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Can remote sensing be used to support sustainable forestry in Malawi?

Gemma Cassells

Doctor of Philosophy
University of Edinburgh

November 2012



Declaration

I declare that the work contained in this thesis is my own, unless indicated otherwise. No part of this thesis has been previously submitted or accepted for a degree or professional qualification.

Gemma Cassells

November 2012

Abstract

Sustainable forest management is a key issue in Malawi. Malawi is a relatively small, resource poor, densely populated country, which in some areas is close to exceeding the energy capacity of the environment to support it. Despite the importance of forestry in Malawi, there is a severe lack of knowledge about the current state of Malawi's forest resources. Remote sensing has the potential to provide current and historical insights into forest cover change. However, Malawi faces a number of key challenges with regards to in-country remote sensing. These include technical capacity for obtaining accurate and consistent forest area and biomass estimates, with errors at acceptable levels, as well as the necessary supporting capacity development for individuals and institutions.

This thesis examines how remote sensing can be used to support sustainable forestry in Malawi, by assessing the use of both optical and Synthetic Aperture Radar (SAR) data for mapping forest cover, forest cover change and aboveground biomass (AGB). L-band SAR data was used to try and establish a relationship between radar backscatter and biomass, which has been achieved many times in other areas. However, no correlations between any field-based forest metric and backscatter explained enough of the variability in the datasets to be used to develop empirical relationships between the variables. There were also differences between my field measured AGB and AGB values predicted by a published backscatter-biomass relationship for African dry forests. The speckle inherent in SAR imagery, the heterogeneity of Malawi's dominant miombo savanna, and Malawi's variable topography are likely to have played a significant role in this.

Two different MODIS products were investigated for their potential for mapping forest cover change, with regards to potential REDD+ schemes.

As part of this, a published equation was used to calculate the break-even point for REDD+ schemes in Malawi, using estimates of forest area and deforestation for the United Nations Forest Resources Assessment 2010. The results of this equation show that measurement error is the most important factor in determining whether or not Malawi can make REDD+ economically viable, particularly at lower levels of deforestation. While neither of the MODIS products were able to produce a verifiable forest cover change map, they do confirm that Malawi is experiencing some level of forest loss, and help to narrow down the range of possible forest loss rates Malawi is experiencing to between 1-3% net forest loss per year.

Finally, this thesis examines global trends in the engagement of developing country researchers with global academic remote sensing research, to investigate differences in in-country capacity for monitoring forests using remote sensing. The results of this found that while a significant proportion of Earth observation research (44%) has developing countries as their object of research, less than 3% of publications have authors working, or affiliated to, a developing country (excluding China, India and Brazil, which are not only countries in transition, but have well established EO capacity). These patterns appear consistent over the past 20 years, despite the increasing awareness of the importance of capacity development over this period.

Despite inconclusive results from the approaches examined here, remote sensing can play a role in improving understanding about the dynamics of Malawi's forest resources. There is a need for nationwide accurate, validated forest maps that can be repeated at least on a yearly basis, and remote sensing could produced these without the resources needed to conduct full national ground inventories each year. If remote sensing is to be useful as a forest mapping tool in Malawi, it needs to provide consistent, verifiable and updatable estimates of forest cover and biomass

change. This ideally needs to be achieved using free or low cost data, and by using open source or open access software, as this will better enable in-country researchers to conduct on-going forest mapping activities.

Acknowledgements

There are many people who have provided encouragement, advice and ideas over the last four years. First of all, many thanks to my supervisors, Iain Woodhouse, Genevieve Patenaude, and Casey Ryan for their support, guidance and patience. You have shaped my progress as a researcher. Casey deserves special thanks for introducing me to Matlab and putting up with all the questions that entailed. Ed Mitchard has been an invaluable source of technical support.

The UK Natural Environment Research Council funded my PhD, and some fieldwork costs. Additional thanks to Derek and Maureen Moss for their generous contribution to my PhD funding, through the Moss Centenary Scholarship. Without their support I would not have been able to spend nearly as much time in the field chasing difficult hypotheses.

I am grateful to the staff and students of the Departments of Forestry and Land Management, Mzuzu University, Department of Forestry, Bunda College, and Department of Geography, Chancellor College, University of Malawi, who have greatly added to the data collection and analysis presented here, as well as providing insights into Malawian life. The staff at the Department of Forestry in Lilongwe, and the Forest Research Institute of Malawi in Zomba generously shared their data and expertise, as well as patiently answering my endless questions. Special thanks to Jarret Mhango, who was never too busy for me, and looked after me like another daughter, Lucky Kabanga, who generously shared his office whenever I was in need of a desk and Mwayi Mchuchu, who somehow manages to keep computers functioning in difficult circumstances. John Blythe, Mavuto Tembo, Dalo Njera, Bennet Mataya, Mike Chirwa, and Nyuma Mughogo all contributed much to my time in Malawi.

In my Edinburgh life, thanks are due to the inhabitants of the Barra suite, past and present, and those who encouraged my occasional migration to the Crew Attic. You have been great companions and tolerated me with a smile. In particular, Sara, who encouraged my crazy ideas and kept me from climbing the walls alone, and Rachel who made the hard days less hard by having someone to share them with. Special thanks to Rob, for indulging my geeky ways and introducing me to some new ones, and reminding me that wisdom can always be found in tea, ice cream or Terry Pratchett.

To all the muzungus I have been fortunate enough to share Mzuni life with: here's to mango wine, greens and sachets, fuel queues, movie nights, power cuts, no water on Sundays, Hot 'n Spice, Key Lounge and weekends at the lake. Special thanks to: Amy and Manda, who both have stories best not shared and made tramping through the bush more fun than it should have been; Sanchia, who's still speaking to me after I came to stay for a week and ended up leaving 2.5 months later; Mike, who helped in more ways than he knows; Don, who encouraged me when I was flagging; and Becca and Nick, for letting me see everything with new eyes and reminding me just how lucky I am to keep adventuring.

Finally, a heartfelt thank you to my wonderful parents for keeping me just the right side of sanity, and having faith in my ability to finish this thing even when I didn't. And thanks to my lovely sister who did the same, but in different ways. This PhD is dedicated to you.

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“My word,” said Nanny Ogg, whose grasp of the principles of cartography was even shakier than Granny’s. “Amazing how we can all fit on that little bit of paper.”

from *Witches Abroad*, by Terry Pratchett

1. Introduction

1.1 Introduction to the thesis

This thesis describes work undertaken in Malawi to evaluate how remote sensing can be used to support sustainable forest management (SFM) activities in Malawi. To set the context for this work, I will describe why forest mapping is important to Malawi, and introduce potential methods for mapping forest cover change using remote sensing. This chapter will provide an introduction to Malawi, including some background to the current state of Malawi's forest resources and socio-economic dynamics, as they relate to forest use. I also describe the historical development and current state of Malawi's forest management sector to provide some background for the context in which remote sensing methodologies will be applied. This chapter concludes with a summary of why Malawi is particularly unusual, both in terms of physical and human geographic factors. In Chapter 2, I provide an overview of the different satellite remote sensing options available for monitoring forests, and provide some additional background information on the field data used alongside the remote sensing data in this thesis.

Chapter 3 presents results from an investigation into the current level of engagement of developing country researchers with remote sensing research being conducted in their own country. Remote sensing is unusual in that, by definition, research can be done remotely, without visiting or engaging with researchers in the country in question. The aim of this chapter is to assess how much remote sensing (applied to forestry) is being conducted about developing countries, compared to the proportion of authors from developing countries. This is key for this thesis, as using remote sensing for forest management will require sufficient indigenous expertise and capacity. Chapter 4 then focuses on the main data evaluated in this thesis and assesses the use of two different coarse resolution optical data products from the MODerate

Imaging Spectrometer (MODIS) sensor, namely Vegetation Continuous Fields (VCF) and the Enhanced Vegetation Index (EVI), for mapping forests and forest cover change in Malawi. The aim of this chapter is to assess how globally-derived remote sensing products perform in mapping sub-national scale changes. Chapter 5 assesses the use of synthetic aperture radar for providing estimates of biomass, biomass change and forest cover change, including the use of a generic backscatter/biomass regression relationship. Chapter 6 synthesises the findings presented in the previous chapters, and evaluates the different remote sensing options for mapping forests and forest cover change in Malawi, with regard to Malawi's unique circumstances examined in Chapter 1. It also provides suggestions for avenues of future research. Chapter 7 gives a summary of the key conclusions and recommendations.

1.2 Introduction to Malawi

Malawi is a small, landlocked country in south-east Africa. It has an area of 118, 484 km², of which 94, 080 km² is land, with the vast majority of the remainder being taken up by Lake Malawi and the smaller Lake Chilwa. Malawi is located in the dry tropics (figure 1.1), with a typical savanna climate characterised by a long cool dry season (March-April to November-December), where little or no rainfall will occur, and a short, hot rainy season (December-March) (Frost 1996).

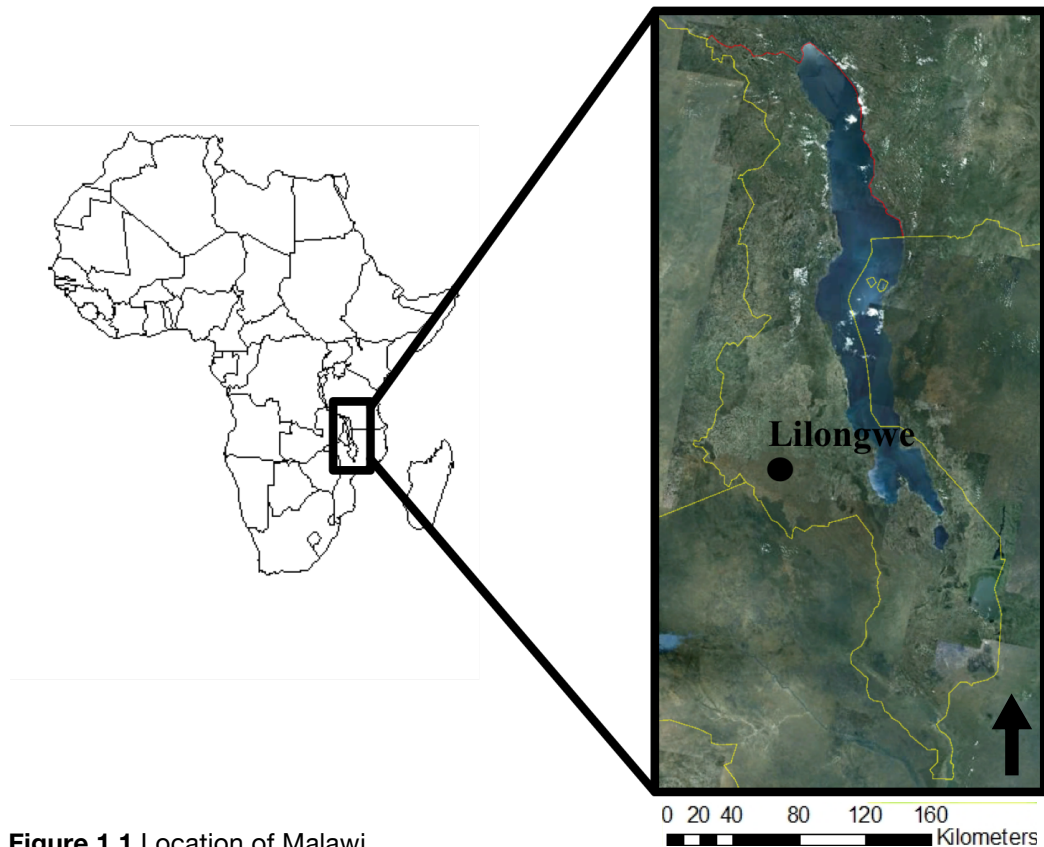


Figure 1.1 Location of Malawi

Malawi has a population of around 15 million (National Office of Statistics 2010), and this expected to double by 2030 (National Office of Statistics 2010). Almost half of the population is under the age of 15, with an average life expectancy of 50. 15% of the population is estimated to be HIV positive or living with AIDS, although this number is probably an underestimate due to the lack of reporting and testing facilities. Malawi stands out from other sub-Saharan African countries because of its high population density (168 people/km²) (figure 1.2) - it is third highest behind Rwanda (281 people/km²) and Burundi (229 people/km²) (estimates from SEDAC 2010 gridded population data). This has led to a unique situation in Malawi, compared to its neighbouring countries, as too many people compete for too few resources. In some of the most populated areas of southern Malawi, almost 100% of ecosystem function is being used to support the current population (Imhoff et al. 2004). Around 82% of the population lives in rural areas, depending on subsistence farming to meet their basic needs (McConnell et al. 2007). 53% of the population lives below the poverty line on less than US\$2 per

day (McConnell et al. 2007). Agriculture dominates the country's economy, accounting for more than one-third of its GDP and 90% of its export earnings (National Office of Statistics 2010). Tobacco accounts for more than 50% of total export earnings (National Office of Statistics 2010).

Malawi has been relatively politically stable since independence. This has been beneficial, as aid donors viewed the country as a relatively safe country to invest and work in. However, this stability has contributed to an influx of refugees fleeing the civil war in Mozambique into southern Malawi, which led to increased resource pressures in Malawi's already most populous region. Over the last 3 or 4 years, Malawi has experienced an increasing number of social and political pressures, primarily due to the increasingly severe fuel shortages that are affecting the country. These fuel shortages are a manifestation of a lack of foreign exchange, primarily due to falling prices for Malawi's main export, tobacco. These protests resulted in outbreaks of rioting. Following the death of Malawi's former president, Bingu wa Mutharika, in April 2012 Joyce Banda took over the presidency and has taken steps to redress many of the issues that marred Mutharika's presidency, which has resulted in the resumption of donor support that had been suspended by the UK and the EU, two of Malawi's major aid donors.

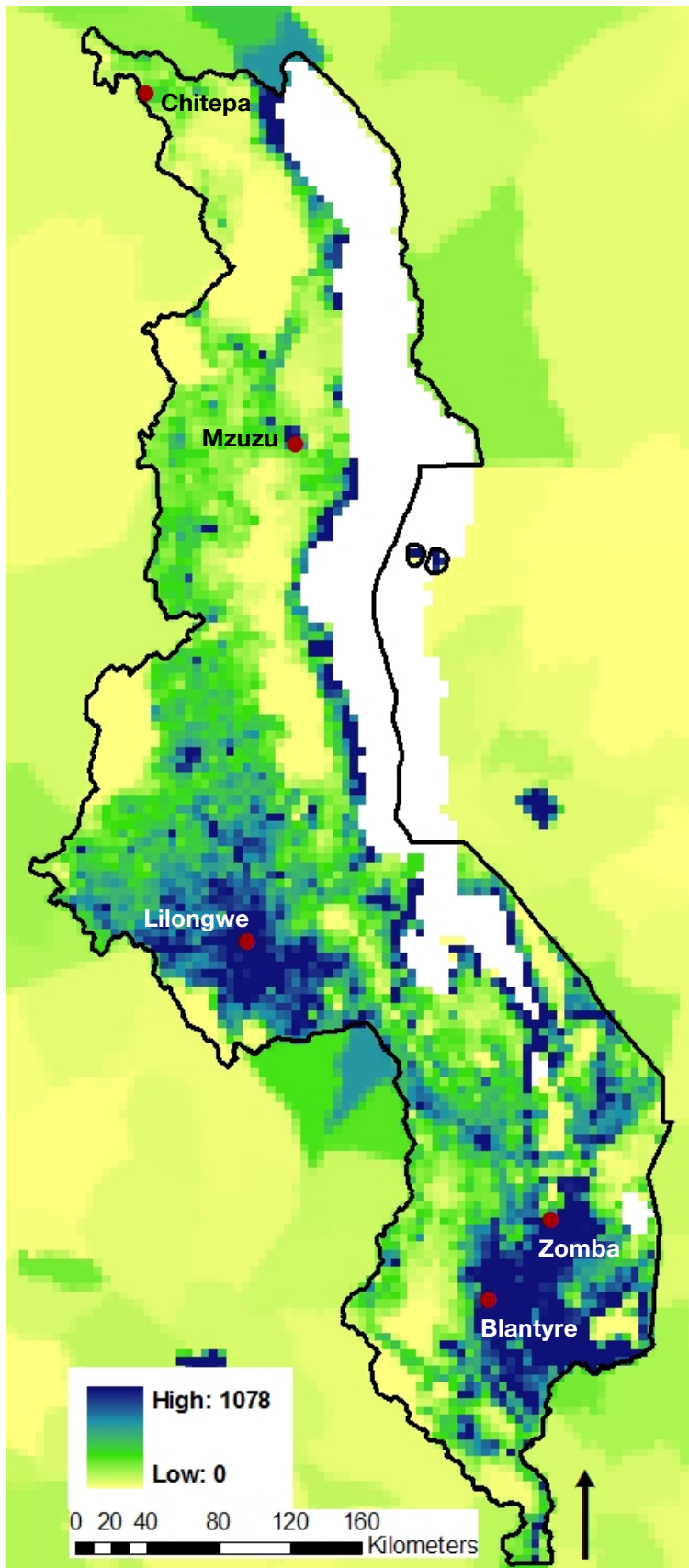


Figure 1.2 Population density (people per km²) across Malawi, using gridded population data from the Socioeconomic Data and Applications Center, hosted by the Center for International Earth Science Information Network at Columbia University (<http://sedac.ciesin.columbia.edu/gpw.>) for the year 2010. Much of Malawi's population is concentrated in the southern and central regions. Also, note the higher population densities in Malawi compared to Mozambique and Zambia.

