UNIVERSITI PUTRA MALAYSIA

ASSESSMENT OF ALOS PALSAR L-BAND SAR FOR ESTIMATION OF ABOVE GROUND BIOMASS IN TROPICAL FORESTS

HAMDAN BIN OMAR

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ASSESSMENT OF ALOS PALSAR L-BAND SAR FOR ESTIMATION OF ABOVE GROUND BIOMASS IN TROPICAL FORESTS

By

HAMDAN BIN OMAR

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

February 2015

DEDICATION

"Praise to Almighty Allah, Alhamdulillah for all He granted"
To my late mother, Almarhumah Che Bidah Che Him (1939 – 2014)
To my late father, Almarhum Omar Abdullah (1933 – 2009)
My beloved Wife, Noor Azura Awang
My beloved daughters, Ayu Zharifa, Ain Zahra, Afia Zarin & Alya Zenia
My late daughter, Noorul Firdausi (24/05/2013)
Family and friends
I went through the toughest time in my life during the study
Thank you for all the supports and encouragements

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the Degree of Doctor of Philosophy

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February 2015

Chair : Lt. Cdr. Assoc. Prof. Mohd Hasmadi Ismail RMNVR, PhD
Faculty : Forestry

Tropical forest biomass is one of the key parameters in addressing issues relating to climate change as it known to store large amount of carbon. Retrieving biomass over large forest areas has been challenging due to the limited data resource, accessibility, and various technical issues. Remote sensing data has been used actively for forest biomass estimation since the last three decades and it is proven to be effective. Although there are issues and arguments raised in the estimation accuracy, research is continuously being carried out. Synthetic aperture radar (SAR) system has its own potential in retrieving biomass but several issues are remaining unaddressed. One of the biggest issues in the system is signal saturation at high level of biomass and this has been identified as the most critical challenge. Studies concentrating on the use of SAR system for biomass retrieval in Malaysia are very limited and literatures on this subject matter are scarce. This study therefore was conducted to address this issue and attempted to produce estimations of aboveground biomass (AGB) on several types of forests in Peninsular Malaysia by using Phased Array L-band SAR (Palsar) on board the Japanese Advanced Land Observing Satellite (Alos). The study was conducted on three forest types, which are lowland dipterocarp, hill dipterocarp, and mangroves. A number of sampling plots have been established in respective forest types. By using these sample plots information, factors contributing to the variation in L-band SAR signal has been identified. Empirical models for the estimation of AGB in these forests have been developed. The level of saturation of AGB has been also determined for each forest types. The study found that the allometric equation used for AGB calculation did affects the estimation and pixel degradation from 25 m to 50 m was found most appropriate for AGB estimation in lowland and dipterocarp forests. While there is no significance difference of backscatter response towards natural and logged forests, the study found that biomass in canopies of trees with dbh $\geq$ 30 cm has better interaction with the backscatter. The inclusion of trees with dbh >10 cm also improved the estimation. The AGB in lowland and hill dipterocarp forests in the whole Peninsular Malaysia, which has an extent of 4,709,806.34 ha, has been estimated at 1,650,819,055 Mg with and root means square error (RMSE) of ±19.32 Mg ha^{-1} (at AGB < 200 Mg ha^{-1}) and ±79.58 Mg ha^{-1} (at AGB > 200 Mg ha^{-1}). The saturation level for these forests was at 200 Mg ha^{-1} at backscatter of -12 dB in HV polarization. The study also established empirical models for mangrove forest. It was estimated that the AGB in the whole mangroves of Peninsular Malaysia, which has an extent of 115,108 ha was at 11,441,795 Mg with RMSE at ±33.90 Mg ha^{-1}. The saturation level for this forest type occurred at around 100 -

150 Mg ha^{-1} at backscatter of -15 dB in HV polarization. The study revealed that the incorporation of texture measures in the images has improved the estimation accuracy as compared to images without texture measure. Overall, the study found that the HV polarization is the best for AGB estimations. The capability of Palsar data in estimating AGB on the forest types is evaluated. The potential, issues and challenges of Palsar data in the retrieval of AGB on these forests are elaborated in details and explained critically in this thesis.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan Ijazah Doktor Falsafah

PENILAIAN TERHADAP ALOS PALSAR SAR BERJALUR-L UNTUK PENGANGGARAN BIOJISIM ATAS TANAH DALAM HUTAN TROPIKA

Oleh

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Februari 2015

Pengerusi : Lt. Kdr. Prof. Madya Mohd Hasmadi Ismail PSSTLDM, PhD
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Biojisim hutan tropika merupakan salah satu parameter utama dalam merungkai isu-isu berkaitan dengan perubahan iklim kerana ia mampu menyimpan karbon dalam jumlah yang besar. Penilaian biojisim bagi kawasan hutan yang luas adalah satu cabaran yang besar antara lain disebabkan oleh kekurangan data, akses yang terhad dan pelbagai isu-isu teknikal. Data penderiaan jauh telah digunakan secara aktif dalam penilaian biojisim semenjak tiga dekad yang lalu dan ia terbukti efektif. Walaupun terdapat beberapa isu dan pertelingkahan dari segi ketepatan anggaran, namun kajian masih tetap dilaksanakan. Sistem radar bukaan sintetik (SAR) mempunyai keupayaan tersendiri dalam penilaian biojisim namun beberapa isu berkaitan masih tidak terungkai. Salah satu isu terbesar dalam sistem tersebut adalah ketepuan isyarat terhadap biojisim yang berkadar tinggi dan ini telah dikenal pasti sebagai cabaran paling kritikal. Kajian yang menumpukan penggunaan sistem SAR untuk penilaian biojisim di Malaysia adalah sangat terhad dan rujukan berkenaan perkara ini juga jarang ditemui. Justeru, kajian ini telah dijalankan untuk merungkai isu tersebut dan cuba untuk menghasilkan anggaran biojisim atas tanah (BAT) di dalam kawasan hutan di Semenanjung Malaysia dengan menggunakan Phased Array L-band SAR (Palsar) yang terdapat pada Japanese Advanced Land Observing Satellite (Alos). Kajian dijalankan terhadap tiga jenis hutan, iaitu hutan dipterokarp pamah, dipterokarp bukit, dan hutan paya laut. Sejumlah bilangan plot sampel telah ditubuhkan di dalam kawasan hutan berkaitan. Dengan menggunakan maklumat plot sampel ini, faktor yang menyumbang kepada perubahan isyarat SAR berjalur L telah dikenal pasti. Beberapa model empirikal telah dihasilkan untuk mengaggar BAT bagi jenis-jenis hutan tersebut. Kadar ketepuan bagi BAT juga telah dutentukan. Kajian mendapati bahawa persamaan alometri yang digunakan untuk pengiraan BAT memainkan peranan dalam hasil anggaran dan degradasi piksel daripada 25 m kepada 50 m adalah paling sesuai untuk penentuan BAT di dalam kawasan hutan dipterokarpa pamah dan bukit. Walaupun tiada perbezaan ketara dalam tindak balas serak balik di antara hutan asli dan hutan dibalak, kajian mendapati bahawa biojisim yang terkandung dalam kanopi pokok bersaiz ≥ 30 cm mempunyai interaksi yang baik dengan serak balik SAR. Penglibatan pokok bersaiz ≥ 10 cm juga menambah baik hasil anggaran. Dianggarkan bahawa BAT yang terkandung di dalam hutan dipterokarpa pamah dan bukit di seluruh Semenanjung Malaysia ialah 1,650,819,055 Mg dengan purata ralat ±19.32 Mg ha^{-1} (pada BAT < 200 Mg ha^{-1}) dan ±79.58 Mg ha^{-1} (pada BAT > 200 Mg ha^{-1}). Kadar ketepuan untuk kedua-dua jenis hutan ini adalah 200 Mg ha^{-1} berlaku pada serak balik -12 dB dalam polarisasi HV. Kajian

juga telah menghasilkan model empirical untuk hutan paya laut. Telah dianggarkan bahawa BAT yang terkandung di dalam hutan paya laut di seluruh Semenanjung Malaysia adalah 11,441,795 Mg dengan purata ralat ±33.90 Mg ha^{-1}. Ketepuan untuk jenis hutan ini berlaku pada kadar sekitar 100 – 150 Mg ha^{-1} pada serak balik -15 dB dalam polarisasi HV. Kajian mendedahkan bahawa penglibatan ukuran tekstur dalam imej telah meningkatkan kemampuan penilaian berbanding imej tanpa ukuran tekstur. Secara umum didapati bahawa polarisasi HV merupakan yang terbaik untuk menganggar BAT hutan. Keupayaan data Palsar dalam penganggaran BAT bagi kesemua jenis hutan tersebut telah dinilai. Potensi, isu serta cabaran dalam penganggaran BAT dalam hutan-hutan tersebut menggunakan data Palsar diulas secara teperinci dan dijelaskan secara kritikal di dalam tesis ini.

