18.6 + 0.03036872 \cdot (X^2) \cdot Z + 0.5739685 \cdot X \cdot \text{SQRT}(Z)$	DBH in cm, H in m (7, 200)*	T+GB+B+S	-	100	2 Forster, H. (1994)
228	idem	$Y(dm3) = -129.11 + 9.2599 \cdot X + 0.02659 \cdot (X^2) \cdot Z$	DBH in cm, H in m (11, 200)**	T+B+S	-	100	2 Forster, H. (1994)
229	in Kabo forest reserve in Ghana (1442)	$Y(dm3) = -9.304 + 0.0335525 \cdot (X^2) \cdot Z$	DBH in cm, H in m (7, 200)*	T+GB+B+S	60	100	2 Forster, H. (1994)
230	idem	$Y(dm3) = -113.62 + 0.87401 \cdot (X^2)$	DBH in cm (12, 55)*	T+GB+B+S	0.89*	100	3 Forster, H. (1994)
231	idem	$Y(dm3) = -10.832 + 2.22052 \cdot X \cdot Z$	DBH in cm, H in m (20, 200)*	T+B+S	60	98	2 Forster, H. (1994)
232	idem	$Y(dm3) = -840.99 + 53.21335 \cdot X$	DBH in cm (16, 55)*	T+GB+B+S	0.89*	100	3 Forster, H. (1994)
233	in Guinea-Bisseau	$Y(m3) = 12 \cdot (X^2) - 0.09$	DBH in m (0.09, 1.69)**	T	-	100	2 CTFT (1986)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
234	in Côte d'Ivoire	$Y(m3) = 0.024 - 1.126 * X + 13.521 * (X^2)$	DBH in m (0.04, 1.69)*	T+GB+B+S	-	100	2 CTFT (1988)
235	idem	$Y(m3) = 0.590 + 10.629 * (X^2)$	DBH in m (0.01, 1.69)**	T	-	83	1 CTFT (1967)
236	in Bossématié in Côte d'Ivoire (1325)	$Y(m3) = 12 * (X^2) - 2.9 * X + 0.28$	DBH in m (0.12, 1.69)**	T	-	100	2 Pieper, Y., and Laumans, P. (1992)
237	in Nigeria	$Y(m3) = -0.0768 + 0.000156 * (X^{(1.7972)}) * (Z^{(0.8976)})$	DBH in cm, Hme in m (12, 200)**	T	51	100	2 Akindele, S.O. (2005)
238	in Onigambari in Nigeria (1316)	$Y(m3) = -0.46023 + 0.0661 * X - 0.003 * (X^2) + 0.0001 * (X^3)$	DBH in cm (10, 200)**	T+B	0.62	18	1 Osho, J. S. A. (1991)
239	idem	$Y(m3) = -11.0625 + 2.19641 * X + (1.145 * \log_{10}(z))$	DBH in cm, H in m (5, 200)**	T+B	0.87	0	1 Osho, J. S. A. (1991)
240	in RCA	$Y(m3) = 13.16 * (X^{(2.34)})$	DBH in m (0.01, 1.69)**	T	-	99	2 CTFT (1964)
241	Testulea gabonensis in Gabon	$Y(m3) = 9.72 * (X^{2.46})$	DBH in m (0.01, 0.7)*	T	-	100	2 Bilé Allogho, J. (1999)
242	Tetraberlinia bifoliolata in Gabon	$Y(m3) = 9.72 * (X^{2.46})$	DBH in m (0.01, 0.4)*	T	-	100	2 Bilé Allogho, J. (1999)
243	Tetraberlinia polyphylla in Gabon	$Y(m3) = 9.28 * (X^{2.07})$	DBH in m (0.01, 0.7)*	T	-	84	1 Bilé Allogho, J. (1999)
244	Tetrapleura tetraptera in Nigeria	$Y(m3) = 0.1198 + 0.00001 * (X^{(2.1258)}) * (Z^{(1.3961)})$	DBH in cm, Hme in m (1, 200)**	T	14	93	2 Akindele, S.O. (2005)
245	Tieghemella africana in Gabon	$Y(m3) = 0.72 + 11.32 * (X^2)$	DBH in m (0.01, 0.7)*	T	-	43	1 Bilé Allogho, J. (1999)
246	Tieghemella heckelii in Côte d'Ivoire	$Y(m3) = -0.723 + 11.317 * (X^2)$	DBH in m (0.26, 1.69)**	T	-	100	2 CTFT (1967)
247	Trichilia gilgiana in Nigeria	$Y(m3) = -0.071 + 0.000073 * (X^{(2.1097)}) * (Z^{(0.8126)})$	DBH in cm, Hme in m (12, 200)**	T	6	100	2 Akindele, S.O. (2005)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
248	Trichilia monadelpha in Nigeria	$Y(m3) = 0.0281 + 0.000006 * (X^{(2.6881)}) * (Z^{(1.0475)})$	DBH in cm, Hme in m (1, 200)**	T	14	63	1 Akindele, S.O. (2005)
249	Trichilia prieureana in Nigeria	$Y(m3) = 0.0133 + 0.000141 * (X^{(1.7424)}) * (Z^{(0.9536)})$	DBH in cm, Hme in m (1, 200)**	T	25	96	2 Akindele, S.O. (2005)
250	Trichilia retusa in Nigeria	$Y(m3) = 0.1884 + 0.00000027 * (X^{(2.7502)}) * (Z^{(1.9723)})$	DBH in cm, Hme in m (1, 200)**	T	5	37	1 Akindele, S.O. (2005)
251	Trilepisium madagascariense in Nigeria	$Y(m3) = -0.042 + 0.000499 * (X^{(1.4052)}) * (Z^{(0.9385)})$	DBH in cm, Hme in m (8, 200)**	T	33	100	2 Akindele, S.O. (2005)
252	Triplochiton scleroxylon in Cameroon	$Y(m3) = 0.000209 * (X^{(2.3528)})$	DBH in cm (1, 80)*	T	-	100	Palla, F. and Louppe, D. (2002)
253	idem	$Y(m3) = 1.192 - 0.0465 * X + 0.00162 * (X^2)$	DBH in cm (14, 60)*	T	-	83	Palla, F. and Louppe, D. (2002)
254	in Guinea-Bissau	$Y(m3) = 15.15 * (X^2) - 3.12 * X + 0.24$	DBH in m (0.1, 1.69)**	T	-	100	2 CTFT (1986)
255	in Côte d'Ivoire	$Y(m3) = -0.108 + 12.092 * (X^2)$	DBH in m (0.1, 0.55)	T	-	100	2 CTFT (1990)
256	idem	$Y(m3) = -1.357 + 13.951 * (X^2)$	DBH in m (0.32, 1.69)**	T	-	100	2 CTFT (1967)
257	idem	$Y(m3) = -0.094 + 11.496 * (X^2)$	DBH in m (0.2, 0.55)	T+B	-	100	Palla, F. and Louppe, D. (2002)
258	in Bossématié in Côte d'Ivoire (1325)	$Y(m3) = 15.15 * (X^2) - 3.12 * X + 0.24$	DBH in m (0.1, 1.69)**	T	-	100	Pieper, Y., and Laumans, P. (1992)
259	in Nigeria	$Y(m3) = 0.0333 + 0.000092 * (X^{(1.8307)}) * (Z^{(1.017)})$	DBH in cm, Hme in m (1, 200)**	T	46	97	2 Akindele, S.O. (2005)
260	in RCA	$Y(m3) = 11.73 * (x^{(2.1)})$	DBH in m (0.01, 1.69)**	T	-	97	2 CTFT (1964)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations					
261	Turraeanthus africanus in Guinea-Bisseau	$Y(m3) = 6.67 \cdot (X^2) + 0.07$	DBH in m (0.01, 1.69)**	T	-	92	2 CTFT (1986)
262	in Côte d'Ivoire	$Y(m3) = -0.131 + 6.811 \cdot (X^2)$	DBH in m (0.14, 1.69)**	T	-	100	2 CTFT (1967)
263	Xylopia aethiopica in Nigeria	$Y(m3) = -0.0286 + 0.000239 \cdot (X^{(1.6937)}) \cdot (Z^{(0.8309)})$	DBH in cm, Hme in m (8, 200)**	T	72	100	2 Akindele, S.O. (2005)
264	All in Nkamouna in cameroon (1654)	$Y(m3) = 0.000347 \cdot X^{(2.211969)}$	DBH in cm (1, 200)**	T	-	99	2 Azegue Temgoua, R. C. (2004)
265	in Fernan-Vaz in Gabon (1953)	$Y(m3) = -0.47207 + 10.1186 \cdot (X^2)$	DBH in m (0.22, 1.69)**	T	-	100	2 CTFT (1979)
266	in Ghana	$Y(m3) = 0.0004478 \cdot (X^{(2.216)})$	DBH in cm (1, 200)**	T	-	96	2 Wong, J.L.G. (1989)
267	idem	$Y(m3) = 0.0004634 \cdot (X^{(2.201)})$	DBH in cm (1, 200)**	T	-	96	2 Wong, J.L.G. (1990)
268	idem	$Y(m3) = 0.0005229 \cdot (X^{(2.140)})$	DBH in cm (1, 200)**	T	-	96	2 Wong, J.L.G. (1989)
269	in Subiri in Ghana (1792)	$Y(m3) = -0.627153 + 0.00095007 \cdot (X^2)$	DBH in cm (40, 150)	T+GB+B+S+D	101	100	2 Alder, D (1982)
270	idem	$Y(m3) = 0.000490047 \cdot (x^{(2.28048)}) \cdot 0.7410$	DBH in cm (40, 150)	T+GB+B+S+D	101, 0.85*	100	3 Alder, D (1982)
271	idem	$Y(m3) = 0.000490047 \cdot (x^{(2.28048)})$	DBH in cm (40, 150)	T+GB+B+S+D	101, 0.85*	100	3 Alder, D (1982)
272	idem	$Y(m3) = -0.984221 + 1.00437 \cdot 10^{(-3)} \cdot (X^2)$	DBH in cm (32, 200)**	T	-	100	2 Alder, D. (1982)
273	in Guinea-Bisseau	$Y(m3) = 11.6 \cdot (X^2) - 1.4 \cdot X + 0.1$	DBH in m (0.06, 1.69)**	T	2878	97	2 CTFT (1986)
274	in Bossématié in Côte d'Ivoire (1325)	$Y(dm3) = -168.02 + 1.02092 \cdot (X^2)$	DBH in cm (13, 200)**	T	2878,	100	2 Pieper, Y., and Laumans, P.

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
				0.86			(1992)
275	idem	$Y(dm3) = -541.8 + 0.039808 \cdot (X^2) \cdot Z + 0.32088 \cdot (X^2)$	DBH in cm, Ht in m (27, 200)**	T	47, 0.97	100	2 Pieper, Y., and Laumans, P. (1992)
276	idem	$Y(dm3) = -169.7 + 0.24421 \cdot (X^2) + 0.040606 \cdot (X^2) \cdot Z$	DBH in cm, H in m (15, 200)**	T	2878, 0.96	100	2 Pieper, Y., and Laumans, P. (1992)
277	idem	$Y(dm3) = -568.7 + 1.1375 \cdot (X^2)$	DBH in cm (23, 200)**	T	47, 0.87	100	2 Pieper, Y., and Laumans, P. (1992)
278	in Nigeria	$Y(m3) = 0.0011 \cdot (X^2) - 0.0165 \cdot X$	DBH in cm (15, 200)**	T	2391, 0.8	100	2 Akindele, S.O. (2005)
279	idem	$Y(m3) = 0.0009 \cdot (X^2) - 0.0147 \cdot x$	BD in cm (17.33, 225.33)**	T	-, 0.81	100	2 Akindele, S.O. (2005)
280	in RCA	$Y(m3) = 10.35 \cdot (X^{(2.08)})$	DBH in m (0.01, 1.69)**	T	-	92	2 CTFT (1964)
Individual tree in tropical rainforest (group of tree species)							
281	Group 58 in Ghana	$\log_{10}Y(m3) = \text{LOG}_{10}(0.0001346) + 2.538 \cdot \text{LOG}_{10}(X)$	DBH in cm (1, 200)**	T	-	100	2 Wong, J.L.G. (1990)
282	Group 57 in Ghana	$\log_{10}Y(m3) = \text{LOG}_{10}(0.0006426) + 2.058 \cdot \text{LOG}_{10}(X)$	DBH in cm (1, 200)**	T	-	95	2 Wong, J.L.G. (1990)
283	Group 59 in Ghana	$\log_{10}Y(m3) = \text{LOG}_{10}(0.0003494) + 2.287 \cdot \text{LOG}_{10}(X)$	DBH in cm (1, 200)**	T	-	97	2 Wong, J.L.G. (1990)
284	Group 56 in Ghana	$\log_{10}Y(m3) = \text{LOG}_{10}(0.0006027) + 2.104 \cdot \text{LOG}_{10}(X)$	DBH in cm (1, 200)**	T	-	95	2 Wong, J.L.G. (1990)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
285	Group 55 in Ghana	$\log_{10}Y(m3) = \text{LOG10}(0.0002678) + 2.337 * \text{LOG10}(X)$	DBH in cm (1, 200)**	T	-	99	2 Wong, J.L.G. (1990)
286	Group 62 in Ghana	$\log_{10}Y(m3) = \text{LOG10}(0.0006245) + 2.114 * \text{LOG10}(X)$	DBH in cm (1, 200)**	T	-	94	2 Wong, J.L.G. (1990)
287	Group 61 in Ghana	$\log_{10}Y(m3) = \text{LOG10}(0.0006724) + 2.117 * \text{LOG10}(X)$	DBH in cm (1, 200)**	T	-	93	2 Wong, J.L.G. (1990)
288	Group 60 in Ghana	$\log_{10}Y(m3) = \text{LOG10}(0.0004639) + 2.204 * \text{LOG10}(X)$	DBH in cm (1, 200)**	T	-	96	2 Wong, J.L.G. (1990)
289	Group 4 in Subiri in Ghana (1792)	$Y(m3) = 2.20514 + 5.7881 * 10^{(-4)} * (X^2)$	DBH in cm (1, 200)**	T	-	74	1 Alder, D. (1982)
290	Group 8 in Subiri in Ghana (1792)	$Y(m3) = 0.788905 + 4.9658 * 10^{(-4)} * (X^2)$	DBH in cm (1, 200)**	T	-	82	1 Alder, D. (1982)
291	Group 2 in Subiri in Ghana (1792)	$Y(m3) = -1.511335 + 1.07504 * 10^{(-3)} * (X^2)$	DBH in cm (38, 200)**	T	-	100	2 Alder, D. (1982)
292	Group 3 in Subiri in Ghana (1792)	$Y(m3) = -0.966844 + 1.0322 * 10^{(-3)} * (X^2)$	DBH in cm (31, 200)**	T	-	100	2 Alder, D. (1982)
293	Group 5 in Subiri in Ghana (1792)	$Y(m3) = -0.891429 + 8.81682 * 10^{(-4)} * (X^2)$	DBH in cm (32, 200)**		-	100	2 Alder, D. (1982)
294	Group 6 in Subiri in Ghana (1792)	$Y(m3) = -0.857533 + 9.0746 * 10^{(-4)} * (X^2)$	DBH in cm (31, 200)**	A	-	100	2 Alder, D. (1982)
295	Group 7 in Subiri in Ghana (1792)	$Y(m3) = 0.854324 + 6.06056 * 10^{(-4)} * (X^2)$	DBH in cm (1, 200)**		-	81	1 Alder, D. (1982)
296	Group 1 in Subiri in Ghana (1792)	$Y(m3) = -0.826005 + 1.0255 * 10^{(-3)} * (X^2)$	DBH in cm (29, 200)**	A+E	-	100	2 Alder, D. (1982)
297	Group 10 in Subiri in Ghana (1792)	$Y(m3) = -1.75185 + 1.15209 * 10^{(-3)} * (X^2)$	DBH in cm (39, 200)**	A	-	100	2 Alder, D. (1982)
298	Group 9 in Subiri in Ghana (1792)	$Y(m3) = -1.46159 + 1.16385 * 10^{(-3)} * (X^2)$	DBH in cm (36, 200)**	A	-	100	2 Alder, D. (1982)
299	Group 11 in Subiri in Ghana (1792)	$Y(m3) = -1.54161 + 1.15891 * 10^{(-3)} * (X^2)$	DBH in cm (37, 200)**		-	100	2 Alder, D. (1982)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations					
Stand in tropical rainforest							
300	Eucalyptus grandis in Uganda	$Y(m3\ ha^{-1})= 0.00003805-0.00009789*(X^2)+0.0001325*X*Z+0.00002967*(X^2)*Z$	DBH in cm, H in m (-, -)	T+GB+TB5+B+S	-	-	2 Alder, D., Drichi, P., et al. (2003)
301	Nauclea diderichii in Omo in Nigeria (2293)	$Y(m3\ ha^{-1})= 63.98+21.02*X-0.55*(X^2)+0.016*(X^3)$	Yr in Yr	T+B	-	-	2 Onyekwelu, J. C. (2007)
302	Pinus caribaea in Uganda	$Y(m3\ ha^{-1})= 0.00004534*(X^{(1.8875)})*(Z^{(1.0304)})$	DBH in cm, Hd in m (-, -)	T+GB+TB5+B+S	594, 0.97*	-	2 Alder, D., Drichi, P., et al. (2003)
Sprout in tropical rainforest							
303	Acacia auriculiformis in Lama in Benin (1065)	$Y(m3)= 0.00259+0.407*(X^2)*Z$	DBH in m, H in m (-, -)	T+GB+TB3+B+S	190, 0.94	-	2 Fonton, N. H., Kakai, R. G., et al. (2002)
Individual tree in tropical moist deciduous forest (classification per tree species)							
304	Acacia mangium in Côte d'Ivoire	$Y(m3)= 1.3511*(X^2)-0.5872*X+0.0861$	C in m (0.22, 5.31)**	A+E	435, 0.98	100	2 Dupuy, B. and N'Guessan, K. (1989)
305	Afzelia africana in Badénou in Côte d'Ivoire (1211)	$Y(m3)= 0.1271-0.5633*X+1.0608*(X^2)$	C in m (0.25, 5.31)**	A+B+E+F	84	99	2 Louppe, D., M'BlaKoua, et al. (1994)
306	idem	$Y(m3)= -0.9121+1.3419*X-0.1806*(X^2)$	C in m (0.79, 3.68)**	A+E+F	84	100	2 Louppe, D., M'BlaKoua, et al. (1994)
307	idem	$Y(m3)= -0.0019+0.04846*(X^2)*Z$	C in m, H in m (0.09, 5.31)**	A+B+E+F	84	100	2 Louppe, D., M'BlaKoua, et al. (1994)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
308	Baikiaea plurijuga in Zambia	$Y(m3) = 0.2421143 + 0.0029874 * (X/2)^{(2)}$	DBH in cm	245, 0.95	-	-	Banks, P. F. and Burrows, P. M. (1966)
309	Brachystegia floribunda in Dedza in Malawi (896)	$\log_{10}Y(m3) = -4.22 + 2.77 * \log_{10}(X)$	DBH in cm (1, 200)**	166, 0.92	100	2	Abbot, P., Lowore, J., et al. (1997)
310	Brachystegia spiciformis in Chimaliro in Malawi (923)	$\log_{10}Y(m3) = -3.63 + 2.35 * \log_{10}(X)$	DBH in cm (1, 200)**	20, 0.93	100	2	Abbot, P., Lowore, J., et al. (1997)
311	in Dedza in Malawi (896)	$\log_{10}Y(m3) = -4.30 + 2.85 * \log_{10}(X)$	DBH in cm (1, 200)**	47, 0.92	100	2	Abbot, P., Lowore, J., et al. (1997)
312	Brachystegia utilis in Chimaliro in Malawi (923)	$\log_{10}Y(m3) = -4.03 + 2.72 * \log_{10}(X)$	DBH in cm (1, 200)**	54, 0.94	100	2	Abbot, P., Lowore, J., et al. (1997)
313	Combretum fragrans in Sikasso in Mali (1067)	$Y(m3) = -0.0066 + 0.0023 * X + 0.4752 * (X^2)$	C in m (0.15, 0.7)	-, 0.93	100	2	Bagnoud, N. and Kouyaté, A. M. (1996)
314	Combretum ghazalense in Siani in Mali (954)	$Y(cm3) = 0.23 / (1 + (95 * \exp(-29 * X)))$	DBH in cm (1, 200)**	-	100	2	Manlay, R.J., Kairé, M., et al. (2002)
315	Daniellia oliveri in Sikasso in Mali (1067)	$Y(m3) = -0.0057 - 0.0386 * 2 + 0.5539 * (X^2)$	C in m (0.41, 0.94)*	60, 0.95*	100	3	Bagnoud, N. and Kouyaté, A. M. (1996)
316	idem	$Y(m3) = -0.04295 + 0.21910 * X + 0.38396 * ((X^3))$	C in m (0.22, 1.5)	94	100	2	Nouvellet, Y. (2002)
317	Diospyros mespiliformis in Badénou in Côte d'Ivoire (1211)	$Y(m3) = -0.0982 + 0.1066 * X * \text{SQRT}(Z) + 0.03628 * (X^2) * Z$	C in m, H in m (0.25, 5.31)**	82	100	2	Louppe, D., M'BlaKoua, et al. (1994)
318	idem	$Y(m3) = 0.2304 + 0.2001 * (X^2)$	C in m (0.03, 5.31)**	82	91	2	Louppe, D., M'BlaKoua, et

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
							al. (1994)
319	idem	$Y(m3) = 0.0602 - 0.3299 * X + 0.8604 * (X^2)$	C in m (0.19, 5.31)**	A+B+E+F	82	99	2 Louppe, D., M'BlaKoua, et al. (1994)
320	idem	$Y(m3) = -0.203 + 0.03694 * X * \text{SQRT}(Z) + 0.03383 * (X^2) * Z$	C in m, H in m (0.53, 5.31)**	A+B+E+F	82	100	2 Louppe, D., M'BlaKoua, et al. (1994)
321	idem	$Y(m3) = -0.2893 + 0.509 * (X^2)$	C in m (0.75, 5.31)**	A+B+E+F	82	100	2 Louppe, D., M'BlaKoua, et al. (1994)
322	idem	$Y(m3) = 0.2668 + 0.01048 * (X^2) * Z$	C in m, H in m (0.03, 5.31)**	A+B+E+F	82	91	2 Louppe, D., M'BlaKoua, et al. (1994)
323	idem	$Y(m3) = -0.0715 + 0.02370 * (X^2) * Z$	C in m, H in m (0.5, 5.31)**	A+E+F	82	100	2 Louppe, D., M'BlaKoua, et al. (1994)
324	Guibourtia coleosperma in Zambia	$Y(m3) = -0.2925408 + 0.0033458 * (X/2)^2$	DBH in cm		75, 0.94	-	- Banks, P. F. and Burrows, P. M. (1966)
325	Isoberlinia doka in Badénou in Côte d'Ivoire (1211)	$Y(m3) = 0.0408 + 0.06187 * (X^2) * Z$	C in m, Ht in m (1, 2.2)	A+E	85	100	2 Louppe, D., Koua, M., et al. (1994)
326	idem	$Y(m3) = -0.2229 + 0.6627 * (X^2)$	C in m (1, 2.2)	A+B+C+E+F+H	85	0	1 Louppe, D., Koua, M., et al. (1994)
327	idem	$Y(m3) = -0.3554 + 0.1682 * X * \text{sqrt}(Z) + 0.003023 * (X^2) * Z$	C in m, H in m (1, 2.2)	A+E	85	100	2 Louppe, D., Koua, M., et al. (1994)
328	idem	$Y(m3) = -0.7131 + 1.0422 * X - 0.006513 * (X^2)$	C in m (1, 2.2)	A+E	85	100	2 Louppe, D., Koua, M., et al.