1.3 Why are forests important?

There is now a general consensus among scientists that the Earth is getting warmer (IPCC, 2007, Mann et al. 1998, Oreskes 2004, Good et al. 2011), although the magnitude of this increase and its potential impacts are subject to debate (for example Gosling et al. 2011, Samson et al. 2011, Beaumont et al. 2011 and Schlenker and Lobell 2010). The primary mechanism behind this increase is the anthropogenic impact on the global carbon cycle, through the burning of fossil fuels. As a response to this, the United Nations Framework Convention on Climate Change adopted the Kyoto Protocol in 1997 (entered into force in 2005), which created binding targets for 37 industrialised countries and the European Union to reduce their carbon emissions relative to 1990 levels (UNFCCC 1998).

Trees, particularly the large expanses of forest in the tropics and subtropics, are important carbon sinks that are under increasing threat from anthropogenic activities. Carbon emissions from deforestation account for between 6-17% of total anthropogenic carbon emissions (van der Werf et al. 2009; Eliasch 2008; Baccini et al. 2012). Apart from being an important global carbon stock, forests also provide a number of other important services. They provide vital livelihood resources primarily as a fuel resource, but also as building materials, for medicinal products and dietary supplements to an estimated 1.6 billion people (FAO 2006). Forests also provide globally important ecosystem services, such as maintaining biodiversity, improving water quality and helping to prevent soil erosion (Ferraro et al. 2012, Chazdon 2008, Hein et al. 2006).

Carbon emissions from forest loss were not dealt with under the Kyoto Protocol, giving rise to a situation where countries would have been economically better off under the Kyoto Protocol to fell all their existing native forests and replace them with fast-growing exotics. This gave rise to REDD (Reduced Emissions from Deforestation and Degradation) at the

United Nations Framework Convention on Climate Change (UNFCCC) Conference of Parties (COP) in 2007, as part of the mechanisms for an international climate change protocol to follow on from the Kyoto Protocol. REDD was designed to incentivise countries to conserve their forest resources as important global carbon sinks. The 16th and 17th COP (2010 and 2011 respectively) agreed on a policy framework to incentivise REDD as well as conservation, sustainable forest management (SFM) and enhancement of forest carbon stocks in developing countries. These policy approaches are collected under the umbrella of REDD+ (UNFCCC 2011).

At the time of writing, much of the practical implementation of REDD+ remains unknown. However, many developing countries are taking steps to improve their capacity to undertake REDD+, with the support of bilateral or multilateral aid, coordinated by UN REDD. These activities are usually grouped under the title of 'REDD+ readiness'. While the details of REDD+ implementation are still being negotiated, there are basic data requirements that countries will be required to fulfil if they are going to participate in the REDD+ process. This data is required for the monitoring, reporting and verification (MRV) of carbon stocks, and their rate of change relative to a baseline. Countries will need to be able to provide a robust monitoring, reporting and verification strategy for national-scale accounting of their forest carbon stocks (Herold and Skutsch 2011, Obersteiner et al. 2009, Maniatis and Mollicone 2010, Lederer 2011). This will need to include a map of current forest area, preferably directly measuring forest biomass, and a historical baseline of change in forest area (Gibbs et al. 2007, Huettner et al. 2009). This monitoring will need to be easily and quickly updatable to provide new information on forest cover change, particularly loss, so that areas of loss can be identified quickly, as these will affect any carbon credits paid to that country (Gibbs et al. 2007, Olander et al. 2008). There will also need to be multiple systems in place, as measurements will need to be validated using a different methodology.

There has been increasing interest in using satellites to map forests and the carbon stocks they contain, particularly in developing countries due to the proposal of REDD, and subsequently REDD+. Given the lack of resources facing many forest management institutions in developing countries, remote sensing offers the potential to conduct national forest inventories, and in some cases direct estimation of carbon stocks. Additionally, the need to for a historical baseline to calculate changes in rates of forest loss means that many countries, including Malawi, will have use remote sensing as they lack comprehensive historical national forest inventories. If countries are going to use remote sensing as an on-going forest management tool, even outside the requirements of REDD+, they will need to develop in-country remote sensing capacity so that locally appropriate forest mapping solutions can be implemented.

1.4 Motivation for the thesis

Savanna woodlands are often ignored or under-represented in global forest discussions, despite the fact they cover approximately 30% of the Earth's surface and 50% of the tropics (Peel et al. 2007, Mistry 2000a). Much of the literature surrounding REDD+ implementation, and consequently deforestation monitoring in developing countries has focused on the major rainforest nations (for example Maniatis and Mollicone 2010, Saatchi et al. 2011, Huettner et al. 2009). However, Kutsch et al. (2011) argue deforestation in dryland savannas, particularly in Africa, is increasing rapidly, primarily driven by an increasing demand for charcoal from a growing population. Additionally, Bremner et al. (2011) outline the strong links between poverty and degraded ecosystems. As shown by figure 1.3 (details in Appendix 1), forests and woodland in Africa are a lived environment, in that forests (defined here as tree-dominated ecosystems) coincide with where people are, much more strongly than in the Amazon, for example.

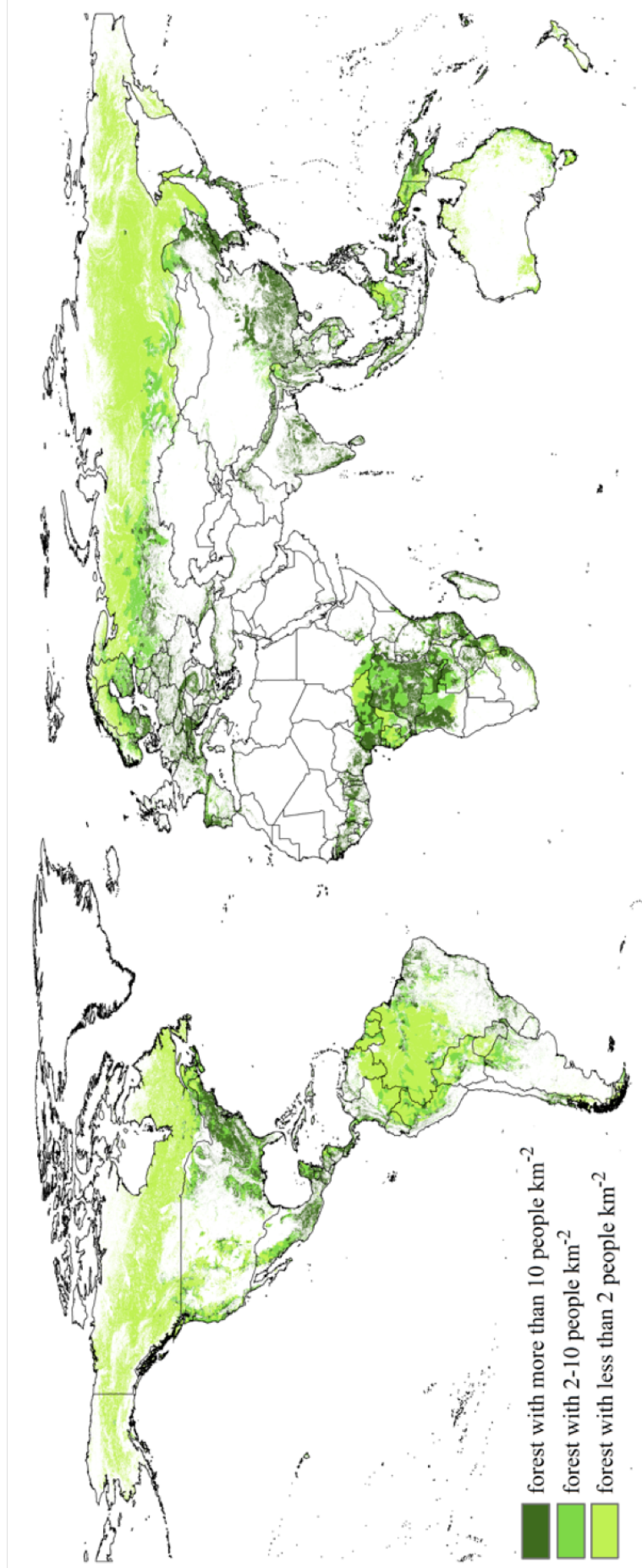


Figure 1.3 Global forest extent, from GLC2000 data, stratified by population density. The GLC2000 classes for all tree dominated ecosystems, including deciduous and evergreen forest and woody savanna were amalgamated to produce a global forest map. The boreal forests of Russia and Canada, and the Amazon are the largest forest areas with low population densities. The high population density of India and China means that most of the forest in these two countries has a large population living close by. Africa stands out from the other forest areas, as it appears that forest areas here coincide with a thinly spread population.

The dry woodlands of central and southern Africa have experienced rapid changes over the last century (Mayaux et al. 2005), and Malawi is no exception. There have been some recent studies across sub-Saharan Africa (Mitchard et al. 2011a, Mitchard et al. 2011b, 2009b, Baccini et al. 2008), and in neighbouring countries (Ryan et al. 2011a). However, there is a severe shortage of information about forest cover change in miombo woodlands, and about the current state of Malawi's forests in particular. Malawi's last nationally updated forest map was produced using Landsat imagery in 1991 (Kayambazinthu pers. comm.). There have been no national-scale maps of deforestation produced since, and data submitted to the United Nations Food and Agriculture Organisation (UN FAO) Forest Resources Assessment (FRA) has been based on extrapolations from this data. Grey literature from the Department of Forestry gives the national deforestation rate as 2.8% per year, but the methodology for calculating this figure is not explicit. The FAO FRA 2010 cites Malawi's deforestation rate at 0.9% (FAO 2010a). There have also been smaller scale studies, which focused on mapping historical deforestation patterns in specific areas, which give different deforestation rates. For example Hudak and Wessman (2000) found a deforestation rate of 1.8% in Mwanza district, southern Malawi between 1982-1998. Given the heterogeneity of Malawi's landscapes and the rapidly expanding population, there is a real need to understand current ecosystem dynamics, and how human activity is shaping Malawi's forests.

Malawi's environmental problems have a long history, and have been recognised since the colonial period. Archival records from the colonial period indicate that the language of 'crisis' has been used to describe the state of soil erosion and forest loss in southern Malawi since the 1930s (Walker and Peters 2007). French (1986) argued that deforestation in Malawi was an 'unsolvable problem', and indeed many of his criticisms of Malawi's forestry sector are still true today, particularly the low price of timber obtained from customary land, and the low level of incentives for

smallholders to replant. Work by Imhoff et al. (2004) calculated Human Appropriated Net Primary Productivity (HANPP) using MODIS data for the globe. Their results indicate that much of Malawi is living close to its ecosystem limits, with areas of southern Malawi extracting up to 80-100% of all energy being input into the ecosystem to support the current population. This is particularly concerning, as Malawi's population is one of the fastest growing in Africa (United Nations 2012)¹.

There has been considerable work on the social aspects of forest use in Malawi; particularly its importance for rural livelihoods (Fisher 2004, Fisher et al. 2005, Bandyopadhyay et al. 2011) and how people understand deforestation in Malawi (Walker and Peters 2001, 2007). Research by Walker and Peters (2007) indicates that Malawian smallholders in southern Malawi (Malawi's most deforested region) see tree scarcity as a problem of access, rather than actual resource shortage, because of the presence of small pockets of forest cover on privately owned land. Bandyopadhyay et al. (2011) used a MODIS product (MOD44B Vegetation Continuous Fields, which gives percentage tree cover data), combined with Landsat data to estimate biomass density for 2004. They combined this data with socio-economic data and household interviews to investigate patterns of biomass use and biomass scarcity in Malawi. They conclude that Malawi is in 'biomass distress', with biomass resources concentrated in the less densely populated northern region. This backs up work by Imhoff et al. (2004), who found that several areas of Malawi, particularly in the southern region are almost at the limits of the ecosystem to provide enough resources for human consumption.

Abbot and Holmwood (1999) estimate that in the Lake Malawi National Park in southern Malawi, intensive timber extraction caused the rapid

¹ Malawi's average population growth rate for the period 2007-2011 was 3.2%, which ranks equal fifth (tied with Uganda) in Africa, behind Zambia (4.8%), South Sudan (3.6%), Niger (3.5%), and Liberia (3.3%). The African average is 2.4%.

loss of closed canopy forest cover between 1982-1990, which was ultimately replaced with sparse canopy woodland. This raises two interesting points, the first of which is that protected areas in Malawi are not necessarily protected. National Parks and Forest Reserves should be protected from deforestation, but as forest resources become scarcer on customary land, local people are using these remaining areas of forest as sources of timber. The Department of Forestry (responsible for Forest Reserves), and Department of National Parks and Wildlife (responsible for National Parks) are chronically underfunded, and have limited resources for ensuring that villagers are not extracting timber illegally (Obedi *pers. comm.*). Secondly, the fact that the ecosystems did not recover to their former status as closed canopy woodlands raises some potential problems for woodland restoration in Malawi, as there are many degraded ecosystems that may not recover without external assistance. The loss of ecosystem function is a critical problem that will impact many sectors of Malawian society.

Although the bulk of Malawi's woodlands are low carbon miombo woodlands, there are areas of high endemism, or areas that provide habitats to endangered larger herbivores (elephants, leopards, hippopotamuses). One of the most significant areas is the Mount Mulanje, where the endangered endemic cedar (*Widdringtonia whytei*) is under threat from illegal logging, primarily for carvings for the tourist trade (Bayliss et al. 2007). Another area is Mkuwazi Forest Reserve, which was surveyed as part of this thesis (see next chapter for details). These areas often have very limited areal extent, and they are often the least well-mapped using global datasets. Developing Malawi-specific forest maps would enable a better understanding of these sub-national dynamics.

Regardless of how REDD+ progresses, Malawi faces a severe capacity gap for monitoring its own forests, which provide key government revenue and livelihood resources and ecosystem services to local communities. While REDD+ has provided increased interest and funding for forestry

activities, sustainable forest management is still a priority in Malawi (and many other developing countries), regardless of whether or not REDD+ is adopted into any post-Kyoto frameworks. Conducting wall-to-wall forest mapping and monitoring at national and sub-national scales is a key first step in understanding how forests are currently being used, and where the areas under greatest threat are. The issues surrounding the sustainable use of forest resources are complex and varied, and as such are often specific to a particular time or place. In order to target Malawi's limited resources most effectively, it would be beneficial to have a consistent, updatable framework to monitor forest cover, which would enable areas at greatest risk of forest loss to be identified.