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I certify that a Thesis Examination Committee has met on 17 February 2015 to conduct the final examination of Hamdan bin Omar on his thesis entitled "Assessment of Alos Palsar L-Band Sar for Estimation of Above Ground Biomass in Tropical Forests" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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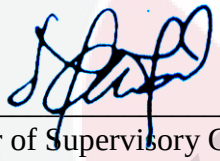
Signature: 
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7.8 Interval plot indicates the distribution of AGB for each strata extracted from the estimation, with the figures denote the mean distribution. The horizontal line indicates the overall mean of the distribution. 115

LIST OF ABBREVIATIONS

AGB	Aboveground biomass
ALOS	Advanced Land Observing Satellite
ANOVA	Analysis of Variance
AVNIR	Advanced Visible and near-infrared radiometer
CF	Calibration factor
COP	Committee of the Parties
CTFS	Center for Tropical Forest Sciences
DBH/dbh	Diameter at breast height
DEM	Digital Elevation Model
DN	Digital Number
DR	Direct remote sensing
DTC	Dungun Timber Complex
ECV	Essential Climate Variable
EOL	End of Life
EORC	Earth Observation Research Centre, Japan
ERS	Erath Resources Satellite
FBD	Fine-beam dual
FNF	Forest-non-forest
FRIM	Forest Research Institute Malaysia
GIS	Geographic Information System
GPS	Global Positioning System
HH	Horizontal-horizontal
HV	Horizontal-vertical
K&C	Kyoto & Carbon Initiative
LiDAR	Light Detection and Ranging
NDVI	Normalised Difference Vegetation Index
RSO	Rectified Skew Orthomorphic
SAR	Synthetic Aperture Radar
FDPM	Forestry Department Peninsular Malaysia
FMU	Forest Management Unit
FRIM	Forest Research Institute Malaysia
GIS	Geographic Information System
GLCM	Gray-level co-occurrence matrix
GHG	Greenhouse House Gases
ITTO	International Tropical Timber Organization
IPCC	Intergovernmental Panel on Climate Change
JAXA	Japan Aerospace Exploration Agency
JERS	Japan Earth Resources Satellite
JPL	Jet Propulsion Laboratory, USA
KPKKT	Kumpulan Pengurusan Kayu-Kayan Terengganu
LiDAR	Light Detection and Ranging
LULUCF	Land Use Land Use Change and Forestry
LUT	Lookup table
MRV	Measurement, Reporting and Verification
NDFI	Normalized difference fraction index
NFI	National Forest Inventory
NGO	Non-Governmental Organization
NRCS	Normalized Radar Cross Section

NRE	Ministry of Natural Resources and Environment
PALSAR	Phase Array Type L-Band SAR
PRF	Permanent Reserved Forests
PRISM	Panchromatic radiometer with high resolution
R^2	Coefficient of determination
REDD	Reducing emissions from deforestation and forest degradation
REDD+	Reducing emissions from deforestation and forest degradation and forest conservations
RESTEC	Remote Sensing Technology Centre, Japan
RIL	Reduced Impact Logging
RMSE	Root mean square error
SAR	Synthetic Aperture Radar
SFM	Sustainable Forest Management
SM	Stratify and multiply
SMS	Selective Management System
SRTM	Shuttle Radar Topography Mission
SVS	Stand visualization system
UAV	Unmanned Aerial Vehicle
UNFCCC	United Nations Framework on Climate Change
YEAL	Year Elapsed After Logging
VH	Vertical-horizontal
VJR	Virgin Jungle Reserve
VV	Vertical-vertical

CHAPTER 1

INTRODUCTION

1.1 General background

Malaysia is one of the highest percentages of forested land among tropical countries with 19.5 million hectare of its land covered with natural forest. Out of this, about 10.37 million hectare is reserved for production purposes. It means that more than 50% of the forest cover is managed principally for harvesting. It was estimated that more than 40% of the world's tropical forest cover is in secondary state where logging were take place (Brown and Lugo, 1990). Consequently, the timber and timber products industry are very important and play a significant role not only in Malaysia's economy but also the countries that have tropical forest. As such, Malaysia has accorded the management of the forests on a sustainable basis a high priority.

All inland production forests in Malaysia are currently being managed under the Selective Management System (SMS). The system allows trees to be removed based on a flexible cutting regime where all trees above a prescribed cutting limit are removed. The determination of the cutting limit takes into consideration the existing growing stock, its increment and mortality, as well as a specified future crop at the end of a 30-year cutting cycle. However, there are concerns that the assumptions for the above factors in the implementation of SMS are not being met consistently and thus affecting the productivity of the residual stands. Therefor instead of deforestations that occur mainly from land conversion, which is more permanent in terms of land usage, forest degradation is also one of the great concerns as it also reduces the living biomass.

It was estimated that the carbon loss for Peninsular Malaysia between 1971 and 1981 was 26.8 Mt $year^{-1}$ (Houghton, 1991). However Hall and Uhlig, (1991) estimated that the carbon emission in 1990 in response to landuse change for the whole of Malaysia was 25.2 Mt, which was very close to the average of 26.89 Mt $year^{-1}$ between 1981 and 1990 (Henson, 2005). These estimates were performed by using secondary information but the emphasis was paid for forestry sector. From these scenario cases, logging was likely the main cause of biomass degradation in Malaysian forests. However, there is a gap in information pertaining to rates of deforestation and forest degradation at the national level in the past and present.

As a result, biomass was identified as an Essential Climate Variable (ECV) by the United Nations Framework Convention on Climate Change (UNFCCC), which is needed to reduce uncertainties and to fill the knowledge gaps of the climate system (Sessa and Dolman, 2008). Further strong impetus to improve methods for measuring global biomass comes from the Reduction of Emissions due to

Deforestation and Forest Degradation (REDD) mechanism, which was introduced in the UNFCCC Committee of the Parties (COP-13) Bali Action Plan. REDD is dedicated to the developing countries around the world including Malaysia, where there is expected to be high deforestation rate. Its implementation relies fundamentally on systems to monitor carbon emissions due to loss of biomass from deforestation and forest degradation (Le Toan et al. 2011). Besides measuring the biomass, there is also an increasing recognition of the protective roles of the forests such as the conservation of biodiversity, protection of soil and water resources and stabilizing the climate. These concerns finally brought the "plus" in REDD+. In Malaysia the REDD+ mechanism under the UNFCCC currently being discussed, presents an incentive that may encourage implementation of improved management practices to reduce forest degradation.

One of the elements of REDD+ is the development of a reference level before the status of current storage of biomass in the forests can be compared. This will be followed by monitoring (and/or measuring), reporting and verification (MRV) processes in order to make REDD+ is implemented. Therefore, accurate methods for estimating aboveground biomass (AGB) in tropical rainforest are needed assess the baseline for nations' carbon storage on the REDD+ scheme (Gibbs et al. 2007; Angelsen, 2008). This kind of forest also needs for new research utilizing new technology and current trend of forest management (Jong et al. 2001; Wright 2010). National REDD+ Strategy is currently considering the MRV methodology during proceeding implementations steps. Other countries are also at about the similar status. Since then, many studies have been carried out to measure forest biomass at various levels, i.e. pilot sites, sub-national and national.

Remote sensing has been recognized as one of the primary spatial inputs for this process (Gibbs et al. 2007; Angelsen, 2008; Angelsen et al. 2009). Satellite remote sensing technologies are currently widely tested and suggested as a tool in REDD+ MRV. Along with scientific programs and field tests, there is also a debate as to the overall feasibility and cost-benefit ratio of remote sensing approaches, depending on the wide range of ecosystem and land use conditions as well as the range of approaches to carbon credit accounting (Holmgren, 2008).

In many parts of the world, especially in tropical region, the frequent cloud conditions often restrain the acquisition of high-quality remotely sensed data by optical sensors. The acquisition of cloud-free, wall-to-wall optical satellite images in tropical countries is almost impossible (Asner, 2001). Thus, synthetic aperture radar (SAR) data become the only feasible way of acquiring remotely sensed data within a given timeframe because the SAR systems are independent of cloud coverage, weather and light conditions. Due to this unique feature compared with optical sensor data, the SAR data have been used extensively in many fields, including forest-cover identification and mapping, discrimination of forest from other land covers and forest biomass estimation.

Reviews on the use of remote sensing systems for forest biomass retrieval can be found in several reviews such as Lu, (2006), Gibbs et al. (2007), Goetz et al. (2009), Goetz and Dubayah, (2011), and Vashum and Jayakumar, (2012). More specific review on the progress and recent advancements in SAR systems for biomass estimation is found in Shi et al. (2012) and Le Toan et al. (2011), respectively. Different radar data have their own characteristics in relating to forest stand parameters. For example, radar backscatter in the P and L bands is highly correlated with major forest parameters, such as tree age, tree height, tree size, basal area, and biomass. Previous research has indicated that long-wavelength radar data have the advantage in AGB estimation for complex forest stand structure. Specifically, SAR L-band data have proven to be valuable for biomass estimation, particularly AGB (Quinones and Hoekman, 2004; Hamdan et al. 2011; Le Toan, 2011).