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations					
			Variables X (min, max), W, Z, U and V				
							(1994)
329	idem	$Y(m3) = -0.2186 + 0.1346 * X * \sqrt{Z} + 0.03615 * (X^2) * Z$	C in m, H in m (0.5, 2.2)	A+B+E+F	85	100	2 Louppe, D., Koua, M., et al. (1994)
330	idem	$Y(m3) = 0.1355 - 0.6999 * X + 1.3266 * (X^2)$	C in m (0.5, 2.2)	A+B+E+F	85	100	2 Louppe, D., Koua, M., et al. (1994)
331	idem	$Y(m3) = 0.0491 + 0.03037 * (X^2) * Z$	C in m, H in m (1, 2.2)	A+B+C+E+F+H	85	0	1 Louppe, D., Koua, M., et al. (1994)
332	in Sikasso in Mali (1067)	$Y(m3) = -0.05182 + 0.24489 * X + 0.56703 * ((X^3))$	C in m (0.22, 1.5)	A+B+E+F	100	100	2 Nouvellet, Y. (2002)
333	idem	$Y(m3) = 0.0444 - 0.3464 * X + 1.0141 * (X^2)$	C in cm (15, 100)	A+B+E+F	60, 0.96*	0	1 Bagnoud, N. and Kouyaté, A. M. (1996)
334	Julbernardia paniculata in Bunda in Malawi (837)	$\log_{10}Y(m3) = -4.00 + 2.65 * \log_{10}(X)$	DBH in cm (1, 200)**	A+B+C+E+F	40, 0.95	100	2 Abbot, P., Lowore, J., et al. (1997)
335	in Chimaliro in Malawi (923)	$\log_{10}Y(m3) = -3.84 + 2.48 * \log_{10}(x)$	DBH in cm (1, 200)**	A+B+C+E+F	101, 0.9	100	2 Abbot, P., Lowore, J., et al. (1997)
336	Khaya senegalensis in Badénou in Côte d'Ivoire (1211)	$Y(m3) = 0.0498 + 0.05757 * (X^2) * Z$	C in m, Ht in m (0.03, 5.31)**	A+E	84	94	2 Louppe, D., M'BlaKoua, et al. (1994)
337	idem	$Y(m3) = -0.1743 + 0.02705 * (X^2) * Z$	C in m, H in m (0.66, 5.31)**	A+E	84	100	2 Louppe, D., M'BlaKoua, et al. (1994)
338	idem	$Y(m3) = -0.3972 + 0.6291 * (X^2)$	C in m (0.82, 5.31)**	A+E	84	100	2 Louppe, D., M'BlaKoua, et al. (1994)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
339	idem	$Y(m3) = 0.3207 - 1.1957 * X + 1.4870 * (X^2)$	C in m (0.41, 5.31)**	A+B+E+F	84	100	2 Louppe, D., M'BlaKoua, et al. (1994)
340	idem	$Y(m3) = -0.00537 * X + 0.06233 * (X^2) + 0.54878 * ((X^3))$	C in m (0.2, 1.5)		81	100	2 Nouvellet, Y. (2002)
341	idem	$Y(m3) = -0.00485 + 0.04211 * (X^2) * Z$	C in m, H in m (0.16, 5.31)**	A+B+E+F	84	100	2 Louppe, D., M'BlaKoua, et al. (1994)
342	Pterocarpus angolensis in Chimaliro in Malawi (923)	$\log_{10}Y(m3) = -3.68 + 2.34 * \log_{10}(x)$	DBH in cm (1, 200)**	A+B+C+E+F	25, 0.89	100	2 Abbot, P., Lowore, J., et al. (1997)
343	in Zambia	$Y(m3) = -0.3687583 + 0.0041467 * (X/2)^{(2)}$	DBH in cm		91, 0.9	-	- Banks, P. F. and Burrows, P. M. (1966)
344	Terminalia sp in Sikasso in Mali (1067)	$Y(m3) = -0.01564 + 0.13174 * X + 0.57929 * ((X^3))$	C in m (0.22, 1.4)		116	100	2 Nouvellet, Y. (2002)
345	idem	$Y(m3) = 0.0067 - 0.1114 * X + 0.6995 * (X^2)$	C in cm (15, 79)	A+B+E+F	60, 0.92*	0	1 Bagnoud, N. and Kouyaté, A. M. (1996)
346	Terminalia superba in Ghana	$Y(m3) = (1.915 * \log_{10}(X^2)) + (0.942 * \log_{10}(z)) - 4.281$	DBH in cm, H in m (8, 200)**	A+E	-	82	1 JAFTA (1999)
347	Uapaca kirkiana in Dedza in Malawi (896)	$\log_{10}Y(m3) = -4.19 + 2.76 * \log_{10}(X)$	DBH in cm (1, 200)**	A+B+C+E+F	75, 0.91	100	2 Abbot, P., Lowore, J., et al. (1997)
Individual tree in tropical moist deciduous forest (classification per group of species)							
348	Group 65 in Chimaliro in Malawi (923)	$\log_{10}Y(m3) = -3.68 + 2.37 * \log_{10}(X)$	DBH in cm (1, 200)**	A+B+C+E+F	39, 0.89	100	2 Abbot, P., Lowore, J., et al. (1997)
349	Group 66 in Chimaliro in Malawi (923)	$\log_{10}Y(m3) = -3.88 + 2.53 * \log_{10}(X)$	DBH in cm (1, 200)**	A+B+C+E+F	84,	100	2 Abbot, P., Lowore, J., et al.

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
				0.91			(1997)
350	Group 67 in Dedza in Malawi (896)	SQRTY(m3)= -0.08+0.0268*X	DBH in cm (3, 200)**	A+B+C+E+F	22, 0.96	100	2 Abbot, P., Lowore, J., et al. (1997)
Generalized equations for individual tree in tropical moist deciduous forest							
351	Generalized in Chimaliro in Malawi (923)	log10Y(m3)= -3.86+2.52*log10(X)	DBH in cm (1, 200)**	A+B+C+H+E+F	330, 0.91	100	2 Abbot, P., Lowore, J., et al. (1997)
352	idem	log10Y(m3)= -3.87+2.4310*log10(X)	DBH in cm (1, 200)**	A+B+C+H+E+F	101, 0.91	100	2 Abbot, P., Lowore, J., et al. (1997)
353	in Dedza in Malawi (896)	SQRTY(m3)= -0.0722+0.0273*X	DBH in cm (3, 200)**	A+B+C+H+E+F	110, 0.93	100	2 Abbot, P., Lowore, J., et al. (1997)
354	idem	log10Y(m3)= -4.29+2.78*log10(X)	DBH in cm (1, 200)**	A+B+C+H+E+F	237, 0.92	100	2 Abbot, P., Lowore, J., et al. (1997)
355	in Sikasso in Mali (1067)	Y(m3)= 0.0148-0.1497*X+0.719*(X^2)	C in m (0.15, 1.95)	A+B+E+F+H	286, 0.91*	100	3 Bagnoud, N. and Kouyaté, A. M. (1996)
356	idem	Y(cm3)= -0.03263*X+0.16223*(X^2)+0.49948*((X^3))	C in cm (1.6, 1.6)**	A+B+E+F	725, 0.95*	100	3 Nouvellet, Y. (2002)
Individual tree in tropical dry forest (classification per tree species)							
357	Acacia karo in Umguza in Zimbabwe (513)	Y(m3)= -0.042+0.000668*X	As in cm2 (63.62, 22431.81)**	A+B+C5+E+F	138, 0.96	100	3 Gourlay, I. D., Smith, J. P., et al. (1996)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
358	idem	$Y(m3) = -0.089 + 0.000634 * X$	BA in cm2 (168.95, 39878.77)**	A+B+C5+E+F	138, 0.93	100	3 Gourlay, I. D., Smith, J. P., et al. (1996)
359	Afzelia africana in Bamako in Mali (1152)	$Y(m3) = 0.0782 + 0.05665 * (X^2) * Z$	C in m, Ht in m (0.03, 5.31)**	A+E+F	84	93	2 Louppe, D., M'BlaKoua, et al. (1994)
360	idem	$Y(m3) = 2.3731 - 3.5751 * X + 1.7462 * (X^2)$	C in m (1.04, 5.31)**	A+B+E+F	84	100	2 Louppe, D., M'BlaKoua, et al. (1994)
361	idem	$Y(m3) = -0.6023 + 0.2531 * X * \text{SQRT}(Z) - 0.00566 * (X^2) * Z$	C in m, H in m (0.66, 3.42)**	A+E+F	84	100	2 Louppe, D., M'BlaKoua, et al. (1994)
362	idem	$Y(m3) = 1.0481 - 0.3698 * X * \text{SQRT}(Z) + 0.06082 * (X^2) * Z$	C in m, H in m (0.72, 5.31)**	A+B+E+F	84	100	2 Louppe, D., M'BlaKoua, et al. (1994)
363	Baikiaea plurijuga in Botswana	$Y(m3) = 0.0000785 * X^{(2.598)}$	DBH in cm		142, 0.98	-	- Norwegian Forestry Society (1992)
364	Bombax buonopozense in Bamako in Mali (1152)	$Y(m3) = -0.00387 * X + 0.04665 * (X^2) + 0.58410 * (X^3)$	C in m (0.22, 1.5)	A+B+E+F	103	100	2 Nouvellet, Y. (2002)
365	Brachystegia boehmii in Phuyu in Malawi (800)	$\log_{10}Y(m3) = -3.85 + 2.49 * \log_{10}(X)$	DBH in cm (1, 200)**	A+B+C+E+F	27, 0.96	100	2 Abbot, P., Lowore, J., et al. (1997)
366	Brachystegia spiciformis in Tanzania	$100Y(m3) = 10^{(-1.2875 + 2.8436 * \log_{10}(X))}$	DBH in cm		-	-	- Temu, A. B. (1981)
367	idem	$100Y(m3) = -271 + 1.401 * X^{(2)}$	DBH in cm		-	-	- Temu, A. B. (1981)
368	Burkea africana in Botswana	$Y(m3) = 0.0000214 * (3.030)$	DBH in cm		40, 0.93	-	- Norwegian Forestry Society (1992)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
369	Colophospermum mopane in Botswana	$Y(m3) = 0.0001065 * X^{(2.471)}$	DBH in cm	18, 0.89	-	-	Norwegian Forestry Society (1992)
370	Combretum ghazalense in Mali	$Y(m3) = 0.23 / (1 + 95 * \exp(-29 * X))$	DBH in cm (1, 200)**	A+B+E+F+H	-	92	Alexandre, D.-Y., and Kairé, M. (2001)
371	Combretum glutinosum in Bamako in Mali (1152)	$Y(m3) = -0.00707 * X + 0.07584 * (X^2) + 0.57874 * (X^3)$	C in m (0.22, 1.1)	A+B+C3.2+E+F	110	100	2 Nouvellet, Y. (2002)
372	Cordyla pinnata in Bamako in Mali (1152)	$Y(m3) = -0.02038 * X + 0.13130 * (X^2) + 0.51060 * (X^3)$	C in m (0.22, 1.5)	A+B+E+F	663	100	2 Nouvellet, Y. (2002)
373	Dalbergia melanoxylon in Tanzania	$\log Y(m3) = -9.887 + 1.824 * \text{LOG}(X) + 1.155 * \text{LOG}(Z)$	DBH in cm	24, 0.99	-	-	Malimbi, R. E., Luoga, E., et al. (2000)
374	idem	$Y(m3) = 0.00023 * X^{(2.231)}$	DBH in cm	24, 0.97	-	-	Malimbi, R. E., Luoga, E., et al. (2000)
375	Julbernardia globiflora in Tanzania	$100Y(m3) = 369 - 88.2315 * X + 6.4175 * X^2 - 0.1168 * X^3 + 0.0009 * X^4$	DBH in cm	-	-	-	Temu, A. B. (1981)
376	in Kitulanghalo forest reserce in Tanzania ()	$Y(m3) = 0.0295 * X^{(3.015)}$	DBH in cm	-, 0.75	-	-	Malimbwi, R. E., Solberg, B., et al. (1994)
377	idem	$Y(m3) = -35.85 + 0.76 * X^2 * Z$	DBH in cm	-, 0.95	-	-	Malimbwi, R. E., Solberg, B., et al. (1994)
378	Khaya senegalensis in Badénou in Mali ()	$Y(m3) = -0.00537 + 0.06233 * X + 0.54878 * (X^2)$	C in m (0.06, 1.5)*	A+B+C5+E+F	-	93	2 Clément, J. (1982)
379	Lannea sp in Bamako in Mali (1152)	$Y(m3) = -0.00442 * X + 0.05448 * (X^2) + 0.56476 * (X^3)$	C in m (0.22, 1.3)	A+B+E+F	98	100	2 Nouvellet, Y. (2002)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
380	<i>Pterocarpus erinaceus</i> in Bamako in Mali (1152)	$Y(m3) = -0.01161 * X + 0.10180 * (X^2) + 0.54409 * (X^3)$	C in m (0.22, 1.5)	A+B+E+F	104	100	2 Nouvellet, Y. (2002)
381	<i>Pycnanthus angolensis</i> in Botswana	$Y(m3) = 0.0000686 * X^{(2.678)}$	DBH in cm	50, 0.95	-	-	Norwegian Forestry Society (1992)
382	in Tanzania	$100Y(m3) = -170 + 35.8721 * X - 2.1968 * X^2 + 0.08011 * X^3 - 0.0006 * X^4$	DBH in cm	-	-	-	Temu, A. B. (1981)
383	in Kitulanghalo forest reserce in Tanzania ()	$Y(m3) = 0.092 * X^{(2.59)}$	DBH in cm	-, 0.97	-	-	Malimbwi, R. E., Solberg, B., et al. (1994)
384	<i>Vitellaria paradoxa</i> in Mali	$Y(m3) = 2.4612 * x - 1.5130$	C in m (0.63, 3.1)*	A+B+C3.2+E+F	405, 0.53	100	3 Nouvellet, Y., Kassambara, A., et al. (2006)
385	in Badougou in Mali (814)	$Y(m3) = 0.6868 * x - 0.1314$	C in m (0.22, 2)*	A+B+C3.2+E+F	63, 0.42	100	3 Nouvellet, Y., Kassambara, A., et al. (2006)
386	idem	$Y(m3) = 162.52 * x - 51.264$	C in m (0.35, 3.1)*	A+B+C3.2+E+F	63, 0.49	0	1 Nouvellet, Y., Kassambara, A., et al. (2006)
387	idem	$Y(m3) = 328.3 * x - 167.34$	C in m (0.53, 3.1)*	A+B+C3.2+E+F	405, 0.56	0	1 Nouvellet, Y., Kassambara, A., et al. (2006)
388	in Massala in Mali (640)	$Y(m3) = 0.0141 * x - 0.1065$	C in m (2, 2)**	A+B+C3.2+E+F	122, 0.45	100	3 Nouvellet, Y., Kassambara, A., et al. (2006)
389	idem	$Y(m3) = 280.36 * x - 142.44$	C in m (0.53, 3.1)*	A+B+C3.2+E+F	122, 0.46	0	1 Nouvellet, Y., Kassambara, A., et al. (2006)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
390	in M'Péresso in Mali (883)	$Y(m3) = 222.32 \cdot x - 78.062$	C in m (0.38, 3.1)*	A+B+C3.2+E+F	121, 0.55	0	1 Nouvellet, Y., Kassambara, A., et al. (2006)
391	idem	$Y(m3) = 0.0200 \cdot x - 0.2007$	C in m (2, 2)**	A+B+C3.2+E+F	121, 0.55	100	3 Nouvellet, Y., Kassambara, A., et al. (2006)
392	in Ténéfi in Mali (986)	$Y(m3) = 0.0328 \cdot x - 0.6301$	C in m (3.1, 3.1)**	A+B+C3.2+E+F	99, 0.62	100	3 Nouvellet, Y., Kassambara, A., et al. (2006)
393	idem	$Y(m3) = 368.01 \cdot x - 189.97$	C in m (0.53, 3.1)*	A+B+C3.2+E+F	99, 0.56	0	1 Nouvellet, Y., Kassambara, A., et al. (2006)
Individual tree in tropical dry forest (classification per group of species)							
394	Group in Phuyu in Malawi (800)	$\log_{10}Y(m3) = -4.20 + 2.69 \cdot \log_{10}(X)$	DBH in cm (1, 200)**	A+B+C+E+F	30, 0.94	100	2 Abbot, P., Lowore, J., et al. (1997)
General equations for individual tree in tropical dry forest							
395	All in Burkina Faso	$Y(m3) = 0.01225 + 0.00599 \cdot (X^2)$	CD in m (1, 29.25)**	B	7, 0.81	78	1 Paquet, J. (1981)
396	idem	$Y(m3) = 0.01433 - 0.75661 \cdot X + 7.35209 \cdot (X^2)$	DBH in m (0.08, 1.69)**	A	7, 0.86	100	2 Paquet, J. (1981)
397	idem	$Y(m3) = 0.01173 + 0.44527 \cdot (X^2) \cdot Z$	DBH in m, H in m (0.01, 1.69)**	A	7, 0.88	96	2 Paquet, J. (1981)
398	idem	$Y(m3) = 0.10364 + 0.01206 \cdot Z^2 \cdot X$	DBH in m, CD in m (0.01, 1.69)**	B	7, 0.88	38	1 Paquet, J. (1981)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations					
		Variables X (min, max), W, Z, U and V					
				0.79			
399	idem	$Y(m3) = -0.0309 + 7.8477 \cdot (X^2) + 0.1754 \cdot X$	DBH in m (0.06, 1.69)**	A+B+F+E	0.68	100	2 Paquet, J. (1981)
400	idem	$Y(m3) = 0.11068 - 1.7905 \cdot X + 13.08245 \cdot (X^2)$	DBH in m (0.07, 1.69)**	A+B+F+E	0.83	99	2 Paquet, J. (1981)
401	idem	$Y(m3) = 0.06576 + 0.72532 \cdot (X^2) \cdot Z$	DBH in m, H in m (0.01, 1.69)**	A+B+F+E	0.86	92	2 Paquet, J. (1981)
402	in Boucle du Mouhoun in Burkina Faso (796)	$Y(m3) = -0.0018199 + 0.0011781 \cdot X + 0.000021004064 \cdot ((X^3))$	DBH in cm (2, 200)**	A+B+E+F+H	0.92*	100	2 Kaboré, C. (1992)
403	in Phuyu in Malawi (800)	$SQRTY(m3) = 0.0570 + (0.000918 \cdot X^2)$	DBH in cm (1, 200)**	A+B+C+H+E+F	0.88	34	1 Abbot, P., Lowore, J., et al. (1997)
404	idem	$\log_{10}Y(m3) = -4.22 + 2.76 \cdot \log_{10}(X)$	DBH in cm (1, 200)**	A+B+C+H+E+F	0.95	100	2 Abbot, P., Lowore, J., et al. (1997)
405	in Mali	$Y(cm3) = 3107.5 - 331.1 \cdot X + 13.998 \cdot (X^2)$	Cb in cm (12.57, 160)*		1410	100	2 Nouvellet, Y. (2002)
406	idem	$Y(m3) = -0.03263 + 0.16223 \cdot X + 0.49948 \cdot (X^3)$	C in m (0.19, 1.6)*	A+B+C5+E+F	0.95*	100	3 Bagnoud, N. and Kouyaté, A. M. (1996)
407	idem	$Y(m3) = 0.03879 - 0.33235 \cdot X + 0.83915 \cdot (X^2)$	Cb in m (0.21, 7.08)**		0.95*	100	2 PIRL (1991)
408	in Bamako in Mali (1152)	$Y(m3) = -0.0326 \cdot X + 0.16223 \cdot (X^2) + 0.49948 \cdot (X^3)$	C in m (0.22, 1.3)	A+B+C5+E+F	0.93	100	2 PIRL (1991)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations					
			Variables X (min, max), W, Z, U and V				
409	in Cinzana in Mali (725)	$Y(\text{cm3}) = 10.442 \cdot (X^2) - 179.68 \cdot X + 1666.8$	Cb in cm (10, 50)	A+B+C+E+F	150, 0.93*	100	3 Nouvellet, Y., Ladj Sylla, M., et al. (2000)
410	idem	$Y(\text{cm3}) = 5.9788 \cdot (X^2) - 44.356 \cdot X + 359.7$	Cb in cm (10, 45)	A+B+C+E+F	150, 0.93*	100	3 Nouvellet, Y., Ladj Sylla, M., et al. (2000)
411	idem	$Y(\text{cm3}) = 6.5439 \cdot (X^2) - 1.6117 \cdot x - 557.09$	Cb in cm (12.57, 85)*	A+B+C+E+F	150, 0.93*	100	3 Nouvellet, Y., Ladj Sylla, M., et al. (2000)
412	idem	$Y(\text{cm3}) = 13.59 \cdot (X^2) - 434.7 \cdot X - 978.89$	Cb in cm (37.7, 60)*	A+B+C+E+F	150, 0.93*	100	3 Nouvellet, Y., Ladj Sylla, M., et al. (2000)
413	idem	$Y(\text{cm3}) = 6.188 \cdot (X^2) - 55.855 \cdot X + 510.21$	Cb in cm (10, 35)	A+B+C+E+F	150, 0.93*	100	3 Nouvellet, Y., Ladj Sylla, M., et al. (2000)
414	idem	$Y(\text{cm3}) = 5.463 \cdot (X^2) + 52.748 \cdot X - 978.89$	Cb in cm (12.57, 80)*	A+B+C+E+F	150, 0.93*	100	3 Nouvellet, Y., Ladj Sylla, M., et al. (2000)
415	in Kitulangalo forest, Morogoro in Tanzania (935)	$\log Y(\text{m3}) = 0.0000442 + (1.373 \cdot \log(X)) + (1.781 \cdot \log(Z))$	DBH in m, H in m (0.01, 0.5)	A+E+F	30, 0.97	0	1 Chamshama, S. A. O., Mugasha, A. G., et al. (2004)
416	idem	$\log Y(\text{m3}) = 0.0000312 + (2.721 \cdot \log(X))$	BD in m (1, 2.25)	A+E+F	30, 0.97	100	3 Chamshama, S. A. O., Mugasha, A. G., et al. (2004)
417	idem	$\log Y(\text{m3}) = 0.000048 + (1.445 \cdot \log(X)) + (1.7026 \cdot \log(Z))$	DBH in m, H in m (1, 1.69)	A+B+C+E+F+H	30, 0.97	0	1 Chamshama, S. A. O., Mugasha, A. G., et al. (2004)
418	idem	$\log Y(\text{m3}) = 0.00002 + (0.88 \cdot \log(X)) + (1.80 \cdot \log(Z))$	BD in m, H in m (1, 2.25)	B+C+H	30, 0.78	0	1 Chamshama, S. A. O., Mugasha, A. G., et al. (2004)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
419	idem	$\log Y(m3) = 0.000047 + 2.56 * \log(X)$	BD in m (1, 2.25)	A+B+C+E+F+H	30, 0.98	100	3 Chamshama, S. A. O., Mugasha, A. G., et al. (2004)
420	idem	$\log Y(m3) = 0.000328 + (2.163 * \log(X))$	DBH in m (1, 1.69)	B+C+H	30, 0.89	100	3 Chamshama, S. A. O., Mugasha, A. G., et al. (2004)
421	in Kitulanghalo forest reserce in Tanzania (956)	$Y(m3) = 0.0001 * (X^{(2.032)}) * (Z^{(0.659)})$	DBH in cm, H in m (1, 200)**	A+B+C+H+E+F	-	100	2 Luoga, E. L., Witkowski, E. T. F., et al. (2002)
Stand in tropical dry forest							
422	in Mozambique	$Y(m3) = 6.18 * X^{0.86}$	BA in m2 ha-1	A+B+C5+E+F	-, 0.89	-	2 Williams, M., Ryan, C.M., et al. (2008)
individual tree in tropical shrubland (classification per tree species							
423	Acacia mellifera in Kazgail in Sudan (414)	$Y(m3) = 0.7245 * X - 0.0009 * Z + 0.020009 * W - 0.15673$	BD in m, CD in m, H in m (0.05, 2.25)**	A+E	32, 0.72	91	2 Mohie el Deen, F. A. . (1991)
424	Acacia nilotica in Kazgail in Sudan (414)	$Y(m3) = 0.2437 * X - 0.0215 * Z + 0.021434 * W - 0.02144$	BD in m, CD in m, H in m (0.01, 2.25)**	A+E	31, 0.69	95	2 Mohie el Deen, F. A. . (1991)
425	Acacia senegal in Fété Olé in Senegal (224)	$\log_{10} Y(m3) = (2.55 * \log_{10}(X)) + 0.07$	Cb in cm (4.19, 707.91)**		-, 0.99	70	1 Poupon, H. (1979)
426	in Kazgail in Sudan (414)	$Y(m3) = 0.6881 * X - 0.012238 * Z + 0.002957 * W - 0.07137$	BD in m, CD in m, H in m (0.11, 2.25)**	A+E	18, 0.76	100	2 Mohie el Deen, F. A. . (1991)
427	Afzelia africana in Fété Olé in Senegal (224)	$Y(cm3) = -0.05182 * X + 0.24489 * (X^2) + 0.56703 * (X^3)$	C in cm (22, 150)	A+B+C3.2+E+F+H	100	100	2 Nouvellet, Y. (2002)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations					
			Variables X (min, max), W, Z, U and V				
428	Aucoumea klaineana in Equatorial Guinea	$Y(m3) = 0.000106837 * (X^{2.0742}) * Z^{0.665713}$	DBH in cm, H in m (1, 200)**	A	1206	100	2 FAO (1991)
429	Balanites aegyptiaca in Fété Olé in Senegal (224)	$\log_{10}Y(m3) = (2.55 * \log_{10}(X)) + 0.07$	Cb in m (0.96, 7.08)**	A+E+F	-, 0.99	100	2 Poupon, H. (1979)
430	Boscia senegalensis in Fété Olé in Senegal (224)	$\log_{10}Y(m3) = 2.26 * \log_{10}(X) + 0.38$	Cb in m (0.04, 7.08)**	A+E+F	179, 0.99*	0	1 Poupon, H. (1979)
431	Commiphora africana in Fété Olé in Senegal (224)	$\log_{10}Y(m3) = (2.26 * \log_{10}(X)) + 0.38$	Cb in m (0.04, 7.08)**	A+E+F	-, 0.99	41	1 Poupon, H. (1979)
432	Cupressus lusitanica in Usambaras in Tanzania (558)	$Y(m3) = 0.0355 + 0.00003X^2 * Z$	DBH in cm, H in m (1, 200)**	A+B+F+E	-	96	2 Mugasha, A. G., Chamshama, S. A. O., et al. (1997)
433	Dalbergia melanoxylon in Kazgail in Sudan (414)	$Y(m3) = 0.3425 * X - 0.00859 * Z - 0.10698 * W$	BD in m, CD in m, H in m (-, -)*	A+E	10, 0.97	0	1 Mohie el Deen, F. A. . (1991)
434	Grewia bicolor in Fété Olé in Senegal (224)	$\log_{10}Y(m3) = (2.26 * \log_{10}(X)) + 0.38$	Cb in m (0.04, 7.08)**	A+E+F	-, 0.99	0	1 Poupon, H. (1979)
435	Rhizophora racemosa in Saint Louis in Senegal (302)	$Y(cm3) = 5620.3 * X - 23349.6$	H in cm (291.83, 5369.09)**	A+B+C+E+F	9, 0.85*	45	1 Doyen, A. (1983)
436	idem	$Y(cm3) = 1267 * X - 17867.4$	Cb in cm (16.76, 707.91)**	A+B+C+E+F	9, 0.85*	100	2 Doyen, A. (1983)
437	Tarrietia utilis in Côte d'Ivoire	$Y(cm3) = 1.95 * (X^{(2.7)})$	C in cm (3.14, 140)*	A	144	100	2 Martinot-Lagarde, P. (1961)
General equations for individual tree in							

