ALLOMETRIC RELATIONSHIPS OF TROPICAL TREE SPECIES IN INDONESIA AND SENEGAL

By

Reinardus Liborius

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

Forestry - Master of Science

2016

ABSTRACT

ALLOMETRIC RELATIONSHIPS OF TROPICAL TREE SPECIES IN INDONESIA AND SENEGAL

By

Reinardus Liborius

This study focused on development of allometric relationships for tropical trees in Senegal and Indonesia as a new approach to estimating the annual rate of biomass and carbon accumulation. A total of 57 trees from seven different tree species were selected from five different protected forest areas of Senegal. Eight existing models from various references were screened through regression analyses in order to attain a best fitted specific-composite model in describing the relationship between age as a function of DBH, age as a function of height, and height as a function of DBH. A total of 407 trees from four different species are chosen from Indonesia. Eight existing models have been applied from several references to be able to formulate the best relationship between age as a function of DBH from four different species and one combination. For Indonesia trees, above-ground biomass was calculated based on existing formula in the literature of annual growth rates.

Power model fitted well for describing age as a function of DBH and age as a function of height, while cubic model was the best to describe height as a function of DBH for Senegalese trees. However, in general, the relationships from Senegal were weak with low indications in coefficient of determination (R^2). The cubic model turned out to be the best described model for age as a function of DBH to all species-specific equations and composite equation of Indonesian trees. *Araucaria cuninghamii* has a highest total ABG compared to other species. In contrast, *Drancontumelum* sp., has higher annual growth rates compared to other Indonesian tree species considered.

ACKNOWLEDGMENTS

I would like to convey my deep gratitude to my major advisor, Dr. Sophan Chhin for the relentless support, guidance, motivation and opportunity to accept me as an international student. Through my time spending at Michigan State University, you have been mentoring me with millions of assistances in both academic and non-academic areas. I would also like to thank the rest of my thesis committee, Dr. David Skole and Dr. Pascal Nzokou for your time guiding me and providing precious views. Your valuable comments and inputs are fundamental for my academic accomplishment are hugely appreciated.

Great data contributors either for Senegal and Indonesia are really appreciated. Without great collaboration with Dr. Cheick Mbow, from World Agroforestry Center in Kenya, field data measurement from Senegal would not be available. Great thanks also go to Center for Forest Research Institute in Manokwari, West Papua, Indonesia for a great opportunity in collecting data from their forest monitoring plot. I would like to express many thanks to the support staff, professors, and colleagues from the Department of Forestry at MSU.

A huge thanks in particular I want to convey to USAID for the support and opportunity to pursue my master at Michigan State University, USA. Rachael Fellabaum, Kate van Emrik from IIE Washington, D.C. who have been regularly monitored my progress while I am in the USA and providing unbelievable extra supports and information for me as an international student. My deep respect and gratitude also go to IIEF Indonesia through PRESTASI program that has been selecting me through various academic steps and put my name as one of USAID scholars. Your extra efforts are really appreciated.

An incredible thank also I want to convey to my lab mates Kaelyn Finley, Katie Minnix, Christal Johnson and Isaac Hayford for our togetherness inside lab group discussions who have been together and struggling to accomplish their own dream.

Finally, I would like to thank my family: my parents, Octo Cabuy (†) and Paula Samkakai (†) as well as my brother Cosmas Thadeus Cabuy and Antonius Jacky Cabuy.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

1.1. Introduction

An upswing of global concern about climate change has been a main issue over the last couple of decades. Mitigating efforts in general have been carried out in reducing the large scale impact of climate change and partly consist of measuring and monitoring global forest conditions and collecting the whole data related to how much forest can be actively reduce global emissions (Dolsak 2001; Brennan 2008; Bausch and Mehling 2011). Tropical regions in particular (e.g., Asia, South America, and Africa) have been targeted for rebalancing our global climate on account of their great ability and capable of absorbing global CO_2 emissions from the atmosphere which is led by industrial and anthropogenic activities (Malhi et al. 1999; Hendry et al. 2009; Malhi 2010; Aragao et al. 2014).

Covering more than 30% of worldwide land area, global forests cover around 638 gigatonnes (Gt) of carbon of which 238 Gt (44 percent) is stored in the forest biomass and another is stored in soil (around 46 percent), while dead wood and forest litter covered 6 percent and 4 percent respectively (Madeira 2008). Even though, great endeavor has been made so far with regard to forest carbon measurements through an array of scientific studies, observation reports and management actions. Still in the some cases, the information are not thorough enough to support and make better decisions for the future particularly for tropical regions which is claimed to be difficult and more challenging to measure (Condit 2008; Chandler et al. 2002).

Indonesia along with Senegal are important countries for global climate mitigation effort because of their wide forest areas. Such large forest potencies are likely to be having a great contribution and impact on global carbon absorptions. However, studies regarding carbon measurement and biomass contained for most of tree species in those areas are still lacking. This study focuses on some tree species from those countries and through the analysis of allometric relationships, the amount of biomass accumulation and annual growth rate contained can be measured which has implications carbon sequestration in the tropical forests (Vashum and Jayakumar 2012; Clark and Kellner 2012; Hunter et al. 2013).

1.2. Carbon Absorption Mechanisms

The proliferation of carbon dioxide (CO_2) emission in the atmosphere has been unstoppable and brought a new challenge for the global community. Coincident with the industrial revolutions and increased deforestation level, the amount of carbon concentration and other trace gases have been increasing over the last three decades which could produce higher global temperatures and changes in precipitation patterns which has been considered as human-driven cause. For example in the United States, CO_2 emission account for 98% of the total emissions in 2007 (Kothandaraman 2010). Data derived from Scripps Institution of Oceanography, University of California, in San Diego shows the increasing level of CO_2 concentration every year in average has been increasing upward since 1958 and in 2014 its concentration was 398.60 ppm which is unprecedented.

Limiting carbon emission through forest carbon absorption mechanism is one of the mechanisms to address climate change. Forests have been playing a key role in mitigating CO_2 emissions because it is needed for their energy. Through photosynthesis process, which is the process of using sunlight of most of green plants to synthesize their foods from carbon dioxide and water with yielding oxygen and as a byproduct, CO_2 is converted to become energy for growing process throughout their lifespan (Lewis et al. 1999).

Functioned as natural pollution filters of pollutant gasses, forest in general has been primarily a cornerstone and spur for global mitigating action in reducing emissions (Jacob et al. 2014). A cascade of attentions for preserving it are equivocally undertake particularly in the densely populated forest regions all over the world. Reducing Emissions from Deforestation and Forest Degradation (REDD) is one of the global tangible actions which is mainly focused on maintaining tropical regions in the world. Through it, expectedly all mitigating efforts to hinder global emissions should be realized despite in some places, it was still having problems as has happened in Indonesia (Wadsworth et al. 2009).

Long-lived trees can effectively function as a good storage of carbon for a long time (Gorte 2009; Kauppi et al. 2015). Through photosynthesis mechanism, carbon from atmosphere would be ending up as one component of wood structures and stored in their leaves, branches, stems, barks, and roots. Apparently, as much as half of dry weight of trees' biomass are carbon. Based on assumptions made, trees in the forests at age 30 years have capable of restoring 200 to 520 tons CO_2 per hectare (Johnson and Coburn 2010).

1.2.1. Allometric relationships

Allometric equations in general emphasize the relationship between two components or more and seeing the statistical significance of those in comparison (Goldman et al. 1990). It has been used in numerous field of studies to help scientists understand and recognize the fundamental aspect of the relationships. In recent years, allometry has been applied in medical disciplines to discern the correlation between bone size and human morphology, muscle characteristics and body sizes, etc. (Klingenberg 1996). It has been used also to acknowledge the relationships among agricultural crop productions such as maize estimating yield and productivity, soybean's trend of growth, etc. (Reddy et al. 1998; Tittonell et al. 2005; Misle and Kahlaoui 2015).

In forestry, tree allometry has been widely established to see quantitative relationships among tree components (stems, branches, leaves, roots, crowns, etc.) and also their relationship to growing factors such as micro-climates, soil nutrients, rainfalls and temperature (Ackerly and Donoghue 1998). The main purpose of developing this allometry for trees is to scrutinize the relationship among those components toward tree growth mechanism and how big each component plays their roles and functions throughout tree growth period. Trees throughout their development process, have been influenced by all the surrounding factors and global conditions.

Biomass is an accumulation of biological materials derived from living organisms or plants and has categorized as plant-based components (FAO 2009). Measuring tree biomass through allometry has been widely applied throughout the world. It is considered as a representative tool in defining tree correlations either internal among tree components or external which is intimately correlated with environments. These days, even though there are lots of components in tree that can be used for approaching tree biomass contained and quantifying carbon sequestration, tree diameters and height measurements have been widely useful predictor variables in estimating biomass contained in trees.

Tree allometry can result in a better understanding of tree biomass contained and carbon sequestration. It should be taken into account that not all of the forests regions and different climates can be effectively represented by one general measuring model and equation. The formula and equation for measuring biomass and discern the correlation among trees will be varied because the difference related to forest compositions, tree characteristics, and surrounding environments (Chave et al. 2005; Picard et al. 2012).

1.3. Variation in Tree Growth

In general, there are a lot of variations among trees. Such great numbers are affected by the internal and external factors of life. It is understood that different type of tree species will clearly provide different characteristics and traits during their living period. However, numerous studies have pointed out that even in the same species, the high number of variations also can be seen. The fact shows that each tree has a different way in response to multiple factors that can be affected them during their growing period (Plomion et al. 2008).

During trees growth, both genetic and environmental factors have inherently impacted them and bringing a great variation among species. Genetic variations provide specific characters to be more exist for trees in their circumferences. In addition, tree genotype will specifically determine the preferable zones and regions for tree to grow. It means, all trees will have different circumstances to allow them grow and develop as a young individual organism (Parks et al. 2014). Environmental factor, on the other hand, has been playing a pivotal role for trees to be exist for a long time. As with most of the references, different locations and regions will bring a huge implication for trees. It automatically alters their phenotypic appearances on the outside and structural and physiological function inside the trees. More globally, environment-related climate factor have widely influenced tree dynamic populations and distributions. As for climatic variation throughout the regions, trees have undergone a huge adaptation and transition. Besides, alteration and adjustment in physiological and morphological characteristics are also being made (Nath et al. 2006).

As we can see, anatomically most of trees that growing in sub-temperate zones had a simple structural and mechanical function of their tissues if compared to hardwood tree species which is dominantly growing up in tropical regions (Forest Products Laboratory 2010). Another distinguishing factor is type of ecological condition and forested area covers of which each region has different characteristic. For instance, forest type in Africa regions will be significantly different with those that grow either in Asia or America. Such tangible implications will automatically generate distinct differences among trees to grow and develop for a longer period of time.

1.4. Environmental Factors Affecting Tree Growth

Over the course of tree growing period, internal and external factors have been inherently incorporated in trees. The high impact correlation between trees and surrounding environments have brought a new insight of better understanding of growth mechanism. Those either come from inside which is tree genetic factor or external environmental factors. However, in general, it could not be denied that environmental aspects have been tremendous in impacting trees growth mechanism during their entire growing process (Coomes and Allen 2007). Those below are some influential factors that affecting tress during their growth period.

1.4.1. Water

In order to be a well-grown tree, supply of water should be regularly available with the enough rate for photosynthesis and transpiration purposes. Definitely, water has being a much-needed component for trees in particular during their vertical and secondary diameter growth. Surely, with the lack of it, a number of problems will be happening and result an un-balancing of the whole physiological mechanism in trees (Davis et al. 1999). Haverkamp (1988) pointed out some effects which can happen in trees related to the lack of water availability such as: reduction in the size of leaf, stunting the top of trees, hampering the flowering time mechanism, and potentially will be decreasing the number of seeds, their size and viability. In addition, water availability is a crucial factor also in influencing cambial activity and wood formation, while in stem, more of cambial expansions and generated tracheid cells are processes that are highly imprinted with the plant's water status (Savidge 2001).

1.4.2. Temperature

Trees are also sensitive to temperature. Variations in temperature can impact tree growth mechanisms and potentially alter their cambial activities and cell differentiations particularly in their early growing process (Balducci et al. 2013). In the recent a couple of decades, number of studies regarding temperature and tree growth relationship has shown a positive linear correlation. For example, several variations on phenological traits of xylem formation have found in yearly measurements of *Pinus leucodermis* Ant., which is mainly caused by temperature fluctuations in southern Italy (Deslauriers et al. 2008). Coincident with global climate change issue all around the world, it is likely that variations in temperature will, in turn, lead to alteration on tree physiological mechanism and appearances.

1.4.3. Light

Undoubtedly, trees are very dependent on light for survival. By having light from the sun, it will allow tree to synthesize and produce their food by photosynthesis mechanism to uphold tree growth functions. Lacking of light intensity, duration, and quality will lead to a problem in tree growth mechanism because photosynthesis processes will be depressed and subsequently distribution of food and energy to entire parts are interrupted (Canham 1988). Despite light is indispensable, some tolerant tree species are still able to grow with less of it. However, light has been tremendously beneficial for most of the tropical tree species because it can be occurred during all years and significantly impacted on tree growth process.

As a fact, tropical regions have highly abundant tree species and capable of influencing trees to reach their maximum size.

1.4.4. Nutrients

Soil nutrient is essential component for trees to grow and develop. Soil with high abundance of nutrients will lead tree to be healthier and rapidly catalyze them to grow vertically and laterally. Soil is composed of numerous mineral components which is roughly influencing tree growth, but the primary of those are nitrogen, phosphorous, potassium. Insufficiency of it will induce to lessen forage production, modified composition of vegetation, an in general will hinder growing process of tree (Haverkamp 1988). As with in nature, through decomposition process, soil will be more abundant with nutrients and organic matters and serve as reservoir of nutrients for tree, presenting soil aggregation, bumping up nutrient exchange, and increasing water infiltration into soil.

1.5. Study Area: Climate and Vegetation Type

1.5.1. Senegal

Senegal is one of the African countries and geographically has been considered as one of hottest areas in sub-Saharan region (USAID, 2013). With a total area of 196,190 km^2, it has been quite dense in terms of plant growth in particular in the southern half where rainfall is higher. In light of weather, is has been classified as tropical with rainy and dry seasons during a year. In terms of annual rainfall, there are variations among the areas. For example, in the northern part which is classified as drier land, the amount of annual rainfall of about 600mm that occurs between June and October, while in the south and close to coast area, it can exceed 1,500mm. In addition, temperature and precipitation rate are also quite variable among the areas. In general, the terrain and landscape condition is low (less than 330 feet above sea level), rolling and plains rising to foothills in the southern area. As with other African countries, Senegal has been faced with a couple of environmental issues such as deforestation, overgrazing, soil erosion, flood, and periodic drought (World Bank 2011; Vincke et al. 2010; Herrmann and Tappan, 0213).

On account of Senegal position in the westernmost point, it turns out that Senegal lies at an ecological boundaries where semiarid grasses, oceanfront, and tropical rainforest converge which has endowed Senegal with an array variety of plants. In terms of vegetation distribution, the southern region is slightly more abundant of trees to grow than north. Almost 80 percent of plants has been growing in the southern where more rainfall occurred and consists of savanna wood land species.

1.5.2. Indonesia

Indonesia has a climate type that is almost entirely tropical. In terms of micro-climate, there are numerous variations of it which spread across all the regions. Indonesia consist of thousands of islands from west to east and with a lot of terrains and landscapes topography. Annual temperature in the coastal area is about 28°C, while in the higher mountain, it could be 23°C. Climate in Indonesia is mostly driven by an equatorial monsoon system with a distinction of rainy season which is from November to March and dry season from June to October (Schollaen et al. 2013). By and large, western and northern parts of Indonesia experience the high precipitation with rainfall measuring more than 2,000mm per year. Meanwhile, some southern parts are likely to be dry with rainfall less than 1,000mm per year.

Owing to the position in the equator, Indonesia has been tremendously acknowledged for its rich biodiversity. According to FAO (2012), about 52 percent or 94,432,000 hectare of Indonesia is forested of which 50 percent is categorized as primary forest and 3,549,000 hectare is for planted forest. However, the issue of deforestation and land use change have increased and percentage of forest-land covered has dramatically changed over the course of the last decades. This has resulted in global carbon emissions with a high level of intensity (Murdiyarso et al. 2012). Considered as the second largest biodiversity country in the world, Indonesia's forest covers about 28,000 species of flowering plants, 6,000 of traditional medicinal plants, 122 species of bamboo, 350 species of rattan, and some of them are known as endemic. The distribution of Indonesia woody plants are dominated by broadleaf evergreen forests, while for some parts, needle leaf species are quite abundant in particular high regions with low temperature zones.

1.6. General Objectives and Thesis Structure

Tropical region has been considered as an abundant land in terms of trees species covered. Despite having similar climate type and weather pattern from Senegal and Indonesia, there are some particular aspects that have to be taken into account in measuring the rate of abundance. Tree biomass and carbon measurements are among those factors which will be analyzed. The objectives of this study are to address following questions:

1. What is the best allometric model to describe the relationships between age as a function of DBH, age as a function of height and height as a function of DBH from Senegal tree species?
2. What is the best allometric model to describe relationships between age as a function of DBH for Indonesian tropical tree species?
3. To understand the annual growth rate from Indonesian tropical forest in the context of biomass and carbon estimation.

REFERENCES

REFERENCES

Ackerly D., D. and Donoghue M., J. 1998. Leaf size, sapling allometry, and corner's rules: Phylogeny and Correlated evolution in Maples (*Acer*). The American Naturalist, 152, No-6.

Aragao L., E., O., C., Poulter B., Barlow J., B., Anderson L., O., Mahli Y., Saatchi S., Phillips O., L. and Gloor E. 2014. Environmental change and the carbon balance of Amazonian forests. Biol. Review, 89: 913-931.

Balducci L. Deslauriers A. Giovannelli A. Rossi S. and Rathgeber C.B.K. 2013. Effects of temperature and water deficit on cambial activity and woody ring features in Picea mariana saplings. Tree physiology, 33: 1006-1017.