While L-band SAR system offers some advantages in estimating forest biomass, the saturation problem is common in radar data. It means that the sensitivity of the returned signal (i.e. backscatter intensity) will cease at certain threshold of biomass. This has been identified as a critical challenge in the last decade (Lu, 2006). The saturation levels depend on the polarization and the structure of the forests such as the size, density and distribution of the branches and leaves (Imhoff, 1995; Guo et al. 2009). However, the sensitivity of the backscatter and the saturation level seem to be rather site dependent, since forest structure influences the relative contribution of the scattering mechanism (Lucas et al. 2010). Some SAR systems have the capability to send and receive energy with different polarizations (i.e. HH, HV, VH and VV). Since Phased Array L-band SAR (Palsar) on board the Japanese Advanced Land Observing Satellite (Alos) has this capability, it is expected that the L-band Palsar could promise better potentials in assessing forest biomass in tropical ecosystem. Moreover, the logged forest characteristics which typically contain lower biomass could make the study more feasible.

These are issues and concerns that this study attempts to address. Since Alos Palsar ended it mission in 2011, there will no similar satellite in the space until the Alos-2 that was launched recently in May 2014, replaced the mission. This study provides baseline in biomass assessment by using L-band SAR system, with special reference to Palsar in Peninsular Malaysia's forest ecosystems, particularly in dipterocarp and mangroves.

1.2 Problem statements

There are several issues that can be related to the biomass estimations using remotely sensed data in Malaysia's forests. These issues can be generalized into three major groups, which are (i) the natural conditions of the forest that are native to Malaysia, (ii) the forest management system being practiced, and (iii) the technical issues related to the remote sensing system being used. These issues are concisely described as follows, which focuses on the use of L-band SAR system.

Previous studies demonstrated that the L-band polarimetry tend to saturate at certain level of biomass hence limiting the accuracy of estimates. However, the saturation level varies with the type and structure of the forest. It was demonstrated that the sensitivity of polarimetric SAR is depending on the structure, density and the tree elements (i.e. trunk/stem, branches and leaves) of the forests (Imhoff, 1995). The accuracy also mostly influenced by the tree density, soil surface roughness, soil moisture, tree sizes, and the layering effects of the SAR itself (Quinones and Hoekman, 2004). An experiment has been made to assess how the tree size influence the backscattering intensity and found that only trees with diameter at breast height (DBH) larger than 15 cm (that dominating the higher canopies) gave the best response to backscatter in HV polarization of L-band Palsar (Hamdan et al. 2013). Other factors such as orientation of the forest, polarimetry, incidence angle, and crown structure also play important role in the estimated biomass (Watanabe et al. 2006; Guo et al. 2009). However, these studies were conducted in the ecosystem and forest types where they are different from Malaysia's conditions. Different types of forest would have different backscattering effects and thus differ in sensitivity.

In Malaysia there are limited studies on the applications of SAR for estimating biomass. Out of many studies conducted worldwide, as summarized in Chapter 2, very few have been done in Malaysia (viz. Morel et al. 2011; Morel et al. 2012; Hamdan et al. 2011). This indicates that the potential, limitations and advances of L-band SAR in estimating tropical forest in Malaysia are not extensively explored. Methods to applying this SAR system are also scarcely exploited.

Malaysia is currently practicing Sustainable Forest Management (SFM) and within this system Selective Management System (SMS) is applied in logging. This system which has been practiced since 1978 was designed to be implemented in lowland and hill dipterocarp forest. It is to ensure optimum timber harvesting with an economic cuts while maintaining the sustainability of forest and minimize the cost for forest development (Norizah et al. 2011). However, forest degradation in terms of carbon stocks is occurring in production forests as a result of logging operations (Mazzei et al. 2010). Logging operations in Malaysia in the past have also been reported to be damaging (Brown and Lugo, 1990; Huth and Ditzer, 2001; Huth et al. 2004; Huth et al. 2005; Okuda et al. 2003; Mohd Hasmadi and Norizah, 2010), but of late, significant improvements have been made (e.g. Norizah et al. 2012). While at least about 10.37 million hectares of production forest in reserved areas in Malaysia, the biomass in this region is still uncertain so as to the remaining natural virgin forests. Therefore the extent of current forest degradation and dynamics of the carbon stocks (i.e. living biomass) need to be further studied as it is still not well understood in Malaysia.

The allometric equations used to estimate biomass will also affect the results at plot level estimation and thus alter the sensitivity of the SAR backscattering. It is well known that the large number of published allometric equations can give substantial variation in stand-level biomass estimates (e.g. Araújo et al. 1999; Chambers et al. 2001 and Chave et al. 2005). However, it is not known whether the observed patterns of biomass change are sensitive to the equation used to estimate biomass.

An experimental study hence required to assess these variation in relation to the sensitivity of the L-band SAR backscatter.

This study is conducted therefore to address all the issues and problems arising from the technical configurations of the polarimetric L-band SAR as well as the circumstances of forests in Malaysia. The study allows all possible parameters that can be generated from both imagery and forestry aspects to be tested and experimented. It is in line with the effort to produce reliable method and to make L-band SAR system viable for estimating biomass of forest in Malaysia.

1.3 Research questions

Having all issues and problems stated above the following research questions are asked:

1. What are the most significant factors that contribute to the variation of the L-band SAR backscatters on the tropical forest biomass, and why?
2. How much biomass in the tropical forests that can be retrieved accurately by L-band SAR backscatter and if it saturates, at what level of biomass?
3. Do the succession levels and the logging practices of the forest affect the backscatter?
4. What is the best method that can be employed to estimate AGB in tropical forest ecosystems in Malaysia?

1.4 Aim and objectives

The primary objective of this study is to evaluate the capability of Polarimetric L-band Alos Palsar data in estimating AGB on the forests of Peninsular Malaysia, mainly lowland dipterocarp, hill dipterocarp and mangroves. The specific objectives are as follows:

i. To identify factors affecting L-band Alos Palsar backscatter on tropical forest biomass.
ii. To determine L-band saturation level for aboveground biomass of dipterocarp forests.
iii. To estimate biomass of mangrove forest by using L-band Alos Palsar.
iv. To develop empirical model for estimating aboveground biomass in logged forest using L-band SAR.
v. To compare direct remote sensing (DR) and stratify and multiply (SM) methods for estimating biomass in logged tropical forest using Palsar data and GIS.

1.5 Scopes of the study

This study was conducted to examine the capability of L-band Palsar in estimating biomass of tropical forest. However several confinements were defined to provide the scopes of the study. Some parameters were considered and some were excluded in the experiment. The main carbon pools in tropical forest ecosystems are the living biomass of trees and understory vegetation and the dead mass litter, woody debris and soil organic matter. The carbon stored in the living biomass of trees is typically the largest pool and the most directly impacted by deforestation and degradation (Gibbs et al. 2007). Thus, estimating AGB is the most critical step in quantifying carbon stocks and fluxes from tropical forests, hence the focus of this study. The other carbon pools were not included in this study. Measurement protocols for other carbon pools are described elsewhere (e.g. Brown and Masera, 2003; Pearson et al. 2005; IPCC, 2006).

Tropical forests are principally ecosystems that reside on the tropical belt of the Earth. However, the study focused and referred to only tropical forest in Malaysia, which was more specific to Peninsular Malaysia. In Peninsular Malaysia, more than 50% of its forests is reserved for productions where logging and wood extraction occur rapidly. Most of the forests occupy lowland and hill dipterocarp forests (of elevation < 750 m a.s.l). Therefore this study concentrated only in the lowland and hill dipterocarp forests, regardless the logging practices being adapted. Mangrove forest is also one of the ecosystems occurs in Peninsular Malaysia and it is also included in this study. The other forest types such as, upper hill dipterocarp, montane, and peat swamp forests were not included in the study.

Many allometric equations were developed for different forests ecosystem in the world and can be found in the literature. Allometric equations that were developed earlier, appropriate for tropical forests (i.e. Kato et al. 1978; Chave et al. 2005; Basuki et al. 2009; Kenzo et al. 2009) were adapted and used to estimate biomass in this study. No new allometric equation has been developed for this particular study.

Many space borne SAR systems available in various wavelengths (L-, X-, and C-bands) and polarizations (HH, HV, VH, and VV) that provide options for biomass estimation. However, only some are adequate to address issues on biomass estimation in tropical forest ecosystems. This study concentrated only on the L-band SAR system, specifically Alos Palsar L-band data. While there are evidences that longer wavelength of P-band could produce better estimates, its applications were found limited to small scale projects that use aerial-based platform or unmanned aerial vehicle (UAV) systems and too expensive to be operationalize at large scales (Dobson et al. 1992; Santos et al. 2003; Le Toan et al. 2011).

1.6 Significances of the study

Currently there are no study that use L-band SAR for biomass estimation in tropical forests of Malaysia. A number of gaps exist pertaining its applications including the technical issues on backscattering properties, stand and canopy structures of the forest and L-band SAR response characteristics towards biomass. These situations are yet to discover as they are not well understood. This study was therefore conducted to fill these gaps and to understand better the sensitivity and capability of L-band SAR in estimating tropical biomass in Malaysia. It would contribute to enhancing the methodology that could be useful for biomass and carbon stock monitoring of major forests in Peninsular Malaysia. This is one of the primary elements of REDD+ MRV and its implementation in Malaysia.