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
tropical shrubland							
438	All in Gaborone in Botswana (552)	Y(m3)= 0.003295+0.00001272*(X^3)	DBH in cm (1, 200)**	A+B+C+E+F	0.91	99	2 Mabowe, R. B. (2006)
439	in Burkina Faso	Y(m3)= 0.11068-1.7905*X+13.08245*(X^2)	DBH in m (0.07, 1.69)**	A+B+C5+E+F	0.89	99	2 Clément, J. (1982)
440	in Equatorial Guinea	Y(m3)= 0.000059541*(X^2.061)*Z^0.87907	DBH in cm, H in m (1, 200)**	A	1206	100	2 FAO (1991)
441	in Malawi	Y(m3)= 0.0213+0.000011*(X^3)+0.0115*Z	DBH in cm, Ht in m (6, 35)	A+E	88, 0.97	80	1 Abbot, P., Lowore, J., et al. (1997)
442	idem	Y(m3)= 0.0168+0.000023*(X^3)	DBH in cm (5, 35)	A+B+C2+E+F	88, 0.92	97	3 Abbot, P., Lowore, J., et al. (1997)
443	in Mali	Y(m3)= 1.14*X+9.986*Z-9.4	DBH in cm, BA in m2 (9, 200)**	A+B+C5+E+F	6511, 0.95	0	1 Clément, J. (1982)
444	in Sudan	Y(m3)= 0.000406*X^(2)*Z	CD in m, H in m (-, -)		58, 0.95	-	- Glen, W. M. (1996)
445	in Kitonga in Tanzania (621)	Y(m3 ha-1)= 6.18*(X^(0.86))	BA in m2 ha-1 (0, 3.99)**	A+B+C+E+F	-	91	2 Isango, J. A. (2007)
Individual tree in tropical mountain (classification per tree species)							
446	Cederella serrata in Nyungwe in Rwanda (1412)	Y(dm3)= 182.65-5.482*X-24.9*Z-0.0701*(X^2)+1.7777*X*Z+0.004679*(X^2)*Z	DBH in cm, H in m (7, 24)*	A+E+F	263, 0.99	100	3 Deleporte, P. (1987)
447	idem	Y(dm3)= 183.39+9.879*X+0.7365*(X^2)	DBH in cm (3, 24)	A+E+F	263,	5	1 Deleporte, P. (1987)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations					
		Variables X (min, max), W, Z, U and V					
				0.97			
448	Cupressus luastica in Ruhande in Rwanda (1104)	$Y(dm3) = 121.6 - 22.845 * X + 1.9909 * (X^2) - 0.012 * (X^3)$	DBH in cm (10, 40)	A+E+F	422, 0.95*	100	3 Deleporte, P. (1987)
449	idem	$Y(dm3) = 418.96 - 81.524 * X + 3.3418 * (X^2) + 1.1237 * X * Z - 0.02771 * (X^3) - 0.000288 * (X^2) * (Z^2)$	DBH in cm, H in m (11, 40)*	A+E+F	422, 0.96*	100	3 Deleporte, P. (1987)
450	Cupressus lusitanica in Kakamega forest in Kenya (2002)	$Y(m3) = 0.007 * X - 0.0440$	DBH in cm (7, 15)*	A+B+C+E+F+H	-	100	Bradley, P. N. and Kuyper, J.B.H. (1988) 2
451	idem	$Y(m3) = 0.0258 * X - 0.3216$	DBH in cm (15, 200)*	A+B+C+E+F+H	-	100	Bradley, P. N. and Kuyper, J.B.H. (1988) 2
452	in Nyungwe in Rwanda (1412)	$Y(m3) = 6.828 * 10^{(-4)} * (X^2) - 6.223 * 10^{(-3)} * X + 2.212 * 10^{(-2)}$	DBH in cm (7, 32)	A+E	170, 0.93*	100	3 Pleines, V. (1987)
453	Eucalyptus globulus in Munessa Shashamane in Ethiopia (983)	$Y(dm3) = (0.08283 * (X^{1.873})) * (Z^{0.8242})$	DBH in cm, H in m (1, 33)	A+E	-	100	Pukkala, T. and Pohjonen, V. (1989) 2
454	Eucalyptus saligna in Kakamega forest in Kenya (2002)	$\log_{10} Y(m3) = (2.41141 * \log_{10}(X)) - 1.90244$	DBH in cm (16, 45)		137	0	1 Bradley, P.N. (1988)
455	Grevillia robusta in Ruhande in Rwanda (1104)	$Y(dm3) = -11.93 + 3.0386 * X + 0.2063 * (X^2)$	DBH in cm (7, 23)	A+E+F	38, 0.95	100	3 Deleporte, P. (1987)
456	idem	$Y(dm3) = -3.27 + 0.2353 * (X^2) * Z$	CD in m, CH in m (7, 23)		33, 0.5	100	3 Deleporte, P. (1987)
457	idem	$Y(dm3) = -0.0046 + 0.3855 * (X^2)$	DBH in cm (7, 23)	A+E+F		100	3 Deleporte, P. (1987)
				33,			

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations					
				0.89*			
458	idem	$Y(dm3) = 9.68 + 0.025 \cdot (X^2) \cdot Z$	DBH in cm, H in m (7, 23)	33, 0.93	100	3	Deleporte, P. (1987)
459	idem	$Y(dm3) = -29.41 + 6.02 \cdot X \cdot 3.3318 \cdot (X^2)$	CD in m (7, 23)	A+E+F 33, 0.47	0	1	Deleporte, P. (1987)
460	idem	$Y(dm3) = 0.1979 + 0.2859 \cdot (X^2) \cdot Z$	CD in m, CH in m (7, 23)	33, 0.5	100	3	Deleporte, P. (1987)
461	idem	$Y(dm3) = -4.04 + 0.3197 \cdot (X^2)$	DBH in cm (7, 23)	33, 0.66	6	1	Deleporte, P. (1987)
462	idem	$Y(dm3) = 1.0696 \cdot X^{(0.9159)}$	Vs in dm3 (7, 23)	33, 0.58	0	1	Deleporte, P. (1987)
463	idem	$Y(dm3) = -1.87 + 0.1063 \cdot (X^2) \cdot Z$	CD in m, CH in m (7, 23)	38, 0.73	100	3	Deleporte, P. (1987)
464	idem	$Y(dm3) = 5.12 - 2.46 \cdot X + 0.5496 \cdot Z$	H in m, DBH in cm (7, 25)	38, 0.96	0	1	Deleporte, P. (1987)
465	idem	$Y(dm3) = -39.85 + 21.05 \cdot X$	CD in m (7, 23)	38, 0.58	100	3	Deleporte, P. (1987)
466	idem	$Y(dm3) = 15.65 - 7.0320 \cdot (X^2) + 0.8998 \cdot (X^2) \cdot Z$	CD in m, CH in m (7, 23)	38, 0.82	100	3	Deleporte, P. (1987)
467	idem	$Y(dm3) = 1.45 + 0.009617 \cdot (X^3)$	DBH in cm (7, 23)	38,	100	3	Deleporte, P. (1987)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
				0.89			
468	idem	$Y(dm3) = 0.4376 * (X^{(0.8839)})$	Vs in dm3 (7, 23)	38, 0.92	100	3	Deleporte, P. (1987)
469	idem	$Y(dm3) = -15.59 + 7.51 * X$	CD in m (7, 23)	38, 0.64	100	3	Deleporte, P. (1987)
470	idem	$Y(dm3) = -18.86 + 3.3635 * (X^2)$	CD in m (7, 23)	33, 0.47	100	3	Deleporte, P. (1987)
471	Nauclea diderichii in Miango in Nigeria (1378)	$Y(m3) = 0.0001416 * (X^2) + 0.0000314 * (X^2) * Z - 0.0124$	DBH in cm, H in m (6, 200)**	-, 0.89	100	2	Abayomi, J. O. (1983)
472	idem	$Y(m3) = 0.00002134 * (X^2) + 0.00003023 * (X^2) * Z$	DBH in cm, H in m (1, 200)**	-, 0.92	100	2	Abayomi, J. O. (1983)
473	Pinus patula in Kakamega forest in Kenya (2002)	$Y(m3) = -0.00041 - 0.00005711 * X + 0.0001352 * (X * Z) + 0.00003313 * (X * Z)$	DBH in cm, H in m (1, 200)**	-	100	2	Bradley, P. N. and Kuyper, J.B.H. (1988)
474	in Nyungwe in Rwanda (1412)	$Y(m3) = 8.42 * 10^{(-4)} * (X^2) - 7.354 * 10^{(-3)} * X + 2.506 * 10^{(-2)}$	DBH in cm (6, 40)	181, 0.93*	100	3	Pleines, V. (1987)
475	All in Uluguru in Tanzania (1474)	$Y(cm3) = 194.8803 * X^{(2.3982)}$	DBH in cm (6, 200)*	30, 0.99	100	3	Brown, S. and Lugo, E. Q. (1992)
Stand in tropical mountain							
476	Pinus patula in Sao Hill Forest in Tanzania (867)	$Y(m3\ ha^{-1}) = \text{Exp}(-0.0476 + (1.00679 * \log(X)) - (1.4379/Z) + (0.88471 * \log_{10}(W)))$	As in m2, yr in yr, Hd in m (-, -)	-	0	2	Malimbwi, R. E., Mugasha, A. G., et al. (1998)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations			Variables X (min, max), W, Z, U and V		
Individual tree in tropical Subtropical humid forest (classification per tree species)							
477	Eucalyptus Camadulensis in Teza in South Africa (1344)	$\log_{10}Y(m3) = -4.584 + \log_{10}(X) + \log_{10}(z)$	DBH in cm, Ht in m (1, 20)*	0.99	100	2	Little, K. M. (2007)

Appendix V: Allometric equations predicting individual tree and stand biomass in sub-Saharan Africa.

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
Individual tree in tropical rainforest (classification per tree species)							
478	Gmelina arborea in Oluwa forest reserve in Nigeria (1545)	$\log Y(\text{kg}) = -3.38 + (0.92 * \log((X^2) * z))$	DBH in cm, H in m (1, 200)**	T+GB+TB+L+B+S+D	25, 0.99	100	2 Onyekwelu, J. C. (2004)
479	idem	$\log Y(\text{kg}) = -3.45 + (0.91 * \log((X^2) * z))$	DBH in cm, H in m (1, 200)**	T+B+S	25, 0.99	100	2 Onyekwelu, J. C. (2004)
480	idem	$\log Y(\text{kg}) = -5.57 + (0.94 * \log((X^2) * z))$	DBH in cm, H in m (1, 200)**	GB+TB+D	25, 0.99	100	2 Onyekwelu, J. C. (2004)
481	idem	$\log Y(\text{kg}) = -6.91 + (0.94 * \log((X^2) * z))$	DBH in cm, H in m (1, 200)**	L	25, 0.98	100	2 Onyekwelu, J. C. (2004)
482	idem	$\log Y(\text{kg}) = -5.82 + (2.41 * \log(X))$	DBH in cm (1, 200)**	L	25, 0.98	100	2 Onyekwelu, J. C. (2004)
483	idem	$\log Y(\text{kg}) = -4.36 + (2.39 * \log(X))$	DBH in cm (1, 200)**	GB+TB+D	25, 0.98	100	2 Onyekwelu, J. C. (2004)
484	idem	$\log Y(\text{kg}) = -2.24 + (2.3 * \log(X))$	DBH in cm (1, 200)**	T+B+S	25, 0.99	100	2 Onyekwelu, J. C. (2004)
485	idem	$\log Y(\text{kg}) = -2.07 + (2.3 * \log(X))$	DBH in cm (1, 200)**	T+GB+TB+L+B+S+D	25, 0.99	100	2 Onyekwelu, J. C. (2004)
486	Nauclea diderichii in Omo in Nigeria (2293)	$\log Y(\text{kg}) = -1.47 + 0.06 * X + 1.27 * \log((X^2))$	DBH in cm (1, 200)**	GB+TB	-	0	1 Onyekwelu, J. C. (2007)
487	idem	$\log Y(\text{kg}) = -3.65 + 1.46 * \log(X^2) + 0.00003 * (X^2) * z + 0.43 * \log(z)$	DBH in cm, H in m (1, 200)**	L	-	0	1 Onyekwelu, J. C. (2007)
488	idem	$\log Y(\text{kg}) = -2.92 + 1.28 * \log(X^2) + 0.06 * X$	DBH in cm (1, 200)**	L	-	0	1 Onyekwelu, J. C. (2007)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References
		Equations					
			Variables X (min, max), W, Z, U and V				
489	idem	$\log Y(\text{kg}) = -2.26 + 0.56 * \log((X^2) * Z) + 0.0009 * (X^2)$	DBH in cm, H in m (1, 200)**	GB+TB	-	28	1 Onyekwelu, J. C. (2007)
490	idem	$Y(\text{kg}) = 0.05 + 3.71 * X + 0.0007 * (X^2)$	DBH in cm (1, 200)**	T+GB+TB+L+B+S+D	-	96	2 Onyekwelu, J. C. (2007)
491	idem	$\log Y(\text{kg}) = 3.56 + 0.09 * X - 7.85 * (X^{-1})$	DBH in cm (1, 200)**	T+B	-	27	1 Onyekwelu, J. C. (2007)
492	idem	$\log Y(\text{kg}) = 0.35 + (1.38 * \log(X^2)) + 0.05 * X$	DBH in cm (1, 200)**	T+B	-	0	1 Onyekwelu, J. C. (2007)
493	idem	$\log Y(\text{kg}) = -0.07 + (0.55 * \log((X^2) * z)) + 0.0008 * (X^2)$	DBH in cm, H in m (1, 200)**	T+GB+TB+L+B+S+D	-	30	1 Onyekwelu, J. C. (2007)
494	idem	$\log Y(\text{kg}) = -0.216 + (0.55 * \log((X^2) * z)) + 0.0008 * (X^2)$	DBH in cm, H in m (1, 200)**	T+B	-	26	1 Onyekwelu, J. C. (2007)
495	idem	$\log Y(\text{kg}) = -1.97 + 0.5 * \log((X^2) * Z) + 0.0009 * (X^2) + 0.015 * Z$	DBH in cm, H in m (1, 200)**	GB+TB	-	27	1 Onyekwelu, J. C. (2007)
496	Terminalia ivorensis in Mbalmayo in Cameroon (2445)	$Y(\text{kg}) = 0.7631 * X$	As in cm2 (1, 22432)**	T+GB+TB+L+B+S+D	6, 0.99	96	2 Norgrove, L. and Hauser, S. (2002)
497	Terminalia superba in Kumasi in Ghana (1405)	$Y(\text{kg}) = 0.066 * (X^{(2.565)})$	DBH in cm (1, 200)**	T+GB+TB+L+B+S+D	-, 0.97	100	2 Asomaning, G. (2006)
498	Terminalia sp in Mbalmayo in Cameroon (2445)	$Y(\text{kg}) = 0.02489 * (X^2) * Z$	DBH in cm, H in m (1, 200)**	T+GB+TB+L+B+S+D+R1+R2+R3	6, 0.99	100	2 Deans, J. D., Moran, J., et al. (1996)
499	idem	$Y(\text{kg}) = 0.7631 * X$	As in cm2 (1, 22432)**	T+GB+TB+L+B+S+D+R1+R2+R3	6, 0.99	98	2 Deans, J. D., Moran, J., et al. (1996)
500	idem	$Y(\text{kg}) = 30.56 + 0.02435 * (X^2) * Z$	DBH in cm, H in m (1, 200)**	T+GB+TB+L+B+S+D+R1+R2+R3	6, 0.99	96	2 Deans, J. D., Moran, J., et al. (1996)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References
		Equations					
501	idem	Y(kg)= 26.15+0.7487*X	As in cm2 (1, 22432)**	T+GB+TB+L+B+S+D+R1+R2+R3	6, 0.99	95	Deans, J. D., Moran, J., et al. (1996)
General equations for individual tree in tropical rainforest							
502	Generalized in Mbalmayo in Cameroon (2445)	Y(kg)= 0.02477*(X^2)*Z	DBH in cm, H in m (1, 200)**	T+GB+TB+L+B+S+D+R1+R2+R3	14, 0.99	100	Deans, J. D., Moran, J., et al. (1996)
503	idem	Y(kg)= -0.259+0.1669*X+0.0006809*(X^2)	BA in cm2 (6, 120)*	GB+TB+D	-, 0.99	0	Deans, J. D., Moran, J., et al. (1996)
504	idem	Y(kg)= -0.969+0.236*X	BA in cm2 (6, 120)*	GB+TB+D	-, 0.98	0	Deans, J. D., Moran, J., et al. (1996)
505	idem	Y(kg)= -3.37+0.02483*(X^2)*Z	DBH in cm, H in m (5, 200)**	T+GB+TB+L+B+S+D+R1+R2+R3	14, 0.99	100	Deans, J. D., Moran, J., et al. (1996)
506	idem	Y(kg)= -30.87+0.7684*X	As in cm2 (50, 22432)**	T+GB+TB+L+B+S+D+R1+R2+R3	14, 0.97	100	Deans, J. D., Moran, J., et al. (1996)
507	idem	Y(kg)= 0.7489*X	As in cm2 (1, 22432)**	T+GB+TB+L+B+S+D+R1+R2+R3	14, 0.97	98	Deans, J. D., Moran, J., et al. (1996)
508	in Boi Tano in Ghana (2155)	Y(kg)= 0.30*X^(2.31)	DBH in cm (2, 180)*	T+GB+TB+L+B+S+D	42, 0.98adj	99	Henry, M., Besnard, A., et al. (2010)
509	in Maseno in Kenya (1819)	logY(kg)= (0.93*log((X^ 2)*Z))-2.97	DBH in cm, H in m (5, 32)	T+GB+TB+L+B+S	26,		3 Henry, M. (2009)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
				0.94adj			
510		$Y(kg) = \exp(-2.977 + \log(X \cdot Z^2 \cdot W))$	WD in g.cm-3, DBH in cm, H in m (-, -)**	T+GB+TB+L+B+S+D	143, 0.97adj	100	3 Chave, J., Andalo, C., et al. (2005)
511		$Y(kg) = \exp(-2.134 + 2.530 \cdot \log(X))$	DBH in cm (1, 80)*	T+GB+TB+L+B+S+D	-, 0.97adj	100	2 Ponce-Hernandez, R. (2004)
512		$Y(kg) = \text{EXP}(-2.409 + 0.9522 \cdot \text{LN}((X^2) \cdot Z \cdot W))$	DBH in cm, H in m, wd in g cm-3 (5, 130)	T+GB+TB+L+B+S+D	94, 0.99adj	100	3 Brown, S.A.J., Gillespie, J.R., et al. (1989)
513		$Y(kg) = \exp(-3.1141 + (0.9719 \cdot \log((X^2) \cdot Z)))$	DBH in cm, H in m (5, 130)	T+GB+TB+L+B+S+D	168, 0.97adj	100	3 Brown, S.A.J., Gillespie, J.R., et al. (1989)
514		$Y(kg) = 21.297 - 6.953 \cdot (X) + 0.740 \cdot ((X^2))$	DBH in cm (5, 112)*	T+GB+TB+L+B+S+D	169, 1adj	100	3 Brown, S. (1997)
515		$Y(kg) = \exp(-2.557 + 0.940 \cdot \log(X \cdot Z^2 \cdot W))$	WD in g.cm-3, DBH in cm, H in m (-, -)**	T+GB+TB+L+B+S+D	143, 0.97adj	100	3 Chave, J., Andalo, C., et al. (2005)
516		$Y(kg) = X \cdot \exp(-1.349 + (1.980 \cdot \log(Z)) + (0.207 \cdot (\log(Z))^2) - (0.0281 \cdot (\log(Z))^3))$	WD in g.cm-3, DBH in cm (-, -)**	T+GB+TB+L+B+S+D	143, 0.97adj	100	3 Chave, J., Andalo, C., et al. (2005)
517		$Y(kg) = X \cdot \exp(-1.239 + (1.98 \cdot \log(Z)) + (0.207 \cdot (\log(Z))^2) - (0.0281 \cdot (\log(Z))^3))$	WD in g.cm-3, DBH in cm (-, -)**	T+GB+TB+L+B+S+D	143, 0.97adj	100	3 Chave, J., Andalo, C., et al. (2005)
Stand in tropical rainforest							
518	Nauclea diderichii in Akure for in Nigeria (1390)	$\log Y(kg \text{ ha}^{-1}) = 38.41 - 8.23 \cdot X$	H in m	T+GB+TB+L+B+S+D	12, 0.71	-	2 Fuwape, J. A., Onyekwelu, J. C., et al.