Bausch C. and Mehling M. 2011. Addressing the challenge of global climate mitigation. An assessment of existing venues and institutions. Friedrich Ebert Stiftung.

Bombelli A., Hendry M., Castaldi S., Abu-Bredu S., Arneth A., Grandcourt A., de., Grieco E., Kutsch W., L., Lehsten V., Rasile A., Reichstein M., Tansey K., Weber U. and Valentini R. 2009. Biogeosciences, 6: 2193-2205.

Brennan E., J. 2008. Reducing the impact of global warming on wildlife: The science, management and policy challenges ahead. Defenders of Wildlife. Washington, D.C.

Canham C.D. 1988. Growth and canopy architecture of shade-tolerant trees: Response to canopy gaps. Ecology, 69: 786-795.

Chandler W. Shukla P.R. Tudela F. Davidson O. Dadi Z. Alpan-Atamer S. Schaeffer R. 2002. Climate change mitigation in developing countries. Brazil, China, India, Mexico, South Africa, and Turkey. Pew Center Global Climate Change.

Chave J. Andalo C. Brown S. Cairns M.A. Chambers J.Q. Eamus D. Folster H. Fromard F. Higuchi N. Kira T. Lescure J.-P. Nelson B.W. Ogawa H. Puig H. Riera B. and Yamakura T. 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologie, 145: 87-97.

Clark D., B. and Kellner J., R. 2012. Tropical forest biomass estimation and the fallacy of misplaced concreteness. J. of Vegetation Science; Doi: 10.1111/j.1654-1103.2012.01471.x

Condit R. 2008. Methods for estimating above-ground biomass of forest and replacement vegetation in the tropics. Center for tropical forest science and ForestGeo Smithsonian Tropical Research Institute.

Coomes D.A. and Allen R.B. 2007. Effect of size, competition and altitude on tree growth. Journal of Ecology, 95: 1084-1097.

Davis M.A. Wrage K.J. Reich P.B. Tjoelker M.G. Schaeffer T. and Meurmann C. 1999. Survival growth, and photosynthesis of tree seedlings competing with herbaceous vegetation along a water-light-nitrogen gradient. Plant Ecology, 145: 341-350.

Deslauriers A. Rossi S. Anfodillo T. and Saracino A. 2008. Cambial phenology, wood formation and temperature thresholds in two contrasting years at high altitude in southern Italy. Tree physiology, 28: 863-871.

Dolsak N. 2001. Mitigating global climate change: Why are some countries more committed than others? Policy Studies Journal, 29 (3): 414-436.

FAO. 2009. Biomass. Assessment of the status of the development of the standards for the terrestrial essential climate variables. Global Terrestrial Observing System. Rome.

FAO. 2012. State of the world's forests. United Nation Food and Agriculture Organization. Rome, Italy.

Forest Products Laboratory. 2010. Wood handbook-wood as an engineering material. General Technical Report FPL-GTR-190. Madison, WI: U.S. Department of Agriculture, Forest Service. Forest Product Laboratory.

Goldman C.A. Snell R.R. Thomson J.J. and Brown D.B. 1990. Principle of allometry. Pages 43-72, in Tested studies for laboratory teaching. Volume 11. (C. A. Goldman, Editor). Proceedings of the Eleventh Workshop/Conference of the Association for Biology Laboratory Education (ABLE), 195 pages.

Gorte R., W. 2009. Carbon sequestration in forests. Congressional Research Service 7-5700.
Herrmann S. M., and Tappan G., G. 2013. Vegetation impoverishment despite greening: A case study from central Senegal. J. Arid Environ, 90: 55–66.

Haverkamp M.R. 1988. Environmental factors affecting plant productivity. Fort Keogh Research Symposium, Miles City, MT.

Hunter M., O., keller M., Vitoria D. and Morton D., C. 2013. Tree height and tropical forest biomass estimation. Biogeosciences Discuss, 10: 10491-10529.

Jacob M., Steckel J., C., Klasen S., Lay J., Grunewald N., Martinez-Zarzoso I., Renner S. and Edenhofer O. 2014. Feasible mitigation actions in developing countries. Natural Climate Change, 4: 961-968.

Johnson I and Coburn R. 2010. Trees for carbon sequestration. Primefacts, 981.

Kauppi P., E., Birdsey R., A., Pan Y., Ihalainen A., Nojd P. Lehtonen A. 2015. Effects of land management on large trees and carbon stocks. Biogeosciences, 12: 855-862.

Klingenberg C., P. 1996. Multivariate allometry. Advances in morphometrics, Plenum Press, New York.

Kothandaraman A. 2010. Carbon Dioxide capture by chemical absorption: A solvent comparison study. Thesis. Massachusetts Institute of Technology.

Lewis, J.D., D.M. Olszyk and D.T. Tingey. 1999. Seasonal patterns of photosynthetic light response in Douglas-fir seedlings subjected to elevated atmospheric CO_2 and temperature. Tree Physiol, 19: 243-252.

Madeira E.C.M. 2008. Policies to reduce emissions from deforestation and degradation (REDD) in developing countries. An examination of the issues facing the incorporation of REDD into market-based climate policies. Washington DC 20026-1400.

Malhi Y. 2010. The carbon balance of tropical forest regions, 1990-2005. Current Opinion in Environmental Sustainability, 2: 237-244.

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

Misle E. and Kahlaoui B. 2015. Nonlinear allometric equation for crop response to soil salinity. J. of Stress Physiology & Biochemistry, 11 (2): 49-63.

Murdiyarso D. Kauffman J.B. warren M. Pramova E. and Hergoualc K. 2012. Tropical wetlands for climate change adaptation and mitigation: Science and policy imperatives with special reference to Indonesia. Working paper 91. CIFOR, Bogor, Indonesia.

Nath C.D. Dattaraja H.S. Suresh H.S. Joshi N.V. and Sukumar R. 2006. Patterns of tree growth in relation to environmental variability in the tropical dry deciduous forest at Mudumalai, southern India. J. Biosci, 32 (5): 651-669.

Parks A. Jenkins M. Ostry M. Zhao P. and Woeste K. 2014. Biotic and abiotic factors affecting the genetic structure and diversity of butternut in the southern Appalachian Mountains, USA. Tree Genetics & Genomes, 10: 541-554.

Picard N. Saint-Andre L. and Henry M. 2012. Manual for building tree volume and biomass allometric equations. From field measurement to prediction. Food and Agriculture Organization, Rome, Italy.

Plomion C. Leprovost G and Stokes A. Wood formation in trees. Plant physiology, 127: 1513-1523.

Reddy V., R., Pachepsky Y., A. and Whisler F., D. Allometric relationships in field-grown soybean. Annals of Botany, 82: 125-131.

Savidge R.A. 2001. Intrinsic regulation of cambial growth. J. Plant Growth Regul, 20: 52-77.
Schollaen K. Heinrich I. Neuwirrth B. Krusic P.J. D'Arrigo R.D. Karyanto O. and Helle G. 2013. Multiple tree-ring chronologies (ring width, 13C and 18O) reveal dry and rainy season signals of rainfall in Indonesia. Quaternary Science Reviews, 73: 170-181.

Tittonell P., Vanlauwe B., Leffelaar P., A. and GillerK., E. 2005. Estimating yields of tropical maize genotypes from non-destructive, on-farm plant morphological measurements. Agriculture Ecosystem & Environment, 105: 213-220.

USAID 2013. The ARCC West Africa regional climate change vulnerability assessment – Background paper. http://community.eldis.org/.5b9bfce3/Background%20Paper%20-%20West%20Africa%20Final.pdf

Vashum K., T. and Jayakumar S. 2012. Methods to estimate above-ground biomass and carbon stock in natural forests – A review. L. Ecosyst Ecogr, 2 (4): 1-7.

Vincke C., Diédhiou I., and Grouzis M. 2010. Long term dynamics and structure of woody vegetation in the Ferlo (Senegal). J. of Arid Environments, 74: 268-276.

Wadsworth F., H., Adams J., Holmgren P., H., Jimenez A., B. and Whitmore J., L. 2009. Management of Teak plantations for solid wood products. Special Report, ISTF News. Zobel Forestry Associates, Inc.

World Bank. 2011. Climate risk and adaptation country profile. Vulnerability, risk reduction, and adaptation to climate change. Global Facility for Disaster Reduction and Recovery. The World Bank Group. Washington DC 20433.

CHAPTER 2

ALLOMETRIC EQUATION DEVELOPMENT FOR SENEGAL TREE SPECIES

2.1. Introduction

Senegal has abundant forest cover on more than 45 percent of their lands. The importance of these available forests for the surrounding people and ecosystems as well as the need to ensure continued maximization of the vital goods and services they provide cannot be overemphasized (USAID, 2012; Lo and Tumusiime, 2013). Lying on the coastal western part of African region, Senegal presents a variety of environmental conditions. In general, Senegalese climate is considered to be tropical and hot with distinct seasons in a year. Rainy season starts from May to November coupled with strong southern winds, while dry season is expected from December to April and often dominated by harmattan winds (Camberlin et al. 2001; Knippertz and Fink, 2008). The annual rainfall is about 600 mm and the temperature ranges from 18° C to more than 30° C. However in some parts, the temperature, precipitation, and other climatic variables are potentially extreme (BBC WST, 2010; McSweeney et al. 2012).

The ecology of Senegal is quite varied and primarily driven by the topography and climate condition between northern and southern part of the nation. The drier climatic condition in the north is potentially caused by the sub-Sahel-ecoclimatic and biogeographic zone of transition between Sahara desert and semi-arid climate zone in the south (USAID, 2013). Such conditions have brought a huge gap of ecosystem zone and vegetation distribution across the country. The northern part in general has been dominated by savanna grass, with scattered clumps of trees and spiny shrubs. However, the trees in the south are usually evenly distributed particularly along the Gambia River. Another vegetation zone in the south is mangrove swamps which is normally found in the coastal areas (Vincke et al. 2010; Herrmann and Tappan, 0213).

Currently, the Senegalese forests are in critical conditions due to a wide variety of factors including forest conversions for agricultural purposes, land use change driven by people's invasion for settlements, deforestation and degradation. Agriculture is a major source of majority of citizenry and plays a dominant role in the Senegalese economy (Käser, 2001; FAO, 2012; Diaw, 2006). Consequently, huge areas of lands are converted to fulfill the necessity of agriculture expansion annually throughout the region including densely forested areas. The aftermath effects of forest transitions are huge for the long-term existence of Senegal and people who live there. With the huge transition, forests' function as global environmental trade-offs will be slowly diminished, spurring the intensity of climate change and increasing global warming. Forest management and plantation expansion are the forefront solutions for Senegal and currently practiced across the world. Managing forest with a better understanding is needed not only for the narrower purposes, but for the globe due to the importance of forests in providing endless benefits for the entire world.

Allometric equation development for understanding forest contributions through biomass and carbon accumulation into the trees across Senegal is one of the straightforward methods to help people realize the huge global impacts of forests. It has been found many in places that, this method is simpler with the great results compared to other measurements such as satellite measurement (Pearson et al. 2007; Litton, 2008; Pretzsch, 2009; Picard et al. 2012). Due to the simplicity of allometric equation in tree measurement, it has been applicable for various forest types including African forests. Understanding forest mechanisms in sinking and accumulating biomass and carbon through photosynthesis is necessary for countries such as Senegal. Along with global consensus on climate change, forest contributions towards balancing global temperature is now valued legally (Laitat et al. 2000; Nabuurs et al. 2007; Streck et al. 2009). Thus, through knowledge of how allometric formula could be utilized to measure biomass production and carbon accumulation in trees at certain period of time in Senegal is necessary. Moreover, compensation schema as internationally mandated could be applied to bring a new era of forests payment mechanism for countries or forest communities to be more sustainable (Hoogeveen et al. 2008; McNeely and Mainka, 2009; Mbow et al. 2013: Mbow et al. 2014). Reducing emission from deforestation and forest degradation plus (REDD+) is one of the pivotal mechanisms that is potentially applicable for tropical countries including Senegal due to their forest capabilities for trading-off global emissions and advance a benefit for economic adaptability.

One of the main importance of understanding tree age from tropical forests is to be able to estimate a tree's ability in accumulating biomass in a particular time and understand the annual growth rate from the tropical forests (Weiskittel et al. 2011; He´rault et al. 2011). Even though it is a pivotal part of tropical forest's dynamic, age as a major index for tropical forests is often misinterpreted that leads to ineffectiveness of recording forest productivity and abundance. In order to sort out these issues, modelling and developing equations to estimate real forest dynamics is inevitably needed. In general, estimating ages from tree ring counting approach (dendrochronology) has been effective for some regions, despite having major challenges due to discern annual rings on wood surface (Bowman et al. 2013).

In this study, the main objective is to develop a new allometric formula or equation to predict age from either diameter or tree height and also to estimate height from diameter in Senegal, Western Africa. Age as a function of DBH is a common relationship for forest biometric including how to predict forest biomass accumulation. The contribution of this will be useful to estimate annual rates of biomass growth and carbon sequestration for Senegalese trees to deal with carbon mitigation and climate change.

2.2. Methods

2.2.1. Study Area

This study was conducted in summer 2007 in Senegal, Western Africa. The study locations were specifically chosen with some fundamental considerations such as the current status of trees, types of trees, the ecological landscape, and environmental ecosystem which is related to topography, land covers, soils, etc. The study was conducted in five separate forest locations including: Bala, Patako, Welor, Kantora, and Ouli. All these locations are classified as protected forest areas situated in the middle and southern part of Senegal. Welor and Patako reserve forests are located in the mid-west of Senegal, while Bala and Ouli forests reserve are situated in the Mid-east and Kantora is in the Southern part, right beneath the Gambia River. The trees in these forested areas were selectively chosen based on some physiological characteristics and health conditions, in order to get the best measurement results and prediction output. In this study, a total of 57 trees were selected from 7 different species and include: *Acacia seyal* with 6 trees, *Combretum glutinosum* with 20 trees, *Acacia macrostachy* with 9 trees, *Cordila pinnata* with 7 trees, *Terminalia macroptera* with 8 trees, *Balanites aegyptica* with 4 trees, and *Petrocarpus erinaceus* with 3 trees. There were variations in number of tree species measured as presented above. *Combretum glutinosum* was the species with the highest number and *Petrocarpus erinaceus* had the lowest number of trees measured (Mbow et al. 2014).

The Welor Forest Reserve contains forty-six woody species from 39 genera and 25 families, where the most numerous families are *Combretaceae*, *Capparidaceae*, *Mimosaceae* and *Caesalpiniaceae*. Shrub savannas are the most dominant species with approximately 95% where *Acacia seyal* and *Balanites aegyptiaca* are the most dominant woody species with the finest population structure (Lawesson, 1995; Sambou et al. 2008). The geographical characteristic is plateaus and consist of valleys which is likely filled with water during rainy season. The soil is ferruginous in the most part, while in the valleys, clay has been found to be dominant (Stancioff et al. 1986). Forbes (1973) indicates ferruginous as a very sandy soil and less of organic mineral with thin surface horizon. It is also hard, bulk and rigid during dry season when temperature is high.

The Patako Forest Reserve is one of the large national forests in the mid-west Senegal and has abundant shrub savanna and wood savanna species. The area is classified as a lowland with ferruginous soil and dune material that is very sandy with loamy and sandy loam at depth with rainfall of about 600-700mm/year (Tappan et al. 2000; Li et al. 2004). In general, this type of forest ecosystem and tree component is quite the same with the Welor Forest Reserve due to the fact that they are found in the same eco-region (Tappan et al. 2004).

The Bala Forest Reserve is located in the mid-east of Senegal and consists mainly of wooded savannas and tree savannas with woody cover ranging from 5 to 20 percent. Rainfall is between 500 to 800mm/year with geomorphological area of sandstone plateaus of the continental sedimentary basin. Soil is identic with leached tropical ferruginous in the valleys and terraces, and shallow loamy over laterite on plateaus (Tappan et al. 2004).

The Ouli Forest Reserve is situated in the middle of Senegal and close to the Gambia River with an estimated terrain elevation above sea level of 52 meters. Geographically, the forest is closed to the Bala Forest Reserve and presents a quite similar forest ecosystem and structure of vegetation which is mostly dominated by wooded savannas and tree savannas.

The Kantora Forest Reserve is situated in the south and lies beneath the Gambia River. The overall region is classified as green due to dense forested cover with the intensity average between 20-50 percent. Rainfall is high between 800 to 1400mm/year. Vegetation is dominated by wooded savannas, woodlands and grasslands, riparian, gallery forests along valleys. Soil is predominantly characterized by ferralitic tropical, ferruginous tropical sandy to clayey soil with the geomorphological plateaus of the continental sedimentary basin (Tappan et al. 2004).

2.2.2. Field Measurement

For this study, all field data collections were done manually by measuring with a straightforward method. The basic variables such as diameter at breast height (DBH), total tree height, crown cover were measured from the 7 different species considered in this study. DBH was measured using manual diameter tapes and rolled across the tree's stem to take diameter data. Tree height was measured using clinometer by standing and holding the tool in the proper distance to cover all the angles between the ground and top of the tree. Besides field measurement, the age of individual tree species was determined by ring record accounting through a process referred to as dendrochronology (Fichtler et al. 2004; Wils et al. 2010). The record of ages were measured in the laboratory and further analyses were undertaken using some applicable tree ring programs such as COFECHA to assess the quality of crossdating measurements. Tree ring measurements from those trees have been useful to determine age parameter even though very laborious to carry out. In general, it is extremely difficult to determine the age of tropical tree species from crossdating measurement due to inconsistency of climatic factor and various environmental conditions (Mbow et al. 2013).