Provided that the L-band SAR data are continuously available, the outcomes from this study not only useful for rapid assessments of forest biomass but also contribute to the forest valuation, in terms of non-timber goods and services. The launch of Alos-2, which carrying Palsar-2 that has been taking place in orbit recently will definitely complement the continuous availability of L-band SAR data. It will introduce an alternative to support the national forest inventory (NFI) processes in the near future, which include carbon stock accounting as one of its compulsory outputs. Finally, the operational use of remote sensing system, especially L-band SAR will introduce more efficient ways in managing forests in line with the currently practiced SFM. The study, which focused on the use of L-band Palsar data for biomass assessments on various types of forests in Peninsular Malaysia is the novelty of the thesis.

1.7 Research design

The study is designed and outlined to meet the primary aim and the specific objectives of the study. Figure 1.1 shows the framework of the study. It shows the connectivity from the data used, parameters and processes involved in the study to the results, represented by chapters corresponding to the objectives of the study.

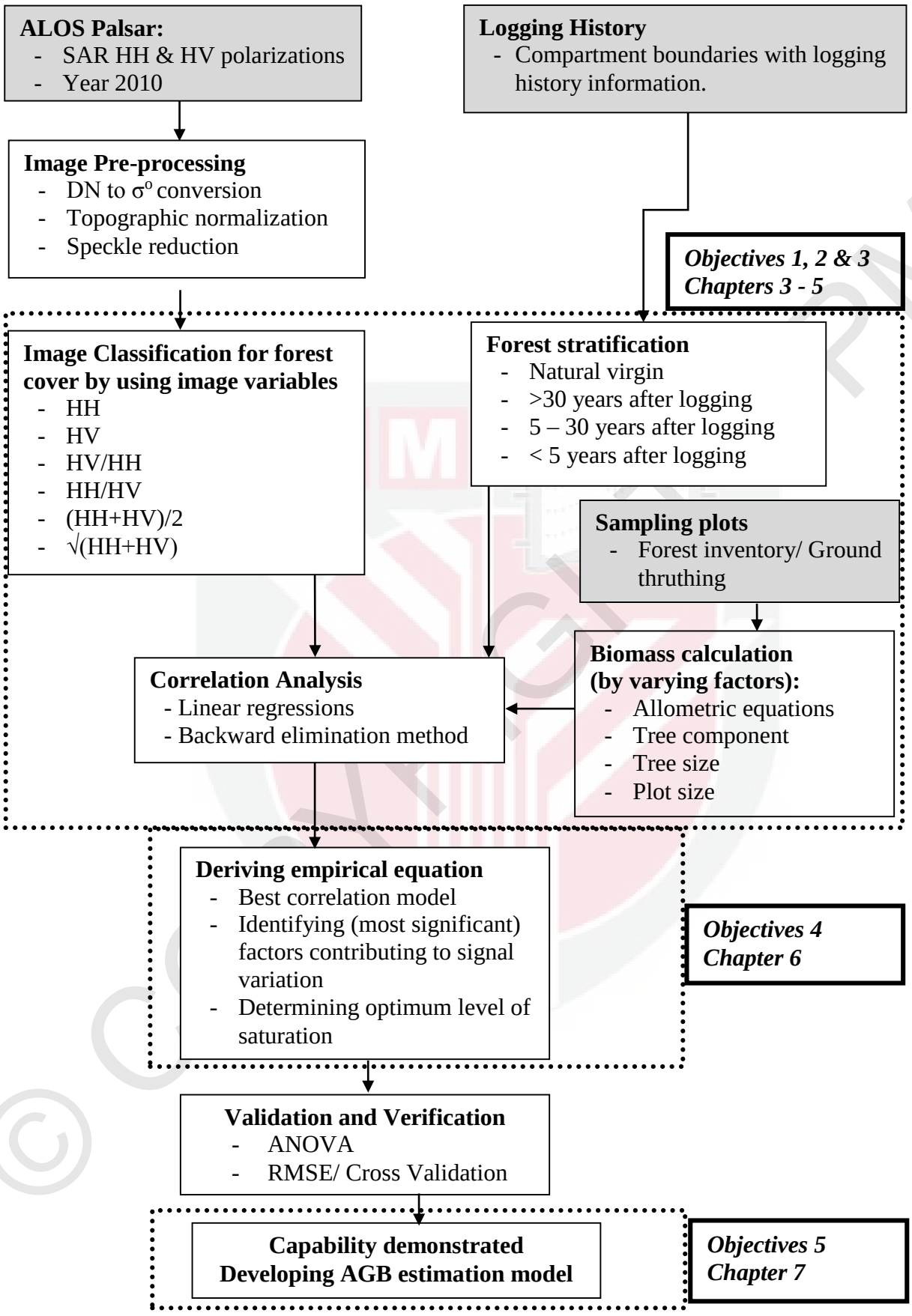

Figure 1.1. Framework of the study

1.8 Organization of the thesis

The thesis was organized as follows:

Chapter 1 presents an overview of the entire study. It comprises the general background, problem statements, research questions, aim and objectives, scopes of the study, significances of the study, research design and organization of the thesis. The first chapter highlights the needs for continuous research in forest biomass by using spatial information systems toward sustainable forest management and global climate balance.

Chapter 2 reviews the issues, challenges and previous studies that have been conducted worldwide. From the review, research gaps have been identified and the design of study was constructed based on the findings. Studies that are closely related to this study are summarised and included in this chapter and arranged in the form of a review paper. The paper was published in journal of 'The Malaysian Forester'.

Chapters 3 to 7 are organized as a series of article papers related to the objectives and scopes of the study. All the papers have been submitted to reputable journals and some were published. Others are either accepted for publication or still under reviews. Because each of these article papers is designed to stand alone, some redundancy exists. The articles are as follow:

Chapter	Title	Journal	Status during thesis submission
3	Factors affecting L-band Alos Palsar backscatter on tropical forest biomass	Global Journal of Science Frontier Research (D) 14(3): 51 - 63	Published in May 2014
4	Determining L-band saturation level for aboveground biomass assessment of dipterocarp forests in Peninsular Malaysia	Journal of Tropical Forest Science 27(3): 1-12	Published in July 2015
5	L-band Alos Palsar for biomass estimation of Matang Mangroves, Malaysia	Remote Sensing of Environment 155: 69 - 78	Published in May 2014
6	Development of empirical models for estimating aboveground biomass in logged forest using L-band SAR	Jurnal Teknologi	Accepted for publication
7	Estimating Biomass in Logged Tropical Forest Using L-Band SAR (PALSAR) Data and GIS	Sains Malaysiana	Accepted for publication in June 2015

Finally, Chapter 8 summarizes the overall findings and concludes the study. Recommendations on future work of potential use of L-band Alos Palsar and other similar SAR systems in estimating biomass of forests in Malaysia are also included.

REFERENCES

Abdul Rashid, A.M., Shamsudin, I., Ismail, P. & Fletcher, S.C. (2009). The Role of FRIM in Addressing Climate-Change Issues. *Research Pamphlet* No. 128, Forest Research Institute Malaysia, Kepong.

Alongi, D.M. (2002). Present state and future of the world's mangrove forests. *Environmental Conservation*, 29: 331 – 349.

Amini, J. & Sumantyo, J.T.S. (2009). Employing a method on SAR and optical images for forest biomass estimation. *IEEE Transaction on Geoscience and Remote Sensing* 47(12): 4020 – 4026.

Angelsen, A., Brown, S., Loisel, C., Peskett, C., Streck, C. & Zarin, D. (2009). Reducing emission from deforestation and degradation (REDD): An options assessment report. A report prepared for the government of Norway. Meridian Institute. pp. 100.

Anonymous. 2010. *The Economic of Ecosystems and Biodiversity: Ecological and Economic Foundations*. Earthscan, London and Washington.

Anys, H., Bannari, A., He, D.C. & Morin, D. (1994). *Texture analysis for the mapping of urban areas using airborne MEIS-II images*. Proceedings of the First International Airborne Remote Sensing Conference and Exhibition, Strasbourg, France, Vol. 3: pp. 231-245.

Araújo, T.M., Higuchi, N. & Carvalho, J.A. (1999). Comparison of formulae for biomass content determination in a tropical rain forest site in the state of Pará, Brazil. *Forest Ecology and Management*, 117: 43 – 52.

Asner, G.P. (2001). Cloud cover in Landsat observations of the Brazilian Amazon. *International Journal of Remote Sensing*, 22: 3855 – 3862.

Austin, J.M., Mackey, B.G. & Van Niel, K.P. (2003). Estimating forest biomass using satellite radar: an exploratory study in a temperate Australian Eucalyptus forest. *Forest Ecology and Management*, 176: 575 – 583.

Azhar, M. & Shah, N.M. (2003). A Working Plan for the Matang Mangrove Forest Reserve, Perak: The Third 10-Year Period (2000–2009) of the Second Rotation. Perak State Forestry Department.

Baccini, A., Laporte, N., Goetz, S.J., Sun, M. & Dong, H. (2008). A first map of tropical Africa's above-ground biomass derived from satellite imagery. *Environmental Research Letter*, 3: 9 pp.

Baccini, A., Goetz, S.J., Walker, W.S., Laporte, N.T., Sun, M., Sulla, D., Menashe, Hackler, J., Beck, P.S.A., Dubayah, R., Friedl, M.A., Samanta, S. & Houghton, R.A. (2012). Estimated carbon dioxide emissions from tropical

deforestation improved by carbon-density maps. *Nature Climate Change*, 2: 182–185.