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References
		Equations					
		Variables X (min, max), W, Z, U and V					
							(2001)
519	idem	$Y(\text{kg ha}^{-1}) = 26.341 - 10.16 * X$	H in m	12, 0.62	-	2	Fuwape, J. A., Onyekwelu, J. C., et al. (2001)
520	Terminalia superba in Gambari in Niger (1231)	$Y(\text{kg ha}^{-1}) = 1.51 + 10.5 * X$	yr in yr	-	-	2	Mbaekwe, E. I. and Mackenzie, J. A. (2008)
Individual tree in tropical moist deciduous forest (classification per tree species)							
521	Acacia erubescens in Botswana	$Y(\text{kg}) = 0.0137 * (X + Z + W)^{(3.2840)}$	H in m, CD in m, CD in m (3, 54)**	38, 0.91	0	1	Tietema, T. (1993)
522	Acacia karoo in Botswana	$Y(\text{kg}) = 0.0079 * (X + Z + W)^{(3.1858)}$	H in m, CD in m, CD in m (3, 54)**	41, 0.91	0	2	Tietema, T. (1993)
523	Acacia mellifera in Botswana	$Y(\text{kg}) = 0.0548 * (X + Z + W)^{(2.5767)}$	H in m, CD in m, CD in m (3, 54)**	27, 0.9	0	2	Tietema, T. (1993)
524	Acacia tortillis in Botswana	$Y(\text{kg}) = 0.0096 * (X + Z + W)^{(3.3015)}$	H in m, CD in m, CD in m (3, 54)**	50, 0.9	0	2	Tietema, T. (1993)
525	Combretum geitonophyllum in Saré Yorobana in Senegal (1022)	$Y(\text{kg}) = 0.103 * (X^{2.44})$	DBH in cm (1, 200)**	40, 0.95	99	3	Manlay, R.J., Kairé, M., et al. (2002)
526	idem	$Y(\text{kg}) = 0.2046 * x^{(1.63)}$	DBH in cm (1, 200)**	41, 0.86	93	2	Kaire, M. (1999)
527	idem	$Y(\text{kg}) = 0.205 * (X^{1.63})$	BD in cm (1, 225)**	41, 0.88	89	1	Manlay, R.J., Kairé, M., et al. (2002)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References
		Equations					
528	idem	Y(kg)= 0.283*(X^2.17)	DBH in cm (1, 20)*	T+GB+TB+L+B+S+D	40, 0.97	90	1 Manlay, R.J., Kairé, M., et al. (2002)
529	idem	Y(kg)= 0.0682*(X^1.74)	Bd in cm (1, 25)*	L	40, 0.95	100	3 Manlay, R.J., Kairé, M., et al. (2002)
530	idem	Y(kg)= 0.07*x^(1.74)	DBH in cm (1, 200)**	L	40, 0.94	99	3 Manlay, R.J., Kairé, M., et al. (2002)
531	idem	Y(kg)= 0.0947*(X^2.15)	DBH in cm (1, 200)**	GB+TB+D	40, 0.96	93	3 Manlay, R.J., Kairé, M., et al. (2002)
532	Combretum glutinosum in Saré Yorobana in Senegal (1022)	Y(kg)= 0.0512*X^(2.63)	DBH in cm (1, 20)*	T+GB+TB+L+B+S+D	41, 0.97	100	3 Kaire, M. (1999)
533	idem	Y(kg)= 0.0676*(X^1.99)	DBH in cm (1, 200)**	L	41, 0.94	98	3 Manlay, R.J., Kairé, M., et al. (2002)
534	idem	Y(kg)= 0.149*(X^2.33)	Bd in cm (1, 25)*	T+GB+TB+L+B+S+D	41, 0.98	83	1 Manlay, R.J., Kairé, M., et al. (2002)
535	idem	Y(kg)= 0.0782*(X^2.16)	DBH in cm (1, 200)**	GB+TB+D	41, 0.95	97	3 Manlay, R.J., Kairé, M., et al. (2002)
536	idem	Y(kg)= 0.175*(X^1.78)	BD in cm (1, 225)**	S	40, 0.81	89	1 Manlay, R.J., Kairé, M., et al. (2002)
537	idem	Y(kg)= 0.0965*(X^2.43)	DBH in cm (1, 200)**	T+B	41, 0.97	100	3 Manlay, R.J., Kairé, M., et

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations					
							al. (2002)
538	idem	Y(kg)= 0.1753*x^(1.78)	DBH in cm (1, 200)**	S	40, 0.8	91	2 Kaire, M. (1999)
539	Dichrostachys cinerea in Botswana	Y(kg)= 0.0029*(X+Z+W)^(3.7422)	H in m, CD in m, CD in m (3, 54)**	T+GB+TB+L+B+S+D	33, 0.94	0	1 Tietema, T. (1993)
540	Khaya senegalensis in Badénou in Ivory Coast (1211)	Y(kg)= 2.2598-3.4804*x+1.6684*(X^2)	C in m (1, 6)**	T+GB+TB+B+S+D	84	100	2 Louppe, D., M’BlaKoua, et al. (1994)
541	idem	Y(kg)= 0.0213+0.01953*(X^2)*Z	C in m, H in m (3, 628)**	T+GB+TB+B+S+D	84	0	1 Kaire, M. (1999)
542	Piliostigma thonningii in Saré Yorobana in Senegal (1022)	Y(kg)= 0.0554*(X^1.79)	DBH in cm (1, 200)**	L	40, 0.88	99	3 Manlay, R.J., Kairé, M., et al. (2002)
543	idem	Y(kg)= 0.0898*(X^2.29)	DBH in cm (1, 200)**	T+B	40, 0.94	100	3 Manlay, R.J., Kairé, M., et al. (2002)
544	idem	Y(kg)= 0.149*(X^1.66)	DBH in cm (1, 200)**	S	40, 0.89	95	3 Manlay, R.J., Kairé, M., et al. (2002)
545	idem	Y(kg)= 0.97*X^(1.66)	BD in cm (1, 225)**	S	40, 0.87	31	1 Kaire, M. (1999)
546	idem	Y(kg)= 0.157*(X^2.27)	DBH in cm (1, 20)*	T+GB+TB+L+B+S+D	40, 0.97	100	3 Manlay, R.J., Kairé, M., et al. (2002)
547	idem	Y(kg)= 0.0785*(X^1.99)	DBH in cm (1, 200)**	GB+TB+D	40, 0.96	97	3 Manlay, R.J., Kairé, M., et al. (2002)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References	
		Equations						Variables X (min, max), W, Z, U and V
548	Terminalia macroptera in Saré Yorobana in Senegal (1022)	Y(kg)= 0.035*(X^2.02)	DBH in cm (1, 200)**	L	40, 0.88	99	3	Manlay, R.J., Kairé, M., et al. (2002)
549	idem	Y(kg)= 0.0966*(X^2.52)	DBH in cm (1, 200)**	T+B	40, 0.96	100	3	Manlay, R.J., Kairé, M., et al. (2002)
550	idem	Y(kg)= 0.0626*(X^2.38)	DBH in cm (1, 200)**	GB+TB+D	40, 0.97	97	3	Manlay, R.J., Kairé, M., et al. (2002)
551	idem	Y(kg)= 0.0507*x^(1.97)	BD in cm (1, 225)**	S	40, 0.95	93	2	Kaire, M. (1999)
552	idem	Y(kg)= 0.155*(X^1.69)	DBH in cm (1, 200)**	S	40, 0.92	95	3	Manlay, R.J., Kairé, M., et al. (2002)
553	idem	Y(kg)= 0.0979*(X^2.4)	DBH in cm (1, 20)*	T+GB+TB+L+B+S+D	40, 0.96	100	3	Manlay, R.J., Kairé, M., et al. (2002)
554	Ziziphus mucronata in Botswana	Y(kg)= 0.013*(X+Z+W)^(2.8625)	H in m, CD in m, CD in m (3, 54)**	T+GB+TB+L+B+S+D	17, 0.96	0	2	Tietema, T. (1993)
Individual tree in tropical moist deciduous forest (classification per group of tree species)								
555	Group 69 in Saré Yorobana in Senegal (1022)	Y(kg)= 0.0965*(X^2.42)	Bd in cm (1, 25)*	T+B	161, 0.95	100	3	Manlay, R.J., Kairé, M., et al. (2002)
556	idem	Y(kg)= 0.172*(X^2.29)	DBH in cm (1, 20)*	T+GB+TB+L+B+S+D	161, 0.94	100	3	Manlay, R.J., Kairé, M., et al. (2002)
557	idem	Y(kg)= 0.0785*(X^2.17)	Bd in cm (1, 25)*	GB+TB+D	40, 0.98	100	3	Manlay, R.J., Kairé, M., et

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References
		Equations					
			Variables X (min, max), W, Z, U and V				
							al. (2002)
558	idem	$Y(\text{kg}) = 0.0566 \cdot (X^{1.89})$	Bd in cm (1, 25)*	L	40, 0.96	100	3 Manlay, R.J., Kairé, M., et al. (2002)
559	idem	$Y(\text{kg}) = 0.171 \cdot (X^{1.69})$	DBH in cm (1, 200)**	S	40, 0.8	93	3 Manlay, R.J., Kairé, M., et al. (2002)
General equations for individual tree in tropical moist deciduous forest							
560	Generalized in Uganda	$Y(\text{kg}) = -1.198 + 1.556 \cdot \text{LOG}(X) + 0.55 \cdot \text{LOG}(Z) + 0.435 \cdot \text{LOG}(W)$	DBH in cm, H in m, CR in 100 (2, 200)**	T+GB+TB+L+B+S+D	1695, 0.88	0	2 Velle, K. (1995)
561	idem	$Y(\text{kg}) = 13.18334 + 0.06259 \cdot X^{(2)} \cdot Z$	DBH in cm, H in m (1, 200)**	T+GB+TB+L+B+S+D	1695, 0.75	0	2 Velle, K. (1995)
562	idem	$Y(\text{kg}) = -0.89 + 2.053 \cdot \text{LOG}(X)$	DBH in cm (2, 200)**	T+GB+TB+L+B+S+D	1695, 0.81	0	2 Velle, K. (1995)
563	idem	$Y(\text{kg}) = -4.22412 + 0.56 \cdot X^{(2)}$	DBH in cm (3, 200)**	T+GB+TB+L+B+S+D	1695, 0.73	0	2 Velle, K. (1995)
564	in Zambia	$Y(\text{kg}) = 23.34 \cdot X - 218.34$	DBH in cm (10, 30)	T+GB+TB+L+B+S+D	20	0	2 Chimudayo, E. N. (1990)
565	idem	$Y(\text{kg}) = 1.6 \cdot X - 4$	BD in cm (3, 10)*	T+GB+TB+L+B+S+D	7, 0.94	0	3 Chimudayo, E. N. (1990)
566	idem	$\log Y(\text{kg}) = -0.739 + 0.89 \cdot \text{LOG}(X) + 0.132 \cdot \text{LOG}(X^2) + 0.913 \cdot \text{LOG}(Z) - 0.103 \cdot \text{LOG}(Z^2)$	DBH in cm, H in m (2, 70)	T+GB+TB+L+B+S+D	271, 0.72	0	3 Stromgaard, P. (1986)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References
		Equations					
567	idem	$Y(kg) = 0.3623 * X^{(1.382)} * Z^{(0.640)}$	DBH in cm, H in m (2, 70)	T+GB+TB+L+B+S+D	271, 0.71	0	3 Stromgaard, P. (1986)
568		$Y(kg) = X * \exp(-1.499 + (2.148 * \log(Z)) + (0.207 * (\log(Z))^2 - (0.0281 * (\log(Z))^3)))$	WD in g.cm-3, DBH in cm (-, -)**	T+GB+TB+L+B+S+D	1349, 0.99	100	3 Chave, J., Andalo, C., et al. (2005)
569		$Y(kg) = \exp(-2.134 + 2.530 * \log(X))$	DBH in cm (1, 80)*	T+GB+TB+L+B+S+D	-, 0.97	100	2 Ponce-Hernandez, R. (2004)
570		$Y(kg) = \exp(-2.409 + 0.9522 * \ln((X^2) * Z * W))$	DBH in cm, H in m, wd in g cm-3 (5, 148)	T+GB+TB+L+B+S+D	168, 0.99	100	3 Brown, S.A.J., Gillespie, J.R., et al. (1989)
571		$Y(kg) = 42.69 - 12.800 * (X) + 1.242 * ((X^2))$	DBH in cm (5, 148)*	T+GB+TB+L+B+S+D	170, 1*	100	3 Brown, S. (1997)
572		$Y(kg) = \exp(-2.977 + \log(X * Z^2 * W))$	WD in g.cm-3, DBH in cm, H in m (-, -)**	T+GB+TB+L+B+S+D	1349, 0.99	100	3 Chave, J., Andalo, C., et al. (2005)
573		$Y(kg) = \exp(-3.1141 + (0.9719 * \log((X^2) * Z)))$	DBH in cm, H in m (5, 148)	T+GB+TB+L+B+S+D	168, 0.97	100	3 Brown, S.A.J., Gillespie, J.R., et al. (1989)
Stand in tropical rainforest							
574	Generalized in Boulador in Senegal (1124)	$Y(kg\ ha^{-1}) = 24240 * (1 - \exp(-2 * 5111 * X / 24240))^2$	Yr in Yr	T+GB+TB+L+B+S+D	18	-	2 Manlay, R.J., Kairé, M., et al. (2002)
575	in Guiro yorobocar in Senegal (1022)	$Y(kg\ ha^{-1}) = 39435 * (1 - \exp(-2 * 6700 * X / 39435))^2$	Yr in Yr	T+GB+TB+L+B+S+D	17	-	2 Manlay, R.J., Kairé, M., et al. (2002)
576	in Saré Yorobana in Senegal (1022)	$Y(kg\ ha^{-1}) = 42353 * (1 - \exp(-2 * 4364 * X / 42353))^2$	Yr in Yr	T+GB+TB+L+B+S+D	17	-	2 Manlay, R.J., Kairé, M., et al. (2002)

ID	Tree species and location (annual rainfall)	Model	Variables X (min, max), W, Z, U and V	Tree components	n, R2	Interval of possibility (%)	Quality	References
Individual tree in tropical dry forest (classification per tree species)								
577	Acacia auriculiformis in Loandjili in Congo (1208)	$Y(kg) = 4.16 \cdot 10^{(-4)} \cdot X^{(3)} + 11.22$	C10 in cm (4, 653)**	T+GB+TB+B+S+D	8, 0.96	63	1	Bernhard-Reversat, F., Dianganam, D., et al. (1993)
578	idem	$Y(kg) = 2.02 \cdot 10^{(-5)} \cdot X^{(3)} + 2.36$	C10 in cm (4, 653)**	L	8, 0.8	97	2	Bernhard-Reversat, F., Dianganam, D., et al. (1993)
579	Acacia laeta in mare d'Oursi in Burkina Faso (846)	$Y(g) = 142 \cdot X + 216.6$	DBH in cm (1, 200)**	L	-	98	2	Bellefontaine, R., Gaston, A., et al. (1997)
580	Acacia mangium in Loandjili in Congo (1208)	$Y(kg) = 2.69 \cdot 10^{(-5)} \cdot X^{(3)} + 0.25$	C10 in cm (4, 653)**	L	8, 0.87	99	2	Bernhard-Reversat, F., Dianganam, D., et al. (1993)
581	in Pointe noire in Congo (1208)	$Y(kg) = 3.57 \cdot 10^{(-4)} \cdot X^{(3)} + 19.2$	C10 in cm (4, 653)**	T+GB+TB+B+S+D	-	96	2	Bernhard-Reversat, F., Dianganam, D., et al. (1993)
582	Acacia senegal in Boboyo in Cameroon (782)	$Y(kg) = 443.929 \cdot (X^{(2.3783)})$	Cb in m (0, 7)**	T+GB+TB+B+S+D	37, 0.86	98	2	Smektala, G., Hautdidier, B., et al. (2002)
583	Acacia tortillis in mare d'Oursi in Burkina Faso (846)	$Y(g) = 52.5 \cdot X - 44.64$	DBH in cm (1, 200)**	L	-	100	2	Bellefontaine, R., Gaston, A., et al. (1997)
584	in Klaserie in South Africa	$Y(kg) = 0.1975 \cdot (X^{1.1859})$	BA in cm2 (1, 39879)**	T+GB+TB+L+B+S+D	109, 0.93	97	2	Tietema, T. (1993)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References
		Equations					
(410)							
585	Colophospermum mopane in Dukwe in Botswana (351)	Y(kg)= 0.0644*(X^1.3341)	BA in cm2 (1, 39879)**	T+GB+TB+L+B+S+D	36, 0.95	100	2 Tietema, T. (1993)
586	Combretum aculeatum in mare d'Oursi in Burkina Faso (846)	Y(g)= 60.57*X-17.66	H in cm (292, 5369)**	L	-	86	1 Bellefontaine, R., Gaston, A., et al. (1997)
587	Combretum glutinosum in Mali	Y(kg)= 2.8*10^(-3)*X^(2.3)	C in cm (3, 628)**	T+B	-	100	2 Alexandre, D.-Y., and Kaïré, M. (2001)
588	Eucalyptus donai in Evander in South Africa (748)	Y(kg)= -0.0582+0.0206*(X^2)	DBH in cm (3, 11)	L	4, 0.92*	100	3 Schonau, A.P.G. and Boden, D.I. (1981)
589	idem	Y(kg)= 0.0645+0.0223*(X^2)	DBH in cm (3, 11)	B	4, 1*	89	1 Schonau, A.P.G. and Boden, D.I. (1981)
590	idem	Y(kg)= -0.4104+0.0673*(X^2)	DBH in cm (3, 11)	GB+TB	4, 0.99*	100	3 Schonau, A.P.G. and Boden, D.I. (1981)
591	idem	Y(kg)= -0.1960+0.1072*(X^2)	DBH in cm (3, 11)	T+B+S	4, 1*	100	3 Schonau, A.P.G. and Boden, D.I. (1981)
592	Eucalyptus emithii in Evander in South Africa (748)	Y(kg)= -0.4622+0.0445*(X^2)	DBH in cm (4, 11)*	L	4, 0.89*	100	3 Schonau, A.P.G. and Boden, D.I. (1981)
593	idem	Y(kg)= -0.0859+0.0239*(X^2)	DBH in cm (3, 11)	B	4, 0.99*	100	3 Schonau, A.P.G. and Boden, D.I. (1981)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References
		Equations					
594	idem	Y(kg)= -1.5351+0.1294*(X^2)	DBH in cm (4, 11)*	GB+TB	4, 0.94*	25	1 Schonau, A.P.G. and Boden, D.I. (1981)
595	idem	Y(kg)= -0.5217+0.1286*(X^2)	DBH in cm (3, 11)	T+B+S	4, 0.99*	100	3 Schonau, A.P.G. and Boden, D.I. (1981)
596	Eucalyptus globulus in Evander in South Africa (748)	Y(kg)= -0.1459+0.0552*(X^2)	DBH in cm (3, 11)	GB+TB	4, 0.96*	100	3 Schonau, A.P.G. and Boden, D.I. (1981)
597	idem	Y(kg)= -1.1054+0.1924*(X^2)	DBH in cm (3, 11)	T+B+S	4, 0.99*	100	3 Schonau, A.P.G. and Boden, D.I. (1981)
598	idem	Y(kg)= 0.2839+0.0202*(X^2)	DBH in cm (3, 11)	B	4, 0.9*	78	1 Schonau, A.P.G. and Boden, D.I. (1981)
599	idem	Y(kg)= -0.6006+0.0588*(X^2)	DBH in cm (4, 11)*	L	4, 0.89*	100	3 Schonau, A.P.G. and Boden, D.I. (1981)
600	Eucalyptus nitens in Evander in South Africa (748)	Y(kg)= -0.6819+0.077*(X^2)	DBH in cm (3, 11)	GB+TB	4, 0.85*	100	3 Schonau, A.P.G. and Boden, D.I. (1981)
601	idem	Y(kg)= -0.2147+0.0371*(X^2)	DBH in cm (3, 11)	L	4, 0.95*	100	3 Schonau, A.P.G. and Boden, D.I. (1981)
602	idem	Y(kg)= 0.0967+0.0248*(X^2)	DBH in cm (3, 11)	B	4, 1*	89	1 Schonau, A.P.G. and Boden, D.I. (1981)
603	idem	Y(kg)= -0.5847+0.1683*(X^2)	DBH in cm (3, 11)	T+B+S	4, 0.99*	100	3 Schonau, A.P.G. and Boden, D.I. (1981)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References
		Equations					
604	Eucalyptus sp in Pointe noire in Congo (1208)	$Y(kg) = 0.01 * X + (11.67 - 0.084 * X) * (Z^2) * W$	Yr in Yr, DBH in m, H in m (-, -)	D	70, 0.22	-	3 Saint-André, L., M'Bou, A.T., et al. (2005)
605	idem	$Y(kg) = 1249.8 * X^{(2.52)}$	DBH in m (0, 2)**	R1	18, 0.89	100	3 Saint-André, L., M'Bou, A.T., et al. (2005)
606	idem	$Y(kg) = 1.4 * (((X^2) * Z)^{0.46})$	DBH in m, H in m (0, 2)**	R2	18, 0.84	99	3 Saint-André, L., M'Bou, A.T., et al. (2005)
607	idem	$Y(kg) = 5.06 * (((X^2) * Z)^{0.3})$	DBH in m, H in m (0, 2)**	R3	18, 0.84	97	3 Saint-André, L., M'Bou, A.T., et al. (2005)
608	idem	$Y(kg) = 5.37 + 235.2 * (X^2) * Z$	DBH in m, H in m (0, 2)**	T+GB+TB+L+B+S+D+R1+R2+R3	18, 0.84	98	3 Saint-André, L., M'Bou, A.T., et al. (2005)
609	idem	$Y(kg) = 13.73 * ((X^2) * Z)^{0.7}$	DBH in m, H in m (0, 2)**	S	29, 0.95	99	3 Saint-André, L., M'Bou, A.T., et al. (2005)
610	idem	$Y(kg) = 0.22 + (132.4 + 0.27 * X) * (Z^2) * W$	Yr in Yr, DBH in m, H in m (-, -)	T	70, 0.99	-	3 Saint-André, L., M'Bou, A.T., et al. (2005)
611	idem	$Y(kg) = (7.78 + 1224.1 * \exp(-0.18 * X)) * (Z^2) * W$	Yr in Yr, DBH in m, H in m (-, -)	GB+TB	70, 0.77	-	3 Saint-André, L., M'Bou, A.T., et al. (2005)
612	idem	$Y(kg) = 38.1 * ((X^2) * z)^{0.62}$	DBH in m, H in m (0, 2)**	R1	18, 0.98	93	3 Saint-André, L., M'Bou, A.T., et al. (2005)
613	idem	$Y(kg) = 2.76 + 182.7 * (X^2) * z$	Yr in Yr, DBH in m (0, 2)**	T+GB+TB+L+B+S	70, 0.99	98	3 Saint-André, L., M'Bou, A.T., et al. (2005)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References
		Equations					
614	idem	Y(kg)= 1.507+0.0001109*(X^3)+0.00004832*(z^2)*(X^2)	C in cm, Yr in Yr (-, -)	S+R1	80, 0.97	-	2 Laclau, J.-P., Bouillet, J.-P., et al. (2000)
615	idem	Y(kg)= -2.443+2.805*z-0.143*(z^2)- (0.0185+0.0639*z)*X+(0.003357+4.8391^(- 5)*(z^2))*(X^2)	C in cm, Yr in Yr (-, -)	R2	80, 0.69	-	2 Laclau, J.-P., Bouillet, J.-P., et al. (2000)
616	idem	Y(kg)= -0.2051- 0.8321*z+0.1729*X+0.00003008*(z^2)*(X^2)	C in cm, Yr in Yr (-, -)	GB+TB	80, 0.71	-	2 Laclau, J.-P., Bouillet, J.-P., et al. (2000)
617	idem	Y(kg)= (-0.9335-0.5551*z+0.3147*(z^2))+(0.3145- 0.1059*z)*x+0.0007208*z*(X^2)	C in cm, Yr in Yr (-, -)	L	80, 0.88	-	2 Laclau, J.-P., Bouillet, J.-P., et al. (2000)
618	idem	Y(kg)= 0.089+(0.001895+0.000113*z)*x	C in cm, Yr in Yr (-, -)	B	80, 0.98	-	2 Laclau, J.-P., Bouillet, J.-P., et al. (2000)
619	idem	Y(kg)= 9.08*((X^2)*Z)^0.72	DBH in m, H in m (0, 2)**	B	70, 0.98	99	3 Saint-André, L., M'Bou, A.T., et al. (2005)
620	idem	Y(kg)= 0.117-(0.02243*(z^2))*x+0.008852*(X^2)	C in cm, Yr in Yr (-, -)	T	80, 0.99	-	2 Laclau, J.-P., Bouillet, J.-P., et al. (2000)
621	idem	Y(kg)= 0.6+(5.26-0.024*X+565.1*exp(-0.15*X)*(Z^2)*W)	Yr in Yr, DBH in m, H in m (-, -)	L	70, 0.96	-	3 Saint-André, L., M'Bou, A.T., et al. (2005)
622	Eucalyptus viminalis in Evander in South Africa (748)	Y(kg)= -0914+0.1975*(X^2)	DBH in cm (3, 11)	T+B+S	5, 0.98*	100	3 Schonau, A.P.G. and Boden, D.I. (1981)
623	idem	Y(kg)= 0.4964+0.457*(X^2)	DBH in cm (3, 11)	GB+TB	5, 0.64*	0	1 Schonau, A.P.G. and

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References
		Equations					
							Boden, D.I. (1981)
624	idem	Y(kg)= -0.1807+0.0343*(X^2)	DBH in cm (3, 11)	L	5, 0.98*	100	3 Schonau, A.P.G. and Boden, D.I. (1981)
625	idem	Y(kg)= -0.1508+0.0392*(X^2)	DBH in cm (3, 11)	B	5, 1*	100	3 Schonau, A.P.G. and Boden, D.I. (1981)
626	Faidherbia albida in Mali	Y(g)= 98*10^(-6)*(X^2.77)	H in cm (292, 5369)**	L	-, 0.95	86	1 CTFT (1988)
627	idem	Y(g)= (X^2.08)	C in cm (3, 628)**	L	-, 0.98	100	2 CTFT (1988)
628	idem	Y(g)= 0.32*(X^1.26)	As in dm2 (0, 224)**	L	-, 0.96	100	2 CTFT (1988)
629	Guiera senegalensis in Burkina Faso	Y(kg)= 0.39*x^(1.6)	DBH in cm (1, 200)**	T+GB+TB+B+S+D	-	99	2 Neya, B., Kaboré, C., et al. (1998)
630	Vitellaria paradoxa in Mafa Kilda in Cameroon (997)	Y(kg)= 0.080*(X^(2.46))	DBH in cm (15, 53)	T+GB+TB+L+B+S+D	8, 0.7*	100	3 Peltier, R., Njiti, C.F., et al. (2007)
Stand in tropical dry forest							
631	Generalized in Sonkorong in Senegal (682)	Y(kg ha-1)= 33338*(1-exp(-2*2245*X/33338))^2	Yr in Yr	T+GB+TB+L+B+S+D	15	-	2 Manlay, R.J., Kairé, M., et al. (2002)
General equations for individual tree in tropical dry forest							
632	Generalized in Burkina Faso	Y(g)= 1.8*x^(2.5)	C in cm (6, 36)	T+GB+TB+L+B+S+D	-	100	2 Neya, B., Kaboré, C., et al.