1.5 Approaches to forest mapping and monitoring

Having established the need for up-to-date forest maps of Malawi, this section introduces satellite remote sensing as a forest mapping tool. Much of the research conducted by remote sensing scientists often focuses understanding global processes such as climate change and large scale landscape dynamics. Remote sensing scientists often have a background in physics or engineering which encourages this generalised global outlook, rather than considering a particular social or geographic context. This global focus led to the development of a number of sophisticated large scale mapping projects and techniques that have significantly improved our understanding of the Earth system (see for example Hansen et al. 2003, Rosenqvist et al. 2007, Mayaux et al. 2004, De Grandi et al. 2000). Many of the techniques or products developed at a global or regional scale have been applied successfully to research at the national and sub-national scale (Cabral et al. 2011, Bandyopadhyay et al. 2011, Kumar et al. 2007, Field et al. 1995).

The most common approaches to monitoring forest cover, and above ground biomass (AGB) estimation use a combination of ground and satellite data (DeFries et al. 2007, Broich et al. 2009, Gibbs et al. 2007,

Godar et al. 2012). Most forest inventory methodologies focus on measuring tree diameter and tree height, as the two key variables for estimating volume or biomass using allometry (Chave et al. 2005, Vieilledent et al. 2011, Parresol 1999), although more comprehensive surveys include canopy extent, height of the first branch or other variables of interest. The forest inventory methodologies used in this thesis are detailed in the next chapter. Most remote sensing studies use ground data collected from a relatively small area of fieldwork sites, and use that data to extrapolate measured parameters to other locations using image data to find areas that have similar characteristics to the sample sites and characterising the whole range of image data according to these parameters. This is why it is important to have a wide range of fieldwork sites to draw from when extracting biophysical parameters using image analysis.

While this extrapolation approach may work for most cases or at particular scales, there may be certain areas that diverge from the expected trends to such an extent that while global monitoring products may be able to pick up basic trends or patterns, they are not necessarily able to adequately quantify particular environments in a manner that is suitable for national-to-local scale problems. This is not a fault of the global data sets, but simply something they were never designed to do. If the goal of a particular dataset is to understand macro, global scale relationships between biomass and radar backscatter, for example, then it is not a problem if this relationship is over or under predicting biomass in a particular area as long as at the global scale the standard error is low. But when attention is focused on a particular country or region, there is less area to average over, and the nuances in the trends being analysed become more important. It is the argument of this thesis that Malawi faces an unusual combination of challenges when trying to use common satellite remote sensing monitoring approaches for mapping forest cover change.

While remote sensing data is often used in conjunction with field data, remote sensing offers an opportunity to conduct rapid, large scale forest mapping activities that may not be possible to achieve using only fieldwork-based methodologies, due to the costs of training, field equipment and staff time. This is why it is necessary to develop the capacity of in-country remote sensing scientists in developing countries. Local scientists have both data and insights to contribute to global remote sensing products, such as the pan-tropical biomass map produced by the Woods Hole Research Center (Baccini et al. 2008). In-country researchers are also best placed to assess how any particular map or data product would work in their own country. This is discussed in more detail in chapter 3.

Chapter 2 provides an overview of the main remote sensing options available for use in forest monitoring, and introduces the basic criteria that remote sensing data needs to meet in order to be most useful in Malawi, to provide a background on why particular approaches were selected for use in this thesis.

1.6 Aims of research, scope of study and originality

As outlined in the previous sections, Malawi needs to have sustainably managed forests to meet the needs of its population. In order for forests to be sustainably managed, a detailed understanding of where forests are and how they are changing is needed. This is also one of the requirements for potential REDD+ projects. REDD+ offers a possibility source of funding to aid the transition to more sustainable forest use practices. If Malawi wishes to pursue REDD+ activities, in-country capacity for conducting monitoring, reporting and verification (MRV) of carbon stocks will be required to meet FAO requirements. One of the key challenges of using remote sensing to map forest cover change is that many remote sensing studies do not consider the unique environments and ecosystems present in specific countries.

Therefore, the aims of this thesis are to:

- (1) Assess the potential of different remote sensing data for mapping forest cover in Malawi, including both optical and radar data, and make a recommendation on which approach is most appropriate for Malawi.
- (2) Evaluate how REDD will work in Malawi given results of (1), or at best, make recommendation on how Malawi could implement EO monitoring of forests.
- (3) Consider the issue of in-country EO capacity and how that is important to (1) and (2) actually happening.

There are various methods available for using remote sensing to monitor forest cover change. Examining all the potential methodologies for estimating forest area, forest cover change and carbon stocks is well beyond the scope of a single thesis. Many of the requirements for monitoring, reporting and verification of forest carbon stocks for REDD+ are the same as those required for mapping forests to aid sustainable forest management (SFM) activities, although SFM activities may not require as stringent a verification process. Choosing a particular method of analysis depends on the type of sensor data being used, and the expected outcome of the project. These methodologies range from simple visual interpretation of a single scene to more sophisticated digital analysis, involving one or more types of sensor data. This range of methodologies provides many potential options for investigating changes in forest cover and composition. Choosing an appropriate method for mapping forest cover depends on a number of factors including:

- Cost of data and software for processing
- Technical capabilities of personnel and hardware for conducting analysis
- Forest type, main methods of forest loss including size and pattern of forest loss
- Overall size of the country and forest area
- Seasonality of forest.

- Repeatability of measurements, to provide estimates of change (from DeFries et al. 2007)

If remote sensing is going to be used to support sustainable forestry in Malawi the data must be easy to use, easy to access, have a proven track record, link to international criteria and standards, and be fit for purpose for SFM in Malawi. These criteria are expanded on in Chapter 6.

Chapter 2 provides an introduction to the different satellite remote sensing options for monitoring forest cover, and elaborates on the specific criteria that remote sensing methodologies will need to meet in order to meet Malawi's specific mapping challenges.

1.7 Defining a forest

Before continuing, it is necessary to briefly discuss how the term 'forest' will be used in this thesis. Defining a forest is surprising controversial (Putz and Redford 2010), especially when considering the potential impact this definition could have on potential carbon finance or ecosystem service payments. The fact that savannas, woodlands and forests exist on a continuum also complicates this definition in the dry tropics. Even new definitions such as those proposed by Maniatis and Mollicone (2010) of 'intact' (unmanaged) versus 'non-intact' (altered by logging or other degradation processes) are difficult in Malawi, where there are almost no areas of forest that have not been subject to some kind of management or alteration by humans. Malawi's own national forest definition is based on the minimum requirements set by the FAO of 10% canopy cover, extending over at least 0.5 ha, and does not include any reference to carbon content or ecosystem services (Kayambazinthu *pers. comm.*). For the purpose of this thesis, "forest" is used as shorthand for tree-dominated ecosystems, including managed and natural forests, and woody savanna. Where distinction for specific ecosystem types is necessary, these are specifically named. Savanna is used to describe ecosystems where a continuous layer of grass co-exists with trees that do

not form a closed canopy. Woodland is used as a term to describe the woody end of the savanna spectrum, with forest as its endpoint.

1.8 Detailed introduction to Malawi

This section will provide a more detailed introduction to Malawi, and a more detailed insight into the current dynamics impacting forest use and the development and implementation of sustainable forest management policy in Malawi. Many of Malawi's current development issues centre around or impact on forestry. Poverty alleviation activities in Malawi may focus on agriculture or water resources, but all of these issues will affect, and be affected by, forest activities. This section will also provide an overview of some of the key issues impacting sustainable forest use in Malawi, namely agriculture, energy supply, and land tenure.

1.8.1 Malawian Forest Ecosystems

1.8.1.1 Miombo

Malawi's dominant forest ecosystem is miombo, the vernacular name used to describe the savanna woodlands of southern Africa that are dominated the genera *Brachystegia*, *Julbernardia* and/or *Isoberlinia*, three closely related genera from the legume family (Campbell 1996, Palgrave 2002). There are many different definitions of a savanna, but the key similarity is the coexistence of grass and trees (Walker 1985), which is in contrast to most other ecosystems where one will normally dominate to the exclusion of the other (Scholes and Archer 1997). Approximately 63% of miombo woodland is on customary land, with 36% in forest reserves and national parks (FAO 2010a). Specific details on field sites are provided in section 2.3.

About 11% of Malawi's forest area is in government owned plantations, which consist mainly of *Pinus patula* (85%) and Eucalyptus species (FAO 2010a). Malawi relies heavily on its timber resources to generate vital

government revenue. Plantation forests have increased from 285 000 ha in 2000 to 365 000 ha in 2010 (FAO 2010a), with Malawi having the second largest plantation forest area in Africa. Because plantations are managed by companies for profit, they are more routinely and comprehensively monitored than miombo woodland, which has traditionally been overlooked by politicians and some foresters. From a conventional forester's point of view, miombo woodland is distinctly uninteresting. It supports few commercially viable species, and the best areas were logged over long ago (Frost 1996).

However, Malawi's natural miombo woodland is under considerable pressure from the largely rural, impoverished population. Conventional management programmes have often overlooked miombo, instead focusing on commercial timber plantations. It has been estimated that while the annual consumption of forest products is 15 million m³, the sustainable supply is less than 8 million m³ (Mayers et al. 2001). Projections based on primary forest loss experienced between 1990 and 2005 suggest that all primary forest in Malawi will be degraded or deforested by 2020 (Mayers et al. 2001). This forest loss is attributed to agricultural expansion, biomass use for fuelwood, charcoal production, tobacco curing, and brick making, among others (Jumbe and Angelsen 2007, Kamanga et al. 2009b, Orr and Mwale 2001). Over 90% of Malawi's total energy demand is met by biomass use, primarily in the form of charcoal, despite the fact that all charcoal production currently occurring in Malawi is illegal (Zulu 2010, Kambewa 2007). Non-timber forest products also play an important role in Malawian livelihoods, including mushroom collection (over 60 species of edible mushrooms have been identified in Malawi), bush meat, and bee keeping (Syampungani et al. 2009).

Miombo can be classified as a moist/distropic savanna (Van Wilgen 1997). As such, tree cover is limited more by disturbance than by climate (Sankaran et al. 2005), but nutrient constraints also play a role. The

composition and structure of miombo woodland appears superficially to be relatively uniform over large regions, suggesting a broad similarity in key environmental conditions across the miombo belt (Frost 1996). Miombo forms the dominant element of the Zambezian phytochorological region, and covers around 2.7 million km² across southern Africa (Chidumayo, 1997, Campbell 1996). Estimates of forest extent across Malawi vary considerably, and have been the focus of considerable mapping efforts in this thesis, with estimates ranging from Department of Forestry estimates based on unknown data are 26%, and United Nations FAO Forest Resources Assessment 2010 (FRA 2010) estimates are 34%.

The dominance of the three key miombo genera makes miombo floristically distinct from most other African woodlands. Miombo occurs on well-drained soils that are nutrient poor and acidic (Frost 1996), with a low organic content (Ryan et al. 2011b). Miombo trees are variously described as semi deciduous, semi evergreen, drought deciduous or simply deciduous. Most shed their leaves at the end of the dry season, coinciding or just preceding (Frost 1996, Ryan 2009) the onset of the rains, and missing the dry season fires. Tree densities vary from 380-1400 ha⁻¹ (Frost 1996, Chidumayo 1997, Chidumayo and Gumbo 2010). Density is not apparently related to rainfall or to any other single factor (Frost 1996, Chidumayo 1997), but instead appears to be related to moisture availability and soil depth (Savory 1963, Grundy 1995), indicating that water and nutrient availability have strong controls on miombo structure and ecology.

Fires also play an important role in miombo ecology. Fire is used for many purposes, including hunting, clearing land, producing a new flush of grass for grazers and clearing paths around houses and villages to reduce wildlife hazards (Eriksen 2007, Spinage 2012). In general, Southern African savanna structure is more strongly determined by fire

and climate (Bond et al. 2003, Bond and Keeley 2005), than by nutrients (Scholes 1990).

Miombo woodland is often divided into wet and dry miombo based on the 1000 mm isohyet. In dry miombo aboveground woody biomass averages around 55 t dry matter ha⁻¹, whilst wet miombo averages 90 t dry matter ha⁻¹ (Frost 1996). There is a significant correlation between rainfall and woody biomass. These biomass values are slightly lower than dry forests under similar condition in other continents (Frost 1996). Because of the presence of Lake Malawi, and the direction the prevailing winds, Malawi tends to be more humid, and wetter than surrounding areas year round (it still has a marked, long dry season). Most of southern and central Malawi falls below the 1000 mm isohyet. The lakeshore areas of northern Malawi generally average 1200-1600 mm annual rainfall, with areas further inland averaging 1000 mm. Nkhata Bay district is the wettest district in Malawi, averaging 1650-2000 mm annual rainfall (data provided by the Malawian Department of Climate Change and Meteorological Services, 2011).

1.8.1.1.1 Savanna as a human environment and a socio-ecological system

The African savanna pre-dates the evolution of Homo sapiens (Lewin and Foley 2004, Beerling and Osborne 2006, Beerling and Woodward 2001), but has been strongly influenced by humans, initially through the use of fire (Bird and Cali 1998) and then through agriculture (Williams et al. 2007). These impacts are so closely connected with natural savanna processes that it can be difficult to separate them. Savannas are probably the oldest ecosystem used by people (Mistry 2000b), as Homo sapiens evolved in a savanna environment in East Africa about 1 million years ago (Abbate et al. 1998). Hominid remains have been found in Malawi dating back around 2.6 million years BP (Bromage et al. 1995).

Unlike wetter tropical forests, miombo woodlands are heavily populated, with population estimates ranging from 50-150 million people (Campbell and Angelsen 2007, see also Appendix 1). Recent history has been a period of tremendous upheaval; the Arab and European slave trades, colonialism, liberation, resource wars, economic mismanagement and misdirection and corruption are just a few of the reasons why the people of the miombo region are the poorest people on Earth (Campbell 1996, Campbell and Angelsen 2007, Ryan 2009). Miombo has been a rich source of resources for its inhabitants since the upper Pleistocene period (around 100,000 years ago), and continues to be so today (Musonda 1986). Storrs (Storrs 1979) documented 106 medicinal miombo trees, and miombo also provides valuable dietary additions in the form of fruits as well as providing areas for mushroom growth (Ngulube et al. 1999, Fisher 2011). There is a strong gender divide in how miombo resources are perceived (Fisher 2004), with men identifying fewer tree species, and few uses for those species than women.

Over 95% of existing woodland cover in Malawi has been heavily modified (Campbell 1996, Mayers et al. 2001), and Mayers et al. (2001) predict there will be no primary woodland left in Malawi by 2020. Many of the current anthropogenic environmental impacts in Malawi are centred on the widespread impacts of deforestation, both directly and indirectly through changes in ecology, catchment hydrology, and problems associated with desertification (Kalipeni and Zulu 2002, Zulu 2010, French 1986, Stringer et al. 2009). This is shown in numerous studies, for example Kambewa (2004) on the Lake Chilwa basin, south-eastern Malawi, has shown the importance of forests in regulating rainfall and halting desertification. Jamu et al. (2003) researched the effects of land use changes in the Likangala River, one of the rivers leading into Lake Chilwa, and found increasing deforestation was causing high sediment yields, which were leading to a degradation of water quality in the catchment. (Harrison et al. 2008) researched the ecology of hippopotamus in Liwonde National Park, central Malawi, and found that deforestation

was causing increased competition for food resources in the Park, which was negatively impacting the endangered hippos. These issues and many more are causing dramatic environmental changes in Malawi. Removing vegetation impacts the ecology of other flora and fauna, as well as influencing other human activities in the area which often have their own set of processes that shape the environment.

1.8.1.1.2 Miombo and anthropogenic climate change

While savannas in general, and miombo woodland more specifically, do not have the same significance as tropical rain forests for acting as carbon sinks, there are two key arguments from a climate change perspective that are worth considering before dismissing them as irrelevant. Firstly, by one definition (Peel et al. 2007), savannas cover 23% of the global land surface, and 50% of the tropics. The IPCC (2001) estimates that savannas contain approximately 75 PgC in aboveground plant matter. This is comparable to estimates for boreal forests (given as 88 PgC, with a note that this is likely to be overestimated).

Secondly, at a national scale, miombo is a lived environment, and humans have an influence on their ecology, primarily through the use of fire and logging activities. If substantial areas of miombo are cleared for cereal crop agriculture 6-10 Pg of C could be released (Scholes, 1996).

