

**ABOVE-GROUND BOLE CARBON STOCK ESTIMATION USING FOREST
INVENTORY AND REMOTE SENSING OF THE SECONDARY FOREST
ECOSYSTEM IN IBADAN, NIGERIA**

BY

EHIMWENMA VICTOR AGHIMIEN

B. Agric. Forestry and Wildlife (University of Benin)

M.Sc. Forest Biometrics and Remote Sensing (University of Ibadan)

Matriculation Number: 165839

A thesis in the Department of Forest Resources Management,

Submitted to the Faculty of Agriculture and Forestry in partial fulfilment of the requirements for
the Degree of

DOCTOR OF PHILOSOPHY

of the

UNIVERSITY OF IBADAN, NIGERIA.

JULY, 2018

ABSTRACT

Secondary forest ecosystem contributes to global climate change mitigation through carbon sequestration. Above-Ground Bole Biomass (AGBB) is the major component for monitoring and estimating Carbon Stocks (CS) and fluxes in tropical forests. Integrating Remote Sensing (RS) with Forest Inventory (FI) techniques had also been reported to provide accurate estimation of Above Ground Bole Carbon Stock (AGBCS). However, information on AGBCS for the International Institute of Tropical Agriculture (IITA), which hosts relics of the undisturbed secondary forest ecosystem in south-western Nigeria, has not been documented. Therefore, AGBCS of the secondary forest ecosystem was estimated using remote sensing and forest inventory techniques.

Forest inventory and remote sensing data were used for this study. One hundred and forty plots of 50m x 50m were laid in IITA secondary forest using systematic sampling technique at 10% sampling intensity. Trees in each plot were enumerated and identified to species level. The Total Height (TH) and Diameter at Breast Height (DBH) of trees ≥ 10 cm were measured to determine Tree Volume (TV). Sixty wood core samples were randomly collected from dominant trees species at breast height for Wood Density (WD) estimation. The TV and WD were used to determine AGBB, which were converted to CS using standard forest inventory method. Pleiades satellite imagery was acquired using RS technique and spectral data for each sample plot extracted. The spectral indices used for AGBB estimation were: Normalised Difference Vegetation Index (NDVI), Difference Vegetation Index (DVI), Infrared Percentage Vegetation Index (IPVI), Optimised Soil Adjusted Vegetation Index (OSAVI) and Renormalised Difference Vegetation Index (RDVI). The RS data were integrated with FI data to develop regression equations for the prediction of AGBB from where the total CS estimate was obtained. Data were analysed using descriptive statistics and linear regression analysis at $\alpha_{0.05}$.

A total of 9,985 individual trees comprising 121 tree species and 30 families were recorded. The highest and least frequency of species recorded were *Funtumia elastica* (61/ha) and *Cordia alliodora* (1/ha) respectively. The TH and DBH ranged from 4.70 to 39.30 m and 10.76 to 74.50 cm, respectively, while TV ranged from 129.57 to 167,186 m³/ha. The WD of tree species ranged from 0.23 to 0.89 kg/cm³. The AGBB and CS ranged from 101.06 to 881,834.92 kg/ha and 50.53 to 440,917.46 kg/ha, respectively. The DVI had the highest AGBB value which ranged from 187 to 15,577 kg/ha, followed by IPVI, RDVI and OSAVI which ranged from 7,561 to 12,324 kg/ha, 64.0591 to 133.178 kg/ha, 0.0134 to 0.5621 kg/ha, respectively, while NDVI had the least values which ranged from -0.01 to 0.48 kg/ha. The best AGBB estimation model was $AGBB = \exp(3,496.61 + 0.99 \times (RDVI)^{1/2})$; (Coefficient of Determination = 0.93, Bayesian Information = 2129.34). The total carbon stock ranged from 11,035 to 18,774 kg/ha.

Model with renormalised difference vegetation index was most suitable among other indices for estimating above-ground bole carbon stock when integrated with forest inventory data. Therefore, effective integration of different sensor data will be an important research topic for improving above-ground bole biomass estimation performance.

Keywords: Carbon stock prediction; Secondary forest biomass; Vegetation spectral indices; Remote sensing

Word Count: 500

DEDICATION

This research work is dedicated to almighty God for his guidance, strength, divine favour, divine grace and love endowed on me towards the successful completion of this Ph.D. research thesis.