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References
		Equations					
							(1998)
633	idem	Y(kg)= 0.1263+0.1006*X	BA in cm2 (8, 560)	T+GB+TB+B+L+S+D	825	100	2 Nouvellet, Y., Sawadogo, L. (1994)
634	in Boucle du Mouhoun in Burkina Faso (796)	Y(kg)= -1.2286732+0.70230016*X+0.1049166*(X^3)	DBH in cm (2, 200)**	T+GB+B+S+D	118, 0.86*	1	1 Kaboré, C. (1992)
635	in Mali	log10Y(kg)= -2.26+(2.4*log10(X^0.8))	DBH in cm (1, 200)**	T+GB+B+S+D	-, 0.91	100	2 Alexandre, D.-Y., and Kaïré, M. (2001)
636	in Mozambique	Y(kg)= -41.077+2.816554*X+0.35657*(X^2)	DBH in cm (8, 200)**	T+GB+TB+L+B+S+D	290, 0.86	100	2 Sitoe, A. A. and Tchaúque, F. (2007)
637	idem	Y(kg)= (X*(0.214*(Z*3.1416)-0.113)^2)/10	H in m, DBH in cm (3, 54)**	T+GB+TB+L+B+S+D	-, 0.92adj	100	2 de Boer, W.F. (2000)
638	idem	Y(Mg)= 3.01*X-7.48	DBH in cm (3, 100)*	T+GB+TB5+B+S	-, 0.88	0	1 Williams, M., Ryan, C.M., et al. (2008)
639	idem	Y(Mg)= 20.02*X-203.37	DBH in cm (100, 200)*	T+GB+TB5+B+S	-, 0.95	0	1 Williams, M., Ryan, C.M., et al. (2008)
640	in Senegal	Y(kg)= 0.17*x^(2.6)	DBH in cm (1, 200)**	T+GB+TB+B+S+D	-	7	1 Kairé, M. (1998)
641	idem	Y(kg)= exp(-2.289+(2.649*log(X))-(0.021*log((X^2))))	DBH in cm (1, 148)*	T+GB+TB+L+B+S+D	-, 0.95adj	100	2 Kaire, M. (1999)
642	in Kitulangalo forest, Morogoro in Tanzania (935)	logY(kg)= 0.0625+2.553*log(X)	DBH in cm (2, 50)	T+GB+TB+L+B+S+D	30, 0.95adj	0	1 Chamshama, S. A. O., Mugasha, A. G., et al. (2004)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References
		Equations					
643	idem	$\log Y(\text{kg})= 0.0016+0.421*\log(X)+3.712*\log(Z)$	DBH in cm, H in m (2, 50)	GB+TB+L+D	30, 0.93	0	1 Chamshama, S. A. O., Mugasha, A. G., et al. (2004)
644	idem	$\log Y(\text{kg})= 0.0219+1.4498*\log(X)+1.7907*\log(Z)$	DBH in cm, H in m (1, 50)	T+B+S	30, 0.93adj	0	1 Chamshama, S. A. O., Mugasha, A. G., et al. (2004)
645	idem	$\log Y(\text{kg})= 0.0014+(0.898*\log(X))+(3.09*\log(Z))$	BD in cm, H in m (2, 50)	GB+TB+L+D	30, 0.93adj	0	1 Chamshama, S. A. O., Mugasha, A. G., et al. (2004)
646	idem	$\log Y(\text{kg})= 0.01559+2.796*\log(X)$	BD in cm (2, 50)	T+B+S	30, 0.93adj	0	1 Chamshama, S. A. O., Mugasha, A. G., et al. (2004)
647	idem	$\log Y(\text{kg})= 0.0139+(1.9037*\log(X))+(0.327*\log(Z))$	BD in cm, H in m (2, 50)	T+GB+TB+L+B+S+D	30, 0.93adj	0	1 Chamshama, S. A. O., Mugasha, A. G., et al. (2004)
648	in Kitulanghalo forest reserce in Tanzania (956)	$Y(\text{kg})= 0.06*(X^{(2.012)})*(Z^{(0.7)})$	DBH in cm, h in m (1, 200)**	T+GB+TB+B+S+D	17, 0.93adj	100	2 Luoga, E. L., Witkowski, E. T. F., et al. (2002)
649	in Sengwa Wildlife Research area in Zimbabwe (688)	$Y(\text{kg})= 0.0549*(X^{(2.5101)})$	BD in cm (6, 225)*	T+GB+TB6+B+S	-	100	2 Guy, P. R. (1981)
650	idem	$Y(\text{kg})= 1.2102*(X^{(0.9138)})$	CV in cm3	T+GB+TB6+B+S	-	-	2 Guy, P. R. (1981)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References	
		Equations						Variables X (min, max), W, Z, U and V
651		Y(kg)= exp(-2.187+(0.916*log(X*Z^2*W)))	WD in g.cm-3, DBH in cm, H in m (-, -)**	T+GB+TB+L+B+S+D	316	100	3	Chave, J., Andalo, C., et al. (2005)
652		Y(kg)= X*exp(-0.667+(1.784*log(Z))+(0.207*(log(Z))^2-(0.0281*(log(Z))^3))	WD in g.cm-3, DBH in cm (-, -)**	T+GB+TB+L+B+S+D	316	99	3	Chave, J., Andalo, C., et al. (2005)
653		Y(kg)= 34.4703-8.0671*X+0.6589*(X^2)	DBH in cm (6, 40)*	T+GB+TB+L+B+S+D	32, 0.67*	100	3	Brown, S.A.J., Gillespie, J.R., et al. (1989)
654		Y(kg)= exp(-1.996+2.32*log(X))	DBH in cm (1, 40)*	T+GB+TB+L+B+S+D	28, 1*	100	3	Brown, S. (1997)
655		Y(kg)= 10^(-0.535+log ₁₀ (X))	BA in cm2 (1, 707)*	T+GB+TB+L+B+S+D	191, 1*	86	1	Brown, S. (1997)
Individual tree in tropical shrubland (classification per tree species)								
656	Acacia albida in Mali	Y(g)= X^(2.08)	C in cm (5, 61)	L	50, 0.98	100	3	Cissé, M. I. (1980)
657	idem	Y(g)= 98*(10^(-6))*X^(2.77)	H in cm (292, 5369)**	L	50, 0.95	86	1	Cissé, M. I. (1980)
658	idem	Y(g)= 0.32*(X^1.26)	CA in dm2 (78, 67214)**	L	50, 0.96	99	2	Cissé, M. I. (1980)
659	Acacia erioloba in Modubwana in Botswana (471)	Y(kg)= 0.1376*(X^(1.2562))	BA in cm2 (1, 39879)**	T+GB+TB+L+B+S+D	27, 0.92	100	2	Tietema, T. (1993)
660	Acacia erubescens in Dikelestane in Botswana (471)	Y(kg)= 0.1507*(X^(1.2647))	BA in cm2 (1, 39879)**	T+GB+TB+L+B+S+D	88, 0.96	96	2	Tietema, T. (1993)
661	Acacia karoo in Dikelestane in Botswana (471)	Y(kg)= 0.7558*(X^1)	BA in cm2 (1, 39879)**	T+GB+TB+L+B+S+D	36, 0.98	91	2	Tietema, T. (1993)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References	
		Equations			Variables X (min, max), W, Z, U and V			
662	in Dikeletsane in Botswana (471)	Y(kg)= 0.2865*(X^(1.2082))	BA in cm2 (1, 1500)*	T+GB+TB+L+B+S+D	36, 0.96	0	1	Tietema, T. (1993)
663	Acacia luederitzii in Kang in Botswana (400)	Y(kg)= 0.1505*(X^(1.2835))	BA in cm2 (1, 39879)**	T+GB+TB+L+B+S+D	19, 0.94	0	1	Tietema, T. (1993)
664	Acacia mellifera in Gaborone in Botswana (552)	Y(kg)= 0.2081*(X^(1.2193))	BA in cm2 (1, 39879)**	T+GB+B+S	35, 0.96	34	1	Tietema, T. (1993)
665	in Molepolole in Botswana (466)	Y(kg)= 0.2081*(X^1.2193)	BA in cm2 (1, 39879)**	T+GB+TB+L+B+S+D	35, 0.96	89	1	Tietema, T. (1993)
666	Acacia senegal in Tongomayel in Burkina Faso (429)	log10Y(g)= -0.12+(2.64*log(X))	DBH in cm (1, 200)**	L	16, 0.97	98	2	Sanon, H. O., Kaboré- Zoungrana, C., et al. (2007)
667	in Mali	Y(g)= 14.05*(X^(1.40))	C in cm (3, 628)**	L	-, 0.72	99	2	Bellefontaine, R., Gaston, A., et al. (1997)
668	in Fété Olé in Senegal (224)	Y(kg)= -8+0.57*X	R in n (18, 70)*	T+B+S	8, 0.69	64	1	Poupon, H. (1976)
669	idem	log10Y(kg)= -3.07+(2.86*log10(X))	Cb in cm (4, 708)**	T+GB+TB+B+S+D	21, 0.8	78	1	Poupon, H. (1979)
670	idem	log10Y(kg)= -1.01+(1.56*log10(X))	Cb in cm (4, 708)**	R1+R2+R3	6	89	1	Poupon, H. (1979)
671	idem	Y(kg)= -19.2+1.11*X	R in n (18, 70)*	GB	8, 0.99	0	1	Poupon, H. (1976)
672	idem	log10Y(kg)= -1.22+(1.88*log10(X))	Cb in cm (4, 708)**	T+GB+TB+B+S+D+R1+R2+R3	6, 0.99	96	2	Poupon, H. (1979)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References
		Equations					
			Variables X (min, max), W, Z, U and V				
673	idem	$Y(kg) = -18.2 + 1.32 * X$	R in n (18, 70)*	R1+R2+R3	8, 0.99	0	1 Poupon, H. (1976)
674	idem	$Y(kg) = 11.0463 - 2.0733 * X + 0.1067 * X^2 - 0.0009 * X^3$	R in n (12, 63)*	T+GB+TB+B+S+D	8, 0.99	18	1 Poupon, H. (1976)
675	idem	$\log_{10}Y(kg) = -1.55 + (1.57 * \log_{10}(X))$	R in n (12, 70)*	TB	8, 0.99	0	1 Poupon, H. (1976)
676	idem	$Y(kg) = 0.2857 - 0.0863 * X + 0.0502 * X^2 - 0.0001 * X^3$	R in n (12, 70)*	T+GB+TB+L+B+S+D+R1+R2+R3	8, 0.99	0	1 Poupon, H. (1976)
677	idem	$\log_{10}Y(g) = 2.8840315 * (X^{(1.40)})$	C in cm (3, 628)**	L	-, 0.99	22	1 Poupon, H. (1979)
678	idem	$\log_{10}Y(kg) = -3.45 + (2.73 * \log_{10}(X))$	Cb in cm (4, 708)**	T+B+S	21, 0.99	100	2 Poupon, H. (1979)
679	in Somalia	$Y(kg) = \text{Exp}((2.83568 * \log(X) - 3.75637) + 0.043274)$	DBH in cm (1, 200)**	T+GB+TB5+B+S+D	34, 0.99	100	Bird, N. M. and Shepherd, G. (1989)
680	Acacia seyal in Mali	$Y(g) = 0.21 * X^{(1.22)}$	CA in dm2 (78, 67214)**	L	44, 0.93	99	2 Cissé, M. I. (1980)
681	idem	$Y(g) = 20 * (10^{(-6)}) * X^{(3.06)}$	H in cm (292, 5369)**	L	44, 0.99	72	1 Cissé, M. I. (1980)
682	idem	$Y(g) = 0.6 * (X^{2.25})$	C in cm (5, 61)	L	44, 0.76	100	3 Cissé, M. I. (1980)
683	Acacia tortillis in Gaborone in Botswana (552)	$Y(g) = 5.7696 * 10^{(-9)} * (X^{(3.914)})$	H in cm (292, 5369)**	T+GB+TB+L+B+S+D	62, 0.66*	100	2 Tietema, T. (1993)
684	idem	$Y(kg) = 0.5331 * (X^{(1.6488)})$	CA in m2 (1, 672)**	T+GB+TB+L+B+S+D	62, 0.89*	99	2 Tietema, T. (1993)
685	idem	$Y(kg) = 0.1813 * (X^{(1.1504)})$	BA in cm2 (1, 39879)**	T+GB+B+S	62, 0.93adj	97	2 Tietema, T. (1993)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References
		Equations					
686	idem	$Y(kg)= 0.1975*(X^{(1.1859)})$	BA in cm2 (1, 39879)**	T+GB+TB+L+B+S+D	109, 0.93	97	2 Tietema, T. (1993)
687	in Chad	$Y(g)= 0.5*(X^{(2.35)})$	C in cm (3, 628)**	L	-	100	2 Bellefontaine, R., Gaston, A., et al. (1997)
688	Balanites aegyptiaca in Fété Olé in Senegal (224)	$\log_{10}Y(kg)= -2.51+(2.6*\log_{10}(X))$	Cb in cm (4, 708)**	T+GB+TB+B+S+D+R1+R2+R3	14, 0.99	100	2 Poupon, H. (1979)
689	idem	$\log_{10}Y(kg)= -3.19+(2.59*\log_{10}(X))$	Cb in cm (4, 708)**	T+B+S	-, 0.99	100	2 Poupon, H. (1979)
690	idem	$\log_{10}Y(kg)= -2.3+(2.25*\log_{10}(X))$	Cb in cm (4, 708)**	R1+R2+R3	14, 0.98	88	1 Poupon, H. (1979)
691	in Mali	$Y(g)= 38*(10^{(-6)})*X^{(2.97)}$	H in cm (292, 5369)**	L	50, 0.93	75	1 Cissé, M. I. (1980)
692	idem	$Y(g)= 6.46*(X^{1.5})$	C in cm (5, 61)	L	50	100	3 Cissé, M. I. (1980)
693	Beilschmiedia diversiflora in Morwa hill in Botswana (471)	$Y(kg)= 0.0871*(X^{1.2286})$	BA in cm2 (1, 39879)**	T+GB+TB+L+B+S+D	12, 0.97adj	100	2 Tietema, T. (1993)
694	Boscia albitrunca in Kang in Botswana (400)	$Y(kg)= 0.2683*(X^{1.0455})$	BA in cm2 (1, 39879)**	T+GB+TB+L+B+S+D	23, 1	98	2 Tietema, T. (1993)
695	Boscia senegalensis in Mali	$Y(g)= 2.34*(X^{(1.88)})$	C in cm (3, 628)**	L	-, 0.99	100	2 Bellefontaine, R., Gaston, A., et al. (1997)
696	in Fété Olé in Senegal (224)	$\log_{10}Y(kg)= -2.75+(2.04*\log_{10}(X))$	Cb in cm (4, 708)**	T+B+S	20	100	2 Poupon, H. (1979)
697	idem	$\log_{10}Y(kg)= -1.49+(1.81*\log_{10}(X))$	Cb in cm (4, 708)**	T+GB+TB+B+S+D+R1+R2+R3	5, 0.85	99	2 Poupon, H. (1979)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References
		Equations					
698	idem	log10Y(kg)= -1.44+(1.49*log10(X))	Cb in cm (4, 708)**	R1+R2+R3	5, 0.93	97	2 Poupon, H. (1979)
699	Combretum aculeatum in Mali	Y(g)= 3.09*(X^(2.33))	C in cm (3, 628)**	L	-, 0.94	96	2 Bellefontaine, R., Gaston, A., et al. (1997)
700	Combretum apiculatum in Dikelestane in Botswana (471)	Y(kg)= 0.2232*(X^1.1001)	BA in cm2 (1, 39879)**	T+GB+TB+L+B+S+D	58, 0.86	98	2 Tietema, T. (1993)
701	Combretum glutinosum in Gouani in Mali (815)	Y(g)= 4.2597*(X^2.1415)	Cb in cm (4, 708)**	T+GB+TB+L+B+S+D	100, 0.94	100	2 Bazile, D. (1998)
702	Combretum molle in Gaborone in Botswana (552)	Y(kg)= 0.1529*(X^(1.1141))	BA in cm2 (1, 39879)**	T+GB+TB+L+B+S+D	6, 0.98	99	2 Tietema, T. (1993)
703	in Morwa hill in Botswana (471)	Y(kg)= 0.1529*(X^1.1141)	BA in cm2 (1, 39879)**	T+GB+TB+L+B+S+D	6, 0.95	99	2 Tietema, T. (1993)
704	Combretum nigricans in Gouani in Mali (815)	Y(g)= 4.3184*(X^2.0077)	Cb in cm (4, 708)**	T+GB+TB+L+B+S+D	100, 0.99	100	2 Bazile, D. (1998)
705	in N'goukan in Mali (896)	Y(g)= 1.2289*(X^2.5806)	Cb in cm (4, 708)**	T+GB+TB+L+B+S+D	100, 1	100	2 Bazile, D. (1998)
706	Commiphora africana in Fété Olé in Senegal (224)	log10Y(kg)= -2.69+(2.6*log10(X))	Cb in cm (4, 708)**	T+GB+TB+B+S+D+R1+R2+R3	9, 0.99	100	2 Poupon, H. (1979)
707	idem	log10Y(kg)= -4.96+(3.56*log10(X))	Cb in cm (4, 708)**	GB	10, 0.99*	5	1 Poupon, H. (1979)
708	idem	log10Y(kg)= -2.6+(2.37*log10(X))	Cb in cm (4, 708)**	R1+R2+R3	9, 0.97	95	2 Poupon, H. (1979)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References
		Equations					
709	idem	$\log_{10}Y(kg)= -3.43+(2.53*\log_{10}(X))$	Cb in cm (4, 708)**	T+B+S	15, 0.9	100	2 Poupon, H. (1979)
710	in Mali	$Y(g)= 1.51*(X^{1.78})$	C in cm (5, 61)	L	50, 0.85	100	3 Cissé, M. I. (1980)
711	idem	$Y(g)= 0.155*(10^{(-6)})*X^{(3.21)}$	H in cm (292, 5369)**	L	50, 0.85*	100	2 Cissé, M. I. (1980)
712	Croton gratissimus in Morwa hill in Botswana (471)	$Y(kg)= 0.074*(X^{1.2668})$	BA in cm2 (1, 39879)**	T+GB+TB+L+B+S+D	34, 0.89	100	2 Tietema, T. (1993)
713	Detarium microcarpum in Gouani in Mali (815)	$Y(g)= 2.0919*(X^{2.3118})$	Cb in cm (4, 708)**	T+GB+TB+L+B+S+D	100, 0.97	100	2 Bazile, D. (1998)
714	in N'goukan in Mali (896)	$Y(g)= 0.8133*(X^{2.7108})$	Cb in cm (4, 708)**	T+GB+TB+L+B+S+D	100, 0.98	100	2 Bazile, D. (1998)
715	Dichrostachys cinerea in Dikelestane in Botswana (471)	$Y(kg)= 0.2787*(X^{1.0337})$	BA in cm2 (1, 39879)**	T+GB+TB+L+B+S+D	33, 0.88	98	2 Tietema, T. (1993)
716	in Gaborone in Botswana (552)	$Y(kg)= 0.2787*(X^{(1.0337)})$	BA in cm2 (1, 39879)**	T+GB+TB+L+B+S+D	33, 0.7	98	2 Tietema, T. (1993)
717	Excoecaria bussei in Somalia	$Y(kg)= \text{Exp}((4.05271*\log(X)-4.16400)+0.11648)$	CD in m (1, 29)**	T+GB+TB5+B+S+D	49	100	Bird, N. M. and Shepherd, 2 G. (1989)
718	Gardenia ternifolia in N'goukan in Mali (896)	$Y(g)= 4.5738*(X^{2.0836})$	Cb in cm (4, 708)**	T+GB+TB+L+B+S+D	100, 0.68	100	2 Bazile, D. (1998)
719	Grewia bicolor in Fété Olé in Senegal (224)	$\log_{10}Y(kg)= -3.27+(2.45*\log_{10}(X))$	Cb in cm (4, 708)**	T+B+S	16	100	2 Poupon, H. (1979)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References
		Equations					
720	idem	$\log_{10}Y(\text{kg})= -1.67+(1.77*\log_{10}(X))$	Cb in cm (4, 708)**	R1+R2+R3	10, 1	95	2 Poupon, H. (1979)
721	idem	$\log_{10}Y(\text{kg})= -1.81+(2.12*\log_{10}(X))$	Cb in cm (4, 708)**	T+GB+TB+B+S+D+R1+R2+R3	10, 0.99	99	2 Poupon, H. (1979)
722	in Serlo in Senegal (234)	$Y(\text{g})= 6.39*(X^{1.53})$	C in cm (3, 628)**	L	-, 0.96	99	2 Ngom, D., Diatta, S., et al. (2009)
723	idem	$Y(\text{g})= 64.4*(X^{1.68})$	H in m (3, 54)**	L	-, 0.96	97	2 Ngom, D., Diatta, S., et al. (2009)
724	Guiera senegalensis in Tongomayel in Burkina Faso (429)	$\log_{10}Y(\text{g})= 0.55+(1.89*\log(X))$	DBH in cm (1, 200)**	L	20, 0.96	98	2 Sanon, H. O., Kaboré- Zoungrana, C., et al. (2007)
725	in Mali	$Y(\text{g})= 3.09*(X^{(1.89)})$	C in cm (3, 628)**	L	-, 0.6	100	2 Bellefontaine, R., Gaston, A., et al. (1997)
726	in Fété Olé in Senegal (224)	$\log_{10}Y(\text{kg})= -2.18+(2.15*\log_{10}(X))$	Cb in cm (4, 708)**	T+GB+TB+B+S+D+R1+R2+R3	5, 0.84	100	2 Poupon, H. (1979)
727	idem	$\log_{10}Y(\text{kg})= -2.45+(1.93*\log_{10}(X))$	Cb in cm (4, 708)**	R1+R2+R3	5, 0.96	99	2 Poupon, H. (1979)
728	idem	$\log_{10}Y(\text{kg})= -2.54+(1.96*\log_{10}(X))$	Cb in cm (4, 708)**	T+B+S	21	100	2 Poupon, H. (1979)
729	in Guesselbodi in Niger (555)	$Y(\text{kg})= 1.0806*\exp(-2.241+1.8577*\ln(X))$	DBH in cm (1, 200)**	T+GB+TB+L+B+S+D	-, 0.98	100	2 Alegria, J., Heermans, J. G., et al. (1986)
730	Pterocarpus lucens in Tongomayel in Burkina Faso (429)	$\log Y(\text{g})= -0.4+(2.86*\log(X))$	DBH in cm (1, 200)**	L	-, 0.95	98	2 Sanon, H. O., Kaboré- Zoungrana, C., et al. (2007)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References
		Equations			Variables X (min, max), W, Z, U and V		
731	in Mali	Y(g)= 0.95*(X^(2.07))	C in cm (3, 628)**	L	-, 0.9	100	2 Bellefontaine, R., Gaston, A., et al. (1997)
732	idem	Y(g)= 65*(10^(-6))*X^(2.83)	H in cm (292, 5369)**	L	40	86	1 Cissé, M. I. (1980)
733	idem	Y(g)= 0.6*(X^1.22)	CA in dm2 (78, 67214)**	L	40, 0.8	99	2 Cissé, M. I. (1980)
734	idem	Y(g)= 93*X^(2.07)	C in cm (5, 61)	L	40, 0.79adj	0	1 Cissé, M. I. (1980)
735	in Serlo in Senegal (234)	Y(g)= 49.2*(X^1.62)	H in m (3, 54)**	L	-	98	2 Ngom, D., Diatta, S., et al. (2009)
736	idem	Y(g)= 8.02*(X^1.54)	C in cm (3, 628)**	L	-	99	2 Ngom, D., Diatta, S., et al. (2009)
737	Ziziphus mauritania in Mali	Y(g)= 1.38*(X^(1.91))	C in cm (3, 628)**	L	-	100	2 Bellefontaine, R., Gaston, A., et al. (1997)
738	Ziziphus mucronata in Dikelestane in Botswana (471)	Y(kg)= 0.2772*(X^0.8914)	BA in cm2 (1, 39879)**	T+GB+TB+L+B+S+D	30, 0.97	99	2 Tietema, T. (1993)
739	in Gaborone in Botswana (552)	Y(kg)= 0.2772*(X^(0.8914))	BA in cm2 (1, 39879)**	T+GB+TB+L+B+S+D	30, 0.99	99	2 Tietema, T. (1993)
740	Ziziphus mauritiana in Mali	Y(g)= 1.38*(X^1.91)	C in cm (5, 61)	L	46, 0.85adj	100	3 Cissé, M. I. (1980)
741	idem	Y(g)= 0.58*(X^1.1)	CA in dm2 (78, 67214)**	L	46, 0.79adj	99	2 Cissé, M. I. (1980)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References
		Equations					
			Variables X (min, max), W, Z, U and V				
				0.85adj			
742	idem	$Y(g) = 3 \cdot (10^{(-6)}) \cdot X^{(2.83)}$	H in cm (292, 5369)**	L	46	100	2 Cissé, M. I. (1980)
General equations for individual tree in tropical shrubland							
743	Generalized in Gaborone in Botswana (552)	$Y(kg) = 0.1936 \cdot (X^{(1.1654)})$	As in cm2 (1, 22432)**	T+GB+TB+L+B+S+D	512, 0.5*	100	2 Tietema, T. (1993)
744	idem	$Y(kg) = 9.92 - 3.77 \cdot X + 0.468 \cdot (X^2) - 0.01021 \cdot (X^3)$	BD in cm (5, 24)**	T+GB+TB+L+B+S	-, 0.77	100	2 Mabowe, R. B. (2006)
745	in Gouani in Mali (815)	$Y(g) = 3.5057 \cdot (X^{2.1094})$	Cb in cm (4, 708)**	T+GB+TB+L+B+S+D	100, 1adj	100	2 Bazile, D. (1998)
746	idem	$Y(g) = 3.3724 \cdot (X^{2.142})$	Cb in cm (4, 708)**	T+GB+TB+L+B+S+D	500, 0.91	100	2 Bazile, D. (1998)
747	in N'goukan in Mali (896)	$Y(g) = 1.8412 \cdot (X^{2.448})$	Cb in cm (4, 708)**	T+GB+TB+L+B+S+D	500, 0.89	100	2 Bazile, D. (1998)
748	idem	$Y(g) = 2.5347 \cdot (X^{2.359})$	Cb in cm (4, 708)**	T+GB+TB+L+B+S+D	100	100	2 Bazile, D. (1998)
749	in Sudan	$\log_{10} Y(kg) = 0.163 + 0.861 \cdot \log(X^{(2)} \cdot Z)$	DBH in cm, H in m (1, 200)**	T+GB+TB5+B+S+D	18, 0.92	0	1 Helldén, U. and Olsson, K. (1982)
750		$Y(kg) = \exp(-1.996 + 2.32 \cdot \log(X))$	DBH in cm (1, 40)*	T+GB+TB+L+B+S+D	28	100	3 Brown, S. (1997)
751		$Y(kg) = \exp(-2.187 + (0.916 \cdot \log(X \cdot Z^2 \cdot W)))$	WD in g.cm-3, DBH in cm, H in m (-, -)**	T+GB+TB+L+B+S+D	316	100	3 Chave, J., Andalo, C., et al. (2005)
752		$Y(kg) = 34.4703 - 8.0671 \cdot X + 0.6589 \cdot (X^2)$	DBH in cm (6, 40)*	T+GB+TB+L+B+S+D	32, 0.67	100	3 Brown, S.A.J., Gillespie,