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

Beaudoin, A.L. (1994). Retrieval of forest biomass from SAR data. *International Journal of Remote Sensing*, 15: 2777–2796.

Brown, S. & Lugo, A.E. (1990). Tropical secondary forests. *Journal of Tropical Ecology*, 6 (1): 1 – 32.

Brown, S. & Lugo, A.E. (1984). Biomass of tropical forests: a new estimate based on forest. *Science*, 223: 1290–1293.

Brown, S. & Masera, O. (2003). Supplementary methods and good practice guidance arising from the Kyoto Protocol, section 4.3 LULUCF projects.Good Practice Guidance For Land Use, Land-Use Change and Forestry, Intergovernmental Panel on Climate Change National Greenhouse Gas Inventories Programme. In Penman, J. et al. (Ed.) (Kanagawa: Institute for Global Environmental Strategies (IGES)) pp 4.89–4.120.

Brown, S., Gillespie, A.J.R. & Lugo, A.E. (1991). Biomass of tropical forests of south and Southeast Asia. *Canadian Journal of Forest Research*, 21: 111-117.

Burgin, M., Clewley, D., Lucas, R., & Moghaddam, M. (2011). A Generalized Radar BackscatteringModel Based on Wave Theory for Multilayer Multispecies Vegetation. *IEEE Transactions on Geoscience and Remote Sensing*, 49: 4832 – 4845.

Carreiras, J.M.B, Vasconcelos, M.J. & Lucas, R. (2012). Understanding the relationship between aboveground biomass and ALOS PALSAR data in the forests of Guinea-Bissau (West Africa). *Remote Sensing of Environment* 121: 426–442.

Cartus, O., Santoro, M. & Kellndorfer, J. (2012). Mapping forest aboveground biomass in the Northeastern United States with ALOS PALSAR dual-polarization L-band. *Remote Sensing of Environment* 124: 466–478.

Chambers, J.Q., dos Santos, J., Ribeiro, R.J. & Higuchi, N. (2001). Tree damage, allometric relationships, and above-ground net primary production in a tropical forest. *Forest Ecology and Management*, 152: 73-84.

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., Rie´Ra, B. & Yamakura, T. (2005). Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Ecosystem Ecology*, 145: 87–99.

Chave, J., Condit, R., Aguilar, S., Hernandez, A., Lao, S. & Perez, R. (2004). Error propagation and scaling for tropical forest biomass estimates. *Philosophical Transactions of the Royal Society of London*, Series B 359: 409 – 420.

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

Chave J., Maxime R.E., Alberto E.B. & other co-authors (2014). Improved allometric models to estimate the aboveground biomass of tropical trees. *Global Change Biology*. gcb.12629: 14p.

Chen, E., Li, Z., Ling, F., Lu, Y., He, Q. & Fan, F. (2009). *Forest volume density estimation capability of ALOS PALSAR data over hilly region*. Proceedings of the International Workshop on Science and Applications of SAR Polarimetry and Polarimetric Interferometry, PollinSAR. 26-30 January 2009, Frascati, Italy.

Chenli, W., Zheng, N., Xiaoping, G., Zhixing, G. & Pifu, C. (2005). *Tropical Forest Plantation Biomass Estimation Using RADARSAT-SAR and TM Data of South China*. In Liangpei, Z., Jianqing, Z. & Mingsheng, L. (Ed.) Vol. 6043: 61-69. Proceedings of the Fourth International Symposium on Multispectral Image Processing and Pattern Recognition (MIPPR) 31 October – 2 November, 2005, Wuhan.

Clewley, D., Lucas, R., Accad, A., Armston, J., Bowen, M., Dwyer, J., Pollock, S., Bunting, P., McAlpine, C., Eyre, T., Kelly, A., Carreiras, J. & Moghaddam, M. (2012). An Approach to Mapping Forest Growth Stages in Queensland, Australia through Integration of ALOS PALSAR and Landsat Sensor Data. *Remote Sensing*, 4: 2236-2255.

Clough, B.F. & Scott, K. (1989). Allometric relationships for estimating aboveground biomass in six mangrove species. *Forest Ecology and Management*, 27: 117–127.

Condit, R. (2008). *Methods for estimating aboveground biomass of forest and replacement vegetation in the tropics*. Center for Tropical Forest Science Research Manual. pp 73.

Daniel, C.D., Kauffman, J.B., Murdiyarso, D., Kurnianto, S., Stidham, M. & Kanninen, M. (2011). Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience Letters*, NGEO1123. 5 pp.

DeFries, R., Achard, F., Brown, S., Herold, M., Murdiyarso, D., Schmlamadinger, B. & deSouza, C. (2007). Earth observations for estimating greenhouse gas emissions from deforestation in developing countries. *Environmental Science Policy*, 10: 385–394.

Dobson, M.C., Ulaby, F.T., Le Toan, T. et al. (1992). Dependence of radar backscatter on coniferous forest biomass. *IEEE Transaction on Geoscience and Remote Sensing*, 30(2): 412 – 415.

Englhart, S., Keuck, V., & Siegert, F. (2011). Aboveground biomass retrieval in tropical forests – The potential of combined X- and L-band SAR data use. *Remote Sensing of Environment*, 115: 1260-1271.

Ewel, K.C., Twilley, R.R. & Ong, J.E. (1998). Different Kinds of Mangrove Forests Provide Different Goods and Services. *Global Ecology and Biogeography Letters*, 7: 83 – 94.

FAO. 1973. The timber species of the mixed dipterocarp forests of Sarawak and their distribution. A study prepared jointly the Forest Department of Sarawak and the Forestry and Forest Industries Development Project. *FAO Working Paper* 21. FAO, Rome.

FAO. 2005. *State of the World's Forest*. Food and Agriculture Organization of the United Nations, Rome.

FAO. 2007. *The World's Mangrove 1980-2005*. FAO Forestry Paper 153. Food and Agriculture Organization of the United Nations, Rome.

Foody, G.M., Boyd, D.S. & Cutler, M.E. (2003). Predictive relations of tropical forest biomass from Landsat TM data and their transferability between regions. *Remote Sensing of Environment*, 85: 463 – 74.

Forestry Department Peninsular Malaysia (FDPM). (2011). *Annual Report 2010*. Forestry Department Peninsular Malaysia, Kuala Lumpur.

Franklin, S.E., Hall, R.J., Moskal, L.M., Maudie, A.J. & Lavigne, M.B. (2000). Incorporating Texture into Classification of Forest Species Composition from Airborne Multispectral Images. *International Journal of Remote Sensing*, 21(1): 61 – 79.

Fromard, F., Puig, H., Mougin, E., Marty, G., Betoulle, J.L. & Cadamuro, L. (1998). Structure, above-ground biomass and dynamics of mangrove ecosystems: New data from French Guiana. *Oecologia*, 115(1/2): 39 – 53.

Ghasemi, N., Mahmod Reza, S. & Ali, M. (2011). A review on biomass estimation methods using synthetic aperture radar data. *International Journal of Geomatics and Geosciences*, 1(4): 776 – 788.

Gibbs, H. K., Brown, S, O'Niles, J. & Foley, J.A. (2007). Monitoring and estimating tropical forest carbon stocks: making REDD a reality. *Environmental Research Letter*, 2: 13 pp.

Gillespie, A.J.R., Brown, S., & Lugo, A.E. (1992). Tropical forest biomass estimation from truncate extend tables. *Forest Ecology and Management*, 48: 69 – 87.

Giri, C., Ochieng, E., Tieszen, L.L., Zhu, Z., Singh, A., Loveland, T., Masek, J. & Duke, N. (2011). Status and distribution of mangrove forests of the world using earth observation satellite data. *Global Ecology and Biogeography*, 20: 154 – 163.

Goetz, S., Baccini, A., Laporte, N.T., Johns, T., Walker, W., Kellndorfer, J., Houghton, R.A. & Sun, M. (2009). Mapping and monitoring carbon stocks with satellite observations: a comparison of methods. *Carbon Balance and Management*, 4(2): 1 – 7.

Goetz, S. & Dubayah, R. (2011). Advances in remote sensing technology and implications for measuring and monitoring forest carbon stocks and change. *Carbon Management*, 2(3): 231 – 244.

Goh, J.Y, Miettinen, J., Chia, A.S., Chew, P.T. & Liew, S.C. (2013). Biomass Estimation in Humid Tropical Forest Using a Combination of ALOS PALSAR and Spot 5 Satellite Imagery. *Asian Journal of Geoinformatics*, 13(4): 1 – 10.

Gong, W.K. & Ong, J.E. (1990). Plant biomass and nutrient flux in a managed mangrove forest in Malaysia. *Estuarine, Coastal and Shelf Science*, 31 (5): 519 – 530.

Guo, Z., Ni, W. & Sun, G. (2009). Analysis of the effect of crown structure changes on backscattering coefficient using modelling and SAR data. *IEEE Transaction on Geosciences and Remote Sensing*, 4: 386 – 389.

Hall, C.A.S. & Uhlig. J. (1991). Refining estimates of carbon released from tropical land-use change. *Canadian Journal of Forest Research*, 21: 118 – 131.