2.2.3. Data Analysis

The data collected, specifically age, diameter, were used primarily to develop allometric equations for predicting annual growth and biomass from different study locations. SYSTAT 10.2. (SYSTAT Software Inc. 2002), was employed in the data analysis and to come up with cumulative result as the best model from each tested model. In this study, 8 models of statistical combinations were generated and eventually ended up choosing one best model as the ultimate output. Those are consisting of five linear models and three non-linear models. For five linear models, three of them are linear equations and two others are quadratic and cubic equations. Meanwhile, three non-linear models are power model, exponential model and hyperbolic model (Table 1) (Hendricksen 1950; Prodan 1965; Curtis 1967; Bates and watts 1980; Ratkowsky and Reedy 1986; Alexandros and Burkhart 1992; Huang and Titus 1992; Tang 1994; Vanclay 1995; Fang and Bailey 1998; Batista et al. 2001; Scaranello et al. 2012). . The total combination of models were 24, only one best model as well as graph was applied as a best scenario equation from this study. The final best model were 3 from three statistical tests (age as a function of DBH, age as a function of height, and DBH as a function of height).

To select the best appropriate model from each combination, there were several statistical parameters considered to be key indicators. *P-value* from the statistical analysis was definitely a fundamental index in this study. Other indicators such as adjusted square multiple (R^2), standard error of estimate, and statistical coefficient were also reviewed to formulate the finest output of allometric equation. However, the key criterion to opt for choosing a model was primarily based on R^2 value from all eight tested models in one statistical combination by classifying the highest value of it from the result (Hendricksen 1950; Prodan 1965; Curtis 1967; Bates and watts 1980; Ratkowsky and Reedy 1986; Alexandros and Burkhart 1992; Huang and Titus 1992; Tang 1994; Vanclay 1995; Fang and Bailey 1998; Batista et al. 2001; Scaranello et al. 2012).

Even though allometric models for aboveground biomass accumulations in Senegal have been revealed by Mbow et al (2014) through their study in similar forest locations, additional specific information with regard to above-ground biomass (kg) from all species and their annual growth rates have not yet been explained well. Biomass was estimated based on equation developed by Mbow et al (2014). The formula applied in this study was; AGB = ($a0$ x DBH) + ($a1$ x DBH^2) + ($a2$ x DBH^3), where $a0$ was constant value of 1.929, $a1$ was 0.116, and $a2$ was 0.013.

2.3. Results

2.3.1. Age as a Function of DBH

Based on the analyses with the SYSTAT 10.2., power model showed the highest value of R^2 value of 0.368 as compared to others. The lowest R^2, however, was shown by exponential model with 0.295. In general, the average of R^2 for age as a function of DBH relationship was not strong with the overall value just below 0.4. From the graph of age as a function of DBH relationship (Figure 2.1.), the distribution of both age and DBH was non-linear.

2.3.2. Age as a Function of Height

Power model was the best fitted and provided the highest statistical *R-square* value of 0.367. On the other hand, linear model ($Log\ Y = a + b * \log X$) showed a negative relationship with the lowest R^2 value of 0.259. The overall statistical *P-value* is still significant for each model with the value < 0.05. Power model graph for age and height relationship (figure 2.2.) indicated the lowest correlation with linear line.

2.3.3. Height as a Function of DBH

Based on the study, cubic model was well fitted by showing the highest R^2 value of 0.754 and the lowest was hyperbolic. In general, the value of R^2 is tending to be higher in average compared to other two R^2 statistics (age as a function of DBH and age as a function of height). The overall statistical *P-value* is still significant for each model with the value < 0.05. From the graph of height as a function of DBH relationship (Figure 2.3.), the distribution of both height and DBH was linear with the positive trend of growths (as shown by linear line).

In addition, the average biomass accumulation showed the variation among seven species. The high biomass was in *Terminalia macroptera* with 94.03 kg. The annual diameter growth rates and AGB growths were also highest among other six species with 1.08 cm yr^{-1} and 5.40 kg/yr (based on actual age) (Table 2.5.). The classification of shade tolerant ratings among seven species in Senegal were also highlighted in order to provide a better indication of tree life's expectancy (Table 2.6.) (http://www.worldagroforestry.org/treedb2/speciesprofile).

2.4. Discussion

2.4.1. Growth Variable Relationships

2.4.1.1. Age and DBH relationship

Understanding the relationship among tree variables as an indicator in the context of ecological function is important (Pausas and Austin 2001; Austin 2007; Tekeila and Barney 2015). In this study, age as a function of DBH is predicted through statistical models to understand the growing pattern of Senegalese tree species collected from five different eco-regions. Through statistical analysis, the power model showed the best fitted result of growing pattern from heterogeneous tree species in five different locations. The main statistical indicator of R^2 from this model is highest compared to the other seven models tested. However, the overall R^2 value from eight models is categorized as lower with just < 0.368 (Table 2.2.) compared to the sub-temperate in the global forest (R^2> 0.72) as reported by Troxel et al (2013).

Therrell et al (2007) indicated lower relationship between age and radial growth of *Pterocarpus angolensis* from nine locations across southern Africa using tree-ring data analysis. In general, diameter growth has been lower in some African regions such as Tanzania, western Zimbabwe, Namibia, and South Africa where the average growth is less than 0.8mm in a year and require more years to attain an ideal size of minimum cutting diameter of 40cm (Groome et al. 1957; van Daalen et al. 1992; Shackleton 2002; Trouet 2004) Meanwhile, for the sub-temperate zone, Troxel et al (2013), indicate strong relationship between DBH and age for ten most commonly young urban trees (1474 species) in the New Haven, Connecticut of USA with an average R^2> 0.72 and statistically significant allometric relationship at an α–level of 0.05. Another study conducted by Kenefic and Nyland (1999) showed significant relationship (R^2 = 0.81, P< 0.005) between age and diameter of Sugar maple in an uneven-aged northern hardwood stand in Syracuse, New York. In addition, Gwaza and Bridgwater (2002) pointed out a significant result (P<0.05) toward genetic and phenotypic correlations from age and diameter among 191 of *Pinus taeda* L., in the southeastern USA with R^2 of 0.54. There are limited studies that have examined the relationship between age and diameter in tropical regions.

Compared to the study in Senegal, it is apparent that besides extreme ecophysiological conditions and climate variabilities, the number of tree species and equations that generated from the samples are also a distinguished factor. As indicated from the result, the relationship between age and DBH is lower from all five different forests. The likelihoods of such lower relationships are probably led by low number of tree samples that utilized to generate equations which was only 57 trees. Another reason is that in this analysis, the focus was only upon developing mixed-species, composite-equations. Since the number of samples are lower, it would be strenuous to generate species-specific equations from this analysis. Beets et al (2012) highlighted the importance of significant different results between using species-specific equations and mixed-species equations toward carbon stock estimations in natural forests in New Zealand.

There are multiple environmental factors that can limit diameter growth. However, lack of water supply will be a major issue for most of the vegetation that grows in Senegal (O'Connor and Ford, 2014). In fact, the climatic phenomenon and ecological terrain of Senegal have been the deteriorating factors in hampering the evolving process of vegetation life cycle. Abdel-Rahman et al (2003) pointed out that there was a positive significance ($P < 0.006$) of the relationship between tree age and diameter for *Acacia senegal* shoot morphology in El Himairi, North Kordofan site of Senegal. However, this significant growth was indicated in the early ages and when trees are getting older, their growth abilities are decreased significantly (Ahmed 2000). Besides, poor soil nutrients usually dominate across the northern part of Senegal and southern Sudan and provide less opportunity for trees to take advantage of. Also, Senegalese soils are unable to retain water in the ground due to poor structure and form, which allow water to flow through easily and quickly (Forbes, 1973). It is clear that reduced water availability will limit tree growth and productivity in the region. Mohamad (2005) unveiled that the effect of tree size on the amount of water is significant for *Acacia senegal* in Western Sudan. Enough water in living wood structure is also capable of swelling tree diameter and expanding diameter growth. This is because most of the wood cells and vessels are fully filled with water, which automatically distend the size of cells (Kravka et al. 1999; Myburg and Sederoff, 2001).

2.4.1.2. Age and height relationship

Age and total height of Senegal trees were predicted through statistical models. The result pointed out that power model was best fitted as it provided the highest statistical parameter of R^2. However, overall the R^2 was the lowest among two other relationships (age as a function of DBH and height as a function of DBH). Such lower numbers indicated a weak relationship between age as a function of total height from all tree species in Senegal. Lower indication of relationship between age and tree height also found by Diallo et al (2013) in *Acacia senegal* through regression models with low explanatory power. On the contrary, a couple of studies found positive correlations between tree age and total-height from various sub-temperate forests. McCarthy and Weetman (2006) pointed out significant correlation (P<0.001) between tree height-total and age from 568 of balsam fir (*Abies balsamea*) in Newfoundland, Great Northern Peninsula, Canada with R^2 of 0.60. A significant correlation coefficient (P<0.001) of age and height was also reported by Ishikawa and Ito (1989) from mixed forests in Napporo National Forest, Japan with R^2 ranges from 0.59 to 0.97.

The leading factor of differentiations between age and height relationship in Senegal and other sub-temperate regions are mainly spurred by different extreme climate, environment, and type of vegetation. Tappan et al (2004) indicated that in general soils in Senegal were classified as poor with less nutrient contains, low rainfall and precipitation rates available have presented a huge challenge for trees to easily thrive. The fact is that, the characteristic of vegetation such as shrub savannas, tree savannas, wooded savannas, woodlands across the regions have been a fundamental limiting factor that has depressed the heights of trees. These types of vegetation have been categorized as small trees with the limited sizes and tend to have a short-lifespan (Bond 2008; Hoffmann and Franco 2003; Hoffmann et al. 2012).

2.4.1.3. Height and DBH relationship

Height as a function of DBH from the analysis presented a better correlation among various Senegalese trees. Based on the result, statistical parameter of R^2 was higher compared to age as a function of DBH and age as a function of height. Cubic model showed the highest R^2 value, indicating more relevant relationship. Both height and DBH increased as a result of productivity in each individual tree species (Bowman et al. 2013; Rais et al. 2014). Osman et al (2012) indicated the positive relationship between tree height and diameter for some Sudanese tree species with average R^2 ranging between 0.73 – 0.89. Diollo et al (2013) presented a positive significant relationship (P <0.001) of height-diameter for *Acacia senegal* in semi-arid zone of Senegal. Another study by Mugasha et al (2013) pointed out a general trend of positive relationship between height-diameter from various topical forest landscapes in Tanzania. In general, the trend of positive relationship of height and diameter has been reportedly significant in numerous tropical forest types across the regions (Buba 2013; Feldpausch et al. 2013). Even though height and DBH relationship has shown better in this analysis, but in general it was not effective and co-vary. Height variable tended to be useless when it applies to understand the correlation between height and DBH. It means by single variable of DBH, it can show the actual indication of height as a function of DBH.

2.4.2. Biomass and Carbon Accumulation

Biomass and carbon are major components for Senegalese forests in particular and Western Africa in general. With forest cover in almost 50 percent of the regions, Senegal has been one of the pivotal countries in the sub-Saharan territory that provides benefit for the regional environment. Even though forests in Senegal are less abundant compared to other tropical regions in Africa, the contribution has been promising particularly some places with no settlements (Ojima et al. 1993). Higher intensity of rainfall within a year in the South coupled with multiple rivers across the country have provided new possibilities for forests to thrive and more productive growth. In fact, some parts of the regions have forest density covers between 20-50 percent, which means that biomass and carbon accumulations are quite abundantly stored. Even though the northern part has been classified as drier climate, the potency of biomass are reportedly high. Through this study, the average of biomass accumulations were various among seven species. It turned out that *Terminalia macroptera* has the highest amount of biomass accumulation and also annual growth rate based on diameter. It was presumably lead by the high percentage of *Terminalia macroptera* to live and able to adapt with the surrounding environment.

Woomer et al (2004) revealed the total biomass of degraded grassland is about 419 kg C ha^{-1}, grassland with scattered shrubs is about 3,068 kg C ha^{-1}, and shrubland with scattered trees about 6,543 kg C ha^{-1}. Abaker et al 2016 indicate that the higher amounts of biomass accumulation of the forests in southern Senegal due to longer stand ages compared to the North. In terms of growth biomass, study by Okello et al (2001) on *Acacia drepanolobium* in Kenya revealed strong relationship (R^2 = 0.96 and P < 0.001) between woody biomass and stem diameter. Mbow et al (2014), developed allometric models for some Senegalese trees in several similar locations which are Bala, Patako, Welor, Ouli and Kantora. From their analysis, there are some linear correlations of dry biomass among species with statistical parameter of R^2 value of 0.93. Biomass accumulation varies among tree species, but overall is high on a per hectare basis from the five different locations. Even though the amount of total tree biomass can be estimated, there is no information available for annual biomass rates.

By developing the appropriate allometic models attained this study, the ability of understanding annual rate of biomass accumulation and carbon potency is possible (Jenkins et al. 2003; Litton 2008; Chave et al. 2014). Carbon can be derived by multiplying biomass with a carbon fraction of 0.5. In the long run, it will allow people to further emphasize the annual basis of biomass in these five forests of Senegal and provide better estimation for carbon trading off mechanism in Senegal and western Africa.

APPENDICES

Table 2.1. Classification of models that consist of model number, model group, model name, model forms and references as a source where these models are cited. Eight models are listed with five linear models and three non-linear (two-parameter equation) models.

Model No.	Model group	Model name	Model form	References
1.	Linear	Linear equation	$Y = a + bX$	Scaranello et al. (2012); Batista et al. (2001); Vanclay (1995).
2.	Linear	Linear equation	$Y = a + b \log X$	Fang and Bailey (1998); Curtis (1967); Alexandros and Burkhart (1992).
3.	Linear	Linear equation	$Log\ Y = a + b * \log X$	Fang and Bailey (1998); Prodan (1965); Curtis (1967);
4.	Linear	Quadratic equation	$Y = a + bX + cX^2$	Fang and Bailey (1998); Hendricksen (1950); Curtis (1967);
5.	Linear	Cubic equation	$Y = a + bX + cX^2 + dX^3$,,,,,,	Fang and Bailey (1998); Hendricksen (1950); Curtis (1967);
6.	Non- linear	Power model equation	$Y = aX^b$	Scaranello et al. (2012); Batista et al. (2001); Fang and Bailey (1998).
7.	Non- linear	Exponential equation	$Y = e^{a+b/(X+1)}$	Fang and Bailey (1998); Huang and Titus (1992).
8.	Non- linear	Hyperbolic equation	$Y = aX/(b + X)$	Scaranello et al. (2012); Fang and Bailey (1998); Tang (1994); Bates and watts (1980); Ratkowsky and Reedy (1986).

Table 2.2. Model comparison from eight allometric models to determine the best appropriate relationship for age as a function of DBH for Senegal tree species.

Model class	Par. a coeff.	Par. a SE	Par. b coeff.	Par. b SE	Par. c coeff.	Par. c SE	Par. d coeff.	Par. d SE	Model R^2	Model SE
1. Linear	6.08	3.19	1.23	0.25					0.360	8.07
2. Linear	-13.19	7.62	14.21	3.18					0.321	8.32
3. Linear	2.24	1.16	0.06	0.01					0.309	0.41
4. Quadratic	12.75	8.13	0.09	0.31	0.04	0.05			0.357	8.09
5. Cubic	8.56	24.05	1.16	5.9	-0.04	0.43	0.001	0.009	0.340	8.2
6. Power	3.49	1.36	0.72	0.14					0.368	0.87
7. Exponential	35.96	4.09	-170.49	42.11					0.295	0.86
8. Hyperbolic	2.07	1.61	1.02						0.359	0.87

SE = Standard Error

Table 2.3. Model comparison from eight allometric models to determine the best appropriate relationship for age as a function of height for Senegal tree species.

Model class	Par. a coeff.	Par. a SE	Par. b coeff.	Par. b SE	Par. c coeff.	Par. c SE	Par. d coeff.	Par. d SE	Model R^2	Model SE
1. Linear	0.48	4.36	3.07	0.64					0.349	8.14
2. Linear	-16.19	8.65	20.01	4.68					0.301	8.44
3. Linear	2.04	0.23	0.13	0.03					0.259	0.43
4. Quadratic	17.002	12.48	-1.65	3.41	0.31	0.22			0.365	8.04
5. Cubic	-17.52	44.32	13.28	18.7	-1.69	2.47	0.08	0.1	0.360	8.07
6. Power	2.97	1.16	1.02	0.19					0.367	0.87
7. Exponential	43.12	6.04	-160.28	41.39					0.277	0.86
8. Hyperbolic	7.82	6.07	3.85						0.366	0.8

SE = Standard Error

Table 2.4. Model comparison from eight allometric models to determine the best appropriate relationship for height as a function of DBH for Senegal tree species.

Model class	Par. a coeff.	Par. a SE	Par. b coeff.	Par. b SE	Par. c coeff.	Par. c SE	Par. d coeff.	Par. d SE	Model R^2	Model SE
1. Linear	3.04	0.33	0.27	0.02					0.725	1.31
2. Linear	-3.71	0.88	4.24	0.36					0.714	1.34
3. Linear	1.36	0.05	0.03	0.003					0.639	0.21
4. Quadratic	1.93	0.66	0.42	0.08	-0.003	0.001			0.737	1.28
5. Cubic	5.13	1.6	-0.25	0.32	0.03	0.01	-0.0006	0.0002	0.754	1.24
6. Power	1.51	0.18	0.58	0.04					0.742	0.96
7. Exponential	11.66	0.56	-57.32	5.89					0.632	0.95
8. Hyperbolic	20.15	2.44	24.29	4.82					0.737	0.96

SE = Standard Error

Table 2.5. Final summary of average DBH (cm), actual age (yr), estimated age (yr), biomass (kg), growth rate I (biomass [kg]/actual age [yr]) and growth rate II (biomass [kg]/estimated age [yr]) from Senegal tree species.