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References
		Equations					
		Variables X (min, max), W, Z, U and V					
							J.R., et al. (1989)
753		$Y(kg) = X * \exp(-0.667 + (1.784 * \log(Z)) + (0.207 * (\log(Z))^2 - (0.0281 * (\log(Z))^3))$	WD in g.cm-3, DBH in cm (-, -)**	316	99	3	Chave, J., Andalo, C., et al. (2005)
Individual tree in tropical desert (classification per tree species)							
754	Acacia erubescens in Namibia	$Y(g) = 5.719 - (0.349 * X) + (0.00719 * X^2) - (0.0000173 * X^3)$	DBH in cm (27, 200)**	T+GB+TB+L+B+S+D	-	100	2 de Klerk, J.N. (2002)
755	Acacia fleckii in Namibia	$Y(g) = -0.946 + (0.0712 * X) + (0.000514 * X^2) + (0.00000609 * X^3)$	DBH in cm (13, 200)**	T+GB+TB+L+B+S+D	-	100	2 de Klerk, J.N. (2002)
756	Acacia mellifera in Namibia	$Y(g) = -10.970 + 0.768 * X - (0.0124 * X^2) + (0.0000826 * X^3)$	DBH in cm (20, 200)**	T+GB+TB+L+B+S+D	-	100	2 de Klerk, J.N. (2002)
757	Acacia reficiens in Namibia	$Y(g) = 5.093 - (0.2567 * x) + (0.0059 * x^2) + (0.0000116 * x^3)$	DBH in cm (21, 200)**	T+GB+TB+L+B+S+D	-	100	2 de Klerk, J.N. (2002)
758	Colophospermum mopane in Namibia	$Y(g) = 42.119 - 0.068 * x + (0.00275 * x^2) + (0.00000888 * x^3)$	DBH in cm (12, 200)**	T+GB+TB+L+B+S+D	-	100	2 de Klerk, J.N. (2002)
759	Dichrostachys cinerea in Namibia	$Y(g) = 115 - (0.0680 * X) + (0.00275 * X^2) + (0.00000888 * X^3)$	DBH in cm (12, 200)**	T+GB+TB+L+B+S+D	-	100	2 de Klerk, J.N. (2002)
760	Terminalia sericea in Namibia	$Y(g) = 26.866 - (0.609 * x) + (0.00463 * x^2) + (0.00000572 * x^3)$	DBH in cm (59, 200)**	T+GB+TB+L+B+S+D	-	100	2 de Klerk, J.N. (2002)
Individual tree in tropical mountain system (classification per tree species)							
761	Acacia drepanolobium in Laikipia in Kenya (739)	$Y(kg) = 3.7704 * X + 1.1682$	BD in cm (1, 15)*	T+GB+TB+B+S+D	15, 0.96	27	1 Okello, B.D., O'Connora, T.G., et al. (2001)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References
		Equations					
762	idem	Y(kg)= 2.2949*X+4.7997	BD in cm (1, 15)*	T+GB+TB+L+B+S+D	15, 0.98*	45	1 Okello, B.D., O'Connora, T.G., et al. (2001)
763	idem	Y(kg)= 2.9602*X+1.6034	BD in cm (1, 15)*	TB+L	15, 0.69	0	1 Okello, B.D., O'Connora, T.G., et al. (2001)
764	Croton macrostachyus in Kakamega forest in Kenya (2002)	log10Y(kg)= (1.62365*log10(X))+(1.29091*log10(Z))- 2.25217	DBH in cm, CD in m (1, 200)**	T+GB+TB+L+B+S+D	12, 0.98*	100	2 Bradley, P. N. and Kuyper, J.B.H. (1988)
765	Eucalyptus Camadulensis in Jufi in Ethiopia (1502)	Y(kg)= 0.0155*(X^(2.5823))	DBH in cm (1, 200)**	B	9, 0.99	0	1 Hailu, Z. (2002)
766	idem	Y(kg)= 0.0172*(X^(3.1543))	DBH in cm (1, 200)**	T+GB+TB+B+S+D	9, 0.99	34	1 Hailu, Z. (2002)
767	idem	Y(kg)= 0.0414*(X^(2.7175))	DBH in cm (1, 200)**	T+GB+TB+B+S+D	9, 0.99	100	2 Hailu, Z. (2002)
768	idem	Y(kg)= 0.026*(X^(1.949))	DBH in cm (1, 200)**	TB+L	9, 0.93	100	2 Hailu, Z. (2002)
769	idem	Y(kg)= 0.1935*(X^(1.0913))	DBH in cm (1, 200)**	TB+L	9, 0.99	99	2 Hailu, Z. (2002)
770	idem	Y(kg)= 0.0131*(X^(1.8648))	DBH in cm (1, 200)**	L	9, 0.78	100	2 Hailu, Z. (2002)
771	idem	Y(kg)= 0.0256*(X^(2.3711))	DBH in cm (1, 200)**	B	9, 0.99	89	1 Hailu, Z. (2002)
772	idem	Y(kg)= 0.0141*(X^(1.9239))	DBH in cm (1, 200)**	L	9, 0.87	100	2 Hailu, Z. (2002)
773	in Ker Jarso in Ethiopia (1502)	Y(kg)= 0.0129*(X^(2.588))	DBH in cm (1, 200)**	B	9, 0.98	82	1 Hailu, Z. (2002)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References	
		Equations						Variables X (min, max), W, Z, U and V
774	idem	$Y(kg)=0.0686*(X^{(2.5549)})$	DBH in cm (1, 200)**	T+GB+TB+B+S+D	9, 0.97	100	2	Hailu, Z. (2002)
775	idem	$Y(kg)=0.0123*(X^{(2.0202)})$	DBH in cm (1, 200)**	L	9, 0.92	100	2	Hailu, Z. (2002)
776	idem	$Y(kg)=0.0219*X^{(3.0441)}$	DBH in cm (1, 200)**	T+GB+TB+B+S+D	9, 0.99	51	1	Hailu, Z. (2002)
777	idem	$Y(kg)=0.005*(X^{(2.3597)})$	DBH in cm (1, 200)**	L	9, 0.78	100	2	Hailu, Z. (2002)
778	idem	$Y(kg)=0.3647*(X^{(0.8741)})$	DBH in cm (1, 200)**	TB+L	9, 0.81	98	2	Hailu, Z. (2002)
779	idem	$Y(kg)=0.0517*(X^{(1.8393)})$	DBH in cm (1, 200)**	TB+L	9, 0.91	99	2	Hailu, Z. (2002)
780	idem	$Y(kg)=0.0291*(X^{(2.3233)})$	DBH in cm (1, 200)**	B	9, 0.97	89	1	Hailu, Z. (2002)
781	Eucalyptus globulus in Ethiopian Heritage Forestry Park in Ethiopia (1191)	$Y(kg)=1.92-1.48*X+0.22*(X^2)$	H in m (5, 16)*	T	79, 0.7	100	3	Zewdie, M., Olsson, M., et al. (2009)
	idem	$Y(kg)=0.09*(X^{1.9})$	DBH in cm (1, 16)*	L	83, 0.79	69	1	Zewdie, M., Olsson, M., et al. (2009)
	idem	$Y(kg)=0.03*(X^{(1.9)})$	DBH in cm (1, 16)*	TB	83, 0.58	69	1	Zewdie, M., Olsson, M., et al. (2009)
	idem	$Y(kg)=0.27+0.1*(X^{(2.39)})$	DBH in cm (1, 16)*	B	79, 0.74	0	1	Zewdie, M., Olsson, M., et al. (2009)
	785	idem	$Y(kg)=1.17+0.12*(X^{(2.51)})$	DBH in cm (1, 16)*	T+GB+TB+L+B+S+D	83, 0.86	88	1

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References
		Equations					
786	idem	Y(kg)= -0.93+0.17*(X^2)	H in m (3, 16)*	L	83, 0.54	25	1 Zewdie, M., Olsson, M., et al. (2009)
787	idem	Y(kg)= 0.005*(X^(2.33))	H in m (3, 16)*	TB	83, 0.53	80	1 Zewdie, M., Olsson, M., et al. (2009)
788	idem	Y(kg)= 0.59+0.03*X*(Z^2)	DBH in cm, H in m (1, 20)*	T+GB+TB+L+B+S+D	-, 0.86	90	1 Zewdie, M., Olsson, M., et al. (2009)
789	idem	Y(kg)= 1.76-0.53*X+0.05*(X^2)	H in m (5, 16)*	B	79, 0.77	94	3 Zewdie, M., Olsson, M., et al. (2009)
790	idem	Y(kg)= 0.19+7.17*10^(-6)*(X^(5.41))	DBH in cm (1, 16)*	GB	83, 0.94	81	1 Zewdie, M., Olsson, M., et al. (2009)
791	idem	Y(kg)= 4.15-2.46*X+0.36*(X^2)	H in m (3, 16)*	T+GB+TB+L+B+S+D	83, 0.76	100	3 Zewdie, M., Olsson, M., et al. (2009)
792	idem	Y(kg)= 0.45*(X^(-2.01))*(Z^(3.41))	DBH in cm, H in m (0, 20)	L	83, 0.93	45	1 Zewdie, M., Olsson, M., et al. (2009)
793	idem	Y(kg)= 0.56*(X^(0.56))*(Z^(1.45))	DBH in cm, H in m (1, 20)*	TB	83, 0.75	0	1 Zewdie, M., Olsson, M., et al. (2009)
794	idem	Y(kg)= 0.00002*(X^(0.29))*(Z^(0.94))	DBH in cm, H in m (1, 20)*	GB	83, 0.94	100	3 Zewdie, M., Olsson, M., et al. (2009)
795	idem	Y(kg)= 0.01*(X^(0.58))*(Z^(2.17))	DBH in cm, H in m (1, 20)*	B	79, 0.94	35	1 Zewdie, M., Olsson, M., et al. (2009)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References
		Equations					
796	idem	Y(kg)= 0.05*(X^(0.93))*(Z^(1.61))	DBH in cm, H in m (1, 20)*	T	79, 0.84	85	1 Zewdie, M., Olsson, M., et al. (2009)
797	idem	Y(kg)= 0.12*(X^(0.39))*(Z^(2.08))	DBH in cm, H in m (1, 20)*	T+GB+TB+L+B+S+D	83, 0.91	75	1 Zewdie, M., Olsson, M., et al. (2009)
798	idem	Y(Mg ha-1)= -33.6+19.4*X	yr in yr	T+GB+TB+L+B+S+D	10, 0.79	-	3 Zewdie, M., Olsson, M., et al. (2009)
799	idem	Y(kg)= 2.5-0.79*X+0.06*(X^2)	H in m (8, 16)*	GB	83, 0.69	100	3 Zewdie, M., Olsson, M., et al. (2009)
800	idem	Y(kg)= 0.11*(X^(2.3))	DBH in cm (1, 16)*	T	80, 0.74	100	3 Zewdie, M., Olsson, M., et al. (2009)
801	in Weldeab Ager in Ethiopia (980)	Y(kg)= 0.0208*(X^(2.35))	DBH in cm (1, 200)**	TB+L	9, 0.96	100	2 Hailu, Z. (2002)
802	idem	Y(kg)= 0.0228*(X^(2.2829))	DBH in cm (1, 200)**	L	9, 0.96	100	2 Hailu, Z. (2002)
803	idem	Y(kg)= 0.0205*(X^(2.1391))	DBH in cm (1, 200)**	TB+L	9, 0.71	100	2 Hailu, Z. (2002)
804	idem	Y(kg)= 0.1303*(X^(2.2418))	DBH in cm (1, 200)**	T+GB+TB+B+S+D	9, 0.99	100	2 Hailu, Z. (2002)
805	idem	Y(kg)= 0.0334*(X^(2.1323))	DBH in cm (1, 200)**	B	9, 0.96	96	2 Hailu, Z. (2002)
806	idem	Y(kg)= 0.0015*(X^(2.9242))	DBH in cm (1, 200)**	L	9, 0.81	100	2 Hailu, Z. (2002)
807	idem	Y(kg)= 0.0256*(X^(2.2769))	DBH in cm (1, 200)**	B	9, 0.87	96	2 Hailu, Z. (2002)

ID	Tree species and location (annual rainfall)	Model	Variables X (min, max), W, Z, U and V	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations						
808	idem	$Y(kg) = 0.0555 \cdot (X^{2.6725})$	DBH in cm (1, 200)**	T+GB+TB+B+S+D	9, 0.98	100	2	Hailu, Z. (2002)
809	Eucalyptus saligna in Kakamega forest in Kenya (2002)	$\log_{10}Y(kg) = (2.17679 \cdot \log_{10}(X)) + (0.25086 \cdot \log_{10}(Z)) - 1.71514$	DBH in cm, CD in m (1, 200)**	T+GB+TB+L+B+S+D	16, 0.74adj	100	2	Bradley, P. N. and Kuyper, J.B.H. (1988)
810	Markhamia lutea in Kakamega forest in Kenya (2002)	$\log_{10}Y(kg) = (2.18435 \cdot \log_{10}(X)) - (0.20922 \cdot \log_{10}(X)) - 1.13559$	DBH in cm, CD in m (1, 200)**	T+GB+TB+L+B+S+D	4	100	2	Bradley, P. N. and Kuyper, J.B.H. (1988)
811	Psidium guajava in Kakamega forest in Kenya (2002)	$\log_{10}Y(kg) = (0.68554 \cdot \log_{10}(X)) + (1.3879 \cdot \log_{10}(Z)) - 0.14022$	DBH in cm, CD in m (1, 200)**	T+GB+TB+L+B+S+D	10	99	2	Bradley, P. N. and Kuyper, J.B.H. (1988)
812	Sesbania sesban in Kakamega forest in Kenya (2002)	$\log_{10}Y(kg) = (1.25037 \cdot \log_{10}(X)) + (0.20120 \cdot \log_{10}(Z)) + 0.52873$	DBH in cm, CD in m (1, 200)**	T+GB+TB+L+B+S+D	15	95	2	Bradley, P. N. and Kuyper, J.B.H. (1988)
Individual tree in tropical mountain system (classification per group of tree species)								
813	Group 64 in Kakamega forest in Kenya (2002)	$\log_{10}Y(kg) = (2.40225 \cdot \log_{10}(X)) + (0.09071 \cdot \log_{10}(Z)) - 2.53516$	DBH in cm, CD in m (1, 200)**	T+GB+TB+L+B+S+D	11, 0.86*	100	2	Bradley, P. N. and Kuyper, J.B.H. (1988)
814	Group 63 in Kakamega forest in Kenya (2002)	$\log_{10}Y(kg) = (2.88659 \cdot \log_{10}(X)) + 0.11409$	DBH in cm (1, 200)**	T+GB+TB+L+B+S+D	4	0	1	Bradley, P. N. and Kuyper, J.B.H. (1988)
Sprout in tropical mountain system								
815	Dichrostachys cinerea in National Regional State of Tigray in Ethiopia (1987)	$Y(g) = 46.50 \cdot (X^{2.71})$	D30 in cm	T+GB+TB	5	-	2	Cleemput, S., Muys, B., et al. (2004)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References	
		Equations						Variables X (min, max), W, Z, U and V
816	idem	$Y(g)= 0.016*(X^{(1.60)})$	CD in m	L	5	-	2	Cleemput, S., Muys, B., et al. (2004)
817	idem	$Y(g)= 135.24*(X^{(0.83)})$	D30 in cm	T+GB+TB+B+S	5	-	2	Cleemput, S., Muys, B., et al. (2004)
818	idem	$Y(g)= 274.95*(X^{(1.37)})$	D30 in cm	T+B	5	-	2	Cleemput, S., Muys, B., et al. (2004)
819	idem	$Y(g)= 230.98*(X^{(1.47)})$	D30 in cm	T+GB+TB+L+B+S+D	5	-	2	Cleemput, S., Muys, B., et al. (2004)
820	Euclea shimperi in National Regional State of Tigray in Ethiopia (987)	$Y(g)= 57.30*(X^{(1.87)})$	D30 in cm	T+GB+TB+B+S	7, 0.31	-	2	Cleemput, S., Muys, B., et al. (2004)
821	idem	$Y(g)= 4.88*(X^{(3.54)})$	D30 in cm	L	7, 0.67	-	2	Cleemput, S., Muys, B., et al. (2004)
822	idem	$Y(g)= 20.55*(X^{(1.69)})$	D30 in cm	T+B	7, 0.92	-	2	Cleemput, S., Muys, B., et al. (2004)
823	idem	$Y(g)= 63.07*(X^{(1.78)})$	D30 in cm	T+GB+TB+L+B+S+D	7, 0.95	-	2	Cleemput, S., Muys, B., et al. (2004)
824	idem	$Y(g)= 22.09*(X^{(22.09)})$	D30 in cm	T+GB+TB	7, 0.95	-	2	Cleemput, S., Muys, B., et al. (2004)
825	Grewia bicolor in National	$Y(g)= 1.93*(X^{(0.39)})$	D30 in cm	T+GB+TB	8, 0.77	-	2	Cleemput, S., Muys, B.,

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
Regional State of Tigray in Ethiopia (987)							et al. (2004)
826	idem	Y(g)= 7.06*(X^(1.75))	D30 in cm	L	8, 1adj	-	Cleemput, S., Muys, B., et al. (2004)
827	idem	Y(g)= 52.43*(X^(1.99))	D30 in cm	T+GB+TB+B+S	8, 2adj	-	Cleemput, S., Muys, B., et al. (2004)
828	idem	Y(g)= 52.97*(X^(1.91))	D30 in cm	T+GB+TB+L+B+S+D	8, 0.96	-	Cleemput, S., Muys, B., et al. (2004)
829	Otostegia integrifolia in National Regional State of Tigray in Ethiopia (987)	Y(g)= 45.80*(X^(2.26))	D30 in cm	T+GB+TB+L+B+S+D	7, 0.99	-	Cleemput, S., Muys, B., et al. (2004)
830	idem	Y(g)= 43.77*(X^(2.4))	D30 in cm	T+GB+TB+B+S	7, 0.98	-	Cleemput, S., Muys, B., et al. (2004)
831	idem	Y(g)= 0.54*(X^(-0.09))	D30 in cm	L	7, 0.94	-	Cleemput, S., Muys, B., et al. (2004)
832	idem	Y(g)= 14.20*(X^(2.50))	D30 in cm	T+GB+TB	7, 0.91	-	Cleemput, S., Muys, B., et al. (2004)
Stand in tropical mountain system							
833	Eucalyptus globulus in Adis	Y(Mg ha-1)= -33.6+19.4*X	yr in yr	T+GB+TB+L+B+S+D	10, 0.79	-	Zewdie, M. (2008)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, R2	Interval of possibility (%)	Quality	References
		Equations	Variables X (min, max), W, Z, U and V				
abeba in Ethiopia (1191)							
Stand in tropical mountain							
834	Acacia karoo in Crossroads village in South Africa (572)	log10Y(kg)= (3.062*log10(X))-0.304	C in cm (3, 628)**	T+GB+TB+B+S+D	14, 0.79	0	1 Potea, J., Shackleton, C., et al. (2006)
835	Coddia rudis in Crossroads village in South Africa (572)	log10Y(kg)= (0.62*log10(X))+2.23	C in cm (3, 628)**	T+GB+TB+B+S+D	20, 0.3	72	1 Potea, J., Shackleton, C., et al. (2006)
836	Diospyros dichrophylla in Crossroads village in South Africa (572)	log10Y(kg)= (1.09*log10(X))+1.93	C in cm (3, 628)**	T+GB+TB+B+S+D	19, 0.36	13	1 Potea, J., Shackleton, C., et al. (2006)
837	Olea europaea in Crossroads village in South Africa (572)	log10Y(kg)= (2.82*log10(X))+0.16	C in cm (3, 628)**	T+GB+TB+B+S+D	14, 0.81	0	1 Potea, J., Shackleton, C., et al. (2006)
838	Ptaeroxylon obliquum in Crossroads village in South Africa (572)	log10Y(kg)= (2.538*log10(X))+0.42	C in cm (3, 628)**	T+GB+TB+B+S+D	11, 0.38	0	1 Potea, J., Shackleton, C., et al. (2006)
General equations for individual tree in subtropical humid forest							
839	Generalized in Crossroads village in South Africa (572)	log10Y(kg)= (2.74*log10(X))+0.15	C in cm (3, 628)**	T+GB+TB+B+S+D	39, 0.77	0	1 Potea, J., Shackleton, C., et al. (2006)
Individual tree in subtropical dry forest (classification per tree species)						0	