Hamdan, O., Khairunnisa, M.R., Ammar, A.A., Mohd Hasmadi, I. & Khali Aziz, H. (2013). Mangrove carbon stock assessment by optical satellite imagery. *Journal of Tropical Forest Science*, 25(4): 554 – 565.

Hamdan, O., Khali Aziz, H., & Mohd Hasmadi, I. (2012). *The use of polarized L-band Alos Palsar for identifying forest cover in Peninsular Malaysia*. Proceedings of the 33rd Asian Conference on Remote Sensing, 1: 263-272.

Hamdan, O., Khali Aziz, H., Shamsudin, I. & Raja Barizan, R.S. (2012). *Status of mangroves in Peninsular Malaysia*. Forest Research Institute Malaysia. 153 pp.

Hamdan, O., Mohd Hasmadi, I. & Khali Aziz, H. (2014). Combination of SPOT-5 and Alos Palsar images in estimating aboveground biomass of lowland Dipterocarp forest. *IOP Conference Series: Earth and Environmental Science* 18: 012016. 6 pp.

Hamdan, O., Nur Laila, C.M., Khali Aziz, H., & Mohd Hasmadi, I. (2013a). *L-band synthetic aperture radar (SAR) response to the tropical forest stands for carbon stock assessment*. In Ibrahim et al. (Ed.). AIP Conference Proceedings, 1528: 76 – 81.

Hamdan, O., Mohd Hasmadi, I., Khali Aziz, H. & Mohd Hakimi, A.H. (2013b). *Methods for estimating biomass in the tropical forest using remotely sensed data*. In Lai et al. (Ed.) Proceedings of International Forestry Graduate Students' Conference, 2 - 4 July 2013, Universiti Putra Malaysia. 122 – 128.

Hamdan, O., Khali Aziz, H., & Abd Rahman, K. (2011). Remotely sensed L-Band SAR data for tropical forest biomass estimation. *Journal of Tropical Forest Science*, 23(3): 318 – 327.

Harrell, P.A., Kasischke, E.S., Bourgeau-Chavez, L.L., Haney, E.M. & Christensen, N.L. (1997). Evaluation of approaches to estimating aboveground biomass in southern pine forests using SIR-C data. *Remote Sensing of Environment*, 59: 223–233.

Heiberger, R. & Neuwirth, E. (2009). *R Through Excel*. Springer, Verlag.

Held, A., Ticehurst, C., & Lymburner, L. (2003). High resolution mapping of tropical mangrove ecosystems using hyperspectral and radar remote sensing. *International Journal of Remote Sensing*, 24(13): 2739 – 2759.

Henson, I.E. (2005). An assessment of changes in biomass carbonstocks in tree crops and forests in Malaysia. *Journal of Tropical Forest Science*, 17(2): 279-296.

Hikmat, A. (2005). Biomass estimation, carbon storage and energy content of three Virgin Jungle Reserves in Peninsular Malaysia. *Media Konservasi* 5(2): 1 – 8.

Holmgren, P. (2008). *Role of satellite remote sensing in REDD*. UN-REDD Programme, MRV Working Paper 1. UN FAO. Rome.

Houghton, R.A. (2005). *Tropical deforestation as a source of greenhouse gas emissions*. In Mutinho & Schwartzman (Ed.) Tropical deforestation and climate change, Instituto de Pesquisa Ambiental Amazônia (IPAM), Belém, Brazil.

Houghton, R.A. (1991). Releases of carbon to the atmosphere from degradation of forests in tropical Asia. *Canadian Journal of Forest Research*, 21: 132 – 142.

Hughes, R.F., Kauffman, J.B., Jaramillo, V.J. (1999). Biomass, carbon, and nutrient dynamics of secondary forests in a humid tropical Region of Mexico. *Ecology*, 80 (6): 1892 – 1907.

Huth, A., Martin, D. & Peter, K. (2004). Multicriteria evaluation of simulated logging scenarios in a tropical rain forest. *Journal of Environmental Management*, 71: 321 – 333.

Huth, A., Martin, D. & Peter, K. (2005). Using multi-criteria decision analysis and a forest growth model to assess impacts of tree harvesting in Dipterocarp lowland rain forests. *Forest Ecology and Management*, 207: 215 – 232.

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

Huth, A. & Tietjena, B. (2007). Management strategies for tropical rain forests: Results of ecological models and requirements for ecological–economic modelling. *Ecological Economics*, 62: 207 – 215.

Imhoff, M.L. (1995a). A theoretical analysis of the effect of forest structure on synthetic aperture radar backscatter and the remote sensing of biomass. *IEEE Transaction on Geoscience and Remote Sensing*, 33: 341 – 352.

Imhoff, M.L. (1995b). Radar backscatter and biomass saturation: ramifications for global biomass inventory. *IEEE Transaction on Geoscience and Remote Sensing*, 33: 511 – 518.

IPCC. 2006. *IPCC Guidelines for National Greenhouse Gas Inventories*. Prepared by the National Greenhouse Gas Inventories Programme. In H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara & K. Tanabe (Ed.), Japan Institute for Global Environmental Strategies.

IPCC. 2007. *Climate Change 2007: Mitigation of Climate Change*. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (Ed.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC. 2007. *Climate Change 2007: Synthesis Report*. Contribution of Working Group I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In Pachauri R.K. et al. (Ed.) IPCC, Geneva.

Jong, W., Chokkalingam, U., Smith J. & Sabogal, C. (2001). Tropical secondary forests in Asia: introduction and synthesis. *Journal of Tropical Forest Science*, 13(4): 563–576.

Jusoff, K. (2008). Managing sustainable mangrove forests in Peninsular Malaysia. *Journal of Sustainable Development*, 1: P88.

Kandaswamy, U., Adjeroh, D.A. & Lee, M.C. (2005). Efficient Texture Analysis of SAR Imagery. *IEEE Transactions on Geoscience and Remote Sensing*, 43(9): 2075 – 2083.

Kato, A., Watanabe, M., Kobayashi, T., Yamaguchi, Y., Iisaka, J. (2011). *Monitoring Forest Management Activities Using Airborne Lidar and ALOS PALSAR*. IEEE IGARSS, pp 2318 – 2321. Vancouver, Canada.

Kato, R., Tadaki, Y. & Ogawa, H. (1978). Plant biomass and growth increment studies in Pasoh forest. *Malayan Nature Journal*, 30: 211 – 224.

Kenzo, T., Furutani, R., Hattori, D., Kendawang, J.J., Tanaka, S., Sakurai, K., Ninomiya, I. (2009a). Allometric equations for accurate estimation of above-ground biomass in logged-over tropical rainforests in Sarawak, Malaysia. *Journal of Forest Research*, 14:365 – 372.

Kenzo, T., Ichie, T., Hattori, D., Itioka, T., Handa, C., Ohkubo, T., Kendawang, J.J. Nakamura, M., Sakaguchi, M., Takahashi, N., Okamoto, M., Tanaka-Oda, A., Sakurai, K. and Ninomiya, K. (2009b). Development of allometric relationships for accurate estimation of above and below ground biomass in tropical secondary forests in Sarawak, Malaysia. *Journal of Tropical Ecology*, 25(4): 371 – 386.

Ketterings, Q.M., Coe, R., van Noordwijk, M., Ambagau, Y. & 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.

Komiyama, A., Ong, J.E. & Poungparn, S. (2008). Allometry, biomass, and productivity of mangrove forests: A review. *Aquatic Botany*, 89: 128 – 137.

Komiyama, A., Poungparn, S. & Kato, S. (2005). Common allometric equations for estimating the tree weight of mangroves. *Journal of Tropical Ecology*, 21: 471 – 477.

Kuenzer, C., Bluemel, A., Gebhardt, S., Quoc, T.V. & Dech, S. (2011). Remote Sensing of Mangrove Ecosystems: A Review. *Remote Sensing*, 3: 878 – 928.

Kuplich, T.M. (2000). JERS-1 SAR backscatter and its relationship with biomass of regenerating forests. *International Journal of Remote Sensing*, 21: 2513 – 2518.

Kuplich, T.M., Curran, P.J. & Atkinson, P.M. (2003). Relating SAR image texture and backscatter to tropical forest biomass. *IEEE Transaction on Geoscience and Remote Sensing*, 4: 2872 – 2874.

Le Toan, T., Beaudoin, A., Riom, J., & Guyon, D. (1992). Relating forest biomass to SAR data. *IEEE Transaction on Geosciences and Remote Sensing*, 30(2): 403 – 411.

Le Toan, T., Quegan, S., Davidson, M.W.J., Balzter, H. Paillou, P., Papathanassiou, K., Plummer, S., Rocca, F., Saatchi, S., Shugart, H. & Ulander, L. (2011). The BIOMASS mission: Mapping global forest biomass to better understand the terrestrial carbon cycle. *Remote Sensing of Environment*, 115(11): 2850 – 2860.

Le Toan, T., Quegan, S., Woodward, I., Lomas, M., Delbart, N. & Picard, C. (2004). Relating radar remote sensing of biomass to modeling of forest carbon budgets. *Climate Change*, 76: 379 – 402.

Liesenberg, V. & Gloaguen, R. (2013). Evaluating SAR polarization modes at L-band for forest classification purposes in Eastern Amazon, Brazil. *International Journal of Applied Earth Observation and Geoinformation*, 21: 122 – 135.