Conversely, if miombo is managed to maximise carbon storage a similar amount could be taken up (Scholes, 1996). Malawi's forest resources could still have enough economic value under any future carbon finance or payment for ecosystem services mechanisms that may be developed to make them a viable source of revenue to help Malawi transition to more sustainable environmental management practices. Based on estimates produced from currently available data, Malawi could receive between US \$5-40 million per year under a potential carbon finance scheme, dependent on a number of factors including implementation and MRV (monitoring, reporting and verification) costs (calculated in Chapter 4). This subject is dealt with in more detail in chapter 4.

1.8.1.2 Other major vegetative ecosystems in Malawi

Malawi has a number of other vegetation types including grasslands, *Acacia abyssinica*-dominated savanna (on the Nyika plateau) and mopane (*Colophospermum mopane*) woodland (centred around Liwonde National Park, southern Malawi). Due to Malawi's position at the end of the Rift Valley, there are number of plateaus, which because of their elevation and microclimate have different vegetation compositions to the rest of Malawi. The most striking example of this is the endemic cedar forests on Mount Mulanje (Bayliss et al. 2007). The Nyika plateau also contains fire-sensitive evergreen thickets, which are known leopard habitats, leading to management efforts to prevent the thickets from being burned during the fires that sweep across the grassland on the plateau.

Dambos are distinctive features across the miombo region, and Malawi is no exception. Dambos are largely treeless grasslands that occupy seasonally waterlogged shallow valley depressions. Because they retain water, dambos support vigorous growth of grasses when other forms of grazing are in short supply, which makes them an essential source of dry season feed for ruminant livestock (Harrington and Tow 2011).

1.8.2 Agriculture

Agriculture is the backbone of Malawi's economy. It accounts for 38% of GDP, 80% of export earnings and employs 80% of the workforce (Government of Malawi 2006). Tobacco alone accounts for 50% of export earnings. Deforestation in Malawi has largely been driven by agricultural expansion into forest areas to meet the food requirements of a rapidly growing population (Government of Malawi 2006, Mayers et al. 2001, Bandyopadhyay et al. 2011). This is a reality common across much of the miombo region, a consequence of low economic growth restricting resource availability for agricultural intensification (Scholes 1996). It

means that forest management issues are connected much more closely with agricultural planning than is the case in most developed countries.

Prior to the 1950s, Malawians primarily farmed millet and sorghum. However, in the 1950s the World Bank introduced maize to most countries in Africa, including Malawi. Maize is now the most popular crop and is used to make nsima, Malawi's staple food. Smallholders, who farm 80% of Malawi's total agricultural land, devote 85% of their agricultural land to maize production (Government of Malawi 2006). Maize provides more nutrients than millet and sorghum, but needs good soil and nutrients and sufficient water. It is also more susceptible to disease and drought than traditional crops such as cassava, millet and sorghum. Maize is planted at the start of the rainy season, usually in December, to allow early rains to soften the soil to allow it to be planted. It is then harvested in May-July the following year.

Approximately 95% of all arable land in Malawi is utilised and over half of rural households have access to less than 1 ha of land (Government of Malawi 2006, Hazarika 2003, Cross 2002). The conventional figure for a sufficient subsistence livelihood for a 5-person rural household in south central Africa is 2.2 ha (Allan 1965) (the impacts of this on forests are discussed further in the section below). Admittedly this reflects drier environments than generally prevail in Malawi, and refers to farming systems with a larger proportional reliance on pastoralism. Consumption of animal protein is very low in Malawi, even compared to other sub-Saharan African countries, which is a reflection of the low number of households owning animals and the limited purchasing power of consumers, even in urban areas (Reynolds 2006). This land scarcity means that people are forced to expand into previously undesirable or unused areas in order to produce enough food, which causes pressure on forest resources.

Traditional Malawian agricultural practices do not encourage crop rotation, so the same crop is often grown in the same field year after year. At the end of the dry season, the fields are burnt to clear them, leaving very little organic matter in the soil. These practices lead to decreasing per hectare yields, after only short periods of time (Bernard 2000), leading farmers to expand into new areas. This problem is exacerbated by Malawi's rapid population growth (currently around 3% per year, according to the National Office of Statistics, 2010). Due to land scarcity, particularly in the southern and central regions, land is often not allowed to lie fallow, but is used every year (Takane 2008). Because of these factors, and additional impacts from periodic weather shocks, during most of the last 20 years Malawi has experienced problems with grain deficits.

As Malawi's predominantly rural population continues to grow, and the economy fails to keep pace, the number of subsistence farmers inevitably increases and a net conversion of land to agriculture takes place. Traditionally agricultural practices take the form of shifting agriculture, where a patch of land approximately 1 ha in size is cleared of most trees and then farmed for as long as it produces good crop yields, between 5-15 years depending on soil type. In a situation of stable population this cycle of clearance and abandonment followed by regrowth (Williams et al. 2008) is not a net conversion of woodland. However it is now a major driver of deforestation across the continent (Blaser 2007, Kamanga et al. 2009a). The situation in Malawi will continue to worsen if agricultural production does not intensify as Malawi's population is predicted to double by 2030.

As a response to the food shortages of 2005/6, the Malawian Government introduced a fertiliser subsidy, one of the most controversial aid programmes introduced in recent times (for example see Denning et al. 2009, Harrigan 2008, Dorward and Chirwa 2011). It will only be discussed now in the context of its potential impacts on sustainable forest

management. The most recent iteration of the fertiliser subsidy programme started in the 2005/2006 cropping season, as a response to extreme drought in early 2005 (Mhango 2010, Denning et al. 2009). The programme has expanded to reach almost 2 million farmers in the 2009/2010 cropping season (Denning et al. 2009, Kandodo 2010). Combined with recent favourable rains, each growing season since the fertiliser subsidy programme started has enabled Malawi to start exporting grain (Denning et al. 2009). Because smallholders are now getting increased yields from their land, there is presumably less need for them to expand into new areas to maintain their harvest. This has not been investigated, but it could be decreasing national deforestation rates.

This is not to say that the fertiliser subsidy programme has ended food insecurity in Malawi, as only relatively well off smallholders are able to afford the fertiliser, even with the subsidy. The poorest farmers that are not able to participate are also not able to afford to buy the surplus grain that is produced if their yields do not provide enough to feed their families. This means that despite exporting grain, some of Malawi's most vulnerable people are still experiencing food insecurity, and these people may still be turning to forest resources to meet livelihood needs (for example by producing charcoal to sell) or by clearing forest areas for cultivation.

1.8.3 Energy supply

Most Malawians, in both urban and rural areas, rely almost exclusively on charcoal or firewood for heat and fuel (Zulu 2010), despite the fact that all charcoal currently produced in Malawi is produced illegally. Charcoal production is estimated to be the third largest industry in the country after the tobacco and tea industries, providing a source of income for almost a quarter of a million people (Kambewa et al. 2007). Around half of all charcoal production in Malawi originates from forest reserves (Kambewa et al. 2007). The scale of charcoal production required to meet

the energy requirements of Malawi's four major urban areas results in the annual extraction of 1.4 million cubic metres of wood, of which 60% is sourced from forest reserves (Kambewa et al. 2007).

Forests also play an indirect role in ensuring Malawi's electricity supply. All of the electricity produced in Malawi is from three hydroelectric power stations, two along the Shire River and one in the northern region. Deforestation in the upper course of the Shire has led to increasing problems with siltation, which has in turn led to problems with the HEP generators, which are being blamed for frequent power outages (Nangoma 2007).

1.8.4 Land tenure

Debates about land tenure are central to most development issues in Africa. Malawi has a complex system of land tenure, left as a colonial legacy that merges British and traditional elements. Land falls under three broad classes, either public, private or government owned. Public land includes customary land (described in more detail below), and all land held in public trust by the government, including forest reserves and national parks. Government owned land refers exclusively to land owned by the government for the provision of government services, such as government buildings, schools, hospitals and infrastructure. Government land may be sold to private landowners. Private land covers all remaining land types, including freehold and leasehold, and commercial estate land.

Most of Malawi is classed as customary land and governed under the Traditional Authorities (system of chiefs). A particular area of customary land falls under the authority of a village headman, who grants cultivation or use rights rather than ownership. Malawi's National Land Policy (Government of Malawi 2002) outlined a key change in customary land policy, setting up a framework by which Traditional Authority leaders could register title to their land, for exclusive use of the village

aligned with that chief. This was designed to give a more secure system of tenure to customary land, while keeping it out of the general class of land that could be brought and sold as freehold. Lack of secure land tenure for smallholders on customary land is one of the most cited examples for why farmers do not invest more in improving their land (Zhang and Aboagyeowiredu 2007, Peters and Kambewa 2007, Kaarhus 2010, Holmes-Watts and Watts 2008).

Inheritance patterns have a big influence on land tenure issues.

Inheritance patterns vary across Malawi. Customary land tenure is based on complex historical traditions, but does have some flexibility. For example, in the south and central regions, inheritance is primarily matrilineal (due to the dominance of the Chewa), however this is now changing to a patrilineal system in some cases (Munthali 2008).

Conversely, in the northern region inheritance is patrilineal due to the dominance of the Tumbuka. However historically the Tumbuka were matrilineal, and it was through contact with the patrilineal Ngoni that this started to change. It has also been proposed that this flexibility in inheritance may be a response to land scarcity (Takane 2008). Another complicating factor is that security of ownership, and therefore inheritance, can change depending on whether the parents are indigenous or non-indigenous to the village where they are living (regardless of the fact that the children may have been born there) (Matchaya 2009).

It is estimated that 95% of rural households have less than a hectare or farmland, which is causing smallholder farmers to grow crops on steep slopes and riverbanks, or encroach into forest reserves in order to meet their basic livelihood needs (Nkwanda et al. 2008). Mindle et al. (2001) surveyed 90 households in 3 areas of Malawi, and found that over 70% of households that had acquired land between 1992 and 1996 had encroached on adjacent forest reserves.

Land tenure impacts on forest management, as currently around 70% of Malawi's forest resources are on customary land, and how this forest is used and managed is very much dependent on how individual chiefs choose to enforce certain laws. There is some evidence that customary land is facing increased pressures from anthropogenic activities, compared to other types of land, which is resulting in changing woodland floristics and composition (Mwase et al. 2006). The authors also note that customary lands seem especially fragile and prone to anthropogenic disturbance. Logically, this would be the case as the poorest sections of society, and refugees or migrants from other countries, only have access to customary and common lands and will do everything they can to survive on the limited resources they have access to, leading to increased degradation, as environmental protection is not their priority. There is also some evidence that differences in inheritance patterns can impact tree planting in an area, with patrilineal inheritance (where the wife moves to her husband's village) encourages tree planting more than matrilineal inheritance (Hansen et al. 2005).

As a reaction to the strict laws governing access to land and forest resources following the colonial period and under Banda's authoritarian post-independence regime, there is anecdotal evidence that many communities rebelled against this during the transition to multiparty democracy by deforesting forest reserves because they had previously been forcibly denied access to these government-controlled forests, which were seen as a communal resource (Mhango, *pers. comm.*).

1.8.5 Topography

Due to the substantial impacts topography has on the use of remote sensing imagery, a short description of Malawi's major topographical features is necessary.

About three-quarters of Malawi consists of consists of plateaux at elevations of 750-1300 m asl (figure 1.4). The topography is flat to rolling,

with scattered rock inslebergs. The soil is deep, well drained latosols on higher parts of the catena, with poorly drained sand and clay in the hollows forming marshy areas known as dambos (section 1.8.1.2) (Campbell 1996). The lakeshore plains of the Upper Shire Valley cover around 10% of Malawi's land area at 450-600 m asl. The land is flat to gently undulating, with deep calcimorphic soils in the hollows. Mopanosols are found in some areas (Campbell 1996). The Lower Shire Valley is the most southerly, lowest, and most humid part of the country at mostly less than 180 m asl. The highlands consist of isolated mountains between 1350-3000 m asl. The most extensive highland plateaux are the Nyika, Viphiya and Mulanje, while Dedza and Zomba are more isolated. The escarpements associated with major fault lines along the edge of the Rift Valley run the length of the country.

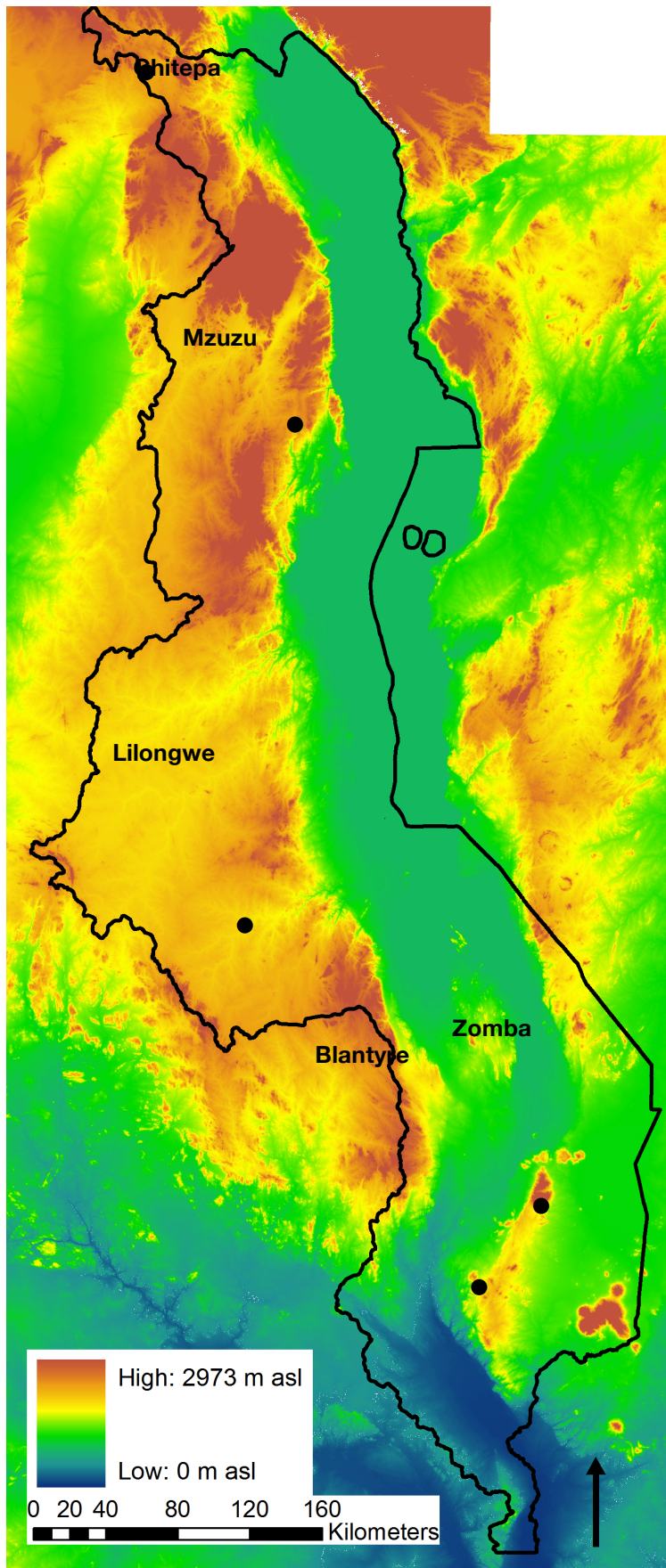


Figure 1.4 Topographic map of Malawi from SRTM data. Malawi has areas of steeply varying topography that can make remote sensing analysis difficult. For much of Malawi, it is the hilly areas that still have forest left on them, which compounds this problem.

1.8.6 Development of Malawian Forestry Policy

Having considered the socio-economics of miombo woodland in Malawi, and some of the complex issues impacting Malawian forest use more generally, this thesis will now consider the development of Malawian forestry policy.

There has been something of a boom of awareness in Malawi relating to the importance of environmental security and sustainability, particularly with regards to forest resources, since the mid-1990s. This occurred for a number of reasons, the first being a change of government in 1994 when Dr Hastings Banda was deposed by a national referendum ending an era of autocratic and authoritarian control that had been in place since the country gained independence from British rule in 1964. The new democratic government headed by Bakili Muluzi (1994-2004) moved the principles of participation, partnership and poverty-focused development to the forefront of the national agenda (Mayers et al. 2001). The importance of forests for maintaining rural livelihoods and producing vital government revenue resulted in the launch of a new Forest Policy in 1996 and the Forestry Act in 1997, highlighting the principles of co-management and increased private sector involvement in the forestry sector. This new forest policy also began to focus attention on the fact that a large proportion of Malawi's population relies on subsistence agriculture to meet their basic needs, and that most households have only a hectare or so of land from which to do this.