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References
		Equations					
840	Protea neriifolia in Jokershoek valley in South Africa (1069)	logY(kg)= -2.23+2.26*log(X)	D20 in cm (1, 191)**	T+GB+TB+L+B+S+D	105, 0.91	100	2 Van Wilgen, B. W. (1982)
841	idem	logY(kg)= -2.23+2.12*LOG(X)	D20 in cm (1, 191)**	GB+TB+L+D	105, 0.87	96	2 Van Wilgen, B. W. (1982)
842	Protea repens in Jokershoek valley in South Africa (1069)	logY(kg)= -2.89+2.36*LOG(X)	D20 in cm (1, 191)**	GB+TB+L+D	241, 0.84	99	2 Van Wilgen, B. W. (1982)
843	idem	logY(kg)= -2.7+2.46*LOG(X)	D20 in cm (1, 191)**	T+GB+TB+L+B+S+D	241, 0.92	99	2 Van Wilgen, B. W. (1982)
844	Widdringtonia nodiflora in Jokershoek valley in South Africa (1069)	logY(kg)= -2.82+2.34*LOG(X)	D20 in cm (1, 191)**	T+GB+TB+L+B+S+D	247, 0.97	100	2 Van Wilgen, B. W. (1982)
845	idem	logY(kg)= 3.19+1.94*LOG(X)	D20 in cm (1, 191)**	TB<6	247, 0.94	0	1 Van Wilgen, B. W. (1982)
Individual tree in subtropical mountain forest (classification per tree species)							
846	Pinus patula in Kwazulu natal in South Africa (600)	Y(kg)= 4.57*0.028*X*Z	DBH in cm, CH in m (1, 200)**	L	-	97	2 Dames, J. F., Scholes, M. C., et al. (2002)
847	idem	Y(kg)= -35.78+1.5*X	DBH in cm (24, 200)**	B	-	100	2 Dames, J. F., Scholes, M. C., et al. (2002)
848	idem	Y(kg)= 9.78+0.171*X*Z	DBH in cm, CH in m (1, 200)**	GB+TB+D	-	93	2 Dames, J. F., Scholes, M. C., et al. (2002)
849	idem	Y(kg)= 50.782+0.104*(X*Z)+0.0003*((X*Z)^2)	DBH in cm, H in m (1, 200)**	T+B+S	-	94	2 Dames, J. F., Scholes, M. C., et al. (2002)

ID	Tree species and location (annual rainfall)	Model	Tree components	n, ,R2	Interval of possibility (%)	Quality	References
		Equations					
			Variables X (min, max), W, Z, U and V				
850	idem	$Y(\text{kg}) = 2.75 + 0.0015 \cdot (X^2) \cdot Z$	DBH in cm, H in m (1, 200)** R1+R2+R3	-	97	2	Dames, J. F., Scholes, M. C., et al. (2002)

Appendix VI: Volume conversion functions

Ecosystem	Location	model	a			b			c			sigma2			k			AIC		RMSE	
			Mean	SD	p	Mean	SD	p	Mean	SD	p	Mean	SD	p	Mean	SD	p	site	plot		
Natural forest																					
Tropical rainforest																					
	Kakum	power	1	-	-	0.06	2.21E-03	***	1.63	0.04	***	1.83E-02	1.11E-02	*	1.29	0.12	***	-571	-585	0.03	
		expo	3.94E-03	3.20E-04	***	0.04	3.75E-03	***	-	-	-	1.75E-04	4.75E-05	***	-	-	-	-476	-504	0.03	
		hyper	1.31E-02	7.70E-04	***	5.50	4.02E-01	***	1.00	0.00	***	2.39E-04	6.18E-05	***	-	-	-	-449	-423	0.03	
	Bobiri	power	1	-	-	0.09	1.08E-03	***	1.58	0.01	***	1.40E-02	6.41E-03	*	1.50	0.11	***	-647	-654	0.05	
		expo	6.69E-03	2.77E-04	***	0.03	1.84E-03	***	-	-	-	1.50E-04	2.96E-05	***	-	-	-	-513	-592	0.05	
		hyper	1.88E-02	5.30E-04	***	5.59	3.03E-01	***	1.00	0.00	***	2.86E-04	4.63E-05	***	-	-	-	-455	-451	0.28	
		model	1	-	-	0.10	1.26E-03	***	1.39	0.01	***	8.16E-01	4.20E-01	ns	2.39	0.12	***	-607	-660	0.05	
		expo	7.34E-03	2.67E-04	***	0.03	1.55E-03	***	-	-	-	1.46E-04	2.12E-05	***	-	-	-	-516	-640	0.05	
		hyper	1.87E-02	7.14E-04	***	4.84	5.08E-01	***	1.00	0.00	***	4.50E-04	8.14E-05	***	-	-	-	-416	-468	0.56	
	Boi Tano	power	1	-	-	0.08	2.13E-03	***	1.50	0.03	***	2.56E-05	2.29E-05	ns	-0.32	0.21	***	-551	-605	0.05	
		expo	6.94E-03	1.48E-04	***	0.03	8.80E-04	***	-	-	-	6.47E-05	1.03E-05	***	-	-	-	-586	-605	0.05	
		hyper	1.55E-02	6.44E-04	***	4.05	6.00E-01	***	1.00	0.00	***	3.31E-04	5.38E-05	***	-	-	-	-442	-451	0.05	
	Luki	power	1	-	-	0.05	0.00E+00	***	1.68	0.05	***	9.02E+00	2.72E+00	ns	2.40	0.06	***	-18452	-25447	0.07	
		expo	2.56E-03	2.02E-03	***	0.05	1.60E-03	***	-	-	-	1.13E-02	1.40E-03	***	-	-	-	-5888	-20436	0.08	
		hyper	1.18E-02	4.81E-02	***	1.46	4.11E-02	***	0.97	0.01	***	7.88E-03	5.07E-04	***	-	-	-	-7184	-14747	0.08	
Tropical moist deciduous forest																					
		power	1	-	-	0.03	3.60E-03	***	3.19	0.13	***	2.97E+00	3.19E+00	***	2.38	0.25	***	-564	-1324	0.46	
		expo	4.50E-05	6.91E-05	***	0.12	5.05E-03	***	-	-	-	5.67E-04	1.24E-04	***	-	-	-	-416	-489	0.36	
		hyper	2.53E-02	4.97E-03	***	0.88	9.85E-03	***	1.00	0.00	***	1.05E-01	6.43E-02	***	-	-	-	66	-181	0.47	
Tropical dry forest																					
	Bawku	power	1	-	-	0.07	3.08E-03	***	1.90	0.09	***	1.14E+06	1.71E-03	***	4.88	0.07	***	-196	-463	0.84	
		expo	1.89E-06	1.66E-06	ns	0.34	6.04E-02	***	-	-	-	7.48E-03	2.61E-03	**	-	-	-	-64	-134	0.79	
		hyper	2.67E-02	7.69E-03	***	1.19	3.76E-02	***	0.91	0.01	***	5.37E-02	2.30E-02	***	-	-	-	5	-70	0.94	
	MafaKilda	power	1	-	-	0.06	1.19E-02	***	3.21	0.20	***	5.91E+00	5.35E+00	ns	1.85	0.20	***	-410	-620	0.32	
		expo	1.92E-03	3.66E-04	***	0.13	7.47E-03	***	-	-	-	4.74E-03	8.91E-04	***	-	-	-	-263	-297	0.32	
		hyper	2.67E-02	7.69E-03	***	2.08	1.24E+00	***	1.00	0.00	***	4.39E-02	2.56E-02	***	-	-	-	-23	-220	0.32	

Ecosystem	Location	model	a			b			c			sigma2		k			AIC		RMSE	
			Mean	SD	p	Mean	SD	p	Mean	SD	p	Mean	SD	p	Mean	SD	p	site	plot	
Moutain forest																				
	Tropical dry forest																			
	MafaKilda	power	1	-	-	0.22	4.57E-02	***	1.30	0.08	***	1.81E+05	1.27E-07	***	3.39	0.03	***	-449	-972	1.19
		expo	1.92E-03	7.51E-04	***	0.23	2.22E-02	***	-	-	-	1.07E-01	1.69E-02	***	-	-	-	212	-346	0.52
		hyper	5.11E-01	2.94E+00	***	0.79	3.51E-02	***	0.98	0.01	***	2.14E-01	2.99E-03	***	-	-	-	1080	1154	0.93
Plantation																				
	Tropical rainforest																			
	Kakum	power	1	-	-	0.67	1.11E-01	***	6.04	1.15	***	2.71E+05	1.00E+01	***	3.79	0.10	***	-74	-74	1.51
		expo	2.38E-05	2.16E-05	***	0.73	7.46E-02	***	-	-	-	3.46E-02	1.23E-02	***	0.00	0.00	-	-8	-9	8.52
		hyper	4.71E-01	2.95E-01	***	0.99	1.02E-01	***	1.00	0.00	***	5.38E-04	3.05E-02	***	0.00	0.00	-	8	948	2.93
	Ejura	power	1	-	-	0.51	8.71E-02	***	8.24	0.69	***	9.58E+05	5.42E-08	***	4.22	0.07	***	-93	-111	0.45
		expo	8.88E-05	6.12E-05	ns	0.64	5.23E-02	***	-	-	-	3.06E-02	1.12E-02	*	0.00	0.00	-	-10	-45	0.58
		hyper	1.85E-01	4.29E-02	***	1.08	6.77E-03	***	0.87	0.00	***	3.12E-03	9.03E-02	**	0.00	0.00	-	8	239	1.45
	Tropical dry forest																			
	Pointe	power	1	-	-	0.07	9.39E-03	***	10.53	0.36	***	9.68E+03	3.38E-06	***	3.06	0.02	***	-341	-642	152.29
		expo	1.63E-03	8.60E-04	***	0.36	4.06E-02	***	-	-	-	5.72E-01	7.03E-02	***	0.00	0.00	-	731	-258	64.54
		hyper	1.53E-01	6.18E-02	***	1.59	2.08E-02	***	0.65	0.01	***	1.22E-02	3.51E-01	***	0.00	0.00	-	2354	2784	2.27
	Bawku	power	1	-	-	0.30	5.32E-02	ns	4.07	0.26	***	5.20E+03	6.80E+03	***	3.04	0.32	***	-59	-90	1.06
		expo	1.57E-03	1.03E-03	*	0.28	3.65E-02	***	-	-	-	1.60E-01	6.60E-02	ns	0.00	0.00	-	36	-38	0.84

Location	model	a			b			c			sigma2			k			AIC			RMSE	
		Mean	SD	p	Mean	SD	p	Mean	SD	p	Mean	SD	p	Mean	SD	p	site	plot			
	expo	2.05E-01	6.53E-02	***	0.82	1.80E-02	***	0.99	0.00	***	2.48E-03	2.45E-02	***	0.00	0.00	-	119	136	1.74		
Agriculture																					
Tropical rainforest																					
luki	power	1	-	-	0.03	2.64E-03	***	2.40	0.09	***	2.29E-01	2.49E-01	***	1.81	0.25	***	-555	-680	0.08		
	expo	2.31E-03	2.93E-04	***	0.06	4.76E-03	***	-	-	-	4.21E-04	1.03E-04	***	-	-	-	-453	-470	0.08		
	hyper	8.80E-03	1.00E-03	**	1.43	5.13E-01	***	0.97	0.05	***	1.95E-03	3.77E-04	***	-	-	-	-308	-369	0.08		
Tropical mountain system																					
Vihiga	power	1	-	-	1.66	3.91E+00	***	1.47	2.75	***	2.88E+03	7.85E+04	ns	1.86	5.67	***	397	-264	1.73		
	expo	4.34E-02	1.78E-02	***	0.14	3.70E-02	***	-	-	-	3.71E-01	8.98E-02	***	-	-	-	382	20	1.47		
	hyper	4.08E-01	2.82E-03	***	1.40	8.59E-02	***	0.79	0.04	***	1.49E-01	1.12E-02	***	-	-	-	3079	599	1.53		
Tropical dry forest																					
Siaya	power	1	-	-	4.00	1.03E+00	ns	3.01	0.10	ns	1.10E+05	8.47E-08	ns	2.43	0.03	***	1612	-24	1.90		
	expo	7.17E-02	3.16E-02	***	0.03	3.74E-03	*	-	-	-	4.65E+00	4.68E-01	***	-	-	-	2692	780	1.63		
	hyper	3.49E-01	1.67E-02	***	1.29	4.84E-01	***	0.94	0.12	***	6.59E-01	6.88E-02	***	-	-	-	2970	3010	1.64		
Sirlawé	power	1	-	-	0.06	1.47E-02	***	2.18	0.21	***	8.29E+02	1.83E+03	ns	3.27	0.46	***	-319	-436	0.33		
	expo	5.05E-03	4.27E-06	ns	0.15	4.96E-02	*	-	-	-	1.57E-03	5.37E-04	***	-	-	-	-229	-286	0.32		
	hyper	1.60E-02	4.53E-03	***	0.82	7.52E-05	***	0.99	0.00	***	2.80E-02	1.19E-02	**	-	-	-	9	-137	0.32		
MafaKilda	power	1	-	-		1.23E-02	***	3.54	0.49	***	7.36E+00	7.19E+00	ns	2.11	0.25	***	-481	-828	0.22		
	expo	9.07E-04	3.39E-04	***	0.16	1.94E-02	***	-	-	-	5.42E-03	1.38E-03	*	-	-	-	-292	-471	0.29		
	hyper	2.00E-02	4.88E-03	***	1.87	3.39E-04	***	0.93	0.00	***	3.27E-02	9.61E-03	ns	-	-	-	-65	-121	0.30		

Appendix VII: Biomass conversion functions

Ecosystem	Location	model	a		b		c		sigma2		k		AIC		RMSE					
			Mean	SD	p	Mean	SD	p	Mean	SD	p	Mean	SD	p		site	plot			
Natural forest																				
Tropical rainforest																				
	Kakum	power	1	-	-	0.044	0.002	***	1.65	0.05	***	1.76E-02	1.13E-02	ns	1.42	0.13	***	-622	-658	0.04
		expo	2.87E-03	2.38E-04	***	0.044	0.004	***	-	-	-	1.06E-04	2.74E-05	***	-	-	-	-518	-546	0.04
		hyper	1.02E-02	6.43E-04	***	5.727	0.445	***	1.00	0.00	***	1.50E-04	4.04E-05	***	-	-	-	-487	-469	0.04
	Bobiri	power	1	-	-	0.065	0.001	***	1.59	0.01	***	1.59E-02	7.31E-03	*	1.71	0.11	***	-710	-720	0.07
		expo	5.15E-03	2.18E-04	***	0.031	0.002	***	-	-	-	9.28E-05	1.79E-05	***	0	0	-	-555	-641	0.08
		model	1.41E-02	3.70E-04	***	5.482	0.281	***	1.00	0.00	***	1.47E-04	2.31E-05	***	-	-	-	-513	-512	0.08
	Boin River	power	1	-	-	0.081	0.001	***	1.41	0.01	***	4.18E-01	2.11E-01	ns	2.35	0.11	***	-650	-714	0.04
		expo	5.85E-03	2.18E-04	***	0.030	0.002	***	-	-	-	9.52E-05	1.37E-05	***	-	-	-	-553	-671	0.06
		hyper	1.49E-02	5.68E-04	***	4.889	0.510	***	1.00	0.00	***	2.77E-04	5.11E-05	***	-	-	-	-458	-512	0.06
	Boi Tano	power	1	-	-	0.069	0.002	***	1.51	0.03	***	1.81E-05	1.76E-05	ns	-0.29	0.22	***	-592	-645	0.06
		expo	5.64E-03	1.12E-04	***	0.027	0.001	***	-	-	-	4.04E-05	6.13E-06	***	-	-	-	-627	-638	0.06
		hyper	1.30E-02	4.61E-04	***	4.251	0.489	***	1.00	0.00	***	2.22E-04	3.57E-05	***	-	-	-	-477	-485	0.06
	Luki	power	1	-	-	0.062	0.030	***	1.59	0.05	***	8.76E+00	2.66E+00	***	2.27	0.07	***	-16449	-23113	0.11
		expo	8.48E-01	9.75E-01	***	-	0.459	***	-	-	-	4.51E-02	2.49E-03	***	-	-	-	-934	-18689	0.16
		hyper	1.65E-02	8.21E-03	***	6.263	0.166	***	1.00	0.00	***	6.54E-03	6.78E-04	***	-	-	-	-7854	-13533	0.07
	Ejura	power	1	-	-	0.058	0.005	***	2.98	0.16	***	2.34E+00	3.00E+00	ns	2.13	0.30	***	-489	-578	0.38
		expo	7.06E-05	1.11E-04	***	0.114	0.005	***	-	-	-	8.91E-04	1.81E-04	***	-	-	-	-375	-445	0.55
		hyper	2.38E-02	4.76E-03	ns	0.878	0.020	ns	1.00	0.00	***	1.13E-01	5.85E-02	***	-	-	-	98	-152	0.45
Tropical dry forest																				
	Bawku	power	1	-	-	0.002	0.006	***	1.95	0.09	***	1.01E+06	2.85E-03	ns	4.88	0.07	***	-200	-220	1.00
		expo	1.87E-06	1.62E-06	ns	0.335	0.060	ns	-	-	-	6.90E-02	2.40E-02	**	-	-	-	-66	-137	1.00
		hyper	2.57E-02	1.20E-02	***	1.185	0.156	***	0.91	4.09	***	4.89E-02	2.27E-01	***	-	-	-	2	-23	0.86
	MafaKilda	power	1	-	-	0.056	0.010	***	3.24	0.17	***	5.37E+00	4.69E+00	ns	1.88	0.19	***	-435	-645	0.34
		expo	1.79E-03	3.44E-04	***	0.127	0.008	***	-	-	-	3.96E-03	7.88E-04	***	-	-	-	-282	-319	0.40
			2.49E-02	4.69E-03	***	2.825	0.927	***	1.00	0.04	***	3.57E-02	2.03E-02	ns	-	-	-	-45	-226	0.30

Ecosystem	Location	model	a		b		c		sigma2		k		AIC		RMSE					
			Mean	SD	p	Mean	SD	p	Mean	SD	p	Mean	SD	p	site	plot				
Mountain Forest																				
	Tropical dry forest																			
	MafaKilda	power	1	-	-	0.214	0.045	***	1.33	0.09	***	1.86E+05	1.35E-07	***	3.42	0.03	***	-485	-1014	1.09
		expo	1.77E-03	1.24E-04	***	0.232	0.023	***	-	-	-	9.93E-02	1.59E-02	***	-	-	-	187	-379	0.47
		hyper	8.88E-02	2.50E-02	***	0.822	0.105	***	0.99	0.01	***	1.40E-01	1.85E-02	***	0	0	-	1363	845	0.89
Plantation																				
	Tropical rainforest																			
	Kakum	power	1	-	-	0.651	0.102	ns	5.93	1.08	**	3.72E+05	1.06E-06	***	3.86	0.10	***	-75	-108	1.25
		expo	2.36E-05	2.11E-05	ns	0.729	0.073	*	-	-	-	3.17E-02	1.13E-02	ns	-	-	-	-10	-11	3.88
		hyper	1.79E-	7.20E-02	***	2.250	0.000	***	0.89	0.00	***	1.11E+00	5.88E-01	ns	-	-	-	95	1300	0.73
	Tropical moist deciduous forest																			
	Ejura	power	1	-	-	0.528	0.089	***	8.25	0.67	***	9.68E+05	5.43E-08	***	4.21	0.07	***	-92	-108	0.44
		expo	8.79E-05	5.99E-05	ns	0.639	0.052	***	-	-	-	3.16E-02	1.15E-02	ns	-	-	-	-9	-43	0.57
		hyper	2.12E-01	9.04E-02	***	1.157	0.050	***	0.90	0.02	***	2.67E-01	7.26E-02	ns	-	-	-	212	239	1.50
	Tropical dry forest																			
	Pointe Noire	power	1	-	-	0.067	0.009	***	10.64	0.35	***	7.79E+03	3.40E-06	ns	3.03	0.02	***	-369	-642	1.86
		expo	1.10E-03	6.33E-04	***	0.392	0.045	***	-	-	-	5.04E-01	6.36E-02	***	-	-	-	691	-242	2.06
		hyper	1.49E-01	6.07E-02	***	1.597	0.008	***	0.66	0.00	***	4.18E-01	3.02E-02	***	-	-	-	1674	2582	2.09
	Bawku	power	1	-	-	0.067	0.009	ns	4.10	0.23	***	1.09E+04	1.43E+04	***	3.30	0.32	***	-72	-100	2.00
	Kakum	power	1.39E-03	8.89E-04	*	0.279	0.035	***	-	-	-	1.18E-01	4.87E-02	ns	-	-	-	27	-46	0.54
		hyper	1.78E-01	5.69E-02	***	1.866	0.000	***	0.93	0.00	***	1.93E+00	8.44E-01	ns	-	-	-	114	166	1.70

Ecosystem	Location	model	a		b		c		sigma2		k		AIC		RMSE						
			Mean	SD	p	Mean	SD	p	Mean	SD	p	Mean	SD	p	site	plot					
Agriculture	Tropical rainforest	luki	power	1	-	-	0.041	0.041	*	2.31	2.31	***	1.23E-01	1.23E-01	ns	1.54	1.54	***	-510	-656	0.10
		expo	2.96E-03	3.59E-04	***	0.058	0.005	***	-	-	-	6.03E-04	1.42E-04	***	-	-	-	-420	-432	0.09	
		hyper	1.08E-02	1.19E-03	***	1.457	0.004	***	0.97	0.00	***	2.71E-03	4.64E-04	***	-	-	-	-278	-326	0.09	
	Tropical mountain system	Vihiga	power	1	-	-	0.554	0.068	***	2.80	0.21	***	1.43E+01	2.00E+01	***	1.66	0.30	***	-497	-1123	2.03
		expo	3.19E-04	1.23E-03	***	0.259	0.033	ns	-	-	-	8.49E-03	1.78E-03	***	-	-	-	-388	-508	1.77	
		expo	5.74E-02	4.31E-26	***	1.367	0.000	ns	0.77	0.00	ns	4.26E-02	7.60E-25	*	-	-	-	-57	-198	0.61	
	Tropical dry forest	Siaya	power	1	-	-	0.840	1.457	***	3.32	0.10	***	4.51E+04	1.37E-06	***	3.08	0.32	***	-870	-2783	3.17
		expo	7.93E-03	2.69E-03	***	0.079	0.013	ns	-	-	-	3.77E-01	6.90E-02	***	-	-	-	1148	-1470	0.53	
		hyper	8.18E-02	7.79E-03	***	1.200	0.061	ns	0.92	0.02	***	1.27E-01	3.65E-02	***	-	-	-	965	162	0.54	
		Sirlawé	power	1	-	-	0.052	0.014	***	2.23	0.23		8.49E+02	1.97E+03	ns	3.32	0.49	***	-330	-450	0.32
		expo	6.19E-04	5.39E-04	ns	0.151	0.052	*	-	-	-	1.38E-03	4.82E-04	ns	-	-	-	-238	-299	0.34	
		hyper	1.51E-02	4.32E-03	***	0.813	0.006	***	0.99	0.00	***	4.46E-02	2.64E-02	ns	-	-	-	-7	-149	0.33	
		MafaKilda	power	1	-	-	0.035	0.011	***	3.66	0.51	***	6.02E+00	5.93E+00	*	2.10	0.25	***	-505	-857	0.16
		expo	7.98E-04	3.12E-04	***	0.162	0.020	***	-	-	-	4.52E-03	1.24E-03	*	-	-	-	-314	-526	0.20	
		hyper	1.84E-02	4.51E-03	***	1.866	0.000	***	0.93	0.00	***	2.88E-02	8.61E-03	*	-	-	-	-81	-155	0.29	