Species	Average DBH (cm)	Actual Age (yr)	Estimated Age (yr)	Above Ground Biomass (AGB) (kg)	AGB Growth Rate I (kg/yr)	AGB Growth Rate II (kg/yr)	Annual Diameter Growth I (cm yr^{-1})	Annual Diameter Growth II (cm yr^{-1})
Acacia seyal	11.18	20.20	16.16	54.76	3.35	4.19	0.56	0.70
Combretum glutinosum	12.08	26.23	20.98	78.17	2.78	3.47	0.48	0.60
Acacia macrostachy	7.87	12.00	9.60	28.21	3.03	3.79	0.78	0.97
Cordila pinnata	13.33	30.50	24.40	93.88	2.68	3.35	0.43	0.53
Terminalia macroptera	12.83	15.37	12.30	94.03	5.40	6.75	0.87	1.08
Balanites aegyptica	14.01	22.50	18.00	85.54	3.81	4.77	0.62	0.78
Petrocarpus erinaceus	12.83	22.00	17.60	89.92	3.69	4.62	0.56	0.70
average	12.02	21.26	17.01	74.93	3.53	4.42	0.61	0.77

Note: AGB is calculated with the formula, ABG = ($a0$ x DBH) + ($a1$ x DBH^2) + ($a2$ x DBH^3) (Mbow et al 2014), where $a0$ = 1.292, $a1$ = 0.116, and $a2$ = 0.013.

Table 2.6. Shade tolerant ratings of Senegal tree species

No.	Species	Tolerant ratings
1.	*Acacia seyal*	Tolerant
2.	*Acacia macrostachy*	Tolerant
3.	*Combretum glutinosum*	Tolerant
4.	*Cordila pinnata*	Tolerant
5.	*Terminalia macroptera*	Tolerant
6.	*Balanites aegyptica*	Relatively tolerant
7.	*Petrocarpus erinaceus*	Tolerant

Figure 2.1. Graph of the power regression relationship between age as a function of DBH from Senegalese tree species. See Table 2.2., for parameter coefficients of regression model.

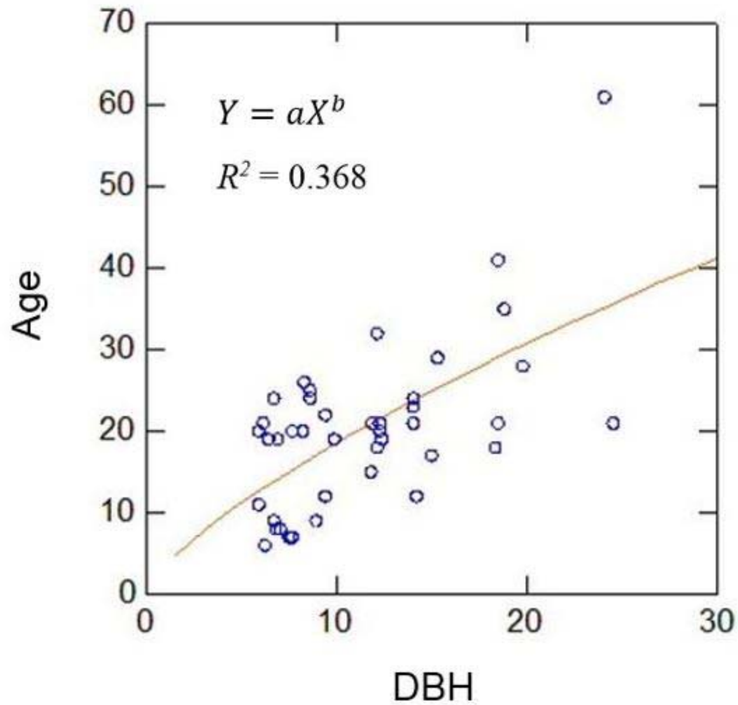


Figure 2.2. Graph of the power regression relationship between age as a function of height from Senegalese tree species. See Table 2.3., for parameter coefficients of regression model.

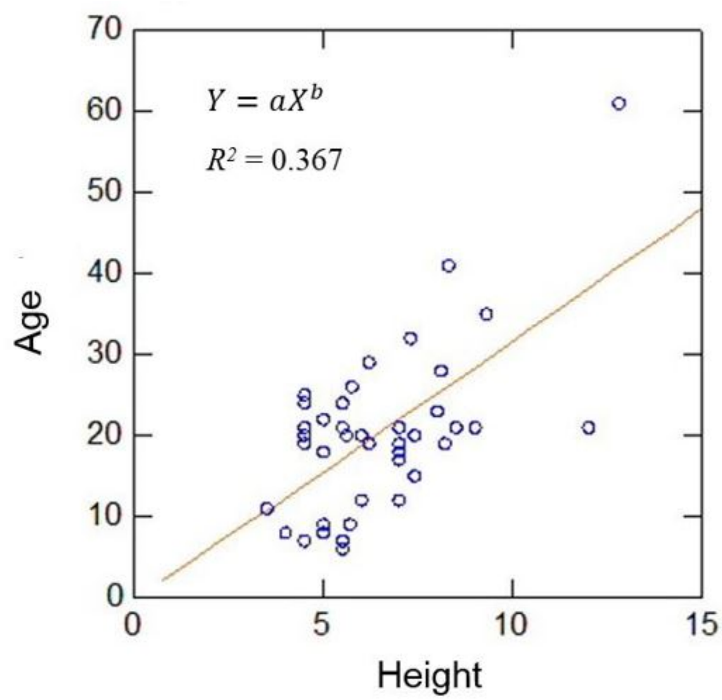
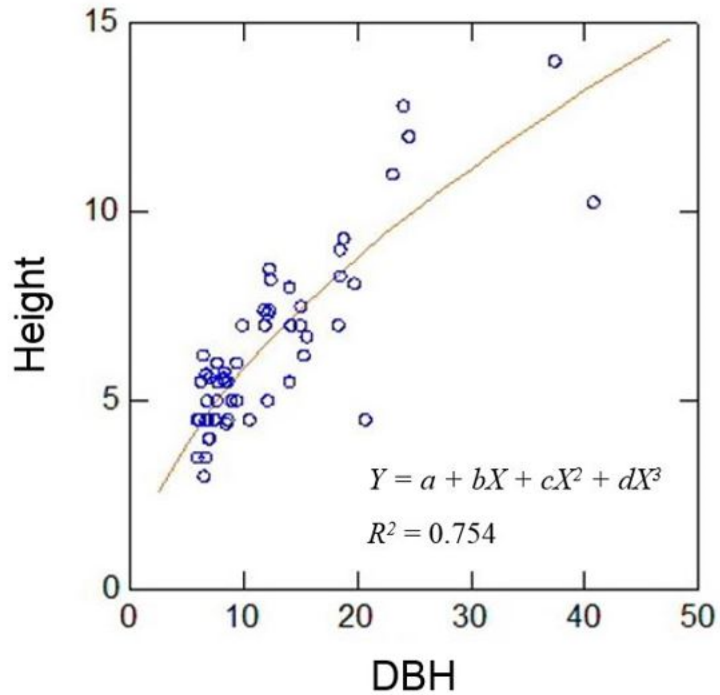


Figure 2.3. Graph of the cubic regression relationship between height as a function of DBH from Senegalese tree species. See Table 2.4., for parameter coefficients of regression model.



REFERENCES

REFERENCES

Abaker W.E., Berninger F., Saiz G., Braojos V. and Starr M. 2016. Contribution of Acacia Senegal to biomass and sild carbon in plantations of varying age in Sudan. For Eco & Man, 368: 71-80.

Abdel-Rahman H., M., Warrag E., I. and Ballal M., E. 2003. Effects of tree age and shoot morphology of *Acacia senegal* (L) Willd. on gum yield in North Kordofan State. Sudan Silva, 9(2): 56-66.

Ahmed R., A. 2000. Effect of irrigation condition on shoot growth of *Acacia senegal* (L) willd., plantation in Kenana site. Thesis, University of Khartoum, Sudan.

Austin M. 2007. Species distribution models and ecological theory: A critical assessment and some possible new approaches. Ecological modelling, 200:1-19.

BBC World Service Trust. 2010. Senegal talks climate: The public understanding of climate change. Research report. http://r4d.dfid.gov.uk/PDF/Outputs/MediaBroad/07-Senegal-Talks-Climate.pdf

Beets P., N., Kimberley M., O., Oliver G., R., Pearce S., H., Graham J., D. and A Brandon. 2012. Allometric equations for estimating carbon stocks In natural forests in New Zealand. Forests, 3: 818-839.

Bond W., J. 2008. What limits trees in C4 grasslands and savanna? Annu. Rev. Ecol. Evol. Syst, 39: 641–59.

Bowman D., M., J., S., Brienen R., J., W., Gloor E., Phillips O., L. and Prior L., D. 2013. Detecting trends in tree growth: Not so simple. Trends in Plant Science, 18 (1): 11-17.

Buba T. 2013. Allometric prediction models of growth variables of Danielle olivera in the Nigerian Guinea Savanna. African J. of Plant Science, 7 (6): 213-118.

Camberlin P., Janicot S., and Poccard I. 2001. Seasonality and atmospheric dynamics of the teleconnection between African rainfall and tropical sea-surface temperature: Atlantic vs. Esno. Int. J. Climatol, 21: 973-1005.

Chave J., Rejou-Mechain M., Burquez A., Chidumayo E., Colgan M., S., Delitti W., B., C., Duque A., Eid T., Fearnside P., M., Goodman R., C., Henry M., Martinez-Yrizar A., Mugashi W., A., Muller-Landau H., C., Mencuccini M., Nelson B., W., Ngomanda A., Nogueira E., M., Ortiz-Malavassi E., Pelissier R., Ploton P., Ryan C.,M., Saldarriaga J. and Vieillendent G. 2014. Improved allometric models to estimate the aboveground biomass of tropical trees. Global Change Biology, 20: 3177-3190.

Diallo A., Agbangba E., C., Ndiaye O. and Guisse A. 2013. Ecological structure and prediction equations for estimating tree age, and dendometric parameters of Acacia Senegal in the Senegalese Semi-Arid Zone-Ferlo. American Journal of Plant Science, 4: 1046-1053.

Diaw O. 2006. The national forest programme in Senegal: Developing decentralized planning and management capacities. Unasylva, 225 (7): 50-55.

Elamin H., M., A., Adam H., E., Taha M., N. and Csaplovics E. 2015. Estimation of Acacia Senegal tree biomass using allometric equation and remote sensing, North Kordofan State, Sudan. Inter. J. of Agr, For and Fish, 3(6): 222-226.

Feldpausch T., R., Banin L., PhillipsO., L., Baker T., R., Lewis S., L., Quesada C., A., Affum-Baffoe K., Arets E., J., M., M., Berry N., J., Bird M., Brondizio v,. P., Camargo de., Chave J., Djagbletey G., Domingues T., F., Drescher M., Fearnside P., M., Franc M,. B,. N,. M,. Fyllas, G. Lopez-Gonzalez, A. Hladik, N. Higuchi, M. O. Hunter, Y. Iida, K. A. Salim, A. R. Kassim, M. Keller, J. Kemp, D. A. King, J. C. Lovett, B. S. Marimon, B. H. Marimon-Junior, E. Lenza, A. R. Marshall, D. J. Metcalfe, E. T. A. Mitchard, E. F. Moran, B. W. Nelson, R. Nilus, E. M. Nogueira, M. Palace, S. Patino, K. S.-H. M. T. Raventos, J. M. Reitsma, G. Saiz, F. Schrodt, B. Sonke´, H. E. Taedoumg, S. Tan, L. White, H. Woll. and J. Lloyd. 2011. Height-diameter allometry of tropical forest trees. Biogeosciences, 8: 1081-1106.

Fichtler E., Trouet V., Beeckman H., Coppin P. and Worbes M. 2001. Climatic signals in tree rings of *Burkea africana* and *Pterocarpus angolensis* from semiarid forests in Namibia. Trees, 18: 442-451.

Food and Agriculture Organization. 2012. State of the world's forests. Rome

Forbes T., R. 1973. Ferrallitic and ferruginous tropical soils of West Africa. Cornell University. Supported by grant csd 2834 by the Agency for International Development under the Institutional Grants Program.

Groome J., S., Lees H., M., N. and Wigg L., T. 1957. A summary of Information on *Pterocarpus angolensis*. Forest Abstr, 18: 153–162.

Gwaze D., P. and Bridgwater F., E. 2002. Determining the optimum selection age for diameter and height in Loblolly pine. Forest Genetics, 9 (2): 159-165.

Herrmann S. M., and Tappan G., G. 2013. Vegetation impoverishment despite greening: A case study from central Senegal. J. Arid Environ, 90: 55–66.

He´rault B. et al. 2011. Functional traits shape ontogenetic growth trajectories of rain forest tree species. J. Ecol, 99: 1431–1440.

Hoffmann W., A. and Franco A., C. 2003. Comparative growth analysis of tropical forest and savanna woody plants using phylogenetically independent contrasts. Journal of Ecology, 91: 475-484.
Hofmann W., A., Geiger E., L., Gotsch S., G., Rossatto R., Silva L., C., R., Lau O., L., Haridasan M. and Franco A., C. 2013. Ecological thresholds at the savanna-forest boundary: how plant traits, resources, and fire govern the distribution of tropical biomes. Ecology Letters, 15: 759-768.

Hoogeveen H., Maini J., S., Moomaw W., Najam A. and Verkooijen P. 2008. Designing a forest financing mechanism (FFM): A call for bold, collaborative & Innovative thinking. The Fletcher School, Tufts University. http://www.worldagroforestry.org/treedb2/speciesprofile

Ishikawa Y. and Ito K. 1989. DBH, height and crown radius growth of some component species of Nappora National Foroest, central Hokkaido, Japan. Environ. Sci, Hokkaido University, 12 (2): 117-138.

Jenkins J., C., Chojnacky D., C., Heath L., S. and Birdsey R., A. 2003. National-scale biomass estimators for United States tree species. Forest Science, 49 (1): 12-35.

Käser M. 2001. Perception of the forest as a “Green Bank” evolved among rural population in the test zone of Dankou, Senegal. Conference on International Agricultural Research for Development. Göttingen, October 8-10, 2003.

Kenefic L., S. and Nyland R., D. 1999. Sugar maple height-diameter and age-diameter relationships in an uneven-aged northern hardwood stand. North J. Appl. For, 16 (1): 43-47.

Knippertz P. and Fink A., H. 2008. Dry-season precipitation in tropical West Africa and its relation to forcing from the extratropics. American Meteorological Society, 136: 3579-3596.

Kravka M., Krejzar T. and Čermák L. 1999. Water content in stem wood of large Pine and Spruce trees in natural forests in Central Sweden. Agriculture and Forest Meteorology, 98-99: 555-562.

Laitat E., Karjalainen T., Loustau D., and Lindner M. 2000. Introduction: Towards an integrated scientific approach for carbon accounting in forestry. Contribution of forests and forestry to mitigate greenhouse effects, COST E21 Worshop. Biotechnol. Agron. Soc. Environ, 4 (4): 241–251.

Lawesson J. E. (1995). Studies of woody flora and vegetation in Senegal. Opera Botanica, Council for Nordic Publications in Botany, Copenhagen.

Li L., Lewis l., Rowland J., Tappan G. and Tieszen L., L. 2004. Evaluation of land performance in Senegal using multi-temporal NDVI and rainfall series. J of Arid Environments, doi:10.1016/j.jaridenv.2004.03.019

Litton C., M. 2008. Allometric models for predicting above ground biomass in two widespread woody plants in Hawaii. Biotropica, 40 (3): 313-320.

Lo H., M., and Tumusiime E. 2013. The influence of US development assistance on local adaptive capacity to climate change: Insights from Senegal. Oxfam America Research Backgrounder Series.
Mbow C., Chhin S., Sambou B. and Skole D. 2013. Potential of dendrochronology to assess annual rates of biomass productivity in savanna trees of West Africa. Dendrochronologia, 31 (1): 41-51.

Mbow C., Verstraeta M., M., Sambou B., Diaw A., T. and Neufeldt H. 2014. Allometric models for above ground biomass in dry savanna trees of the Sudan and Sudan-Guinean ecosystems of Southern Senegal. J For Res, 19: 340-347.

McCarthy J., W. and Weetman G. 2006. Age and size structure of gap-dynamic, old growth Boreal forest stands in Newfoundland. Silva Fennica, 40 (2): 209-230.

McNeely J., A. and S.A., Mainka. 2009. Conservation for a new era. IUCN, Gland, Switzerland.

McSweeney C., New M., and Lizcano G. 2012. UNDP climate change country profiles – Senegal. School of Geography and Environment, University of Oxford. http://country-profiles.geog.ox.ac.uk

Mohamad A., G. 2005. Improvement of traditional *Acacia senegal* agroforestry: Ecophysiological characteristics as indicators for tree-crop interaction on sandy soil in Western Sudan. Dissertation, University of Helsinski, Finland.

Mugasha W., A., Bollandsas O., M. and Eid T. 2013. Relatinship between diameter and height of trees in natural tropical forest in Tanzania. Southern forests, 75 (4); DOI:10.2989/20702620.2013.824672

Myburg A., A. and Sederoff R., R. 2001. Xylem structure and function. Encyclopedia of life science. Nature publishing group.

Nabuurs, G.J., O. Masera, K. Andrasko, P. Benitez-Ponce, R. Boer, M. Dutschke, E. Elsiddig, J. Ford-Robertson, P. Frumhoff, T. Karjalainen, O. Krankina, W.A. Kurz, M. Matsumoto, W. Oyhantcabal, N.H. Ravindranath, M.J. Sanz Sanchez, X. Zhang. 2007. Forestry In climate change 2007: Mitigation. Contribution of working group III to the fourth assessment report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

O'Connor D. and Ford J.2014. Increasing the effectiveness of the "Great Green Wall" as an adaptation to the effects of climate change and desertification in the Sahel. Sustainability, 6: 7142-7154; doi:10.3390/su6107142

Ojima D., S., Dirks B.J., Glenn E.P., Owensby C.E. and Scurlock J.O. 1993. Assessment of C budget for grasslands and dryland of the world. Water Air and Soil Pollution, 70: 95–109.

Okello B., D., O'Connor T., G. and Young T., P. 2001. Growth, biomass estimates, and charcoal production of Acacia drepanolobium in Laikipia, Kenya. Forest Ecology & Management, 142: 143-153.