The policy revision allowed the Forestry Department an opportunity to publicly respond to the increasingly severe problem of forest degradation and the urgent needs of the poor to acquire better access to forest goods and services (Mayers et al. 2001). With the support of two key international agencies (the UK's Department for International Development (DFID) and the UN agencies' Programme on Forests), Malawi began working on developing its National Forest Policy (NFP),

which was launched in 2001. The NFP lays down twelve strategies designed to focus activities in the forestry sector on the development of sustainable forestry and the improvement of forest services for Malawi's smallholders. A revision to the Forestry Act of 1997 is currently in progress, and is designed to update Malawian forestry law to reflect the significant national and international changes taking place in forestry, including the proposed introduction of REDD+.

French (1986) argues that the low price of firewood from customary land in Malawi is a barrier to reforestation efforts, as there is no economic pressure in favour of it, especially when this is combined with the comparatively long waiting time needed for reforestation schemes to have an effect on timber supply. While this study is over 20 years old, it still echoes some of the problems facing Malawi's forestry sector today, as Malawian timber sells for much less than that of surrounding countries due to a fixed government price, increasing demand both externally and internally (Luhanga 2009).

1.8.6.1 Forest management institutions in Malawi

The Department of Forestry (DoF) is the government department designated with the task of managing and regulating all forestry activities in Malawi. While primarily concerned with managing tenders for commercial timber concerns, and forest reserves, the department also engages to a more limited extent with communities who manage village forest areas through extension activities. This is starting to change with the European Union (EU)-funded Improved Forest Management for Sustainable Livelihoods Programme (IFMSLP), which is focused on the role of forests for poverty alleviation. The Forestry Research Institute of Malawi is a satellite institution to the Department of Forestry, and is designed to provide scientific data to inform Department of Forestry activities, although there are often crossovers in their responsibilities.

1.8.6.2 Challenges faced by forest management institutions

The DoF and FRIM are chronically underfunded and face a shortage of trained staff. There is only one person with training in remote sensing image analysis currently working for the DoF, but they are left to create maps from out-of-date imagery using limited GIS software (ArcMap) rather than dedicated remote sensing software that most remote sensing scientists in the developed world take for granted. There are a few others at FRIM that have some training in remote sensing and the use of GIS, but again they rely on limited GIS software (ArcMap or ArcView), and have limited access to remote sensing data.

Both Bunda College and Mzuzu University have forestry degree programmes, with Chancellor College offering degrees in Geography and Environmental Science. However, students at all three institutions are usually taught GIS and remote sensing theoretically, with only a small amount of practical lab time, due to a lack of computing facilities at their institutions. This means that once they graduate, and move onto jobs, many with the DoF or FRIM, they can lack confidence in suggesting or implementing GIS or remote sensing based projects.

Internet access is slow, expensive and subject to frequent outages, although this is changing as 3G coverage becomes more extensive and affordable, and a new cable broadband is being developed. However, it means that access to free data sources such as the Landsat archive is currently difficult and time consuming for many forestry professionals in Malawi. There is also a lack of knowledge about where to access free data, or about projects or foundations offering imagery grants (such as Planet Action or the GeoEye Foundation). Again, this is hampered by a lack of consistent internet, and exacerbated by frequent power outages.

1.8.6.3 Developing practical solutions

There is considerable enthusiasm over the potential uses of GIS and remote sensing from the DoF and FRIM. In order for a forest cover

change or biomass mapping methodology to be handed over to the DoF and FRIM, and actually be useful, easy to update and understandable, it needs to be simple to implement within this environment. In short, data needs to be free or low cost, and people must be able to be trained to utilise it easily with comparatively little computing knowledge if it is to have any value as a repeatable methodology. These constraints have influenced the choice of data and software selected for use in this thesis.

Field measurements of forest parameters needs to be simple to make with minimal equipment. For example the Department of Forestry currently has no access to a total station/EDM so while the use of GPS is vital for linking field measurements with satellite imagery, survey-grade precision is too costly and time-consuming to achieve. Indeed it is probably not necessary given the scales of imagery being dealt with when national mapping is being considered, and few studies bother with the extra time and expense. The key measurements for forestry inventories are coordinates of plot locations and ddb of every tree larger than 5 cm ddb. Height measurements are an advantage but for the allometric equation selected for miombo woodland for use in this thesis it was not necessary. If other allometric equations were used or developed for miombo woodland that did include height it would be an advantage to collect this now so that the data may be archived and used in the future. However, additional time taken to collect height data using clinometers or the extra expense of using vertex hypsometers might mean this is not feasible for routine monitoring.

2. Introduction to data sources

This chapter provides details of both the field and remote sensing data used in this thesis. It gives an overview of the main satellite remote sensing methods for estimating forest cover and AGB, and provides an overview of some of the challenges inherent in each particular type of imagery, as well as providing background on why specific sensors were chosen in for use in this thesis, with regard to the criteria stated in section 1.6, which are elaborated on further here.

Finally, this chapter will provide detailed descriptions of the field sites and methodology used to collect the forest inventory data utilised in this thesis.

2.1 Introduction to remote sensing

There are a number of different ways of using remote sensing data to monitor forests. These include mapping forest extent and species composition, and above-ground biomass (AGB) (and consequently carbon stocks), as well as changes in these metrics. Estimating AGB using satellite data been a major goal as REDD+ gains support and momentum, as it removes some of the problems associated with defining what a forest is, and how deforestation and degradation are defined.

There are three main types of satellite Earth observation sensors suitable for forest mapping, namely radar, lidar and optical. Radar and lidar are both active systems, which means they provide their own energy source as well as measuring the response returned from the Earth surface. Optical sensors are passive systems, and rely on illumination from the Sun. Remote sensing methods provide the opportunity to conduct repeatable observations over large areas that would be prohibitively costly and time-consuming, if not impossible, to conduct on the ground. In many cases it also allows access to a large historical archive that can be

used for historical change detection. This is especially important for most developing countries, as they have been unable to conduct consistent national forest inventories in the past. These different sensor types will be explained in more detail below. Table 2.1 summarises some of the different types of imagery available, as well as the main features and drawbacks of these different data types, and figure 2.1 illustrates these differences.

Table 2.1 Comparison of different remote sensing sensors, using specific platforms to provide examples

	Low resolution optical (MODIS)	Moderate resolution optical (Landsat)	High resolution optical (IKONOS)	Synthetic Aperture Radar (ALOS)
Pros	<ul style="list-style-type: none"> Free Many processed data products available Large tile sizes so calibration of scenes to each other is often not required 	<ul style="list-style-type: none"> Free Long historic archive Data still being collected Moderate resolution (~30m) 	<ul style="list-style-type: none"> High resolution (<2 m) allows individual trees to be seen Can be used to 'eyeball' areas using GoogleEarth 	<ul style="list-style-type: none"> No problem with cloud cover Relatively frequent data passes (42 day repeat) Moderate resolution (supplied at 12.5m, usable at ~25m)
Cons	<ul style="list-style-type: none"> Low resolution (250m - 1km depending on product) HDF files (MODIS standard format) require specialised software to open and manipulate 	<ul style="list-style-type: none"> Strongly affected by atmospheric conditions, particularly cloud cover Landsat 7 ETM+ sensor scan line corrector failure, hampering data collection since 2003 	<ul style="list-style-type: none"> Commercially expensive, although there are some scientific use agreements that give data away free or low cost (for example GeoEye Foundation or Planet Action) 	<ul style="list-style-type: none"> Commercially expensive (~€500 per scene), cheaper to research institutions through scientific use agreements (~€50 per scene) Requires specific software and specialist training to use Problems in areas with lots of topographic variation

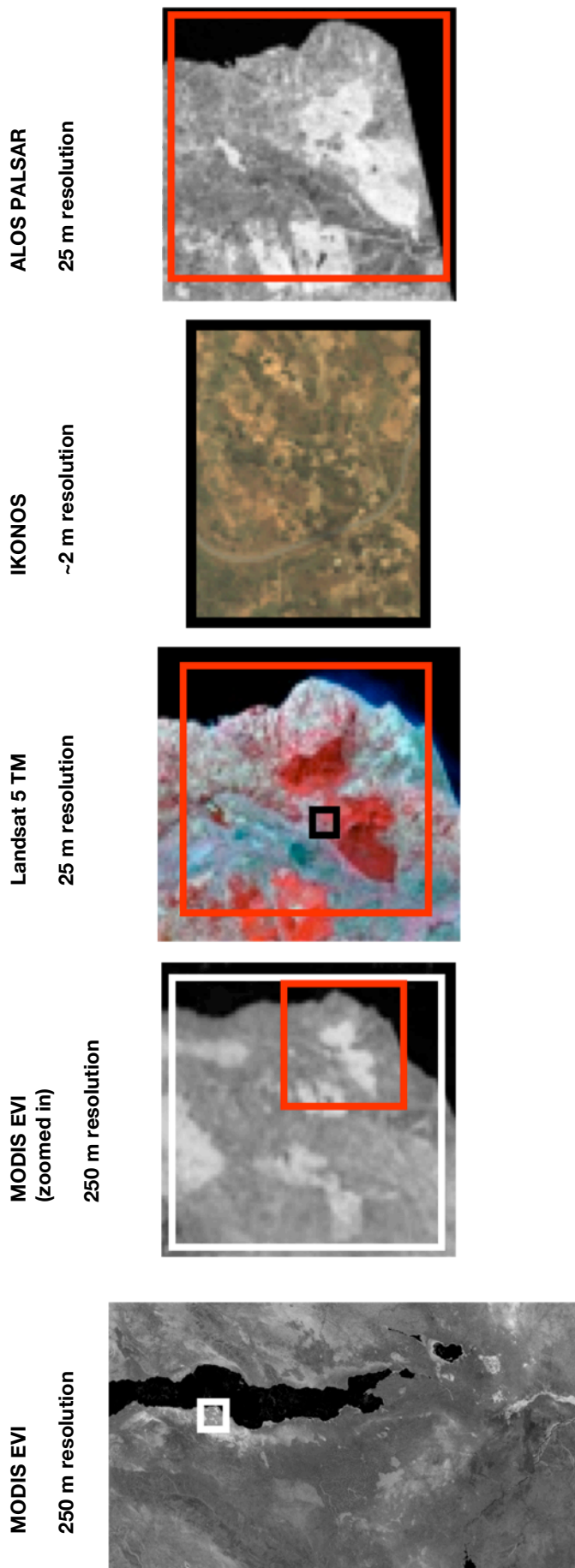


Figure 2.1 Comparison of the resolution of different remote sensing sensors. The white, red and black boxes on or surrounding each image indicate imagery is from the particular geographic area that box covers. From left to right: Malawi, as part of a MODIS EVI product tile; a zoomed-in view of Mkuwazi Forest Reserve from the MODIS EVI tile; additional detail is seen in this false colour Landsat image (designed to highlight vegetation, in red), which is further zoomed in over Mkuwazi Forest Reserve; a portion of a true-colour IKONOS image, which shows the presence of individual trees; an ALOS image (HV polarisation, resampled to 25 m), to show the differences between radar an optical imagery.

Each sensor type has its own particular sensitivities, as well as its own particular error sources and potential artefacts. Users need to be aware of these issues when selecting data sources for a particular research question. Also, these different methods of remote sensing are not exclusive, and a number of studies have used data from multiple sources to obtain a detailed understanding of forest environments (Holecz et al. 2009, Wang and Qi 2008, Schmidt et al. 2012).

Table 2.1 begins to give an indication of why there is no single perfect remote sensing data product. When considering the requirements for mapping forests in Malawi outlined in Chapter 1, it becomes clear that there are compromises inherent in using any particular dataset. For example MODIS and Landsat data are free, and comparatively easy to process, but compromise on resolution or may be strongly impacted by cloud cover which compromises on coverage. Radar data has the potential to provide estimates of biomass, the key variable of interest to REDD+, but is more expensive and complicated to process. Why particular datasets have been selected for use in this thesis is covered in section 2.1.3.

The following sections provide a more detailed overview of satellite remote sensing for forestry, including a brief introduction to how the different sensors work.

2.1.1 Optical sensors

2.1.1.1 Passive

Optical remote sensing is the term used in this thesis for the passive sensing of solar energy reflected from the Earth's surface in the visible, near and middle infrared areas of the electromagnetic spectrum (approximately 0.4 - 2.5 μ m) (figure 2.2). These are normally split into four regions in terms of wavelength: visible, near-infrared (NIR), short-wave infrared (SWIR) and thermal infrared. The most common areas of the

spectrum for monitoring vegetation are the visible, NIR and SWIR. NIR and SWIR are often used in vegetation studies because of the high reflectance of vegetation at these wavelengths (figure 2.3). For thermal infrared, the emission of electromagnetic radiation from the objects themselves is detected, which allows sensors to directly estimate the temperature of objects (Jacob et al. 2004). The optical sensor records these areas of the spectrum as 'bands', which are narrow portions of the spectrum. These bands will be broadly analogous between different sensors, but not necessarily exactly overlap.

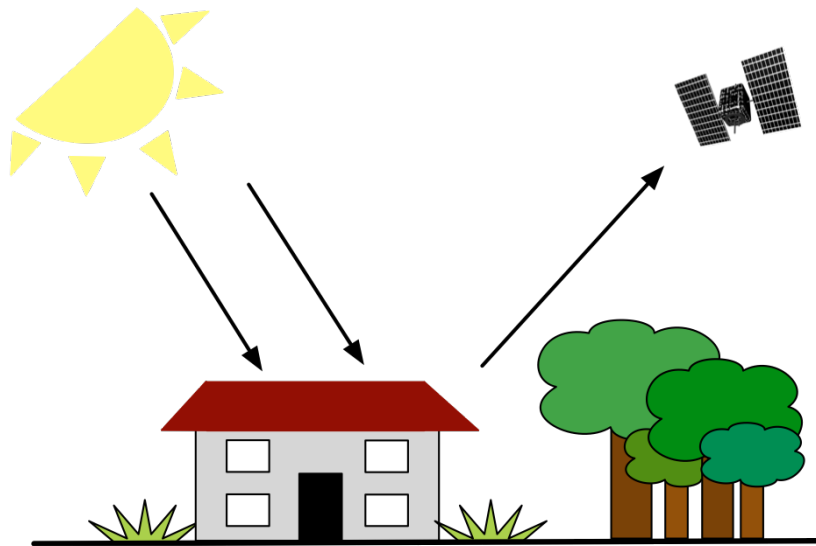


Figure 2.2 Optical sensors record sunlight reflected from the surface of the Earth

The narrower the bands, the greater the sensor's capacity to differentiate between landcover classes/states using spectral information.

Hyperspectral sensors, such as NASA's Hyperion satellite sensor, can give full reflectance signatures using hundreds of narrow bands (Hyperion has 220). This can give sufficient detail of spectral responses to be able to build a full reflectance signature. However, there are no current or planned hyperspectral satellite sensors that cover enough of the Earth's surface at a useful spatial resolution to be used for mapping and monitoring forest cover at national or regional scales. For example, Hyperion's image size is 7.7 x 42 km (for comparison Landsat is 185 x

172 km), and does not cover the entire globe, as coverage is dependent on fulfilling specific user requests. Therefore this thesis only considers multi-spectral optical sensors.