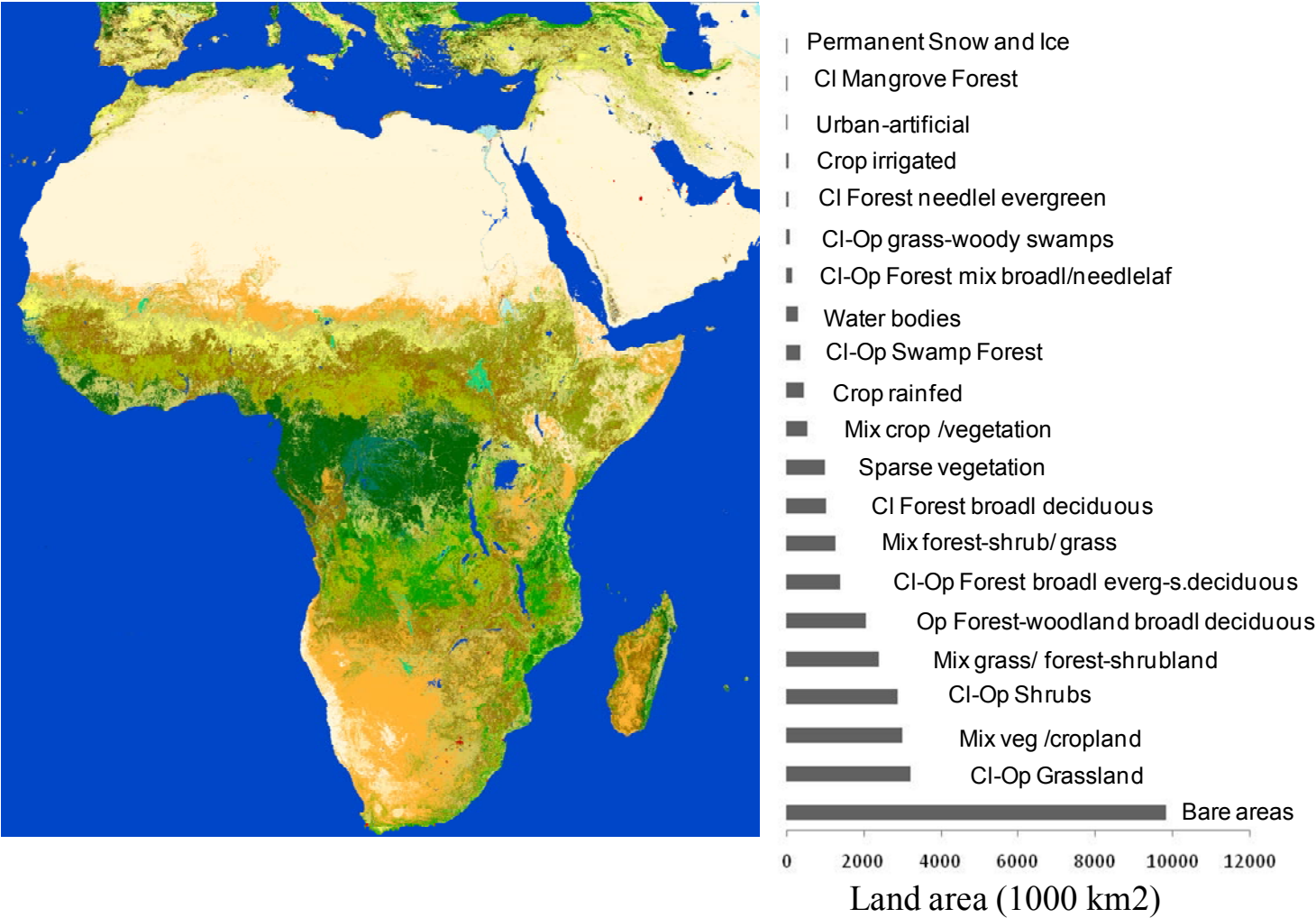
Appendix VIII: The Globcover legend

Code	Legend
11	Post-flooding or irrigated croplands (or aquatic)
12	Post-flooding or irrigated shrub or tree crops
13	Post-flooding or irrigated herbaceous crops
14	Rainfed croplands
15	Rainfed herbaceous crops
16	Rainfed shrub or tree crops (cash crops, vineyards, olive tree, orchards...)
20	Mosaic cropland (50-70%) / vegetation (20-50%)
21	Mosaic cropland (50-70%) / grassland or shrubland (20-50%)
22	Mosaic cropland (50-70%) / forest (20-50%)
30	Mosaic vegetation (50-70%) / cropland (20-50%)
31	Mosaic grassland or shrubland (50-70%) / cropland (20-50%)
32	Mosaic forest (50-70%) / cropland (20-50%)
40	Closed to open (>15%) broadleaved evergreen or semi-deciduous forest (> 5m)
41	Closed (>40%) broadleaved evergreen and/or semideciduous forest (>5m)
42	Open (15-40%) broadleaved semi-deciduous and/or evergreen forest with emergents (>5m)
50	Closed (>40%) broadleaved deciduous forest (>5m)
60	Open (15-40%) broadleaved deciduous forest/woodland (>5m)
70	Closed (>40%) needleleaved evergreen forest (>5m)
90	Open (15-40%) needleleaved deciduous or evergreen forest (>5m)
91	Open (15-40%) needleleaved deciduous forest (>5m)
92	Open (15-40%) needleleaved evergreen forest (>5m)
100	Closed to open (>15%) mixed broadleaved and needleleaved forest (>5m)
101	Closed (>40%) mixed broadleaved and needleleaved forest (>5m)
102	Open (15-40%) mixed broadleaved and .needleleaved forest (>5m)
110	Mosaic forest or shrubland (50-70%) / grassland
120	Mosaic grassland (50-70%) / forest or shrubland (20-50%)
130	Closed to open (>15%) (broadleaved or needleleaved, evergreen or deciduous) shrubland .(<5m)
131	Closed to open (>15%) broadleaved or needleleaved evergreen shrubland (<5m)
134	Closed to open broadleaved deciduous shrubland
140	Closed to open (>15%) herbaceous vegetation (grassland, savannas or lichens/mosses)
141	Closed (>40%) grassland
143	Open (15-40%) grassland
145	Lichens or mosses
150	Sparse (<15%) vegetation
151	Sparse (<15%) grassland
152	Sparse (<15%) shrubland
153	Sparse (<15%) trees
160	Closed to open (>15%) broadleaved forest regularly flooded (semi-permanently or temporarily) - Fresh or brackish water
161	Closed to open broadleaved forest on (semi-) permanently flooded land - Fresh water
162	Closed to open broadleaved forest on temporarily flooded land - Fresh water
170	Closed (>40%) broadleaved forest or shrubland permanently flooded - Saline or brackish water
180	Closed to open (>15%) grassland or woody vegetation on regularly flooded or waterlogged soil - Fresh, brackish or saline
181	Closed to open (>15%) woody vegetation on regularly flooded or waterlogged soil - Fresh or brackish water
185	Closed to open (>15%) grassland on regularly flooded or waterlogged soil - Fresh or brackish water
190	Artificial surfaces and associated areas (Urban areas >50%)
200	Bare areas
201	Consolidated bare areas
202	Non
203	Salt hardpans
210	Water Bodies
220	Permanent Snow and Ice
230	No data
240	plantation_NO_GLC
241	Improved fallow

Appendix IX: Calculation of AGC using Globcover legend, MODIS tree cover and field data

ID	Legend	Average Tree cover	AGC/%TC
11	Crop irrigated	8	
12	Crop irrigated (woody)	6*MODIS_TC	
13	Crop irrigated (herb)	8	
14	Crop rainfed	9*MODIS_TC	
15	Crop rainfed (herb)	9	
16	Crop rainfed (woody)	6*MODIS_TC	
20	Mix crop (60)/veg (35)	0.575 9*0.6+14*0.4*MODIS_TC	
30	Mix veg (60)/crop (35)	0.575 14/AVTC*AvCC*0.6+9*0.4*MODIS_TC	
31	Mix herb-shrub veg (60)/crop (35)	0.575 13/AVTC*AvCC*0.6+9*0.4*MODIS_TC	
32	Mix forest (60)/crop (35)	0.575 11/AVTC*AvCC*0.6+9*0.4*MODIS_TC	
40	Cl-Op Forest broadl everg-s.decid	0.575 1/AVTC*AvCC*MODIS_TC	
41	Cl Forest broadl everg-s.decid	0.700 1/AVTC*AvCC*MODIS_TC	
42	Op Forest broadl everg-s.decid	0.275 1/AVTC*AvCC*MODIS_TC	
50	Cl Forest broadl decid	0.700 2/AVTC*AvCC*MODIS_TC	
60	Op Forest-woodland broadl decid	0.275 2/AVTC*AvCC*MODIS_TC	
70	Cl Forest needlel everg	0.700 3/AVTC*AvCC*MODIS_TC	
90	Op Forest needlel decid-everg	0.275 3/AVTC*AvCC*MODIS_TC	
100	Cl-Op Forest mix broadl/needlel	0.575 4/AVTC*AvCC*MODIS_TC	
110	Mix forest-shrub (60)/ grass (35)	0.575 7*0.4+12/AVTC*AvCC*0.6*MODIS_TC	
120	Mix grass(60)/ forest-shrub(35)	0.575 7*0.6+12/AVTC*AvCC*0.4*MODIS_TC	
130	Cl-Op Shrubs	0.575 6/AVTC*AvCC*MODIS_TC	
134	Cl-Op Shrubs decid	0.575 6/AVTC*AvCC*MODIS_TC	
140	Cl-Op Grassland	0.575 7/AVTC*AvCC	
141	Cl Grassland	0.700 7/AVTC*AvCC	
143	Op Grassland	0.275 7/AVTC*AvCC	
150	Sparse vegetation	0.095 14/AVTC*AvCC	
151	Sparse grassland	0.095 7/AVTC*AvCC	
160	Cl-Op Swamp Forest (fresh-brakish)	0.575 11/AVTC*AvCC*MODIS_TC	
161	Cl-Op Swamp Forest (fresh) s.perm	0.575 11/AVTC*AvCC*MODIS_TC	
162	Cl-Op Swamp Forest (fresh) temp	0.575 11/AVTC*AvCC*MODIS_TC	
170	Cl Mangrove Forest (brakish-saline)	0.700 5/AVTC*AvCC*MODIS_TC	
180	Cl-Op grass-woody swamps (fresh-	0.575 13/AVTC*AvCC*MODIS_TC	
181	Cl-Op woody swamps (fresh-	0.575 6/AVTC*AvCC*MODIS_TC	
185	Cl-Op grass-woody swamps (fresh-	0.575 13/AVTC*AvCC	
190	Urban-artificial	10	
200	Bare areas	0	
201	Consolidated bare areas	0	
202	Non-consolidated bare areas	0	
203	Salt hardpands	0	
210	Water bodies	0	
220	Permanent Snow and Ice	0	

Appendix X: Distribution of land cover classes in sub-Saharan Africa



Appendix XI: Aboveground carbon stocks in vegetation types of Africa

Legend	Area	FAO AGC	Mean	SD	Olson AGC	Mean	SD	Holdridge AGC	Mean	SD	Bailey AGC	Mean	SD	Udvardy AGC	Mean	SD
11	3893	11	3	±0	11	3	±0	26	7	±3	18	5	±2	63	16	±3
12	4	0	25	±76	0	3	±8	0	8	±16	0	5	±12	0	5	±9
13	547	2	3	±0	1	2	±0	4	8	±1	3	6	±2	9	16	±3
14	55040	616	11	±21	755	14	±26	458	8	±15	1022	19	±58	830	15	±26
15	82	1	14	±11	1	11	±7	1	15	±12	1	15	±5	1	15	±4
16	74	1	17	±30	1	13	±38	1	12	±14	1	12	±55	0	4	±7
20	100872	1924	19	±24	1905	19	±17	1824	18	±17	3168	31	±60	2088	21	±20
30	268322	7079	26	±33	6087	23	±25	6242	23	±25	7314	27	±33	6805	25	±32
31	1	0	16	±48	0	8	±18	0	16	±58	0	12	±35	0	16	±34
32	31417	2339	74	±36	2158	69	±33	2161	69	±32	1816	58	±27	2271	72	±37
40	55200	6750	122	±74	6582	119	±57	7482	136	±58	4222	76	±32	5743	104	±74
41	149497	26019	174	±53	25479	170	±44	25241	169	±37	13038	87	±20	23186	155	±49
42	2	0	73	±57	0	45	±35	0	61	±58	0	33	±22	0	32	±31
50	126799	5481	43	±33	5404	43	±28	7845	62	±30	7345	58	±33	6753	53	±27
60	238222	3956	17	±15	3642	15	±9	5460	23	±15	5365	23	±12	4946	21	±12
70	125	9	71	±90	16	131	±94	21	164	±121	17	139	±106	18	146	±101
90	4665	210	45	±29	208	45	±25	272	58	±28	208	45	±30	268	57	±23
100	13635	241	18	±8	884	65	±31	400	29	±35	286	21	±17	330	24	±16
110	139679	4199	30	±40	3822	27	±33	4211	30	±52	2931	21	±28	4562	33	±43
120	43948	960	22	±14	1067	24	±20	1274	29	±18	1079	25	±19	1006	23	±20
130	280835	5441	19	±14	4668	17	±14	4740	17	±14	5053	18	±13	4004	14	±10
134	6743	130	19	±20	81	12	±14	114	17	±12	98	14	±11	125	19	±14
140	162895	784	5	±3	828	5	±2	1280	8	±6	720	4	±4	657	4	±2
141	18337	548	30	±52	475	26	±18	456	25	±14	135	7	±3	256	14	±16
143	138586	300	2	±1	296	2	±1	542	4	±2	339	2	±2	275	2	±1

Legend	Area	FAO AGC	Mean	SD	Olson AGC	Mean	SD	Holdridge AGC	Mean	SD	Bailey AGC	Mean	SD	Udvardy AGC	Mean	SD
150	67290	209	3	±1	268	4	±1	234	3	±1	163	2	±2	341	5	±1
151	33921	18	1	±0	20	1	±0	32	1	±1	17	1	±0	18	1	±0
160	19424	1845	95	±23	2043	105	±26	3280	169	±282	1721	89	±22	1943	100	±26
161	15391	1313	85	±29	1393	90	±32	1598	104	±83	1607	104	±36	1355	88	±31
162	1877	122	65	±47	128	68	±50	151	80	±51	129	69	±50	143	76	±54
170	1906	186	98	±97	200	105	±102	201	105	±103	316	166	±160	140	73	±70
180	8290	124	15	±19	54	6	±9	94	11	±15	93	11	±12	78	9	±10
181	29	1	22	±61	0	17	±21	0	8	±17	1	18	±12	0	9	±24
185	928	10	11	±2	11	12	±2	24	26	±11	17	18	±3	9	10	±1
190	3087	14	5	±4	26	8	±8	15	5	±7	53	17	±30	319	103	±171
200	266094	0	0	±0	2	0	±0	25	0	±1	20	0	±1	0	0	±0
201	391733	0	0	±0	0	0	±0	8	0	±1	0	0	±0	0	0	±0
202	324184	0		±0	0	0	±0	0			0	0	±0	0	0	±0
203	119	0	0	±0	0	0	±0	0	0	±0	0	0	±0	0	0	±0
210	30637	0	0	±0	6	0	±1	182	6	±9	110	4	±5	0	0	±0
220	12	0	0	±0	0	0	±0	0	4	±9	0	0	±0	0	0	±0
	3,004,344	70,843	32	26	68,520	32	21	75,898	38	32	58,425	31	24	68,543	34	24

Appendix XII: Influence of tree cover on forest definition and aboveground carbon stocks

Country	FAO-GAUL	Tree cover =10%			Tree cover =15%			Tree cover =20%			Tree cover =25%			Tree cover =30%		
	AREA (1000 km2)	AGC (Tg)	Mean	SD	AGC (Tg)	Mean	SD	AGC	Mean	SD	AGC (Tg)	Mean	SD	AGC	Mean	SD
Angola	1254	2879	23	27	2754	22	28	2545	20	28	2301	18	29	2071	17	29
Botswana	580	301	5	18	229	4	16	95	2	11	21	0	5	11	0	4
Comoros	2	5	33	20	5	32	21	5	32	21	5	30	23	5	29	24
Kenya	585	780	13	34	588	10	32	410	7	29	314	5	28	247	4	26
Lesotho	31	23	7	12	16	5	12	11	4	11	5	2	8	2	1	5
Madagascar	594	2527	43	75	2365	40	75	2115	36	75	1963	33	75	1859	31	76
Malawi	119	169	14	21	148	12	21	120	10	22	97	8	21	77	6	20
Mayotte	0	2	43	23	2	42	23	2	42	23	2	42	24	2	42	24
Mozambique	789	1841	23	17	1756	22	18	1604	20	19	1399	18	20	1157	15	20
Namibia	828	103	1	10	65	1	9	22	0	5	4	0	2	2	0	1
Seychelles	0	0	3	6	0	3	6	0	1	5	0	1	5	0	1	3
South Africa	1223	1290	11	27	953	8	26	745	6	25	570	5	23	430	4	21
Swaziland	17	31	18	21	27	15	22	23	13	22	20	11	22	16	9	22
Uganda	243	754	31	42	711	29	43	629	26	44	531	22	44	433	18	44
United Republic of Tanzania	948	2402	25	36	2099	22	36	1749	18	35	1408	15	33	1086	11	31
Zambia	756	1478	20	13	1392	18	14	1251	17	15	1077	14	16	890	12	16
Zimbabwe	392	702	18	18	605	15	19	446	11	19	295	8	18	227	6	17
Total Eastern & Southern Africa	8361	15289	331	421	13716	302	421	11773	266	410	10009	233	395	8513	204	383
Algeria	2321	366	2	20	285	1	19	235	1	18	197	1	17	137	1	15
Burkina Faso	275	107	4	8	44	2	6	14	0	3	3	0	2	1	0	1
Chad	1277	353	3	8	223	2	7	128	1	5	84	1	4	53	0	3
Djibouti	22	0	0	5	0	0	5	0	0	4	0	0	4	0	0	4
Egypt	984	1	0	1	1	0	1	0	0	1	0	0	1	0	0	0
Eritrea	121	6	1	6	1	0	4	0	0	2	0	0	1	0	0	1
Ethiopia	1136	2312	20	40	1904	17	39	1497	13	36	1235	11	34	1035	9	33
Libyan Arab Jamahiriya	1621	3	0	2	2	0	1	1	0	1	0	0	0	0	0	0
Mali	1257	232	2	6	148	1	6	95	1	5	53	0	4	25	0	3
Mauritania	1043	1	0	1	0	0	1	0	0	1	0	0	0	0	0	0
Morocco	407	206	5	32	156	4	30	110	3	27	78	2	24	51	1	20
Niger	1189	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Somalia	637	298	5	20	175	3	17	63	1	11	25	0	7	13	0	5
Sudan	2495	1381	6	16	1056	4	15	831	3	13	660	3	12	495	2	11
Tunisia	155	65	4	35	52	3	33	43	3	32	38	2	31	30	2	28
Western Sahara	269	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Northern Africa	15210	5333	50	199	4048	37	180	3019	26	158	2373	20	141	1840	16	125

Country	FAO-GAUL	Tree cover =10%			Tree cover =15%			Tree cover =20%			Tree cover =25%			Tree cover =30%		
	AREA (1000 km2)	AGC (Tg)	Mean	SD	AGC (Tg)	Mean	SD	AGC	Mean	SD	AGC (Tg)	Mean	SD	AGC	Mean	SD
Benin	116	137	12	9	98	8	10	61	5	9	30	3	7	13	1	5
Burundi	27	91	33	41	87	32	42	76	28	44	60	22	45	44	16	44
Cameroon	469	4072	87	78	4039	86	79	4004	85	80	3952	84	81	3870	82	82
RCA	624	2432	39	43	2393	38	43	2349	38	43	2283	37	44	2174	35	45
Congo	344	3700	108	69	3671	107	71	3628	106	72	3570	104	74	3519	102	76
Côte d'Ivoire	324	1290	40	40	1254	39	40	1188	37	42	1067	33	43	902	28	45
DRC	2343	24333	104	77	24240	103	78	24056	103	79	23719	101	80	23311	99	82
Equatorial Guinea	27	404	149	48	403	149	49	403	148	49	402	148	50	400	147	52
Gabon	266	3602	135	57	3594	135	58	3581	134	59	3560	134	60	3532	133	62
Gambia	11	16	15	23	11	10	23	8	8	21	6	5	19	4	4	18
Ghana	240	662	28	36	614	26	37	549	23	38	475	20	38	397	17	38
Guinea	247	701	28	28	679	28	29	640	26	30	595	24	31	509	21	31
Guinea-Bissau	34	140	41	46	137	40	46	133	39	47	127	37	47	118	34	48
Liberia	96	1159	120	50	1157	120	50	1151	119	52	1141	118	54	1123	116	57
Nigeria	915	1499	16	31	1328	15	31	1170	13	31	980	11	31	807	9	31
Rwanda	25	104	41	58	98	39	59	85	34	61	70	28	62	57	22	62
Saint Helena	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sao Tome and Principe	1	12	126	61	12	126	61	12	125	61	12	125	62	12	125	62
Senegal	198	140	7	14	110	6	13	94	5	13	78	4	12	56	3	11
Sierra Leone	73	365	50	39	361	50	39	353	49	40	342	47	41	318	44	43
Togo	57	75	13	13	59	10	14	42	7	14	28	5	13	17	3	11
Total Western and Central Africa	6439	44935	1192	861	44346	1165	872	43583	1131	884	42494	1089	896	41183	1042	905
Total Africa	30010	65557	1573	1481	62110	1504	1473	58375	1423	1452	54876	1342	1431	51536	1262	1413

Appendix XIII: biophysical and socio-economic parameters for analysing carbon sequestration potentials through cocoa agroforestry systems in Ghana

Variables	Scale	Value	Unit	Source
Forest	National	86 750	Km ²	Chapter 9
	Moist ecological zone	53 666	Km ²	-
Forest outside reserve	Moist ecological zone	43 134	Km ²	-
Cacao	National	17 500	Km ²	FAOSTAT (2010)
Deforestation	National	1.9	%	FAO (2006)
Aboveground carbon stocks	National	687	Tg C	Chapter 9
	Forest	299	Tg C	-
	Forest reserve	124	Tg C	-
	Outside reserve in Moist ecological zone	88	Mg ha ⁻¹	-
	Outside forest in Moist ecological zone	21	Mg ha ⁻¹	-
	Shaded cocoa	104	Mg ha ⁻¹	Asase (2010)
	Unshaded cocoa	39	Mg ha ⁻¹	-
Socio-economic background				
Farmers	Cocoa	644 145	-	FAOSTAT (2010) and Asare (2005)
Farm area	Cocoa	3	ha	-
Shaded	Cocoa	63	%	Asare (2005)
Yield	Cocoa	400	Kg ha ⁻¹	FAOSTAT (2010)
Yield	Unshaded cocoa	328	Kg ha ⁻¹ yr ⁻¹	Obiri (2007)
Yield	Shaded cocoa	611	Kg ha ⁻¹ yr ⁻¹	-
Price	Cocoa	0.84	\$	Ministry of Finance & Economic Planning of Ghana (2005)
Inputs	Unshaded cocoa	7	\$	-
Inputs	Shaded cocoa	8	\$	-
Income	Farmer	2 893	\$ yr ⁻¹	UNDP
Area	SC1	17 670	Km ²	-
Carbon sequestration		48	Mg ha ⁻¹	-
Number of farmers		636 125		-
Total carbon sequestration		4	Tg C yr ⁻¹	-
Transaction costs		9.85 (0.23 -28.63)	M\$	-

Variables	Scale	Value	Unit	Source
Country income		87 (92 -81)	M\$	-
Farmer income (cocoa)		557 (553 -559)	\$ ha-1 yr-1	-
Carbon income		51 (47 -53)	\$ ha-1 yr-1	-
Area	SC2	17670	Km ²	-
Carbon sequestration		-17	Mg ha ⁻¹	-
Number of farmers		636 125		-
Total carbon sequestration		-1	Tg C yr ⁻¹	-
Transaction costs		- (- -)	M\$	-
Country income		- (- -)	M\$	-
Farmer income (cocoa)		269 (- -)	\$ ha-1 yr-1	-
Carbon income		- (- -)	\$ ha-1 yr-1	-
Area	SC3	5 950	Km ²	-
Carbon sequestration		65	Mg ha ⁻¹	-
Number of farmers		644 145		-
Total carbon sequestration		1.93	Tg C yr ⁻¹	-
Transaction costs		4.41 (0.18 -9.64)	M\$	-
Country income		68 (71 -64)	M\$	-
Farmer income (cocoa)		620 (614 -626)	\$ ha ⁻¹ yr ⁻¹	-
Carbon income		114 (108 -120)	\$ ha ⁻¹ yr ⁻¹	-
Area	SC4	5 378	Km ² yr ⁻¹	-
Carbon stock		88	Mg C ha ⁻¹	
Emission reduction		68	Mg C ha ⁻¹	
Number of farmers		- -		-
Total carbon sequestration		1.76	Tg C yr ⁻¹	-
Transaction costs		3.99 (0.16 -8.71)	M\$	-
Country income		61 (64 -58)	M\$	-
Farmer income (cocoa)		542 (540 -543)	\$ ha ⁻¹ yr ⁻¹	-
Carbon income		36 (34 -37)	\$ ha ⁻¹ yr ⁻¹	-