Osman E., M., H., Indris E., Z., A. and Ibrahim E., M., M. 2012. Modelling heigh-diameter relationship of selected economically important natural forest species. J. of Forest Products & Industries, 2 (1): 34-42.

Pearson T., R., H., Brown S., L. and Birdsey R., A. 2007. Measurement guidelines for the sequestration of forest carbon. USDA General Technical Report NRS-18. Pennsylvania.

Picard N., Saint-Andre L. and Henry M. 2012. Manual for building tree volume and biomass allometric equations: from field measurement to prediction. Food and Agriculture Organization of the United Nations, Rome.

Pretzsch H. 2009. Forest dynamics, growth and yield: From measurement to model. Springer-Verlag Berlin Heidelberg.

Rais A., Kuilen J., W. and Pretzsch H. 2014. Growth reaction patterns of tree height, diameter, and volume of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) under acute drought stress in Southern Germany. Eur J Forest Res; DOI 10.1007/s10342-014-0821-7

Sambou B., Mbow C. and Goudiaby A. 2008. Studies of the woody vegetation of the Welor Forest Reserve (Senegal) for sustainable use. West Africa Journal of Allied Ecology, 13: 66-76.

Scaranello M., A., D., S., Alves L., F., Vieire S., A., de Camargo P., B., Joly C., A. and Martinelli L., A. 2010. Height-diameter relationships of tropical Atlantic moist forest trees in southern Brazil. Scientia Agricola, 69 (1): 26-37.

Shackleton C., M. 2002. Growth patterns of *Pterocarpus angolensisin* savannas of the South African lowveld. Forest Ecology & Management, 166: 85–97.

Stancioff A., Staljanssens M. and Tappan G. 1986. Cartographie et télédétection des ressources de la république du Sénégal : étude de la géologie, de l'hydrologie, des sols, de la végétation et des potentiels d'utilisation des Sols. Remote Sensing Institute, South Dakota State University, SDSU-RSI-86-01.

Streck C., O'Sullivan R., Janson-Smith T., and Tarasofsky R. 2009. Climate change and forests: Emerging policy and marker opportunities. Commonwealth Forestry Association.

SYSTAT Software Inc. 2002. Systat 10.2 graphics. Copyright @ 2002 by SYSTAT Software Inc. 501, Canal Boulevard, Suite F. Richmond, CA.

Tappan G., Hadj A., Wood E., C. and Lietzow R., W. Use of argon, corona, and landsat imaginary to assess 30 years of land resources changes in West-Central Senegal. Photogrammetric Engineering and Remote Sensing, 66 (6): 727–735.

Tappan G., G., Sall M., Wood E., C. and Cushing M. 2004. Ecoregions and land cover trends in Senegal. J of Arid Environment, 59: 427-462.

Tekiela D., R. and Barney J., N. 2015. System-level changes following invasion caused by disruption of functional relationships among planet soil properties. Ecosphere, 6 (11): Article 294.

Therrell M., D., Stahle D., W., Mukelabai M., M. and Shugart H., H. 2007. Age, radial growth dynamics of Pterocarpus angolensis in southern Africa. Forest Ecology & Management, 244: 24-31.

Trouet V. 2004. The El Nino Southern Oscillation effect on Zambezian miombo vegetation, proxies from tree ring series and satellite-derived data. Ph.D. Thesis. Catholic University, Leuven.

Troxel B., Piana M., Ashton M., S. and Murphy-Dunning C. 2013. Relationship between bole and crown size for young urban trees in the northeastern USA. Urban Forestry & Urban Greening, 12 (2): 144-153.

USAID 2012. Climate change adaptation in Senegal. https://www.climatelinks.org/sites/default/files/asset/document/senegal_adaptation_fact_sheet_jan2012.pdf

USAID 2013. The ARCC West Africa regional climate change vulnerability assessment – Background paper. http://community.eldis.org/.5b9bfce3/Background%20Paper%20-%20West%20Africa%20Final.pdf

Van Daalen J., C., Vogel J., C., Malan F., S. and Fuls A. 1992. Dating of *Pterocarpus angolensis* Trees. S. Afr. Forest J, 162: 1–7.

Vincke C., Diédhiou I., and Grouzis M. 2010. Long term dynamics and structure of woody vegetation in the Ferlo (Senegal). J. of Arid Environments, 74: 268-276.

Weiskittel, A.R. et al. 2011. Forest Growth and Yield Modelling, WileyBlackwell.

White, F. 1983. The vegetation of Africa. A descriptive memoir to accompany the UNESCO/EATFAT/UNSO vegetation map of Africa. Natural resources research 20. UNESCO, Paris.

Wils T., H., G., Sass-Klaassen U., G., W., Eshetu Z., Drauning A., Gebrekirstos A., Couralet C., Robertson I., Touchan R., Koprowski M., Conway D., Briffa K., R. and Beeckman H. 2010. Dendrochronology in the dry tropics: the Ethiopian case. Trees; DOI 10.1007/s00468-010-0521-y

Woomer P., L., Touré A. and Sall M. 2004. Carbon stocks in Senegal's Sahel transition zone. J of Arid Environments, 59: 499-510.

CHAPTER 3

ALLOMETRIC EQUATION DEVELOPMENT FOR INDONESIAN TREE SPECIES

3.1. Introduction

Indonesia is one of the biggest tropical countries in the world with forests cover of almost 90 million hectares from east to west archipelago. The distribution of rainforest in Indonesia has been widely known for its benefits such as providing habitat for the variety of forest organisms, dispensing better balance of environment for instance fresh water, soil nutrients, scaling up the socio-economic benefit for surrounding people, and also more importantly has been functioning as a global control of climate change (Measey 2010; FAO 2010; Verchot et al. 2010; Schollaen et al. 2013). Currently, Indonesia's forest has brought increased incomes through a couple of emerging programs such as REDD+ from Clean Development Mechanism (CDM) concept which is directly specific to forest fringe communities. The Government of Indonesia has also benefited from the global carbon pricing mechanism (Bowen 2011; Angelsen et al. 2014). Since implemented in 2009, the REDD and REDD+ program have provided adequate incomes in the regions and they remain significant and powerful tools to help conserve tropical forests (Murdiyarso et al. 2012). Indonesia has been an active participant during the global climate change consensus and one of the cornerstones in leading the transformation of combating climate change and reducing greenhouse gas (GHG) from anthropogenic activities across the world.

Indonesia's forest is considered a large proportion of Indonesia's economy. It has been extracted for various reasons since the 1960's for economic expansion (Center for Forestry Planning and Statistics Ministry of Forestry, 2009; Agrawal et al. 2013). Stimulating economic growth from forestry sectors at the time had been a promising target and ideal priority besides mining industries. As a result, logging companies as a primary sector were officially accepted and allowed to make a change in the landscape of Indonesia's forests. The activities have continually been undertaken up until now due to their huge contribution toward national income. Research has shown that logging industries have significantly changed Indonesia's forest cover since a huge quality of the total forest area is lost every year (Burgess et al. 2011; World growth, 2011). However, along with the recent recognition of global climate change and the consequent CDM intervention, the orientation of forest has shifted from logging sector to service sector which allows Indonesians to attain more benefits from forests while keeping them from any disturbing activities such as illegal logging, palm oil industry, urbanization and settlements.

To be able to identify the problem and provide solutions of compensational payment for a large tropical country like Indonesia is not easy. A number of crucial issues are still unsolved particularly about how to monitor high density tropical forests through measurement processes (Angelsen et al. 2012; Korhonen-Kurki et al. 2013). Understanding dense tropical forests with the proper methodologies and exact measurement formulas are challenging until now. There are some methodologies which are regularly implemented in order to come up with satisfactory results. Tree allometry measurement is one of the forefront tools in the forestry sector to quantify total tree carbon accumulation and biomass production (Chave et al. 2005; Condit 2008; McHale et al. 2009). It has been applied in many forested areas and provided a better result of understanding the importance of biomass and carbon values. However, it is difficult and laborious to implement tree allometry in tropical forests like Indonesia. It has been challenging due to the variations of forested lands, numerous forest cover stratifications, as well as the climate which have been responsible for the different values of forest compositions. Therefore, to be more accurate, a specific type of allometry is needed to glean a better result of biomass and carbon accumulation from specific target area (Ketterings et al. 2001; Brown 2002).

Despite having one of the largest areas of tropical forests, biomass equations and tree allometry formulas in Indonesia have been well developed in some regions such as Java, Kalimantan and Sumatera. Anitha et al. (2015) compiled tree allometry formulas from multiple sources and indicated that most of them are mainly focused on tree plantation forests, crop lands and secondary upland/logged forests areas. As of 2015, they point out that there are 2,458 biomass equations from 168 destructive sampling studies emanating from twenty-one habitat types and 65 tree species. In additions, several tree allometric studies conducted in low-land dipterocarp forests in Kalimantan for commercial and mixed tree species such as *Dipterocarpus*, *Hopea*, *Palaquium* and *Shorea* genera (Basuki et al. 2009). However, some primary forests are untouched in terms of generating a specific allometric formula particularly Papuan forest that is considered as one of the dense virgin forests in Indonesia.

Tree ages have been a pivotal key in comprehending the importance of forest strength and tree ability in regard to biomass accumulation and terrestrial carbon sink (Obersteiner et al. 2001; Schultze et al. 2001; Birdsey 2006). There are several approaches to estimating tree ages in the forests such as by recording the initial plantation date for some forest-based plantation managements, and currently advanced method is by way of counting tree rings through dendrochronology method (Therrell et al 2007; Zuidema et al 2011). With an error-free data of age, it will be straightforward in estimating how much biomass and carbon are sequestered during a certain period (Saint-André et al. 2005; Melson et al. 2001).

The aim of this study in general is to generate a new allometric formula or equation to estimate age based on tree diameter (DBH) from Indonesia's tropical tree species i.e., *Tectona grandis* L.f., *Styrax bensoin* Dryand., *Araucaria cuninghamii* Aiton ex D.Don., and *Drancontumelum* sp., in West Papua province. Through this formula, the biomass and carbon accumulation in some tropical trees can be understood in the context of annual growth rates.

3.2. Methods

3.2.1. Study Area

This study was conducted in Manokwari District of West Papua Province in Indonesia. The location is in the eastern part of Indonesian archipelago and this island is in one land with Papua New Guineas. In general, the study location is classified as a mountainous area and spreads from Sarong District in the Northwest to Jayapura in the Northeast (Built Environment Directorate General of Forestry, 2009). The altitude of study location is about 500m with a slope angle range of 3° to 10°. Characteristically, the soil of this study area is dominated by yellow and red latosols. Precipitation is considered to be high in most of the northern part of Papua Island, including the study location which is above 2500mm with the annual rainy period from November to March every year and mainly affected by Australian and Pacific wind circulation. The dry season starts from June to November every year (Manokwari Bureau of Meteorology and Geophysics, 2007).

This study focused on four tree species which were *Tectona grandis* L.f., *Styrax bensoin* Dryand., *Araucaria cuninghamii* Aiton ex D.Don., and *Drancontumelum* sp., and a total of 407 trees were considered. In fact, about ten tree species were originally planted in this study area in 1987. The reason to pick these four species is because they have a high percentage of living and considered to grow well in heathy status compared to others in the same location. The total area is 12 hectares and specifically preserved for educational and collective purposes (Fig. 3.6.). Trees were planted based on line within 12 hectares. In general, there are more than one line for each species to grow. Some of them even have four lines and trees distribution were in the random shape. It was because the planted location was not exactly in rectangular shape. The range between each other was approximately four meters. The maintenance of the area is handled by the Forestry Agency under the Indonesian Ministry of Forestry and Environment. Information gathered from the agency indicates that there were several replanting activities carried out in 1990, 1995, 1998, and 2005 to ensure diversified growth.

3.2.2. Species Genera and Distribution

Tectona grandis has been growing well in South and Southeast Asia including Indonesia, spreading from India to Myanmar, Thailand and Indonesia (Fofana et al. 2009; Verhaegen et al. 2010). This species was introduced commercially during 19th century when traditional trading system was thrived in Southeast Asia. In the early of 20th century, *Tectona grandis* or Teak for commercial name, has dominated international market for various purposes in particular for ship industries and harbor constructions. Because of the natural quality of Teak wood, in has been continually developing as one of the prominent wood in Indonesia till date (Lee 2003; Harikrishnan et al. 2012). In fact, the distribution of Teak wood in Indonesia is more representative compared to other wood species. In Papua, *Tectona grandis* has grown in many types of environmental conditions and easily adapt to the extreme and severe climate phenomena.

Styrax bensoin is a native tree of Sumatera, Indonesia and classified as a warm tropical tree species. In general, there are more than 130 species of this genus that belong to *Styracaceae* family (Lobdell 2013). Because of the benzoin resin it contains, this species has been widely extracted for commercial purposes, and besides, its wood is used for construction and ornamental plants (Kashio and Johnson 2001). This tree is commonly found in the terrestrial regions and tends to have a limited growth and size.

Araucaria cuninghamii is an indigenous species of Australia with the ability to live longer than other tree species and can reach a maximum size of vertical growth about 50-70m high and horizontal growth between 1.2-1.7m in diameter (Orwa et al. 2009). This tree has been found in many places in Indonesia, particularly Papua because of its ability to easily adapt to tropical climate condition and relatively warm weather during dry seasons (Dieters et al. 2007). Even though the distribution of *Araucaria cuninghamii* is massive in Indonesia, the rate of utilization as a final product is not promising for industrial sectors (Gray 1968).

Drancontumelum sp., is well known in Indonesia due it its distribution throughout the regions. It is also considered as one of the best wood for various products such as construction for housing, furniture, etc. (Priyadi et al. 2010). In general, this species grows in primary, or secondary forests with semi-deciduous forest types in the suitably altitudinal range of 0-1000m above sea level. Mostly occurs in the Southeast Asia and some parts of China, India and the Pacific islands (Orwa et al. 2009; Lim 2012)

3.2.3. Field Measurement

Data collection was done in summer 2009 through manual field measurement and observation. In this measurement phase, variables such as diameter at breast height (DBH), total tree height, and some of the tree status such as tree health, appearance were inventoried. Besides, the surrounding condition such as soil type was also taken into account during tree selection. The diameter of trees were measured about 1.3m from the ground using diameter tape wrapped around the tree. For tree height measurement process, a clinometer was utilized to get the appropriate value of the tree height from particular distances and angles. Given that the tree growth location is quite dense with tree cover, there were some manual estimations such as predict total height, crown shape, crown cover based on visualization of field supervisor. Soil identification is based on a soil handbook and soil characteristic observed directly in the field. Because this type of forest are human-initiated forests, data of age are taken based on the planting date which was mostly in 1987, and some of them were 1990, 1995, 1998, and 2005.

3.2.4. Data Analysis

Data collected included trees' age, diameter, and height and were primarily used to develop allometric equations for predicting annual biomass accumulation and carbon sequestration from Papua tropical forest. In this analysis, SYSTAT 10.2. (SYSTAT Software Inc. 2002), was used to analyze the data and find the best model generated from each tested model. In this study, there were 8 models of statistical combinations generated and eventually the best model was chosen as the ultimate output (Table 3.1) including model and describing graph. The total combinations of models were 35 from five different categories which are four for species-specific equations and one composite equation and only one best model of each category as well as graph was applied as a best scenario equation from this study. The ultimate best model was 5 that consisted of the relationship between Age as a function of DBH from each species of four trees and one combined model to represent the overall trend of Indonesian allometic model.

To select the best appropriate model from each combination, there were several statistical parameters that were considered to be key indicators. *P-value* from statistical analysis was definitely a fundamental index in this study to determine statistical significance. Other indicators such as the coefficient of determination (R^2), standard error of estimate, and coefficients of the allometric equations were also compiled. However, the key criterion to opt for a model primarily based on R^2 value from all eight tested models in one statistical combination (i.e., for each species and all species combined) by classifying the highest value of it from the result.

To estimate annual biomass accumulation, we adopt a new allometic formula from Basuka et al (2009) in the low-land dipterocarp forest of Kalimantan, Indonesia. The main justification for using this equation is because this type of forest is classified to be densely forested by multiple tropical tree species. Besides, number of tree samples and diameter range are almost similar to our study. The above-ground biomass (AGB) equation that was adopted is AGB = 0.475 x $D^{\wedge 2.188}$ x $WD^{\wedge 0.832}$, where: AGB = aboveground biomass; D = diameter at breast height; WD = wood density values were based on ICRAF database as follows: *Tectona grandis* = 0.6127; *Styrax bensoin* = 0.4533; *Araucaria cuninghamii* = 0.4664; and *Drancontumelum* sp. = 0.6153. Age and estimated age (0.8 from actual age) are utilized in order to generate annual growth rate from these species with the formula: $Annual\ Growth\ Rate\ I = \frac{AGB}{Actual\ year}$ and $Annual\ Growth\ Rate\ II = \frac{AGB}{Estimated\ Age}$.

3.3. Results

3.3.1. Relationship between Age and DBH of *Tectona grandis*

Based on the allometric analysis, cubic model showed the best fit for the data analysis compared to other seven models with *R-square* of 0.88 and *P-value* of < 0.01 (Table 3.2). On the other hand, exponential model recorded lowest in statistical indicators with *R-square* value of just 0.70. The cubic graph in general features a linear line to describe the relationship between age and DBH from all *Tectona grandis* trees species. Even though the graph did not seem to show a perfect linear relationship, but in general, the graph provided a good understanding of the important relationship between age as a function of DBH from *Tectona grandis* growing mechanism in tropical forest of Indonesia.

With the average age of 22.96 years, total AGB accumulation for *Tectona grandis* is about 378.8719 kg. The actual annual growth rate and estimated growth rate are 25.1244 kg yr^{-1} and 31.4056 kg yr^{-1} consecutively. In terms of biomass accumulation, *Tectona grandis* is lower than *Araucaria cuninghamii* and *Drancontumelum* sp., but higher than *Styrax bensoin*.