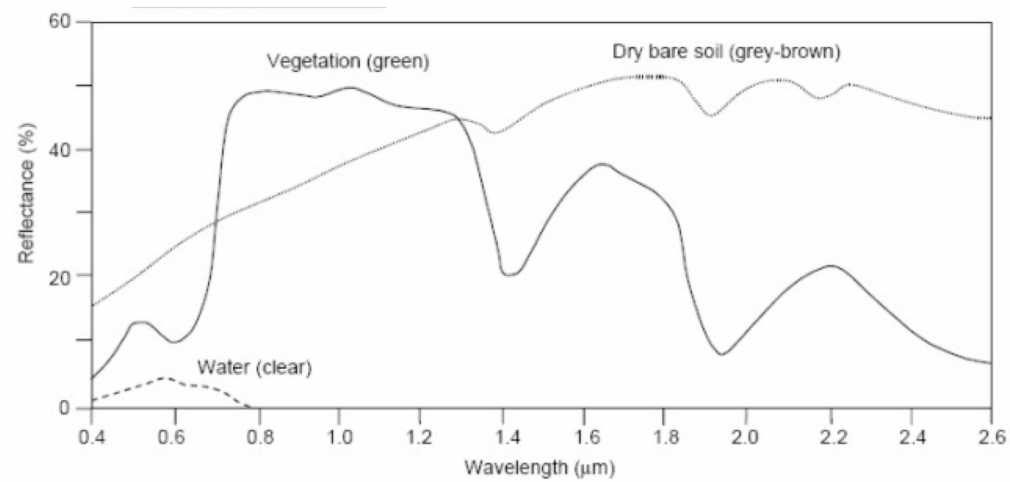


Figure 2.3 Typical spectral reflectance curves for vegetation, soil and water (from Swain et al. 1978)

Different bands are often combined into metrics that give more information on land cover than an individual band. The metrics used in forest mapping are known as ‘vegetation indices’, with the most commonly used being the Normalised Difference Vegetation Index (NDVI), which is a ratio of red and infrared bands, that responds strongly to the amount of green vegetation in a pixel. NDVI was first used in 1973 (Rouse et al. 1973) has been used to map forests since the early 1980s (for an early example, see Berberoğlua et al. 1980).

There are a large number of optical sensors currently in orbit, and they differ in both the spectral bands there are sensitive to, and in their temporal and spatial resolutions. In general, there is a trade-off between spatial resolution and repeat time. The NASA MODIS sensor (on board two satellite platforms, TERRA and AQUA) collects data at 250 m resolution and images the whole surface of the Earth 2-4 times a day. Landsat has a 30 m resolution, and a 16-day repeat cycle (it returns to

the same spot on the Earth's surface every 16 days), while IKONOS has a multispectral resolution of 4 m (0.8 m for its panchromatic band), but a 144-day repeat cycle for true-nadir imagery, although the satellite does have a pointing capability which can be used to reduce this.

The choice of sensor will depend on the type of monitoring activity being conducted. Generally, optical sensors are best suited for the acquisition of horizontal structural information, for example canopy cover (Kellndorfer et al. 2004), but are limited in providing vertical structural information by their inability to penetrate through the vegetation. This is particularly true as canopy density increases (Kellndorfer et al. 2004) and vegetation structural complexity increases. Different applications use varying spatial resolutions (that is, fine, medium and coarse)². Other factors, such as the cost of the imagery (which generally increases with improved resolution, with most coarse resolution data being distributed free of charge), and the availability of comparable historical data if conducting change detection are also considered. Very high resolution satellites have only become available comparatively recently, and as it normally needs to be ordered on demand there is not always consistent coverage. However in some cases aerial photography and/or satellite imagery do allow historical analyses, and this is increasing with the declassification of data collected by military satellites in the 1960s and 1970s (Hamandawana 2011, Donoghue 2000).

MODIS and Landsat are both widely used because of the high number of observations, and the excellent geolocation and radiometric accuracy (Wu et al. 2011), and because all the data collected is freely available and easily accessible online. Landsat is one of, if not the, most widely used

² Fine resolution refers to data with a resolution of less than 10 m. Medium resolution is refers to data measured in tens of meters (most commonly 10-30 m), and includes sensors such as Landsat. Coarse resolution refers to sensors such as MODIS, with a resolution on the scale of hundreds of meters or kilometres.

remote sensing product for land cover mapping, with long historic archive dating back to the 1970s. It has been freely available since 2008. Despite problems that have plagued Landsat 7 since 2003, and Landsat 5 ceasing operations in November 2011, Landsat still offers fairly regular sources of medium resolution land cover data.

2.1.1.2 Active

Lidar (LIght Detection And Ranging) was not used in this thesis, so is only mentioned briefly for completeness. Lidar is an active sensor, which uses visible or shortwave infrared laser data to gain an understanding of the vertical structure of the forest canopy. Lidar sensors normally look vertically down at the surface. Modern lidar sensors can detect the ‘full waveform’ reflected from the surface, which means that for a forest canopy, the relative reflective power of different levels of the canopy can be detected (Lim et al. 2003). ‘Pulse’ lidar gives the first and last returns (that is the top of the canopy and the ground return), and is cheaper to use and can be easier to analyse, although you lose the full profile through the forest canopy (Lim et al. 2003).

Collecting lidar data from space is still a developing technology, and so far only one sensor (ICESat, launched in 2003 and retired in 2009) (NASA, 2003) has successfully collected data useful for retrieving information on forest characteristics. The cost of flying airborne lidar is a significant barrier to its use by developing countries, despite the high resolution data that it can provide (Lim et al. 2003). However, 4.3 million hectares of the Peruvian Amazon have recently been inventoried using lidar (Asner et al. 2010), and Mitchard et al. (2012) have used lidar and ALOS PALSAR to map areas of high biomass in Gabon.

Due to the nature of the lidar system, it is usually used as a sampling tool for calibrating and validating other types of remote sensing data (Wulder et al. 2012, Nelson et al. 2012). This is especially true for spaceborne lidar

systems. For example ICESat had footprints at the equator approximately 0.25 ha in size, separated by several hundred meters along track, and several kilometres across track (part of the reason for this separation is because ICESat was designed to be used for monitoring changes in glaciers and ice sheets, and so was designed with a denser sampling strategy at the poles) (NASA, 2003). The use of ICESat for vegetation studies was a side benefit of the original mission.

2.1.1.3 Challenges when using optical sensors

Passive optical imagery is currently the most widely used operationally for tropical deforestation monitoring (DeFries et al. 2007). However in the tropics, persistent tropic haze can limit its usefulness, as it may be weeks or months before cloud-free images are obtained. Duveiller et al. (2008) used 390 Landsat images to analyse deforestation and forest degradation across the Congo Basin, Central Africa, despite the fact that their estimates in coastal areas were not robust due to a lack of cloud-free imagery. In drier savanna areas optical data has been used with more success. Although Landsat data has been used for previous studies into deforestation in Malawi (Hudak and Wessman 2000), it can be difficult to obtain sufficient imagery. Lake Malawi provides a consistent source of moisture even during the dry season, when one could reasonably expect to find regular cloud free images throughout this region, which can limit the availability of imagery.

When the transparency of the atmosphere is reduced by the condensation of atmospheric water vapour (forming haze or clouds), the spectral characteristics of optical imagery can be changed to such an extent as to render it unusable. Nothing can be seen through cloud by the wavelengths used to map vegetation. If multiple scenes are being used to map an area, then these scenes need to be cross-calibrated to ensure that the effects of the atmosphere are removed as much as possible. Full atmospheric correction is a complex process that is best achieved using

on-the-ground measurements made as the satellite is passing overhead. As this is not usually practical, scenes are commonly corrected using the dark object method. This methodology compares the reflectances of known areas of reflectance (typically water bodies) with expected values (typically close to 0, as objects are chosen to be 'dark objects' or areas with low reflectance), and shifts the spectral response to more closely match the expected reflectance of the dark object.

The frequent repeat rate of MODIS means that some cloud free imagery can normally be guaranteed, although Landsat can be much more challenging. Repeat imagery can be used to fill in areas masked by cloud in other images. Having these repeat passes close in time helps to avoid missing changes in areas covered by cloud. MODIS composite products use this strategy to produce 8- or 16-day averages compiled from daily passes by the Terra or Aqua platforms. The USGS also produces a number of products derived from MODIS data, including a number of vegetation parameters such as NDVI as well as land cover classification products that are based on these composite data products. MODIS products have a relatively coarse resolution, typically ranging from 250m-1km. While this resolution will miss the finer scale trends occurring within a country, it should be sufficient for fast, regular mapping of major trends. MODIS also has large tiles, which means that almost all of Malawi (bar a very small fraction of the northern tip of the country) is on a single MODIS tile, which means problems of cross-calibration between scenes are removed.

One additional challenge with Landsat data is that in 2003 the Scan Line Corrector onboard the Landsat 7 EMT+ sensor failed, which means that approximately a third to a half of each scene is missing, and needs to be filled in using other passes from the sensor. Landsat 5 had continued to collect data intermittently (it was not used continuously to try and extend

the satellite's lifespan), but was switched off indefinitely in November 2011 due to signs of 'impending failure'.

2.1.2 Radar

Radar (RADio Detection And Ranging) sensors use a different area of the electromagnetic spectrum to optical sensors, and are sensitive to very different characteristics of the Earth's surface. Radar sensors are active sensors that use their own energy source to direct a pulse of radiation at the surface, and then detect the returns. Radars use the microwave portion of the electromagnetic spectrum, and the wavelengths typically used for mapping vegetation vary from 1 cm to around 1 m (300 MHz - 30 GHz). All radar systems are side looking, and spaceborne radar sensors normally send the pulse out between 20° and 40° relative to the Earth's surface. The majority of the signal will reflect in the opposite direction, away from the satellite, but some of the radiation pulse interacts with the surface and is scattered back towards the sensor (figure 2.4). This detected radiation is called 'backscatter' and is often reported as sigma-nought (σ^0), defined as the normalised radar cross-section, scaled in dB.

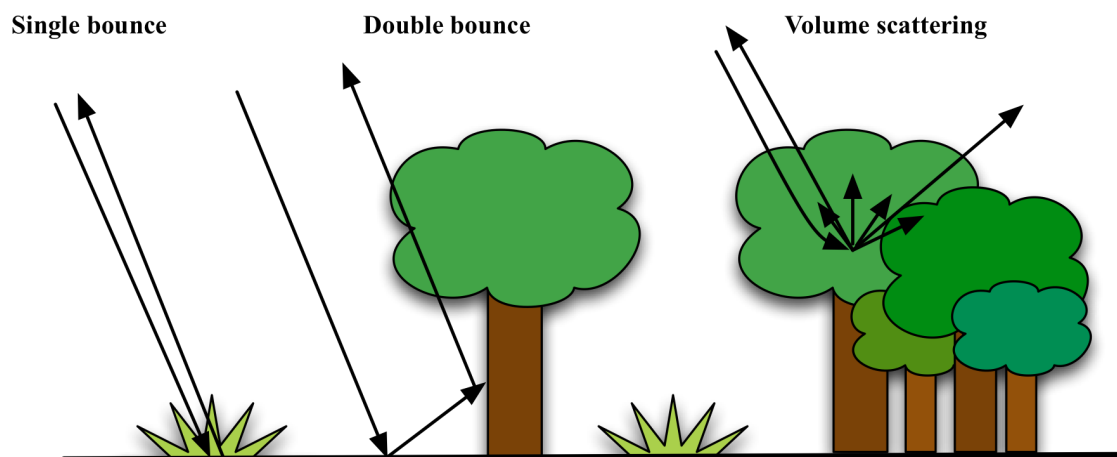


Figure 2.4 Radar scattering mechanisms depend on the type of feature the microwave pulse is interacting with.

Unlike optical EO, microwaves are not impeded by the need to work solely in daylight conditions, or by atmospheric conditions. For example haze, clouds and light rain have little impact on microwave transmission, making them ideal for use over the tropics where persistent haze limits the effectiveness of optical imagery. Imaging radar is the most popular choice for monitoring forest cover, although radar scatterometry, which takes isolated measurements of backscatter response as a function of the depth of the target has been used in previous studies (Hardin et al. 1996, Woodhouse 2000), but at much lower resolution. SAR (Synthetic Aperture Radar) is the most common type of imaging radar.

The use of SAR data is often hindered by the fact that analysis is more complex than that of optical data, and requires a much greater understanding of mathematics and physics in order to use the data effectively, despite their suitability for use over the tropics. Some of the more complex aspects of radar processing, such as interferometry, are not used in this thesis, and it is not necessary to understand the more technical aspects of radar data in detail for the purposes of the analyses presented here. However more details can be found in Woodhouse (2006a).

The wavelength of the radar determines what features it will interact with, and its ability to penetrate into surface features. In general, shorter wavelengths interact with smaller target features, which means they will penetrate less far through any surface (Imhoff et al. 1995, Le Toan et al. 1992), so that longer wavelengths (>20 cm) are typically required to achieve any reasonable penetration through a forest canopy.

Radar bands have an illogical naming structure, a legacy from radar's initial use by the military where bands were code-named for secrecy. Table 2.2 gives a brief description of the different radar bands, and satellites that use them. Using a forest as an example, shorter

wavelengths such as X- or C-band, will interact with leaves and twigs, and get ‘caught up’ in the forest canopy so only interact with the top of the forest canopy (Brolly and Woodhouse 2013). Longer wavelengths, such as L-band, will interact with larger features, such as larger branches and stems, and potentially penetrating through the canopy and interacting to a limited extent with the ground. While all bands should be able to differentiate forest from non-forest because of the changes in backscatter from the different surface characteristics, the ability to quantify forest metrics such as AGB is thought to increase with wavelength, because as the canopy is penetrated, the radar backscatter is more strongly influenced by the objects that contain the biomass (stems and branches) (figure 2.5).

Table 2.2 Radar bands and satellites

Band	Wavelength	Frequency	Typical maximum resolution from satellites	Satellites
X-band	2.5-3.75 cm	8-12 GHz	~1 m	TerraSAR-X (2007-) TanDEM-X (2010-)
C-band	3.75-7.5 cm	4-8 GHz	~3 m	ERS-1 (1991-2000) ERS-2 (1994-) ENVISAT (2002-) RADARSAT 1 (1994-) RADARSAT 2 (2007-)
L-band	15-30 cm	1-2 GHz	~20 m	JERS-1 (1992-1998) ALOS PALSAR (2007-2011)
P-band	70-130 cm	230-430 MHz	~50 m	BIOMASS (potential launch 2016)

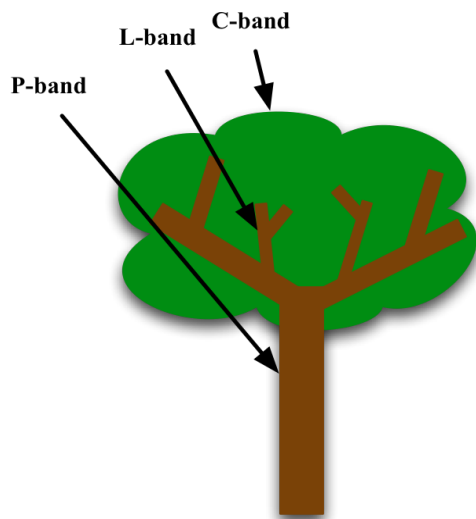


Figure 2.5 Different radar bands interact with different parts of the forest canopy, and penetrate differently into the forest

L-band data from the Phased Array L-band Synthetic Aperture Radar (PALSAR) onboard the Advanced Land Observing Satellite (ALOS) was used in this thesis, as one of the initial goals for this thesis was to map biomass across Malawi in order to evaluate its use for any potential carbon finance mechanisms that may be developed. ALOS was launched in 2006, and ceased operations in 2011. PALSAR principally collected data in the Fine-Beam Dual-polarisation (FBD) mode, giving HH (horizontal-horizontal) and HV (horizontal-vertical) data, supplied at 12.5 m resolution, but typically usable around 20 m resolution (Rosenqvist et al. 2007). ALOS did have the capacity to collect fully polarimetric data, although this was an experimental mode that only collected a small quantity of data.

2.1.2.1 Polarisation

Information about the polarisation of the electromagnetic wave can also provide additional information about the surface. Radar is transmitted ‘polarised’, that is with all the waves oriented in the same plane. When a signal interacts with the Earth’s surface, this polarisation can be changed, so sensors are often designed to detect returning radiation both in the original polarisation and orthogonal to this, in order to detect the

cross-polarised backscatter. Microwave polarisation is associated with the orientation of the electric field in the perpendicular plane relative to the propagation direction. The most commonly used polarisations are HH, VV and HV (or VH). It is usually assumed that the cross polarisation response is the same for both HV and VH. In general, HV polarisation is thought to give the highest contrast for forest canopies, HH polarisation records its highest backscatter from trunks, because of the interaction between the ground and tree trunks, while VV polarisation gives a highest response when interacting with the ground surface (Woodhouse 2006a).