ACKNOWLEDGEMENTS

First and foremost I would like to thank the almighty God for his presence, favour, divine grace, protection and guidance during the study period. My special thanks go to International Institute of Tropical Agriculture (IITA) that provided me with partial sponsorship.

I would like to acknowledge Forest Biometrics and Remote Sensing Unit, especially Prof. J.S.A. Osho for providing me with fatherly supports during the Ph.D. research thesis as my major project supervisor.

My deepest gratitude and great appreciation goes to my co-supervisors; Dr. O. J. Taiwo (Department of Geography, University of Ibadan), Mr. M. Haertel (GIS and Database unit, International Institute of Tropical Agriculture) and Mrs. Deni Bown (Forest Project Manager, International Institute of Tropical Agriculture) for their continuous supportive feedbacks. Your comments were really constructive and I learned a lot.

I am very thankful to the Head of Department (Forest Resources Management, Faculty of Agriculture and Forestry, University of Ibadan, Ibadan), Prof. B. O. Agbeja and other members of staff (Prof. O. Y. Ogunsanwo, Dr. I. O. Ajewole, Dr. I. O. Azeez, Dr. S.O. Jimoh, Dr. S. O. Olajuyigbe, Dr. A. A. Alo, and Dr. O. F. Falade), for all their supports and necessary scientific information provided during the Ph.D. research thesis.

My sincere thanks goes to Federal College of Forestry (FCF), Forestry Research Institute of Nigeria (FRIN), and my amiable students especially Master Alade Afees Abidemi, for their cooperation and support during the Ph.D. research thesis. I cannot but thank all my colleagues and friends, especially Winner Sanctuary Parish (RCCG) for their endless prayers towards the successful completion of my research thesis.

My deepest gratitude goes to my family, especially to my parents for their prayers, encouragement and moral support. God bless you all.

CERTIFICATION

I hereby certify that this research thesis was carried out by EHIMWENMA VICTOR AGHIMIEN at the Department of Forest Resources Management, Forest Biometric and Remote Sensing Unit, Faculty of Agriculture and Forestry, University of Ibadan, Ibadan, Oyo State, Nigeria

Supervisor

Professor J. S. A. Osho

B.Sc. (Hons) Mathematics, University of Ife

M.Sc. Statistics, Iowa State University

Ph.D. Forest Biometrics, University of Ibadan

LIST OF ACRONYMS USED IN THE THESIS

AGBC	Above-ground Bole Carbon
AGB	Above-ground Biomass
BA	Basal Area
BGB	Below-ground Biomass
C	Carbon
CO₂	Carbon Dioxide
CAVIS	Clouds, Aerosols, Water Vapour, Ice and Snow
CM	Centimetre
D	Diameter
DBH	Diameter at Breast Height
DVI	Difference Vegetation Index
EVI	Enhanced Vegetation Index
FAO	Food and Agriculture Organisation
G	Grams
GEMI	Global Environmental Monitoring Index
GHGs	Greenhouse Gases
GIS	Geographical Information Systems
GPS	Global Positioning System
Gt	Giga-tonnes (10 ⁹)
H	Total Height
ha	Hectare
IITA	International Institute of Tropical Agriculture
IPCC	Intergovernmental Panel on Climate Change
IR	Infra-Red
KG	Kilogram
L	Length
M	Metre
MM	Millimetre
NDVI	Normalized Difference Vegetation Index
NIR	Near-Infra-Red
°C	Degree Celsius
RB	Reading at the Base
REDD	Reducing Emissions from Deforestation and Forest Degradation
RS	Remote Sensing
RT	Reading at the Top
IPVI	Infrared Percentage Vegetation Index
OSAVI	Optimized Soil-Adjusted Vegetation Index
UNFCCC	United Nations Framework Convention on Climate Change
UTM	Universal Transverse Mercator
TSP	Temporary Sample Plot
VNIR	Visible, Near-Infra-Red
WSG	Wood Specific Gravity
WD	Wood Density
π	Pi
AGBB	Above-Ground Bole Biomass
P	Pleiades