3.3.2. Relationship between Age and DBH of *Styrax bensoin*

Age as a function of DBH was analyzed to attain a finest relationship by way of statistical parameters and a suitable graph. From eight considered models, the cubic model showed the best fitted result with highest *R-square* indicator value of 0.89 and *P-value* of < 0.01 (Table 3.3). The cubic graph, however, was not really in a linear form to point out the relationship of age as a function of DBH (Figure 3.2).

Total AGB accumulation for *Styrax bensoin* is about 361.2887 kg from 82 trees with the average DBH of 24.84 cm. The actual annual growth rate and estimated annual growth rate are 22.5029 kg yr^{-1} and 28.1286 kg yr^{-1} consecutively. In overall, total ABG accumulation, actual annual growth rate and estimated annual growth rate for *Styrax bensoin* is lowest than other species in this study (Table 3.7).

3.3.3. Relationship between Age and DBH of *Araucaria cuninghamii*

In terms of understanding the potential ability of carbon and biomass sequestration by *Araucaria cuninghamii*, age as a function of DBH was established by way of statistical testing of allometric models. From the eight models, the cubic model emerged as the best with the highest statistical parameter with *R-square* of 0.89 and *P-value* of < 0.01 (Table 3.4). However, the cubic graph is not really linear to determine the relationship between age and DBH (Figure 3.3). The linear line of the graph looks not really representative toward tree distribution in the graph.

Araucaria cuninghamii turns out to be the highest in terms of AGB accumulation with the total of 398.7665 kg from the average DBH of 25.47 cm, while the actual age is lowest (11.55 year) compared to other species (Table 3.7). On the contrary, the actual annual growth rate and estimated annual growth rate are 23.8342 kg yr^{-1} and 29.7928 kg yr^{-1} consecutively which are lower than *Drancontumelum* sp., but higher than *Tectona grandis*, *Araucaria cuninghamii*, and *Styrax bensoin*.

3.3.4. Relationship between Age and DBH of *Drancontumelum* sp.

Age as a function of DBH from *Drancontumelum* sp., was established to see the relationship between both variables. The result indicated that the cubic model was the best among the others by virtue of its highest statistical parameters of *R-square* and *P-value*. The *R-square* for the cubic model was 0.88 and a significant *P-value* of < 0.01 (Table 3.5). The lowest statistical parameter was recorded in exponential model with *R-square* value of 0.70. The cubic graph showed a good relationship between age and DBH of *Drancontumelum* sp. (Figure 3.4).

In terms of AGB accumulation, this species has greater storage ability of 390.7784 kg compared to *Tectona grandis* and *Styrax bensoin*, while lower than *Araucaria cuninghamii*. It is indicated by the average of DBH of 22.9619 cm and highest of actual age of 13.40 year. However, the actual annual growth rate and estimated annual growth rate are highest among other three species with 27.7228 kg yr^{-1} and 34.6535 kg yr^{-1} consecutively (Table 3.7).

3.3.5. Relationship between Age and DBH of All-Species Combined

This section considered age as a function of DBH for all trees species combined from *Tectona grandis*, *Styrax bensoin*, *Araucaria cuninghamii*, *Drancontumelum* sp. The cubic model showed up to be the best expression from this combined test with highest statistical *R-square* value of 0.89 and *P-value* of < 0.01 (Table 3.6). The cubic graph was clear in indicating the relationship between age and DBH (Figure 3.5).

From four species, the total AGB accumulation is about 1529.7056 kg from the average DBH of 24.0624 cm and average actual age of 12.68 year. Additionally, the average of actual annual growth rate and estimated annual growth rate are high with 24.7961 kg yr^{-1} and 30.9951 kg yr^{-1} consecutively. In general, all tree species tend to have similar values in terms of average DBH (cm), actual age (year), estimated age (year) AGB accumulation (kg), average of actual annual growth rate (kg/year), and average of estimated annual growth rate (kg/year) from these four species (Table 3.7). The classification of shade tolerant ratings among four species from Indonesia were also indicated (Table 3.8.) (http://www.worldagroforestry.org/treedb2/speciesprofile).

3.4. Discussions

3.4.1. Tree Distributions and Growth Indicators

Even though these species are relatively young in age (< 14 years), the productivity and growth are prominently fast compared to study conducted by Therrell et al (2007) in southern African region which is less than 0.8mm a year for increment growth. It is likely that environmental and ecophysiological conditions have been a pronounced element for these trees to grow faster in this area (Leigh et al. 2004; Schnitzer and Bongers 2011; Bowman et al. 2013). High rates of annual precipitation has been a beneficial co-factor with averages of total annual precipitation of approximately above 2,000mm (Hendri et al. 2012). The amount of precipitation has been a significant factor controlling tree growth throughout tropical forests (Buckley et al. 2007; Couralet et al. 2010; Grogan and Schulze 2012).

We found that *Araucaria cuninghamii* had the highest amount of total AGB compared to other species. However, the annual growth rate is lower than *Drancontumelum* sp. (Table 3.7). The ability of *Araucaria cuninghamii* to grow faster in the early stages of the growing period could be attributed to its intrinsic characteristics. Full sun-light availability and warm climate conditions tend to be an accelerating factor that allows *Araucaria cuninghamii* to grow ideally. This species is also capable of thriving on a variety of soil characteristics, and moderately tolerant to the salt water are additional advantages of this species (Gilman and Watson 1993; State of Queensland, Department of Agriculture, Fisheries and Forestry, 2013). The typical growth of *Araucaria cuninghamii* tends to be more vertical in height and the regular distribution of the braches allow the tree to reach the top of the forest canopy faster than other species. Don (2009) pointed out that *Araucaria* sp. in general have the ability to adapt to the new environment very quickly and grow with the high rate due to the emerging roots in only several days.

Even though *Drancontumelum* sp., had the highest annual growth rate, the total accumulation of AGB is lower compared to *Araucaria cuninghamii*. The likelihood of this variation is driven by different average of actual age among four tree species. From those four species, *Drancontumelum* sp., turned out to be the highest actual age of 13.40 year compared to others. Schneider et al (2013) found that *Drancontumelum dao* growing in Filipina has an average diameter growth of 0.98cm per year. The highest wood density of *Drancontumelum* sp., in fact is another indicator to be considered since it plays an important role in tree resistance toward various environmental conditions and mechanical disturbances (Table 3.7) (Punches 2004; Shortle and Dudzik 2012). High wood density will enable a tree to adapt well with the surrounding circumstances and create durable structure to resist various environmental stresses (Bucci et al. 2004; Chave et al. 2009; Rowland et al. 2014).

Tectona grandis and *Styrax bensoin* both have lower AGB and average of annual growth rate in this study. Having low wood density is another concern for both species which may have led lower AGB and annual growth rate (Bucci et al. 2004; Chave et al. 2009). Wadsworth et al. (2009) indicated that *Tectona grandis* is quite good in the early growth phases, but the average growth rate for a longer time frame is low. *Tectona grandis* is classified in the deciduous tree's group which periodically allows them to lessen their productivity during the dry season. This circumstance will result in diminishing biomass accumulation. *Styrax bensoin* is lowest in wood density and the species is accumulated by resin during the growing process. Resin is semi-solid viscous substance produced by tree and it functions as protection for tree from any external disturbances. It is assumed that the lowest biomass accumulation of *Styrax bensoin* is likely a result of its internal structures and cell types that mainly consist of pores and tracheid as we found in many similar resin-based production plants (Langenheim 2003).

In general, *Tectona grandis* has been studied and information in regard to its potency and characteristics were available from various sources. Mbaekwe and Mackenzie (2008) studied biomass accumulation and distribution from young ages of *Tectona grandis* plantation forest in Gambari Forest Reserve, Nigeria. Nutrient accumulation and sustainability of *Tectona grandis* also studied by Fernandez-Moyo et al (2015) toward plantation forest of Costa Rica and Panama. Biomass accumulation and carbon sequestration of *Tectona grandis* has been published from Madhya Pradesh district of India (Bohre et al 2013). Similar study of biomass and carbon cycling in *Tectona grandis* also reported by Takahashi et al (2012) in plantation forest in Thailand.

Given that the study location is a managed forest, the trees are well arranged with approximately the same planting distance. This circumstance allows trees to grow bigger with the same intensity and compete with each other as a natural dynamic process in the forest (Fredericksen and Putz, 2003; Bertault et al. 2012). This means that, the overall ecophysiological components in the surrounding forest are enough available to underpin the cycle of tree regeneration. Latosol is common soil type in tropical forests with abundant soil nutrient including nitrogen, kalium, and phosphor. In addition, sufficient yearly precipitation also spurred the growth in this forests besides the availability of sun-light throughout the year for photosynthesis and productivity (Potter and Lee, 1998).

In general, the result of age as a function of DBH and growth rates in this study were high either for species-specific relationship or composite relationship. Syampungani et al (2010) reveled high relationship between number of growth rings and stem diameter of Miambo species in Zambia with R^2 of 0.90. However, the annual growth rates were lower in their study which ranged from 3.6mm to 4.8mm yr^{-1}. Lieberman et al (1985) found that maximum diameter growth rates of tropical tree species in Costa Rica can reach 14.62mm yr^{-1}. Even though there is a tendency of higher growth rates in the tropics, a study conducted by Zuidema et al (2011) found that for most of old tropical trees (>100 years), the growth rates will be lower with the range between 1.81mm to 2.74mm yr^{-1}.

3.4.2. Biomass Accumulation and Annual Growth Rates

In this study, tree biomass accumulation is estimated by way of applying an existing biomass formula developed by Basuki et al (2009) in tropical low-land dipterocarp forests of Borneo, Indonesia. The reasons for choosing the formula was because of some similarities between both locations in terms of ecophysiological conditions such as the naturalness of the forest of which 50 percent is still covered by vegetation, soil characteristics, precipitation gradient in a year, topography and altitude of which both locations are situated in the low land geographical landscape. Likewise, tree measurement in diameter and height are also considered to be large in size and more than one tree species with overall diameter ranges from 5 to 70cm. This allometric formula has been meaningful in generating some biomass and carbon values from similar typical forest conditions across Indonesia (Anitha et al. 2015).

From four tree species, it was found that there were slightly different variation in the results for biomass accumulation, but in general the number is not much different among species. The fact that these trees are growing in the same location with similar ecological factor are the most equal indicator to present common homogeneities. In general, tree growth in the forested lands with appropriate ecophysiological circumstances will present better trend of ideal regeneration compared to other different locations such as open lands and secondary forests. The accumulation of above ground biomass from this study was higher compared to a study conducted in moderate disturbance, high disturbance forests, and logged-over secondary forests of Papua, as reported by Hendri et al (2012). Even though there was a different in a per area basis between both studies, in general the average biomass accumulation from our study was relatively high.

Even though tropical forests have been commonly considered as a huge potential sink for biomass accumulation, there are some variations in terms of its actual amount. Fonseca et al. (2011) indicated total biomass from secondary humid tropical forest in Costa Rica with the average of 174.5 ± 16.4 Mg ha^{-1}. Variation of biomass also pointed out by Combalicer et al (2011) for some tropical tree species (20-year-old) i.e., *Acacia Auriculiformis*, *Acacia mangium*, and *Pterocarpus indicus* with the total biomass of 149.25 t ha^{-1}, 198.84 t ha^{-1} and 122.50 t ha^{-1} consecutively. Oo and Lee (2012) revealed AGB accumulation from plantation forest of 26-year-old Pure Teak (*Tectona grandis* Linn f.) in Myanmar about 225.12 t ha^{-1}. Despite those having a huge number of biomass accumulations, still this study presented a great average result of biomass accumulations in tropical region of West Papua.

Understanding annual rate of tree growth is indispensable in this study to basically estimate annual rates of biomass accumulation. Tree growth in general is an important facet of forest standing dynamics. It can be used to identify if there are any unusual spatial or temporal patterns in growth rates or if the balance between growth and mortality is adequate to sustain a forest ecosystem. There are two methods in accurately measuring annual tree growth from forest stands i.e., based on actual ages date and cross-dating measurement on tree rings (Worbers et al. 2003; Rozendaal and Zuidema 2011). Both have been successfully guiding our understanding on trees' growth dynamics, annual growth rates and climatic factors that affect forest structures and tree growth patterns (Viera et al. 2005; Brienen 2015).

APPENDICES

Table 3.1. Classification of models that consist of model number, model group, model name, model forms and references as a source where these models are cited. Eight models are listed with five linear models and three non-linear (two-parameter equation) models.

Model No	Model group	Model name	Model form	References
1.	Linear	Linear equation	$Y = a + bX$	Scaranello et al. (2012); Batista et al. (2001); Vanclay (1995).
2.	Linear	Linear equation	$Y = a + b\log X$	Fang and Bailey (1998); Curtis (1967); Alexandros and Burkhart (1992).
3.	Linear	Linear equation	$Log\,Y = a + b * \log X$	Fang and Bailey (1998); Prodan (1965); Curtis (1967);
4.	Linear	Quadratic equation	$Y = a + bX + cX^2$	Fang and Bailey (1998); Hendricksen (1950); Curtis (1967);
5.	Linear	Cubic equation	$Y = a + bX + cX^2 + dX^3$,,,,,,	Fang and Bailey (1998); Hendricksen (1950); Curtis (1967);
6.	Non-linear (two-parameter equation)	Power model equation	$Y = aX^b$	Scaranello et al. (2012); Batista et al. (2001); Fang and Bailey (1998).
7.	Non-linear	Exponential equation	$Y = e^{a+b/(X+1)}$	Fang and Bailey (1998); Huang and Titus (1992).
8.	Non-linear	Hyperbolic equation	$Y = aX/(b + X)$	Scaranello et al. (2012); Fang and Bailey (1998); Tang (1994); Bates and watts (1980); Ratkowsky and Reedy (1986).

Table 3.2. Model comparison between eight allometric models to determine the best relationship between age as a function of DBH for *Tectona grandis* from Indonesia.

Model class	Par. a coeff.	Par. a SE	Par. b coeff.	Par. b SE	Par. c coeff.	Par. c SE	Par. d coeff.	Par. d SE	Model R^2	Model SE
1. Linear	-0.1989	0.5275	0.5117	0.0207	-	-	-	-	0.853	2.307
2. Linear	-25.3801	1.6079	12.1849	0.5247	-	-	-	-	0.838	2.426
3. Linear	1.3093	0.0598	0.0434	0.0023	-	-	-	-	0.765	0.261
4. Quadratic	-4.0274	1.0661	0.8356	0.0823	-0.0055	0.0013	-	-	0.872	2.152
5. Cubic	3.6554	2.1508	-0.1491	0.2562	0.0304	0.009	-0.0003	0.00009	0.889	2.007
6. Power	0.5354	0.0766	0.9827	0.0415	-	-	-	-	0.855	0.97
7. Exponential	23.5465	0.821	-239.3286	15.097	-	-	-	-	0.709	0.938
8. Hyperbolic	308.4655	265.6201	577.9398	607.8891	-	-	-	-	0.86	0.969

SE = Standard Error

Table 3.3. Model comparison between eight allometric models to determine the best relationship between age as a function of DBH for *Styrax bensoin* from Indonesia.

Model class	Par. a coeff.	Par. a SE	Par. b coeff.	Par. b SE	Par. c coeff.	Par. c SE	Par. d coeff.	Par. d SE	Model R^2	Model SE
1. Linear	0.311	0.6685	0.516	0.0242	-	-	-	-	0.846	2.623
2. Linear	-27.1572	1.8187	12.995	0.5797	-	-	-	-	0.859	2.507
3. Linear	1.4041	0.07	0.041	0.0025	-	-	-	-	0.761	0.274
4. Quadratic	-5.6767	1.3446	1.012	0.1024	-0.0083	0.0016	-	-	0.88	2.309
5. Cubic	0.9663	2.7342	-0.106	0.3288	0.0332	0.0118	-0.0004	0.0001	0.896	2.157
6. Power	0.6571	0.1106	0.936	0.0479	-	-	-	-	0.852	0.97
7. Exponential	26.2643	0.8722	-274.824	16.8059	-	-	-	-	0.767	0.952
8. Hyperbolic	167.8973	82.1707	283.331	155.3643	-	-	-	-	0.86	0.97

SE = Standard Error

Table 3.4. Model comparison between eight allometric models to determine the best relationship between age as a function of DBH for *Araucaria cuninghamii* from Indonesia.

Model class	Par. a coeff.	Par. a SE	Par. b coeff.	Par. b SE	Par. c coeff.	Par. c SE	Par. d coeff.	Par. d SE	Model R^2	Model SE
1. Linear	1.2579	0.5033	0.4766	0.0176	-	-	-	-	0.859	2.456
2. Linear	-24.7814	1.3608	12.2533	0.4312	-	-	-	-	0.871	2.346
3. Linear	1.5121	0.0536	0.0372	0.0018	-	-	-	-	0.766	0.261
4. Quadratic	-4.1549	1.0272	0.9211	0.0776	-0.0073	0.0012	-	-	0.889	2.7
5. Cubic	1.3597	2.0107	0.2165	0.2358	0.0184	0.0082	-0.0002	0.00008	0.897	2.091
6. Power	0.7948	0.0979	0.8781	0.0348	-	-	-	-	0.867	0.97
7. Exponential	25.6431	0.6749	-259.8302	12.9747	-	-	-	-	0.772	0.956
8. Hyperbolic	111.5304	26.2381	179.23	50.3455	-	-	-	-	0.876	0.975

SE = Standard Error

Table 3.5. Model comparison between eight allometric models to determine the best relationship between age as a function of DBH for *Drancontumelum* sp., from Indonesia.