Lu, D. (2006). The potential and challenge of remote sensing-based biomass estimation. *International Journal of Remote Sensing*, 27: 1297 – 1328.

Lucas, R., Armston, J., Fairfax, R., Fesham, R., Accad, A., Carreiras, J., Kelley, J., Bunting, P., Clewley, D., Bray, S., Metcalfe, D., Dwyer, J., Bowen, M., Eyre, T., Laidlaw, M. and Shimada, M. (2010). An evaluation of the PALSAR L-band backscatter – Aboveground biomass relationship Queensland, Australia: Impacts of surface moisture condition and vegetation structure. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 3(4): 576 – 593.

Lucas, R., Cronin, N., Lee, A., Witte, C. & Moghaddam, M. (2006). Empirical relationships between AIRSAR backscatter and forest biomass, Queensland, Australia. *Remote Sensing of Environment*, 100: 388 – 406.

Lucas, R., Milne, A.K., Cronin, N., Witte, C., Denham, R. (2000). The potential of synthetic aperture radar (SAR) data for quantifying the aboveground biomass of Australia's woodlands. *Rangeland Journal*, 22: 124 – 140.

Lucas, R., Mitchell, A.L., Rosenqvist, A., Proisy, C., Melius, A., Ticehurst, C. (2007). The potential of L-band SAR for quantifying mangrove characteristics and change: case studies from the tropics. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 17(3): 245 – 264.

Lucas, R., Moghaddam, M. & Cronin, N. (2004). Microwave scattering from mixed-species forests, Queensland, Australia. *IEEE Transactions on Geoscience and Remote Sensing*, 42: 2142 – 2159.

Luciani, S., S. Paloscia, P. Pampaloni, G. Schiavon, S. Sigismondi, & Solimini, D. (1994). *Sensitivity of microwave backscattering to crop biomass*. pp.1844-1846. IGARSS '94, Pasadena,

Luckman, A., Baker, J.R., Kuplich, T.M., Yanasse, C.C.F. & Frery, A.C. (1997). A study of the relationship between radar backscatter and regenerating forest biomass for space borne SAR instrument. *Remote Sensing of Environment*, 60: 1 – 13.

Mazzei, L., Sist, P., Ruschel, A., Putz, F.E., Marco, P., Pena, W. & Ferreira, R.E. (2010). Above-ground biomass dynamics after reduced-impact logging in the eastern Amazon. *Forest Ecology and Management*, 259: 367 – 373.

McGaughey, R.J. (1997). *Visualizing forest stand dynamics using the stand visualization system*. Proceedings of the 1997 ACSM/ASPRS Annual Convention and Exposition; Seattle, WA. Bethesda, MD: ASPRS 4: 248 – 257.

Mermoz, S., Le Toan, T., Villarda, L., Réjou-Méchain, M. & Seifert-Granzin, J. (2014). Biomass assessment in the Cameroon savanna using ALOS PALSAR data, *Remote Sensing of Environment* Doi. 10.1016/j.rse.2014.01.029. In Press.

Mohd Hasmadi, I. & Norizah, K. (2010). Soil disturbance from different mechanised harvesting in hill tropical forest, Peninsular Malaysia. *Journal of Environmental Science & Engineering*, 4(1): 34 – 41.

Morel, A.C., Fisher, J.B. & Malhi, Y. (2012). Evaluating the potential to monitor aboveground biomass in forest and oil palm in Sabah, Malaysia, for 2000–2008 with Landsat ETM+ and ALOS-PALSAR. *International Journal of Remote Sensing*, 33(11): 3614 – 3639.

Morel, A.C., Saatchi, S.S., Malhi, Y., Berry, N.J., Banin, L., Burslem, D., Nilus, R., Ong, R.C. (2011). Estimating aboveground biomass in forest and oil palm plantation in Sabah, Malaysian Borneo using ALOS PALSAR data. *Forest Ecology and Management*, 262: 1786 – 1798.

Mougin, E., Proisy, C., Marty, G., Fromard, F., Puig, H., Betoulle, J.L. & Rudant, JP. (1999). Multifrequency and multipolarization radar backscattering from mangrove forests. *IEEE Transactions on Geoscience and Remote Sensing*, 37(1): 94 – 102.

Narvaes, I.S., Queiroz, A.S. & Santos, J.R. (2007). Evaluation of the interaction between SAR L-band signal and structural parameters of forest cover. *IEEE Transactions on Geoscience and Remote Sensing*, 42: 1607 – 1610.

Nellemann, C, Corcoran, E., Duarte, C.M., Valdés, L., De Young, C., Fonseca, L., Grimsditch, G. (Ed). (2009). *Blue Carbon. A Rapid Response Assessment*. United Nations Environment Programme, Norway.

Neumann, M., Saatchi, S.S., Ulander, L.M.H., & Fransson, J.E.S. (2012). Assessing Performance of L- and P-Band Polarimetric Interferometric SAR Data in Estimating Boreal Forest Above-Ground Biomass. *IEEE Transactions on Geoscience and Remote Sensing*, 50: 714 – 726.

Ni, W., Sun, G., Guo, Z., Zhang, Z., He, Y. & Huang, W. (2013). Retrieval of forest biomass from ALOS PALSAR data using a lookup table method. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 6(2): 875 – 886.

Nichol, J.E. & Sarker, M.L.R. (2011). Improved biomass estimation using the texture parameters of two high-resolution optical sensors. *IEEE Transaction on Geosciences and Remote Sensing*, 49(3): 930-948.

Niiyama, N., Kajimoto, T., Matsuura, Y., Yamashita, T., Azizi, R., Abd Rahman, K. & Nur Supardi, M.N. (2010). Estimation of root biomass based on excavation of individual root systems in a primary dipterocarp forest in Pasoh Forest Reserve, Peninsular Malaysia. *Journal of Tropical Ecology*, 26: 271 – 284.

Norizah, K., Mohd Hasmadi, I., Kamaruzzaman, J. & Alias M.S. (2012). Operational efficiency of Rimbaka timber harvester in hill tropical forest. *Journal of Tropical Forest Science*. 24(3): 379 – 389.

Okuda, T., Mariko, S., Adachi, N., Quah, E.S., Nor Azman, H. & Manokaran, N. (2003). Effect of selective logging on canopy and stand structure and tree species composition in a lowland dipterocarp forest in Peninsular Malaysia. *Forest Ecology and Management*, 175: 297 – 320.

Ong, J.E., Gong, W.K. & Clough, B.F. (1995). Structure and productivity of a 20-year-old stand of Rhizophora apiculata Bl. mangrove forest. *Journal of Biogeography*, 22(2/3): 417 – 424.

Ong, J.E., Gong, W.K. & Wong, C.H. (2004). Allometry and partitioning of the mangrove, Rhizophora apiculata. *Forest Ecology and Management*, 188: 395 – 408.

Paloscia, G., Macelloni, P., Pampaloni, S. & Sigismondi. (1999). The potential of C- and L- band SAR in estimating vegetation biomass: the ERS-1 and JERS-1 experiments. *IEEE Transactions on Geoscience and Remote Sensing*, 37(4): 2107 – 2110.

Patenaude, G., Hill, R.A., Milne, R., Gaveau, D.L.A., Briggs, B.B.J. & Dawson, T.P. (2004). Quantifying forest aboveground carbon content using lidar remote sensing. *Remote Sensing of Environment*, 93: 368 – 380.

Pearson, T., Walker, S. & Brown, S. (2005). *Sourcebook for land use, land-use change and forestry projects*. Winrock International and the BioCarbon Fund of the World Bank.

Peregon, A. & Yamagata, Y. (2013). The use of ALOS/PALSAR backscatter to estimate above-ground forest biomass: A case study in Western Siberia. *Remote Sensing of Environment*, 137: 139 – 146.

Proctor, J., Anderson J.M., Chai, P. & Vallack, H.W. (1983). Ecological studies in four contrasting rain forest in Gunung Mulu national park, Sarawak. *Journal of Ecology*, 71: 237-260.

Proisy, C., Mougin, E., Fromard, F. & Karam, M.A. (2000). Interpretation of polarimetric radar signatures of mangrove forests. *Remote Sensing of Environment*, 71: 56 – 66.

Pulliainen, J.T., Kurvonen, L. & Hallikainen, M.T. (1999). Multi temporal behavior of L- and C-Band SAR observations of boreal forests. *IEEE Transactions on Geoscience and Remote Sensing*, 37(2): 927 – 937.

Putz, F. & Chan, H.T. (1986). Tree growth, dynamics, and productivity in a mature mangrove forest in Malaysia. *Forest Ecology and Management*, 17: 211 – 230.

Quinones, M.J. & Hoekman, D.H. (2004). Exploration of factors limiting biomass estimation by polarimetric radar in tropical forests. *IEEE Transaction on Geosciences and Remote Sensing*, 42: 86 – 104.

Rauste, Y. (2005). Multi-temporal JERS SAR data in boreal forest biomass mapping. *Remote Sensing of Environment*, 97(2): 263 – 275.