AOI	Automated Optical Inspection
SFE	Secondary Forest Ecosystem
DN	Digital Number
LULC	Land –Use and Land-Cover
NPV	Non-photosynthetic Vegetation
K-NN	K-Nearest Neighbor
ANN	Artificial Neural Network
SVM	Support Vector Machine
PLS	Partial Least Squares
WWF	World Wide Fund
SFE	Secondary Forest Ecosystem
DAIS	Digital Airborne Imagery Spectrometer
AVHRR	Advance Very High Resolution Radiometer
U	Wind Speed
T_a	Air Temperature
FPAR	Fractional Photo-synthetically Active Radiation
SMA	Spectral Mixture Analysis
TCT	Tasseled Cap Transform
ALS	Airborne Laser Scanning
WIFS	Wide Field Sensor
r_{an}	Aerodynamic Resistance
C/N	Carbon-Nitrogen
GLCM	Gray Level Co-occurrence Matrix
DPI	Dots per inch
PPI	Pixels per inch

TABLE OF CONTENTS

	PAGE
Title page	i
Abstract	ii
Dedication	iii
Acknowledgements	iv
Certification	v
List of Acronyms Used in the Thesis	vi
CHAPTER ONE	1
1.0: Introduction	1
1.1: General Background	1
1.2: Problem of Statement	3
1.3: Objectives of the Study	4
1.4: Justification of the Study	4
1.5: Scope of the Study	5
CHAPTER TWO	6
2.0 Literature Review	6
2.1: Importance of Tropical Forest	6
2.1.1: Forests and Climate change	7
2.1.2: The Carbon Pools	8
2.1.3: Forests as Carbon Sinks	9
2.1.4: The Complexity of Forest Decline	10
2.1.5: Consequences of Deforestation	11
2.2: Carbon Allocation in Woody Plants (Trees and Shrubs)	12
2.2.1: Carbon Sequestration and what is it?	13
2.3: Techniques for Estimating Above-ground Biomass	14
2.3.1: Field Measurement Method of Biomass Estimation	14
2.3.2: Remote Sensing Methods for Biomass Estimation	15
2.3.2.1: Collection and calculation of biomass reference data based on field measurements	15
2.3.3: Use of Remote Sensing and GIS for Biomass Estimation	17

2.3.4:	Above-ground biomass estimation with optical sensor data	19
2.3.4.1:	Fine spatial-resolution data	19
2.3.4.2:	Medium spatial-resolution data	20
2.3.4.3:	Coarse spatial-resolution data	22
2.4:	Allometric Equations for Biomass Estimation	25
2.5:	Identification of suitable variables from remote sensing data for biomass estimation modeling	27
2.6:	Extraction and selection of potential variables from remote sensing data	28
2.7:	Uncertainty analysis of biomass/carbon model predictions	30
2.9:	Importance of Biomass Estimation	32
CHAPTER THREE		34
3.0:	METHODOLOGY	34
3.1:	The Study Area	34
3.1.1:	Location	34
3.1.2:	Drainage	34
3.1.3:	Climate	34
3.1.4:	Vegetation	34
3.2:	Methods	36
3.2.1:	Study 1: Inventory Field Data Collection	36
3.2.2:	Laying of Sample Plots	36
3.2.3:	Bole Height (H)	38
3.2.4:	Diameter at Breast Height (DBH) and Diameter at top	38
3.2.5:	Volume Estimation	39
3.2.6:	Estimation of Wood Density	39
3.2.7:	Above-Ground Bole Biomass Estimation	40
3.2.8:	Estimation of carbon stock within a sample plot for the study	40
3.2.9:	Preliminary data analysis	41
3.3.0:	Study 2: Satellite Data Collection on Land-use and Land-cover	41
3.3.1:	Satellite Data and Pre-processing	41
3.3.2:	Field Observations/Ground Truthing	41
3.3.3:	Data Acquisition for Forest-Cover Study	41

3.3.4: Extraction of Study Sites	42
3.3.5: Forest-Cover Classification Method	42
3.4.0: Study 3: The integration of AGBB with the best spectral variable	42
3.4.1: Vegetation indices (Vis) used	43
3.5.0: Study 4: Future Projection Analysis	44
3.5.1: The developed transition matrix	45
3.6.0: Evaluation of selected models	46
3.6.1: Validation of selected model	48
3.6.2: Model selection criteria	48
3.6.3: Model adequacy	49
CHAPTER FOUR	51
4.0: RESULTS AND DISCUSSION	51
4.1: Vegetation Structure and Forest Composition	51
4.1.1: Above-Ground Bole Carbon Stocks Estimation from Inventory Field Data	58
4.2: Above-Ground Bole Carbon Stocks Estimation from Remote Sensing Data	64
4.3: the integration of AGBB with the best spectral variable to produce total carbon stock map	69
4.3.1: Estimation of the best model using exponential function techniques	82
4.3.2: Estimation of total carbon stock map	101
4.4: Predict future land cover vegetation map	103
4.4.1: Net change in the study area	103
4.4.2: Evaluation and validation of the selected model	108
CHAPTER FIVE	111
5.0: CONCLUSION AND RECOMMENDATIONS	111
5.1: CONCLUSION	111
5.2: RECOMMENDATIONS	114
5.3: CONTRIBUTION TO KNOWLEDGE	114
REFERENCES	115