Model class	Par. a coeff.	Par. a SE	Par. b coeff.	Par. b SE	Par. c coeff.	Par. c SE	Par. d coeff.	Par. d SE	Model R^2	Model SE
1. Linear	-0.1989	0.5275	0.5117	0.0207	-	-	-	-	0.853	2.307
2. Linear	-25.3801	1.6079	12.1849	0.5247	-	-	-	-	0.838	2.426
3. Linear	1.3093	0.0598	0.0434	0.0023	-	-	-	-	0.765	0.261
4. Quadratic	-4.0274	1.0661	0.8356	0.0823	-0.0055	0.0013	-	-	0.872	2.152
5. Cubic	3.6554	2.1508	-0.1491	0.2562	0.0304	0.009	-0.0003	0.00009	0.889	2.007
6. Power	0.5354	0.0766	0.9827	0.0415	-	-	-	-	0.855	0.97
7. Exponential	23.5465	0.821	-239.3286	15.097	-	-	-	-	0.709	0.938
8. Hyperbolic	308.4655	256.6201	577.9398	507.8891	-	-	-	-	0.86	0.969

SE = Standard Error

Table 3.6. Model comparison between eight allometric models to determine the best relationship between age as a function of DBH for all-species combined from Indonesia.

Model class	Par. a coeff.	Par. a SE	Par. b coeff.	Par. b SE	Par. c coeff.	Par. c SE	Par. d coeff.	Par. d SE	Model R^2	Model SE
1. Linear	0.1962	0.2844	0.5186	0.0106	-	-	-	-	0.853	2.478
2. Linear	-26.3712	0.8073	12.718	0.2598	-	-	-	-	0.855	2.467
3. Linear	1.3858	0.0305	0.042	0.0011	-	-	-	-	0.768	0.266
4. Quadratic	-4.8095	0.5805	0.941	0.0449	-0.0072	0.0007	-	-	0.88	2.238
5. Cubic	2.5632	1.1458	-0.0096	0.1365	0.0278	0.0048	-0.0003	0.00005	0.894	2.106
6. Power	0.6251	0.0457	0.9499	0.021	-	-	-	-	0.857	0.97
7. Exponential	25.3852	0.4001	-261.0614	7.5284	-	-	-	-	0.748	0.947
8. Hyperbolic	196.1628	50.2675	338.8416	95.4156	-	-	-	-	0.863	0.971

SE = Standard Error

Table 3.7. Final summary of average DBH (cm), actual age (yr), estimated age (yr), biomass (kg), growth rate I (biomass [kg]/actual age [yr]) and growth rate II (biomass [kg]/estimated age [yr]) from Indonesia tree species.

Species	**Average DBH (cm)**	**Actual Age (yr)**	**Estimated Age (yr)**	**Above Ground Biomass (AGB) (kg)**	**AGB Growth Rate I (kg/yr)**	**AGB Growth Rate II (kg/yr)**	**Annual Diameter Growth Rate I (cm yr^{-1})**	**Annual Diameter Growth Rate II (cm yr^{-1})**
Tectona grandis	22.96	12.65	10.12	378.87	25.12	31.40	1.96	2.45
Styrax bensoin	24.84	13.14	10.51	361.28	22.50	28.12	2.00	2.50
Araucaria cuninghamii	25.47	11.55	09.24	398.76	23.83	29.79	1.96	2.45
***Drancontumelum* sp.**	22.96	13.40	10.72	390.77	27.72	34.65	2.11	2.64
average	24.06	12.68	10.15	382.42	24.79	30.99	2.01	2.51

Table 3.8. Shade tolerant ratings of Indonesian tree species

No.	Species	Tolerant ratings
1.	*Tectona grandis*	Tolerant to shade tolerant
2.	*Styrax bensoin*	Tolerant to shade tolerant
3.	*Araucaria cuninghamii*	Tolerant
4.	*Drancontumelum* sp.	Tolerant

Figure 3.1. Graph of the cubic regression relationship between age as a function of DBH of *Tectona grandis* planted in Indonesia. See Table 3.2., for parameter coefficients of regression model.

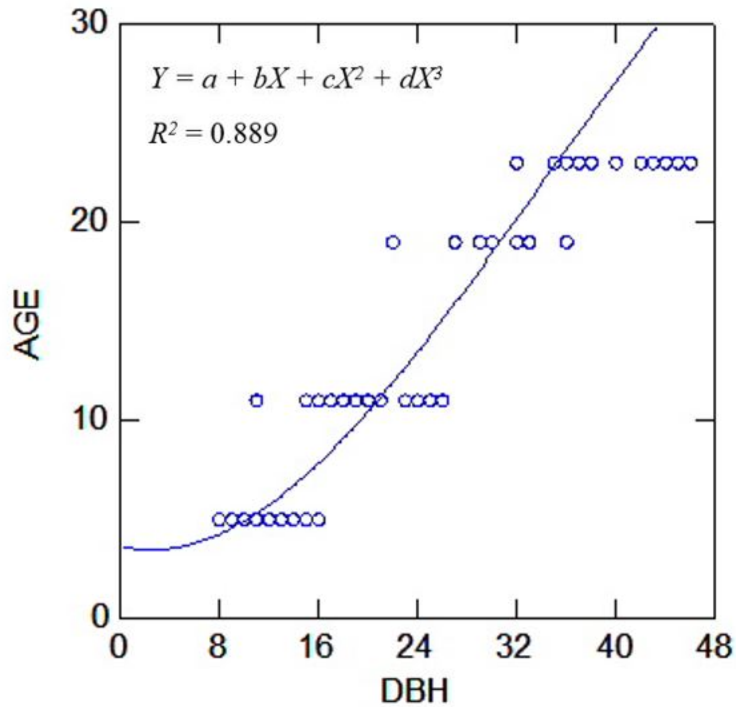


Figure 3.2. Graph of the cubic regression relationship between age as a function of DBH of *Styrax bensoin* planted in Indonesia. See Table 3.3., for parameter coefficients of regression model.

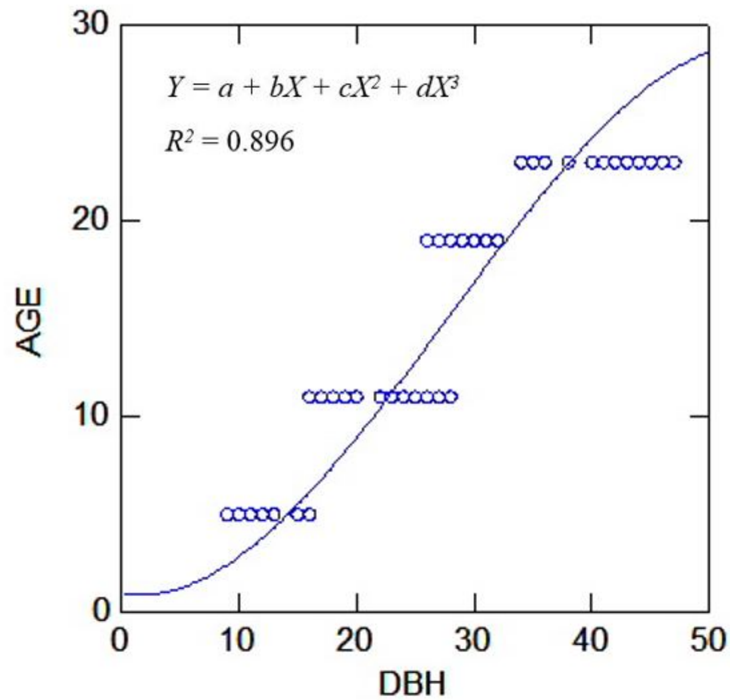


Figure 3.3. Graph of the cubic regression relationship between age as a function of DBH of *Araucaria cuninghamii* planted in Indonesia. See Table 3.4., for parameter coefficients of regression model.

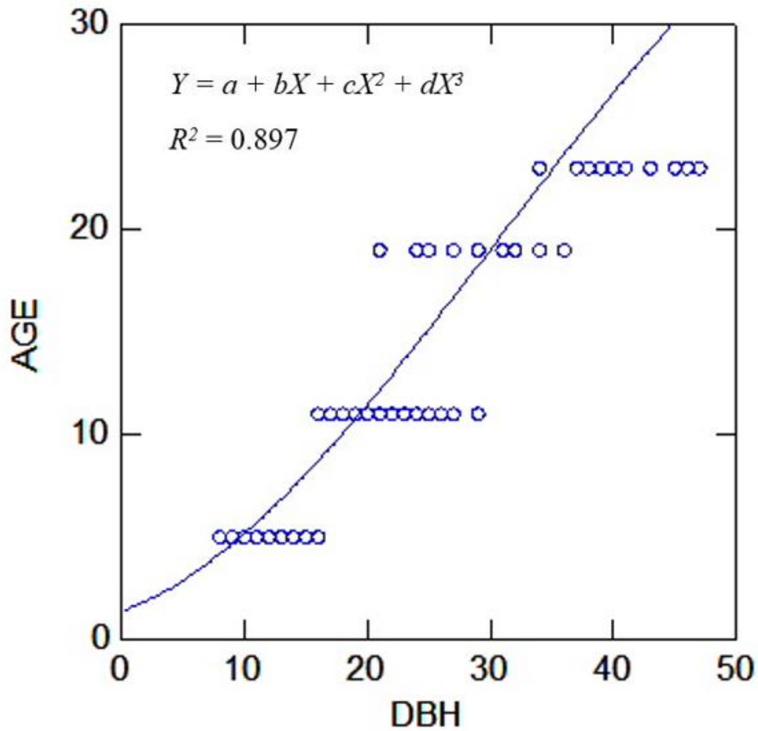


Figure 3.4. Graph of the cubic regression relationship between age as a function of DBH of *Drancontumelum* sp., planted in Indonesia. See Table 3.5., for parameter coefficients of regression model.

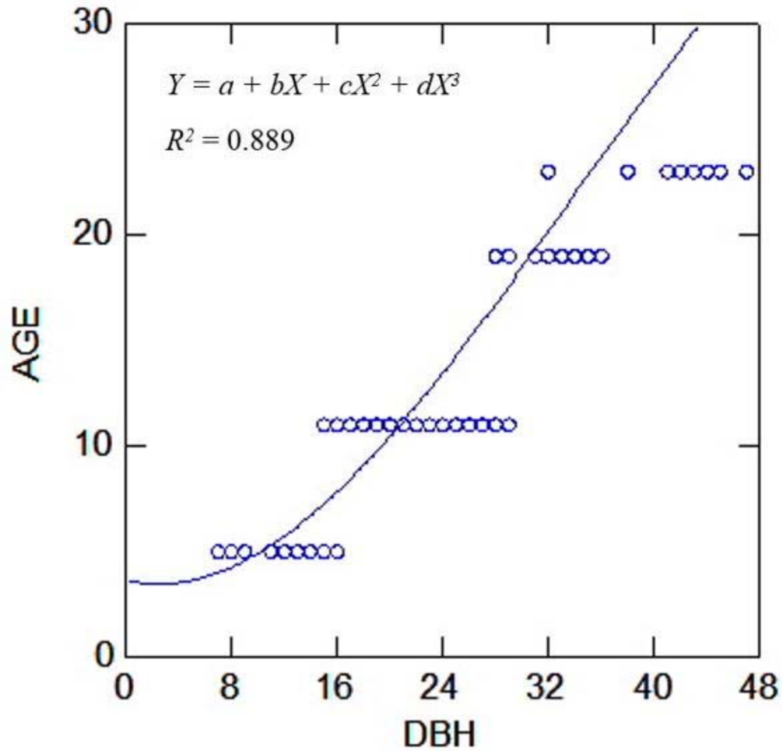


Figure 3.5. Graph of the cubic regression relationship between age as a function of DBH of all-species combined from Indonesia. See Table 3.6., for parameter coefficients of regression model.

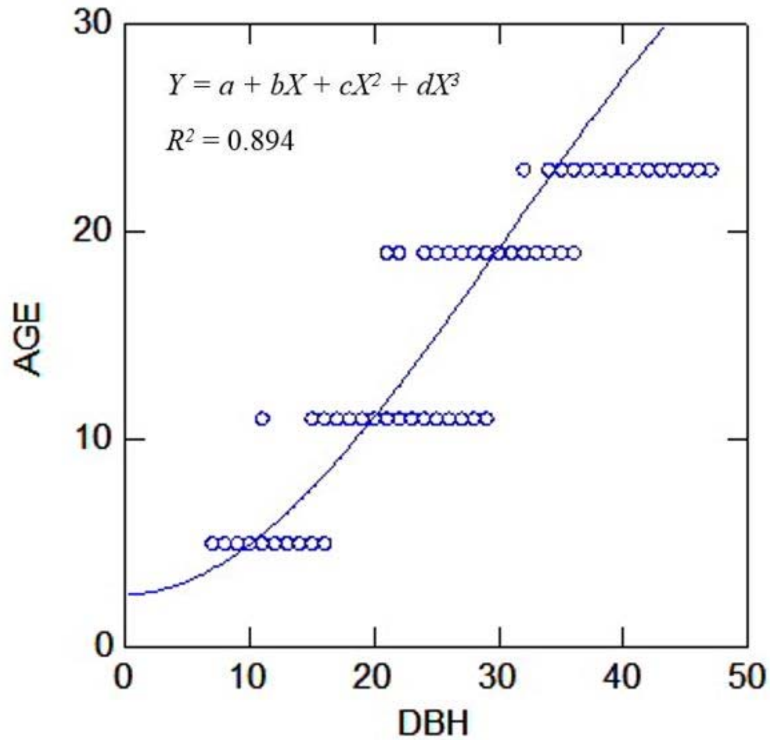
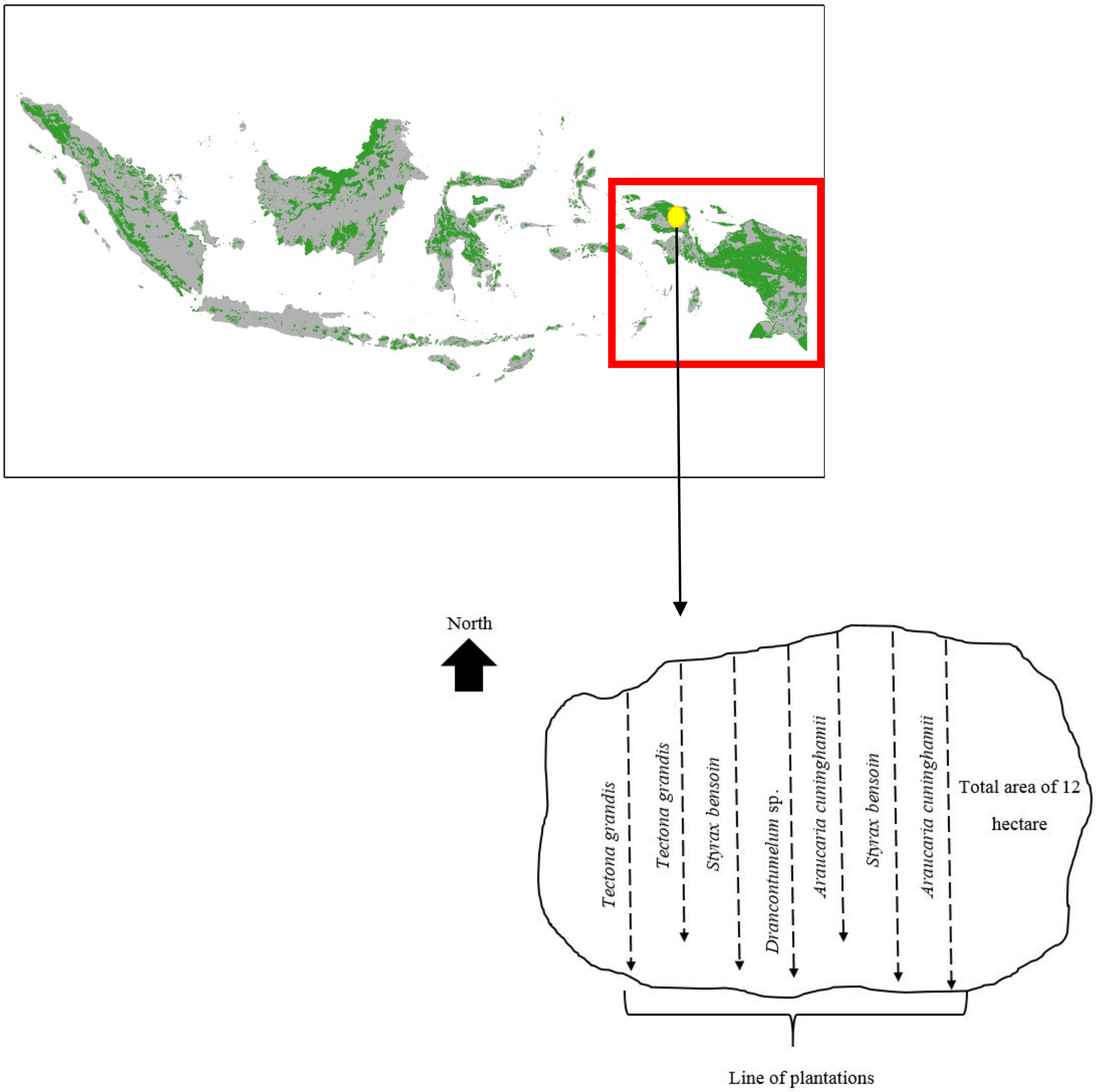


Figure 3.6. Study location map and design of plantation forest in West Papua, Indonesia.



REFERENCES

REFERENCES

Agrawal A., Cashore B., Hardin R., Shepherd G., Benson C. and Miller D. 2013. Economic contributions of forests – Background paper 1. United Nations Forum on Forests, Istanbul, Turkey.

Angelsen A., Brockhaus M., Sunderlin W., D. and Verchot L., V. 2012. Analysing REDD+: Challenges and choices. CIFOR, Bogor, Indonesia.

Angelsen A., Gierloff C., W., Beltran M A. and Elzen den M. 2014. REDD credits in a global carbon market; Options and Impacts. Nordic Council of Ministers, Denmark.