Rauste, Y., Hame, J., Pulliainen, K., Heiska, & Hallikainen, M. (1994). Radar based forest biomass estimation. *International Journal of Remote Sensing*, 15(14): 2797 – 2808.

Robinson, C., Saatchi, S., Neumann, M. & Gillespie, T. (2013). Impacts of spatial variability on aboveground biomass estimation from L-band radar in a temperate forest. *Remote Sensing*, 5: 1001 – 1023.

Rosenqvist, A, Shimada, M., Ito, N. & Watanabe, M. (2007). ALOS PALSAR: A pathfinder mission for global-scale monitoring of the environment, *IEEE Transactions on Geoscience and Remote Sensing*, 45(11): 3307 – 3316.

Rosenqvist, A., Shimada, M., Igarashi, T., Watanabe, M., Tadono, T. & Yamamoto, H. (2003). Support to multi-national environmental conventions and terrestrial carbon cycle science by ALOS and ADEOS-II–the Kyoto and carbon initiative. *IEEE International on Geosciences and Remote Sensing Symposium*, 3: 1471 – 1476.

Rosenqvist, A., Shimada, M., Suzuki, S., Ohgushi, F., Tadono, T., Watanabe, M., Tsuzuku, K., Watanabe, T., Kamijo, S. & Aoki, E. (2014). Operational performance of the ALOS global systematic acquisition strategy and observation plans for ALOS-2 PALSAR-2. *Remote Sensing of Environment*, DOI: 10.1016/j.rse.2014.04.011. In Press.

Saatchi, S., Houghton, R., Avala, R., Yu, Y., & Soares, J. V. (2007). Spatial distribution of live aboveground biomass in Amazon basin. *Global Change Biology*, 13: 816 – 837.

Saatchi, S.S., Marlier, M., Chazdon, R.L., Clark, D.B., & Russell, A.E. (2011). Impact of spatial variability of tropical forest structure on radar estimation of aboveground biomass. *Remote Sensing of Environment*, 115(11): 2836 – 2849.

Sandberg, G., Ulander, L.M.H., Fransson, J.E.S., Holmgren, J., & Le Toan, T. (2011). Land P-band backscatter intensity for biomass retrieval in hemiboreal forest. *Remote Sensing of Environment*, 115(11): 2874 – 2886.

Saner, P., Loh, Y.Y., Ong, R.C., & Hector, A. (2012). Carbon stocks and fluxes in tropical lowland dipterocarp rainforests in Sabah, Malaysian Borneo. *Plos One*, 7(1): 11 pp.

Santoro, M., Fransson, J.E.S., Eriksson, L.E.B., Magnusson, M., Ulander, L.M.H., & Olsson, H. (2009). Signatures of ALOS PALSAR L-Band Backscatter in Swedish Forest. *IEEE Transactions on Geoscience and Remote Sensing*, 47(12): 4001 – 4019.

Santos, J.R., Freitas, C.C., Araújo, L.S., Dutra, L.V., Mura, J.C., Gama, F.F., Soler, L.S. & Sant' Anna, S.J.S. (2003). Airborne P-band SAR applied to the aboveground biomass studies in the Brazilian tropical rainforest. *Remote Sensing of Environment*, 87: 482 – 493.

Santos, J.R., Keil, M., Araújo, L.S., Pardi Lacruz, M.S., Krämer, J.C. & Kandler, M. (2000). Biomass estimation of Forest and savanna transition vegetation zone by JERS-1 and SIR-C backscatter data. *International Archives of Photogrammetry and Remote Sensing*, 33(7): 377 – 381.

Sarker, L.R., Nichol, J., Baki, I.H., Baharin, A., & Alias, A.R. (2013). Forest Biomass Estimation Using Texture Measurements of High-Resolution Dual-Polarization C-Band SAR Data. *IEEE Transactions on Geoscience and Remote Sensing*, 51(6): 3371 – 3384.

Sarker, L.R., Nichol, J., Baharin, A., Ibrahim, B. & Alias, A.R. (2012). Potential of texture measurements of two-date dual polarization PALSAR data for the improvement of forest biomass estimation. *ISPRS Journal of Photogrammetry and Remote Sensing*, 69: 146 – 166.

Sessa, R. & Dolman, H. (Ed.) (2008). *Terrestrial essential climate variables for climate change assessment, mitigation and adaptation*. Rome: FAO GTOS-52.

Shi, J.C., Du, Y., Du, J.Y., Jiang, L.M., Chai, L.N., Mao, K.B., Xu, P., Ni, W.J., Xiong, C., Liu, Q., Liu, C.Z., Guo, P., Cui, Q., Li, Y.Q., Chen, J., Wang, A.Q., Luo, H.J. & Wang, Y.H. (2012). Progresses on microwave remote sensing of land surface parameters. *Science China Earth Science*, 55 (7): 1052 – 1078.

Shimada, M. & Ohtaki, T. (2010). Generating Large-scale High-quality SAR Mosaic Datasets: Application to PALSAR Data for Global Monitoring. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 3(4): 637 – 656.

Shimada, M., Rosenqvist, A., Watanabe, M. & Tadono, T. (2005). *The polarimetric and interferometric potential of ALOS PALSAR*. In Pattier (Ed.). 6p Proceedings in SAR Polarimetric Interferometry (POLinSAR 2005), Frascati.

Shimada, M., Isoguchi, O., Tadono, T. & Isono, K. (2009). PLASAR Radiometric Calibration and Geometric Calibration. *IEEE Transaction on Geosciences and Remote Sensing*, 3: 765 – 768.

Simard, M., DeGrandi, G., Saatchi, S. & Mayaux, P. (2002). Mapping tropical coastal vegetation using JERS-1 and ERS-1 radar data with a decision tree classifier. *International Journal of Remote Sensing*, 23(7): 1461 – 1474.

Simard, M., Hensley, S., Lavalle, M., Dubayah, R., Pinto, N. & Hofton, M. (2012). An empirical assessment of temporal decorrelation using the uninhabited aerial vehicle synthetic aperture radar over forested landscapes. *Remote Sensing*, 4: 975 – 986.

Steininger, M.K. (2000). Satellite estimation of tropical secondary forest abovgeround biomass data from Brazil and Bolivia. *International Journal of Remote Sensing*, 21: 1139 – 1157.

Stern, N. (2006). *Stern Review: The Economics of Climate Change*. Cambridge University Press. Cambridge, UK.

Suzuki, R., Kim, Y. & Ishii, R. (2013). Sensitivity of the backscatter intensity of ALOS/PALSAR to the above-ground biomass and other biophysical parameters of boreal forest in Alaska. *Polar Science*, 7(2): 100 – 112.

Symington, C.F. (1943). *Foresters' manual of dipterocarps*. Malayan Forest Records No. 16. Revised by Ashton PS and Appanah, in Barlow HS (ed.) 2004. Forest Research Institute Malaysia.

Vashum, K.T. & Jayakumar, S. (2012). Methods to estimate above-ground biomass and carbon stock in natural forests - A review. *Journal of Ecosystem and Ecography*, 2(4): 1 – 7.

Walker, S.M., Pearson, T.R.H., Casarim, F.M., Harris, N., Petrova, S., Grais, A., Swails, E., Netzer, M., Goslee, K.M. & Brown, S. (2012). *Standard Operating Procedures for Terrestrial Carbon Measurement: Version 2012.* Winrock International.

Walke,r W.S., Stickler, C.M., Kellndorfer, J.M., Kirsch, K.M. & Nepstad, D.C. (2010). Large-Area Classification and Mapping of Forest and Land Cover in the Brazilian Amazon: A Comparative Analysis of ALOS/PALSAR and Landsat Data Sources. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 3 (4): 594 – 604.

Wan Razali, W.M. (2008). Malaysia's strategic directions and way forward in sustainable forest management – Climate change scenario. UNDP/GEF Peat Swamp Forests Project, Kuala Lumpur.

Wang, Y., Davis, F.W. & Melack, J.M. (1993). Simulated and observed backscatter at P-, L- and C-bands from ponderosa pine stands. *IEEE Transaction on Geosciences and Remote Sensing*, 31: 871 – 879.

Watanabe, M., Shimada, M., Rosenqvist, A., Tadono, T., Matsuoka, M., Romshoo, S.A., Ohta, K., Furuta, R., Nakamura, K. & Moriyama, T. (2006). Forest structure dependency of the relation between L-band σ^o and biophysical parameters. *IEEE Transactions on Geoscience and Remote Sensing*, 44(11): 3154 – 3165.

Watanabe, M. & Shimada, M. (2006). Relation between coherence, forest biomass, and L-band σ^o. *IEEE Transaction on Geoscience and Remote Sensing*, 44(11): 1651 – 1654.

Whittle, M., Quegan, S., Uryu, Y., Stüewe, M. & Yulianto, K. (2012). Detection of tropical deforestation using ALOS-PALSAR: A Sumatran case study. *Remote Sensing of Environment*, 124: 83 – 98.

Wolter, P.T. & Townsend, P.A. (2011). Estimating forest species composition using a multi-sensor fusion approach. *Remote Sensing of Environment*, 115: 671 – 691.

Wright, S.J. (2010). The future of tropical forests. Annals of the New York Academy of Sciences. *Ecological Conservation and Biology*, 1195: 1 – 27.