2.1.2.2 SAR and Forest Mapping

Due to the complexity of the interactions between microwaves and forest canopies, it is often assumed that forest canopies can be considered as essentially a random volume (for example the Water Cloud Model or Random Volume over Ground) (Papathanassiou and Cloude 2001). However, there are other interpretations of the interactions between radar and forests. Woodhouse (2006b) poses a new method of interpreting this relationship, based on the macroecological properties of forests. This model allows for the understanding that forest structures are more complicated than the random models assume, and allows a more detailed explanation of observed backscatter trends, including different circumstances that may cause the saturation point to be reached, as well as the variability seen in many backscatter-biomass studies. Work by Broily and Woodhouse (2012) has extended this by showing that forest structure has a role in causing apparent signal saturation, and changes in basal area are the most significant additional factor impacting forest backscatter.

One of the most common uses for SAR data in forestry studies is to provide estimates of forest biomass, and therefore carbon stocks, as this is the variable of interest for REDD+. Despite some claims to the contrary

(Le Toan et al. 2011), SAR data alone cannot give a quantifiable biomass estimate, it can only identify areas of biomass change (Rosenqvist et al. 2003, Woodhouse et al. 2012). To estimate biomass from a single SAR scene, SAR data has to be combined with field-based estimates of forest biomass. However, this relationship is not always as straightforward as it might appear, and also suffers from a lack of sensitivity (or ‘saturation’), due to a change in the scattering caused by the forest canopy from Rayleigh to optical scattering (Woodhouse 2006a). Exactly where the signal saturates is dependent on wavelength, polarisation, forest structure and the study area more generally.

Studies over different forest types (tropical, temperate and boreal) (Imhoff et al. 1995, Luckman 1997, Hoekman and Quiriones 2000, Kellndorfer et al. 2003, Le Toan et al. 1992) have shown that C-band usually saturates at biomass densities of $\sim 20\text{-}30\text{ t ha}^{-1}$, L-band at $\sim 40\text{-}60\text{ t ha}^{-1}$ and P-band at $\sim 100\text{-}200\text{ t ha}^{-1}$, due to the differing penetrations of wavelengths through the forest canopy. Polarisation also has an impact on saturation, with HV polarisation leading to a higher saturation level, followed by HH and VV in differing orders. The contrast between HH and VV backscatter is greatest for areas with smaller amounts of vegetation due to the greater proportion of bare ground in the image relative to vegetation (Le Toan et al. 1992).

SAR can also be used to obtain biomass estimates by utilising the phase of the returns from two satellite passes over the same area through interferometry. InSAR (Interferometric SAR) can be used to generate height estimates, which through the use of allometric equations can be used to give quantifiable biomass estimates (for example Viergever et al. (2008) who used InSAR for AGB in tropical savanna woodlands). InSAR is only possible over forests using single-pass, as the long repeat intervals for satellite systems inevitably lead to a ‘decoupling’ of the two passes,

due to wind shifting the leaves, for example. For this reason, InSAR was not used in this thesis.

Understanding land use patterns is also essential when interpreting the data, for example shifting cultivation results in a mosaic of clearings that occur over time, which might be mistaken for new deforestation if only one or two images were analysed. Therefore a longer time-series and expert knowledge of the land use patterns and agricultural patterns of the country are required (DeFries et al. 2007). My literature review has shown that there is a distinct lack of information about the backscatter/biomass relationship for African forests, especially for dry tropical woodland savanna or on a sub-regional or national scale. For three of few examples see Mitchard et al. (2009b), Mitchard et al. (2011b), Ryan et al. (2011a).

Research from Belize shows that for sparse canopies, such as savanna woodland, like the *Brachystegia* woody savanna that dominates Malawian forest areas, it is fractional density rather than volume that most influences the biomass/backscatter relationship. Viergever (2008) has shown that L- and P-band backscatter do not have a straightforward correlation with above-ground biomass in savanna areas, despite the common assumption that because these wavelengths saturate at well below the estimated biomass of savanna woodlands they would provide more accurate biomass estimates. It appears that using SAR to map savanna woodlands may require different techniques than those used in closed canopy forest (Viergever et al. 2008).

2.1.3 Using remote sensing in Malawi

Malawi faces a chronic shortage of knowledge about the state of its forest resources, as outlined in the preceding chapter. There has been very little previous research done using remote sensing in Malawi to map land cover or for forestry. As mentioned previously, the last national forest map was

produced by an external consultancy group in 1991/2 using Landsat TM data (Kayambazinthu pers. comm.). A landcover classification was produced with a number of vegetative classes. It is this dataset that has been used to extrapolate Malawi's forest cover change for the national forest reports to the FAO Forest Resources Assessment. Additionally, there have been smaller scaler studies using remote sensing to map forest cover change. For example Hudak and Wessman (2000) used Landsat imagery from 1982 and 1992 to map deforestation in Mzimba district, southern Malawi. They used dry season imagery and NDVI to identify forest areas, and calculated a deforestation estimate of 1.8% forest loss per year over the study period. Only one other study has attempted to use SAR data to map land cover in Malawi. Holecz et al. (2009) used ALOS PALSAR and ASAR data to identify land cover types across Malawi for 2007/8 and found an 80% success rate when compared to in-situ ground classifications.

There have also been studies on the social aspects of using remote sensing to understand environmental processes in Malawi. This research is part of an increasing mass of critical literature on the use of remote sensing to understand the social dynamics of environmental problems (Liverman 1998, Carmenta et al. 2011, Turner 2003). Walker and Peters (2007) worked with communities in two regions of southern and central Malawi to investigate how patterns and trends shown in aerial photography reflect the social drivers of forest cover change, and found that processes that cause deforestation operate at a number of temporal scales, often simultaneously, and these processes cannot be necessarily be inferred from remote sensing data.

As this thesis is focused on the particular challenges and circumstances found in Malawi, the remote sensing options being considered in this thesis are those which best meet the criteria for being most useful within the constraints of Malawi's technical and institutional capacity. These

criteria are summarised here to provide context for why particular datasets were selected. They are expanded on in chapter 6.

In addition to overcoming any technical challenges inherent in a particular methodology or data source, for any remote sensing solution to be made operational in Malawi in a way that is meaningful for Malawi's specific mapping challenges, data needs to be:

- Minimal cost or free. The Department of Forestry has a very limited budget, so low cost data makes it more likely that any methodology will be continue to be used. Distributing data on hard media would also be beneficial, due to Malawi's current slow internet connection.
- Simple to open and analyse by in-country forestry researchers using basic commercial software, or ideally, using freeware or open source software as there is limited access to specialist remote sensing in Malawi. Many remote sensing datasets are distributed in file formats that require specialist software to open, and many also require complex pre-processing prior to use, which can be a barrier to inexperienced users. Any training necessary to utilise the software effectively would need to be given.
- Field measurements of forest parameters need to be simple to carry out with minimal equipment. Height measurements are particularly problematic; clinometers add significantly to the time taken to conduct inventories (meaning increased staff time or fewer areas sampled) and vertex hypsometers are almost prohibitively expensive.
- The remote sensing data needs to produce results that link to international criteria and standards, for example, for REDD+ carbon is the key metric of interest so any methodology for REDD+ will have to be able to calculate carbon (whether directly or indirectly).

These criteria have shaped which remote sensing data products were selected for use in this thesis. While others are available (and outlined above), they have been excluded, as they do not meet these criteria. Chapter 4 examines the use of two different MODIS data products, namely the 250 m resolution Enhanced Vegetation Index and the 500 m resolution Vegetation Continuous Fields. Both of these datasets cover almost all of Malawi in a single scene, and are coarse resolution, which minimises the volume of data required, and as they are products rather than raw data, the processing chain is simplified. They are also freely available to download, and can be processed using open source software. Chapter 5 examines the use of ALOS PALSAR data for mapping forests, and carbon stocks in Malawi. ALOS PALSAR was examined because it was the only spaceborne sensor that could provide estimates of carbon stocks, which is the particular variable of interest to potential REDD+ projects. While SAR data is more expensive, and more complicated to analyse than optical data, this chapter presents results from a number of standardised methodologies that have never been used before in Malawi. If a methodology was found to work, and also met REDD+ requirements, any necessary training could have been provided to in-country scientists in order to make it operational.

2.2 Fieldwork sites

Field data was collected from four sites in Malawi (figure 2.6); the Thazima region of Nyika National Park (10°33'S, 33°50'E), Mkuwazi Forest Reserve (11°72'S, 34°05'E), Kaning'ina Forest Reserve (11°26'S, 34°03'E) and Malosa Forest Reserve (15°11'S, 35°19'E). Historical data from 30 0.25 ha permanent sample plots (last surveyed in 2007) in Liwonde Forest Reserve (15°08'S, 35°18'E) was obtained from the Forest Research Institute of Malawi.

Details of the field data that was used for specific research questions are detailed in the relevant chapters. The descriptions of the fieldwork sites are included here to provide a complete documentation of the both the sites and the methodologies used than is provided in the following chapters.



Figure 2.6 Map of Malawi's national parks (dark green) and forest reserves (light green). Fieldwork locations highlighted in red.

2.2.1 Nyika National Park

Nyika National Park covers an area of 3134 sq km², and is characterised by a mountain plateau ~2600 meters above sea level (m asl), with associated hills and escarpments that descend to ~580 m asl (Department of National Parks and Wildlife 2004). The size of the park prevented a comprehensive study, so efforts were concentrated on the Thazima region, which is located in the Park's southwest quarter, and is characterised by undulating terrain, with only a small area on the plateau. Vegetation is dominated by miombo woodland (figure 2.7), with patches of tropical hardwoods (figure 2.8). There is also an ecotone transition zone between the miombo woodland and the plateau grasslands characterised by scrub-grassland and open canopy woodland dominated by acacia species (figure 2.8).



Figure 2.7 Nyika National Park has a wide variety of miombo environments. Some areas show evidence of historic coppicing as a legacy from when villagers used to live on the plateau, where there can be between 800-1200 stems per hectare (left). There is also evidence of elephant modification, from the herd that lives on the plateau.



Figure 2.8 Nyika National Park has other ecosystems, including open plains and grasslands (top left), acacia-dominated savanna (bottom left) and patches of evergreen forest (right), with 40-50 m high trees, and significant understory growth, including lianas.

2.2.2 Mkuwazi Forest Reserve

Mkuwazi Forest Reserve is located in the Nkhata Bay district of Malawi. Because of its close proximity to Lake Malawi it has a relatively high annual rainfall of up to 2,200 mm, and high temperatures which average 27°C during the day. These conditions create an environment that favours the development of large broadleaved trees. While the species found here include those common to miombo woodland found across the country, they are often older, and consequently larger, than average (figure 2.9). The area is dominated by *Bracystegia speciformis*, *B. Longifolia*, and on the lower drier slopes evergreen forest composed of *Afrosersalisia cerasifera*, *Erythrophloem saueolens*, *Pterocareous stoltzii* and *Chlorophora excelsa* along rivers and in damper areas (Chapman and White 1970).



Figure 2.9 Mkuwazi Forest Reserve has a mix of old growth miombo (40-60+ year old stands) in the centre (left) and younger, denser evergreen species with a thick understory (right) around the edges.

2.2.3 Kaning'ina Forest Reserve

Kaning'ina Forest Reserve covers an area of 142 sq km² and is located to the east of Mzuzu, Malawi's third biggest city. The reserve covers predominantly undulating terrain and is composed primarily of miombo woodland (figure 2.10), but also includes several areas of exotic pine (*Pinus patula*) plantation. In line with current recommendations from the Department of Forestry, priority is being given to log the pines and replace them with native species, but lack of a commercial concession to do the logging is slowing progress. The forest reserve provides vital fuel wood resources for the city, but due to overuse restrictions have been put in place. Only deadwood should be taken and collection is limited to Tuesdays, Thursdays and Saturdays. However these policies are largely ineffective, as people simply collect more wood on the days when they are allowed in to the Forest Reserve, and given the size of the reserve, and the small number of staff to patrol it, collection of live wood is still continuing.



Figure 2.10 Kaning'ina Forest Reserve is well used by local residents, with evidence of paths and collection of dead and live wood. The trees are younger, with significant open space.

2.2.4 Liwonde Forest Reserve

Liwonde Forest Reserve, approximately 189 sq km², is a sparse miombo woodland, dominated by young trees between 5-10 cm dbh, and predominantly *Uapaca kirkiana* in many areas because of disturbance.

Around 200,000 people live around the reserve, which lies approximately 20 km from Zomba, one of Malawi's main towns, and 70 km from Blantyre, Malawi's biggest city. Liwonde Forest Reserve is designated as a key Impact Area for IFMSLP, because of its importance in catchment protection and stabilisation for the lower Shire river, which is used to generate 98% of Malawi's electricity through hydroelectric power stations along the Lower Shire (the remaining 2% comes from an HEP plant in the northern region). Encroachment and illegal settlements are also a problem in the reserve due to unclear boundaries.

2.2.5 Malosa Forest Reserve

Malosa Forest Reserve covers approximately 85 sq km², and is often included as part of Zomba Forest Reserve, which it joins at its southern limits. It is separated by less than a kilometre from Liwonde Forest Reserve, where the two reserves are closest, with a similar climate and forest composition. There is a buffer zone of exotic *Eucalyptus* around the south-west of Liwonde and northern part of Malosa, where the two reserves meet. The reserve covers undulating terrain that is increasingly

steep towards the western edges of the reserve, and increases as towards the Zomba plateau. The western side of the reserve consists of sparse miombo woodland, while the eastern side is almost bare in places due to overuse (figure 2.11). The Zomba-Malosa Forest Reserve is also the main source of water for most inhabitants in the region, with 5 rivers originating in the catchment area. This water supplies many towns and villages including Zomba itself, which is home to several government agencies and Chancellor College, part of the University of Malawi. The 5 km buffer zone around the Zomba-Malosa Forest Reserves contains 496 villages, with 90% of the people in this area being wood dependent for their livelihood (Government of Malawi 2001).



Figure 2.11 Malosa Forest Reserve is predominantly composed of miombo woodland (left), although forest cover is slowly being cleared through overuse (right), primarily for charcoal production, driven by demand from local towns and villages.

2.3 Forest Inventories

2.3.1 Initial Field Campaign

Forest inventories for Nyika and Mkuwazi were collected during October 2008 in collaboration with local communities, the Department of National Parks and Wildlife, the Department of Forestry and the Forest Research Institute of Malawi, as well as staff and students from Chancellor College, Malawi, and the University of Edinburgh. A total survey of 203 plots was undertaken, with individual measurements of 3,733 trees. Twenty plots had to be excluded from analysis due to incomplete or

missing data, leaving a total of 183 0.1 ha plots. Based on visual analysis of Landsat 7 ETM+ data from 2000, existing literature and community interviews, a stratified random sampling technique was implemented, based on the estimated proportional cover of each forest cover type, following standardised methods for forest inventory (Pearson and Walker 2005). Plot locations for each stratum were determined on a regular 250 m grid from random starting points for areas where understory vegetation did not inhibit movement, and by selecting a random distance along existing paths and a random distance from the path (between 20-200 m) in areas with dense understory vegetation. Circular temporary nested sample plots were used in vegetation with a more open structure, while square plots were used in areas with dense understory.

For each plot the longitude, latitude and altitude were recorded, in the centre of the plot for circular plots and in the southeast corner for square plots using a handheld GPS (Garmin 60CS, Garmin, USA), with a horizontal positional accuracy of $\pm 3\text{-}5\text{m}$. Each plot was also assigned one of five designations based on the dominant type of woodland present. These designations were miombo, evergreen/riverine, shrubs and scattered trees/savanna, open grassland and cultivated land. For each tree in the plot greater than 5 cm in diameter, stem diameter at 1.3 m above the ground (dbh), species and height by visual estimation was recorded.