LIST OF TABLES

	PAGE
Table 2.1: Summary of techniques for above-ground biomass estimation	18
Table 2.2: Examples of biomass estimation using landsat TM data	21
Table 2.3: Examples of biomass estimation using coarse spatial-resolution data	24
Table 2.4: Potential variables used in a biomass estimation	29
Table 4.1: Summary of Species Composition	52
Table 4.2: Distribution of Tree Species in the IITA Secondary Forest Ecosystem	55
Table 4.3: Tree Volume and AGBCS per Hectare	57
Figure 4.4: Pearson correlation matrix for forest inventory variables	63
Table 4.5: Characteristics of Pleiades imagery used for the mapping of AGBCS	66
Table 4.6: Pearson correlation matrix for inventory field and spectral variables	71
Table 4.7: Descriptive statistics for inventory field and spectral variables	72
Table 4.8: Best estimated model parameters and performance criteria measures for fitted models	81
Table 4.9: Non-Linear equations for the estimation of AGBB	83
Table 4.10: Transition probability matrix of land-use and land-cover change	107
Table 4.11: Descriptive Statistics of data validation	110

LIST OF FIGURES

	PAGE
Figure 3.1: Map of International Institute of Tropical Agriculture (IITA)	35
Figure 3.2: Plot layout with systematic line transect sampling technique	37
Figure 3.3: Methodology flow chart	50
Figure 4.1: Histogram of bole height in IITA secondary forest ecosystem	59
Figure 4.2: Histogram of diameter at breast height in IITA secondary forest ecosystem	60
Figure 4.3: Histogram of wood density of tree species in IITA secondary forest ecosystem	61
Figure 4.4: Map of IITA showing the boundary and sample plots	65
Figure 4.5: Vegetation indices applied to Pleiades image	67
Figure 4.6: Vegetation indices applied to Pleiades images	68
Figure 4.7: Scattered plot showing the relationship between above-ground bole biomass and NDVI	74
Figure 4.8: Scattered plot showing the relationship between above-ground bole biomass and RDVI	75
Figure 4.9: Scattered plot showing the relationship between above-ground bole biomass and DVI	76
Figure 4.10: Scattered plot showing the relationship between above-ground bole biomass and OSAVI	77
Figure 4.11: Scattered plot showing the relationship between above-ground bole biomass and IPVI	78
Figure 4.12: Scatter plot showing best line of fit for RDVI	84
Figure 4.13: Normal probability plot for RDVI	85
Figure 4.14: Residual plot for RDVI	86
Figure 4.15: Scatter plot showing best line of fit for NDVI	87
Figure 4.16: Normal probability plot for NDVI	88
Figure 4.17: Residual plot for NDVI	89
Figure 4.18: Scatter plot showing best line of fit for DVI	91
Figure 4.19: Normal probability plot for DVI	92
Figure 4.20: Residual plot for DVI	93

Figure 4.21: Scatter plot showing best line of fit for OSAVI	94
Figure 4.22: Normal probability plot for OSAVI	95
Figure 4.23: Residual plot for OSAVI	96
Figure 4.24: Scatter plot showing best line of fit for IPVI	98
Figure 4.25: Normal probability plot for IPVI	99
Figure 4.26: Residual plot for IPVI	100
Figure 4.27: Total Carbon Stock Map	102
Figure 4.28: Transition probability map derived from land –use and land –cover maps of 1986 and 2016 for IITA forest reserve	104
Figure 4.29: Projected Land-Cover Map of IITA for 2047	105
Figure 4.30: Validation map showing the study area and sample plots	109

LIST OF APPENDICES

	PAGE
Appendix 1: Analysis of the Forest Inventory Variables	130