Anitha K., Verchot L., V., Joseph S., Herold M., Manuri S. and Avitabile V. 2015. A review of forest and tree plantation biomass equations in Indonesia. Annals of forest science; DOI 10.1007/s13595-015-0507-4

Basuki T., M., Van Laake P., E., Skidmore A. K. and Hussain Y., A. 2009. Allometric equations for estimating the above-ground biomass in tropical lowland dipterocarp forests. For Ecol Manag, 257: 1684–1694

Bertault J.G., Dupuy B., and Maitre H., F. 2012. Silviculture for sustainable management of tropical moist forest. Unasylva No. 181.

Birdsey R., A. 2006. Carbon accounting rules and guidelines for the United States forest sector. Journal of Environmental Quality, 35: 1518–1524.

Bohre P., Chaubey O., P. and Singhal P., K. 2013. Biomass accumulation and carbon sequestration in *Tectona grandis* Linn. f. and *Gmelina arborea* Roxb. Inter. J. of Bio-Science & Bio-Tech, 5(3): 153-173.

Bowen A. 2011. The case for carbon pricing-policy brief. Grantham Research Institute on Climate Change and the Environment in collaboration to Centre for Climate Change Economics and Policy.

Bowman D., M., J., S., Brienen R., J., W., Gloor E., Phillips O., L. and Prior L., D. 2013. Detecting trends in tree growth: Not so simple. Trends in Plant Science, 18 (1): 11-17.

Brienen R., J., W. 2015. Tree rings in the tropics: a study on growth and ages of Bolivian rain forest trees PROMAB Scientific Series 10 PROMAB-Riberalta, Bolivia.

Brown S. 2002. Measuring carbon in forests: current status and future challenges. Environ pollut, 116: 363-372.

Bucci S., J., Goldstein G., Meinzer F., C., Scholz F., G., Franco A., C. and Bustamante M. 2004. Functional convergence in hydraulic architecture and water relations of tropical savanna trees: from leaf to whole plant. Tree Physiol, 24: 891–899.

Buckley B., M., Duangsathaporn K., Palakit K., Butler S., Syhapanya V. and Xaybouangeun N. 2007. Analysis of growth rings of *Pinus merkusii* from Lao PDR. Forest & Ecology Management, 253: 120-127.

Built Environment Directorate General of Forestry. 2009. Strategic Data Forestry 2009. Jakarta

Burgess R., Hansen M., Olken B., Potapov P. and Sieber S. 2011. The political economy of deforestation in the tropics. LSE Centre for Climate Change Economics and Policy and the Grantham Research Institute on Climate Change and the Environment.

Center for forestry planning and statistics ministry of forestry, 2009. Indonesia forestry outlook study - working paper series. Asia-pacific forestry sector outlook study ii. Food and Agriculture Organization of the United Nations regional office for Asia and the Pacific, Bangkok.

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

Chave J., Coomes D., Jansen S., Lewis S., L., Swenson N., G. and Zanne A., E. 2009. Towards a worldwide wood economics spectrum. Ecol Lett, 12: 351–366.

Combalicer M., S., Lee D., K., Woo S-Y., Park P., S., Lee K., W., Tolentino W., L., Combalicer E., A., Lee Y., K. and Park Y., D. 2011. Aboveground biomass and productivity of nitrogen fixation tree species in the Philippines. Scientific Research and Essays, 6 (27): 5820-5836.

Condit 2008. Methods for estimating above-ground biomass of forest and replacement vegetation in the tropics. Center for Tropical Forest Science Research Manual, 73 p.

Couralet C., Sterck F., J., Sass-Klaaseen U., van Acker J. and Beeckman H. 2010. Species-specific growth responses to climate variations in understory trees of a central African rain forest. Biotropica, 42: 503-511.

Dieters M., J., Nikles D., G. and Keys M., G. 2007. Achievements in forest tree improvement in Australia and New Zealand 6: Genetic improvement and conservation of *Araucaria cunninghamii* in Queensland. Australian Forestry, 70 (2): 75-85.

Don G. 2009. Description of *Araucaria bidwillii*. Agroforestry database. http://www.worldagroforestry.org/treedb/AFTPDFS/Araucaria_bidwillii.PDF

Fernandez-Moya J., Murillo R., Portuguez E., Fallas J., L., Rios V., Kottman F., Verjans J., M., Mata R. and Alvarado A. 2015. Nutrient accumulation and export in teak (Tectona grandis L.f.) plantations of Central America. iForest, 8: 33-44.

Fofana I., J., Ofori D., Poitel M. and Verhaegen. 2009. Diversity and genetic structure of teak (*Tectona grandis* L.f) in its natural range using DNA microsatellite markers. New Forests, 37: 175-195.

Fonseca W., Benayas J., M., R. and Alice F., E. 2011. Carbon accumulation in the biomass and soil of different aged secondary forests in the humid tropical of Costa Rica. Forest Ecology & Management, 262: 1400-1408.

FAO. 2010. Forest and climate change in the Asia-Pacific Region. Forest and climate change working paper 7.

Fredericksen T.D., and Putz F.A. 2003. Silvicultural intensification for tropical forest conservation. Biodiversity and conservation, 12: 1445-1454.

Gilman E., F. and Watson D., G. 1993. Araucaria heterophylla: Norfolk-Island-Pine. Fact Sheet ST-83. USDA Forest Service.

Gray B. 1968. Forest tree and timber insect pests in the territory of Papua and New Guinea. Pacific Insects, 10: 301-323.

Grogan J. and Schulze M. 2012.The impact of annual and seasonal rainfall patterns on growth and phenology of emergent tree species in Southeastern Amazonia, Brazil. Biotropica, 44 (3): 331-340.

Harikrishnan S., Vasudevan K., Udhayan A. and Mathur P., K. 2012. Biodiversity values of abandoned teak, Tectona grandis plantations in southern Western Ghats: Is there a need for management intervention? Basic & Applied Ecology, 13: 139-148.

Hendri., Yamashita T., Kuntoro A., A. and Lee H., S. 2012. Carbon stock measurements of a degraded tropical logged-over secondary forest in Manokwari Regency, West Papua, Indonesia. For. Stud. China, 14(1): 8-19; DOI 10.1007/s11632-012-0105-6. http://www.worldagroforestry.org/treedb2/speciesprofile.

ICRAF, 2016. Tree functional attributes and ecological database: Wood density. http://db.worldagroforestry.org/wd.

Kashio M and Johnson D., V. 2001. Monograph of benzoin (Balsamic resin from styrax species). RAP Publication: 2001/21. Food and Agriculture Organization of the United Nations Regional Office for Asia and the Pacific Bangkok, Thailand.

Ketterings Q., M., Coe R., Noordwijk M., V., Ambagau Y. and Palm C., A. 2001. Reducing uncertainty in the use of allometric biomass equations for predicting above-ground tree biomass in mixed secondary forests. Forest Ecology and Management, 146: 199-209.

Korhonen-Kurki K., Brockhaus M., Duchelle A., E., Atmadja S., Thuy P, T. and Schofield L. 2013. Multiple levels and multiple challenges for measurement, reporting and verification of REDD+. Intr Journal of the Commons, 7(2): 344–366.

Langenheim J., H. 2003. Plant resins: Chemistry, evolution, ecology, and ethnobotany. Timber Press Inc. Portland, Cambridge.

Lee S. 2003. Pathology of tropical hardwood plantations in south-eastasia. New Zealand Journal of Forest Science, 33 (3): 321-335.

Leigh E., G., Jr. Davidar P., Dick C., D., Puyravaud J-P., Terborgh J., Steege H., T. and Wright S., J. 2004. Why do some tropical forests have so many species of trees? Biotropica, 36 (4): 447-473.

Lieberman D., Lieberman M., Hartshorn G. and Peralta R. 1985. Growth rates and age-size relationships of tropical wet forest trees in Costa Rica. J. of Tropical Ecology, 1 (2): 97-109.

Lim T., K. 2012. Edible Medicinal and Non-Medicinal Plants: Volume 1, Fruits, 75 DOI 10.1007/978-90-481-8661-7_9, Springer Science + Business Media B.V.

Lobdell M. 2013. Styrax In Cultivation: Evaluation of an underrepresented ornamental genus. Master of Science Thesis, University of Delaware.

Manokwari Bureau of Meteorology and Geophysics, 2007. Climate report, Manokwari; BMG, 72.

Mbaekwe E., I. and Mackenzie J., M. 2008. The use of a best-fit allometric model to estimate aboveground biomass accumulation and distribution in an age series of teak (Tectona grandis L.f.) plantations at Gambari Forest Reserve, Oyo State, Nigeria. Tropical Ecology, 49 (2): 259-270.

McHale M., R., Burke I., C., Jefsky M., A., Peper P., J. and McPherson E., G. 2009. Urban forest biomass estimates: is it important to use allometric relationships developed specifically for urban trees? Urban Ecosyst, 12: 95-113.

Measey M. 2010. Indonesia: A vulnerable country in the face of climate change. Global majority E-journal, 1(1): 31-45.

Melson S., L., Harmon M., E., Fried J., S. and Domingo J., B. 2011. Estimates of live-tree carbon stores in the Pacific Northwest are sensitive to model selection. Carbon Balance & Management, 6 (2): 1-16.

Murdiyarso D. Kauffman J.B. warren M. Pramova E. and Hergoualc K. 2012. Tropical wetlands for climate change adaptation and mitigation: Science and policy imperatives with special reference to Indonesia. *Working paper* 91. CIFOR, Bogor, Indonesia.

Obersteiner M., Azar C., Kauppi P., Mollersten K., Moreira J., Nilsson S., Read P., Riahi K., Schlamadinger B., Yamagata Y., Yan J., and van Ypersele J., P. 2001. Managing climate risk. Science, 294**:** 786–787.

Oo T., N. and Lee D., K. 2012. Carbon sequestration of Pure Teak (Tectona grandis Linn f.) and mixed species plantation in Bago Yoma Region of Myanmar. http://www.fdmoecaf.gov.mm/sites/default/files/Research%20Books%20file/Leaflet%20No.%203-2012.pdf.

Orwa C., A., Mutua, Kindt R., Jamnadass R. and Anthony S. 2009. Agroforestree Database: A tree reference and selection guide version 4.0 http://www.worldagroforestry.org/treedb/AFTPDFS/Araucaria_cunninghamii.PDF

Potter L., and Lee J. 1998. Tree planting in Indonesia: Trends, impacts and directions. Occasional paper No. 18. CIFOR

Priyadi H., Takao G., Rahmawati I., Supriyanto B., Nursal W., I. and Rahman I. 2010. Five hundred plant species in Gunung Halimun Salak National Park, West Java. A checklist including Sundanese names, distribution and use. CIFOR, Bogor, Indonesia.

Punches J. 2004. Tree growths, forest management, and their implications for wood quality. PNW 576. A Pacific Northwest Extension Publication. Oregon State University, University of Idaho, Washington State University.

Rowland L., Malhi Y., Silva-Espejo J., E., Farfan-Amezquita F., Halladay K., Doughty C., E., Meir P. and Phillips O., L. 2014. The sensitivity of wood production to seasonal and interannual variations in climate in a lowland Amazonian rainforest. Oecologia, 174: 295–306; DOI 10.1007/s00442-013-2766-9.

Rozendaal D., M., A. and Zuidema P., A. 2011. Dendrochronology in the tropics: A review. Trees, 25: 3-16.

Saint-André L., M'Bou A., T., Mabiala A., Mouvondy W., Jourdan C., Roupsard O., Deleporte P., Hamel O. and Nouvellon Y. 2005. Age-related equations for above- and below-ground biomass of a *Eucalyptus hybrid* in Congo. Forest Ecology & Management, 205: 199-214.

Schneider T., Ashton M., S., Montagnini F. and Milan P., P. 2013. Growth performance of sixty tree species in smallholder reforestation trials on Leyte, Philippines. New Forests; DOI 10.1007/s11056-013-9393-5.

Schnitzer S., A. and Bongers F. 2011. Increasing liana abundance and biomass in tropical forests: emerging patterns and putative mechanisms. Ecology Letters; doi: 10.1111/j.1461-0248.2011.01590.x

Schollaen K. Heinrich I. Neuwirrth B. Krusic P.J. D'Arrigo R.D. Karyanto O. and Helle G. 2013. Multiple tree-ring chronologies (ring width, 13C and 18O) reveal dry and rainy season signals of rainfall in Indonesia. *Quaternary Science Reviews.* 73, 170-181.

Schultze E., D,. Wirth C., Heimann M. 2001. Managing forests after Kyoto. *Science*, 289: 2058–2059. 10.1126/science.289.5487.2058.

Shortle W., C. and Dudzik K., R. 2012. Wood decay in living and dead trees: A Pictorial overview. General Technical Report NRS-97. Northern Research Station, United State Department of Agriculture.

State of Queensland, Department of Agriculture, Fisheries and Forestry. 2013. Hoop Pine – Araucaria (plantations). http://era.daf.qld.gov.au/3931/1/hoop_pine_final_factsheet.pdf
SYSTAT Software Inc. 2002. Systat 10.2 graphics. Copyright @ 2002 by SYSTAT Software Inc. 501, Canal Boulevard, Suite F. Richmond, CA. '

Syampungani S., Geledenhuys C. and Chirwa P., W. 2010. Age and growth rate determination using growth rings of selected Miambo woodland species in charcoal and, slash and burn regrowth stands in Zambia. J. of Eco and the Nat Enviro, 2 (8): 167-174.

Takahashi M., Mador D., Panuthai S. and Hirai K. 2012. Carbon cycling in teak plantations in comparison with seasonally dry tropical forests in Thailand. Forests ecosystems – more than just trees. Dr Juan A. Blanco (Ed.), ISBN: 978-953-51-0202-1.

Therrell M., D., Stahle D., W., Mukelabai M., M. and Shugart H., H. 2007. Age, radial growth dynamics of Pterocarpus angolensis in southern Africa. Forest Ecology & Management, 244: 24-31.

Verchot L.V., Petkova E., Obidzinski K., Atmadja S., Yuliani E.L., Dermawan A., Murdiyarso D. and Amira S. 2010. Reducing forestry emissions in Indonesia. CIFOR, Bogor, Indonesia.

Verhaegen D., Fofana I., J., Logossa Z., A. and Ofori D. 2010. What is the genetic origin of teak (*Tectona grandis* L.) introduced in Africa and in Indonesia? Tree Genetics & Genomes, 6: 717-733; DOI 10.1007/s11295-010-0286-x

Viera S., Trumbore S., Camargo P., B., Selhorst D., Chambers J., Q., Higuchi N. and Martinelli L., A. 2005. Slow growth rates of Amazonian trees: Consequences for carbon cycling. PNAS, 102 (51): 18502-18507.

Wadsworth F., H., Adams J., Holmgren P., H., Jimenez A., B. and Whitmore J., L. 2009. Management of Teak plantations for solid wood products. Special Report, ISTF News. Zobel Forestry Associates, Inc.

Worbes M., Staschel R., Roloff A. and Junk W., J. 2003. Tree ring analysis reveals age structure, dynamics and wood production of a natural forest stand in Cameroon. For Ecol Manage, 173:105–123.

World Growth. 2011. The economic benefit of palm oil to Indonesia. World Growth Palm Oil Green Development Campaign, Arlington, VA.

Zanne, A.E., Lopez-Gonzalez, G., Coomes, D.A., Ilic, J., Jansen, S., Lewis, S.L., Miller, R. B., Swenson, N.G., Wiemann, M.C., Chave, J., 2009. Towards a worldwide wood economics spectrum.

Zuidema P., Vlam M. and Chien P., D. 2011. Ages and long-term growth patterns of four threatened Vietnamese tree species. Trees, 25 (1): 29-38.

CHAPTER 4

CONCLUSIONS

In chapter two, eight existing models have been chosen to describe the relationship between age as a function of DBH, age as a function of height and height as a function of DBH for Senegalese tree species. Coefficient of determination (R^2) has been mainly used to indicate the best model from each relationship. Power model was best fitted for describing the relationship between age as a function of DBH, and age as a function of height, while cubic model turned out to be the best for explaining the relationship between height as a function of DBH. However, in general the relationships are considered to be lower ($R^2 < 0.40$) between age and DBH and age and height compared to height as a function of DBH. This is likely a result of the development of mixed-equation models rather than species-specific models. The main consideration is because in this study, number of tree samples were limited (57 trees in total). Senegal is characterized by less annual rainfall, most regions are severely dry, poor soil nutrients usually dominate across the regions and soils are unable to retain water in the ground due to poor structure and form.

Even though forests in Senegal are less abundant compared to other tropical regions in Africa, the contribution has been promising particularly some places with no settlements. By knowing the appropriate allometic models developed through this study, it is possible to determine annual rates of biomass accumulation and carbon sequestration.

In chapter three, from eight models tested, the cubic model has been well fitted to describe the relationship between age as a function of DBH for four species-species allometric relationships and one composite allometric relationship. Coefficient of determination (R^2) was high ($R^2 = 0.89$) for all tested with *P-value* < 0.001. *Araucaria cuninghamii* was the highest in terms of AGB accumulation with the total of 398.7665 kg from the average DBH of 25.47 cm, while the actual age is lowest (11.55 year) compared to other species. *Drancontumelum* sp. actual annual growth rate and estimated annual growth rate higher than the other Indonesian tree species considered in this study. In general, the distribution of trees in Papua are abundant. *Tectona grandis* and *Styrax bensoin* are found lower in both AGB and average of annual growth rate. It is likely that low wood density and internal characteristics and mechanisms such as dormant activity during dry season for *Tectona grandis* and numerous pores in cell structures for *Styrax bensoin* have resulted in low biomass production. Overall, ecophysiological components, soil characteristics, climatic patterns have been supporting surrounding forest to grow bigger by way of providing great essential necessities. Average above ground biomass in this study was higher compared to a study conducted by Hendri et al (2012) in moderate disturbance, high disturbance forests, and logged-over secondary forests in the same region.

REFERENCES

REFERENCES

Hendri., Yamashita T., Kuntoro A., A. and Lee H., S. 2012. Carbon stock measurements of a degraded tropical logged-over secondary forest in Manokwari Regency, West Papua, Indonesia. For. Stud. China, 14(1): 8-19; DOI 10.1007/s11632-012-0105-6.