The results of these field measures were converted to plot-level estimates of above-ground biomass (AGB) using appropriate allometric equations depending on the dominant forest type of the plot. There are very few allometric equations developed specifically for miombo (Abbot 1999, Frost 1996, Chidumayo 1997, Ryan et al. 2011b) and those found all deal with miombo woodlands as a whole rather than on an individual species level. The allometric equation used in this study was developed for miombo woodland in Mozambique by Ryan et al. (2011) after finding that the

other available equations did not accurately predict the growth curves they observed in their sample plots. For the other areas of woodland covered by this field survey other allometric equations from published sources were used. A generic dry tropical woodland equation from Brown (1997) was used for evergreen and riverine forest and the equation developed by Rosenschein et al. (1999) was used for areas of acacia-dominated savanna (Table 2.1).

Table 2.1 Allometric equations for different forest types. Dbh is stem diameter at 1.3 m above the ground in cm², ba is basal area in cm², exp stands for exponential, and ln is natural logarithm.

Allometric equation	Forest type	Source
$0.0267*dbh^{2.5996}$	Miombo	(Ryan et al. 2011b)
$0.079233*ba^{1.359265}$	Evergreen and riverine forest	(Brown 1997)
$Exp(-1.996+2.32*\ln(dbh))$	Acacia-dominated savanna	(Rosenschein et al. 1999)

2.3.2 Subsequent field campaigns

For subsequent field campaigns, larger temporary forest plots were surveyed, in order to reduce geo-location errors between ground and satellite data, and remove some of the impacts of edge effects (Kangas and Maltamo 2006). These plots were collected from Nyika National Park, and Kaning'ina Forest Reserve in June-July 2009. One 0.5 ha plot, three 1 ha plots and one 1.25 ha plot were completed in total, in Thazima region, Nyika National Park and Kaning'ina Forest Reserve. Each plot ran approximately east-west, to accommodate the side-looking geometry of SAR systems, and where possible preference was given to placing the plots on predominantly flat ground to minimise the impacts of topographic variation when analysing the data. Each plot was laid out as a series of 50 x 50 m subplots. The longitude, latitude and altitude of each subplot corner was recorded using a handheld GPS (Trimble GeoXH),

with a horizontal positional accuracy of less than 1 m. The species, dbh and height using a vertex hypsometer (Haglöp Vertex III hypsometer) of each tree larger than 5 cm dbh in the plot were recorded, giving a total of 3,228 individual tree measurements.

Historical plot data from Liwonde Forest Reserve was obtained from the Forest Research Institute of Malawi (FRIM) in Zomba. This data consisted of thirty 0.25 ha permanent sample plots, which were selected by choosing a random bearing and distance from a path for the initial plot, with all subsequent plots selected by choosing a random bearing and distance from the centre of the previous plot. The permanent sample plots were established in 1998, and were measured again in 2002 and 2007. Plot locations were recorded using a handheld GPS. The species, dbh, and height (estimated using a clinometer) of each tree larger than 5 cm dbh was recorded. Eight 0.25 ha temporary sample plots were collected from Malosa Forest Reserve in August 2010, using the same inventory methodology. Plot locations in Malosa were recorded using the Trimble GeoXH.

3. Academic and research capacity development in Earth observation for environmental management

Gemma Cassells¹, Iain H Woodhouse¹, Genevieve Patenaude¹ and
Mavuto Tembo²

¹ School of GeoSciences, The University of Edinburgh, Edinburgh,
Scotland, EH8 9XP, UK

² Department of Land Management, Mzuzu University, Private Bag 201,
Luwinga, Mzuzu 2, Malawi

In-country capacity to conduct remote sensing research is an important part of REDD+ readiness preparations, as many developing countries lack the necessary historical data to estimate historical forest cover change rates. With the current interest in forest mapping, developing countries are of interest to Earth observation researchers around the globe. One of the best ways of building capacity in Earth observation research is to include developing country authors at all stages of a research project. This paper investigates the extent to which this is the case.

I conducted the data collection and analysis, and wrote the manuscript.

Published in Environmental Research Letters

(Appendix 2 shows the final published manuscript, which is also available at <http://iopscience.iop.org/1748-9326/6/4/044002>)

Abstract. Sustainable environmental management is one of the key development goals of the 21st century. The importance of Earth Observation (EO) for addressing current environmental problems is well recognized. Most developing countries are highly susceptible to environmental degradation, however the capacity to monitor these changes is predominantly located in the developed world. Decades of aid and effort have been invested in capacity development (CD) with the goal of ensuring sustainable development. Academics, given their level of freedom and their wider interest in teaching and knowledge transfer, are ideally placed to act as catalyst for capacity building. In this paper, we make a novel investigation into the extent to which the EO academic research community is engaged in capacity development. Using the Web of Knowledge publication database (<http://wok.mimas.ac.uk>), we examined the geographical distribution of published EO related research (a) by country, as object of research and (b) by authors' country of affiliation. Our results show that while a significant proportion of EO research (44%) has developing countries as their object of research, less than 3% of publications have authors working, or affiliated to, a developing country (excluding China, India and Brazil, which are not only countries in transition, but have well established EO capacity). These patterns appear consistent over the past 20 years. Despite the wide awareness of the importance of CD, we show that significant progress on this front is required. We therefore propose a number of recommendations and best practices to ease collaboration and open access.

Keywords: Capacity Development, Earth Observation, Best Practice

3.1 Introduction

Sustainable environmental management is one of the key development goals of the 21st century. EO is increasingly recognised as a key tool for providing large-scale, up-to-date data about Earth surface processes to aid management decisions. There is growing awareness of the need for developing indigenous capacity across all nations in the application of satellite remote sensing. The vulnerabilities of developing countries to the impacts of climate change and environmental degradation have been highlighted many times (for example Ayers and Dodman 2010, Patt et al. 2010, IPCC 2007). Yet many such countries currently lack the necessary scientific and technical capacity within their research communities to fully assess possible future impacts. They are less able to conduct the multi-disciplinary studies needed to fill gaps in understanding climate change impacts at regional and local levels, or to fully take advantage of the global data sets now widely available (DeFries et al. 2007).

While developing countries face the most pressing threats from environmental degradation, the best EO capacity to monitor these changes lies in the developed world. The aim of this paper is therefore to examine whether this ‘capacity versus needs’ polarisation also occurs in the academic EO literature. This is achieved by exploring publication patterns between developed and developing countries. Notably, we query whether EO research, conducted in or about a given country, involves in-country authors. We first explore this issue broadly by examining the proportion of EO research published about a particular country compared to the proportion of in-country affiliated authors associated with that research. Secondly, by utilising the field of forestry as a test case, we then explore geographically the patterns of authorship provenance and countries as research focus. Our discussion considers whether (and if so how) EO research has responded to meet the developing world’s EO CD needs, and examines wider implications for development and policy-

making. We conclude by proposing 3 strategies for promoting academic and research CD in the EO sector. In the next section, we introduce briefly the development of CD thinking, and discuss the importance of academic-led CD in Earth Observation.

3.2 What is capacity development?

Capacity is defined as the “ability or power to do, understand or experience something” (Oxford English Dictionary, 2010). “Capacity building” involves strengthening particular scientific or technical abilities and resources in individuals, institutions or infrastructure (Wignaraja 2009). Some authors and institutions advocate the use of the expression “capacity development” in recognition of the existing knowledge or infrastructure available (Linnell et al. 2003, Lusthaus et al. 1999, Wignaraja and Yocarini 2008). Some have argued that both expressions narrow focus to mainstream development strategies (Fisher 2010). In this paper however, CD is intentionally loosely defined to be inclusive of a broad variety of development focussed-strategies. While most frequently referring to activities conducted in developing countries, CD is not country nor sector specific. In this paper, we focus on academic and research CD in the EO sector.

A summary of EO activities pertaining to CD has recently been published (Group on Earth Observation; GEO 2006) and a key highlight of this report is the demonstration that the success of EO-related CD depends on the building of capacity in all (not only one) of the following three dimensions: human, institutional and infrastructural. Capacity and performance is a result of the interactions within and between these dimensions. Examples of such successful EO-sector CD within the developing world are found in the fields of weather forecasting and disaster monitoring. CD strategies in these fields were primarily driven by the importance of EO technologies for food security and livelihood

resilience (Quansah et al. 2010, Lewis et al. 2010). The success of projects such as those by Jason et al. (2010) partly stems from their clear definition of technical yet specific goals, realistic objectives, and perhaps most importantly, from a long term commitment to projects and associated CD. Other EO fields have recently received attention, notably that of forest mapping. Such attention has been driven largely by both the United Nation's Food and Agriculture Organisation's (FAO) increasing reliance on remote sensing to produce the Forest Resource Assessments (FAO 2010b), and an increased attention to the need to monitor Reduced Emissions from Deforestation and Degradation (REDD+) from developing countries. REDD+ has been proposed as a global policy instrument for mitigating climate change (Gibbs et al. 2007, Obersteiner et al. 2009).

Within a given country, CD can be driven by internal and external pressures or incentives. While some instances of internally led CD activities (conducted independently from external donor activity) can be found (Eade and Williams 1995, Baser and Morgan 2008), foreign aid programmes have had a predominant role to play in CD (Caplan 2004). Successes have ensued from such foreign aid programmes, but some associated CD strategies have led many low-income countries to become dependent on foreign donors. Results were often constrained by a project's life span, which ultimately led to disempowering the very countries that were meant to benefit from the development (Bankoff and Frerks 2004). Current best practice advocates empowerment: developing countries should design and implement development approaches themselves (Wignaraja and Yocarini 2008, Wignaraja 2009, Brinkerhoff 2009), allowing them to articulate a vision of development that best meets their own situation and beliefs. This shift has taken place largely as a result of the recognition that CD must operate at all levels within a country if donor intervention is to have any lasting long-term impact (OECD 2006, 2008, Wignaraja and Yocarini 2008, Samoff and Carrol 2004).

3.2.1 Academic and research capacity development

“... Research in and with developing countries should - and indeed must - lead to the strengthening of their research capacity.”

- Swiss Commission for Research Partnerships with Developing Countries (KFPE) (1998)

Academic and research CD, and the associated CD necessary to support it, is key to engaging developing country researchers in global academic discourse, strengthening their own skills and confidence in conducting internationally recognized research (Crossley and Holmes 2001). The GEO Capacity Building Strategy (GEO 2006) has identified a need for close collaboration between countries to strengthen institutions and infrastructures, beyond technological and capacity development in developing countries. This does not simply mean developed and developing country partnerships, but also partnerships between developing countries. For example South Africa, Algeria and Nigeria have greater capacity than most of the rest of sub-Saharan Africa with regards to EO expertise (Jason et al. 2010, Gottschalk 2010), and could take the lead in partnering with other countries in the region to develop regional EO capacity. Brazil has also taken on a leading role in South-South partnerships in a number of areas including EO research (Peter et al. 2009). This is illustrated by their commitment to providing free EO data to Latin American and Africa as part of the China Brazil Earth Resources Satellite (CBERS) programme (Ferreira and Câmara 2008).

As a broad generalisation, scientists in developing countries are increasingly becoming concerned about external agencies, institutions and individual researchers operating in their countries with limited regard for local CD or alignment with national and regional development priorities (Samoff and Carrol 2004, Jallade et al. 2001). Regional or country-specific EO research activities that cover developing nations are often not conducted in partnership with local research groups or

institutions. This is understandable given that many EO activities, by definition, are done remotely.

To gauge the extent of this problem, we looked at one aspect of research output, namely research publications in peer-reviewed journals, firstly by searching for papers published by a range of countries defined by their economic status and secondly by investigating the geographical distribution of authors compared to countries of research focus. Notwithstanding the obvious limitation that we only cover published research (much in-country research may not find its way to journals or may be conducted by organisations who have no goals for publishing in this way) we believe this analysis provides a valuable perspective on the effectiveness of EO capacity development. Although WoK does include some journals that are in languages other than English, (that publish abstracts in English), we will be focusing on publications in English-language journals as these form the bulk of WoK citations. We recognise that many developing country authors may be writing for publications written in either their local languages or other international languages (for example French or Arabic), which may alter the overall results of this research. However, WoK does represent a large citation database that should provide an overview of how common it is for developing country researchers to be engaged in the global Earth observation research community.

3.3 Methodology

3.3.1 An Assessment of Publication Output

Approach A:

Articles containing any of the following terms were extracted from Web of Knowledge (WoK) (<http://wok.mimas.ac.uk>), for the period from 1971 to present (Oct 2010): remote sensing, Earth Observation, satellite image, ALOS, Landsat, and MODIS. Our intent was not to develop an

exhaustive database of EO research, but rather to generate a representative overview of EO research. This time period was selected as EO emerged as a discipline around the 1970s. Articles related to meteorology, atmospheric science, oceanography and marine science (using the Boolean NOT option) were excluded.

After these initial search criteria were defined, a list of more than one third of the world's (68) countries was created. Our selection, presented in table 1, aimed at being representative of a broad spectrum of economic development status. Countries falling within each one of the World Bank's 4 economic status categories (World Bank, 2010) were selected ensuring a fair distribution of countries in each of the categories (low, low-middle, upper-middle and high income). Once this list was generated, the name of each country was added as the final criteria to the search terms listed above. Using the analysis feature within the WoK, we then quantified the number of articles per country and the number of articles per country with the country's name also appearing within the author(s)' address. This was repeated for all 68 countries.

3.3.2 Investigating geographic trends

Approach B:

While Approach A allows an assessment of the proportion of papers written about a particular country with an in-country author involved, it does not allow to explore changes in practices over time in EO-specific CD, nor does it enable us to investigate and visualise the geographical distribution of authorship (including the division between first and subsequent authors) compared to countries of research focus. To achieve this, a similar selection approach to that described above was adopted, with two differences. (a) Given the size of the database generated, we constrained our search to forestry, a highly topical research area. In addition to the terms listed in Approach A, the terms forest* or woodland* (* as wildcard) were also used to extract articles. All

conference proceedings were excluded, our aim being to explore the extent of collaboration occurring throughout the research process (from design to peer-reviewed publication). Irrelevant papers accidentally included (e.g. from chemistry, zoology, medicine) were also manually filtered out. (b) To explore whether CD progress has been made in this area, two time periods were considered. The inclusion of CD within the international development agenda is relatively recent and can be traced back to approximately 20 years ago (Wignaraja 2009, Wignaraja and Yocarini 2008). The periods considered here, namely 2005-2010 and 1990-1995 inclusively, were selected to fall well within this timeframe.

Using a random number generator, the selected records were then sampled from the searches, using the record number as a unique reference. A sample size of 20% was generated (n=474 for 2005-2010, n=87 for 1990-1995). For each record, the following information was recorded (a) the country, countries or region(s) in which the research was conducted (b) all authors' country affiliation (listed in the address field for each author). Where more than one address was listed for an author, the first one was selected. Because remote sensing studies tend to lend themselves to large-scale studies, some papers focussed on many countries or even on whole regions or continents. Where papers researched multiple countries, each country was included as an individual entry. The results of these searches were then loaded into ArcMap to allow a visual interpretation of the trends in research patterns (figure 5.3). Choropleth maps were created using 4 frequency classes: less than 1% (highlights those countries that occur particularly infrequently, maybe only once or twice), 1-5%, 5-10% and greater than 10%. While a 10% threshold may seem low, it actually represents a strong degree of dominance in the results and a significant volume of research output and interest, with very few countries exceeding 10%.

3.4 Results and discussion

Our selected list of 68 countries is presented in Table 3.1 and our results from Approach A (section 3.3.1) are presented in figures 3.1 and 3.2.

Figure 3.1 presents our results on a country-by-country basis, while figure 3.2 shows averages and standard deviations per economic status categories. Both figures show that EO research conducted about a low income or lower middle-income country is much less likely to have an in-country author than research conducted about an upper-middle or high income country. We nevertheless found three anomalous countries: China, India and the USA. While these were excluded from figures 3.1 and 3.2, they are further discussed below.

Relative to countries within the same economic status categories, China and India had an anomalously high number of in-country authors relative to the total number of papers published about those countries (79% and 85% respectively). Academically, both China and India stand out compared to other developing countries. They have a significant internal publishing communities illustrated by a healthy number of journals such as the *Journal of the Indian Society of Remote Sensing* or the *Chinese Journal of Atmospheric Sciences*, which target predominantly within country scientists. Most articles in these journals are composed and read almost exclusively by indigenous scholars. The availability of facilities and infrastructure for journal printing and distribution has most likely contributed significantly to the development of these flourishing publishing communities. Also, as countries in transition, both countries have already developed in-house internationally influential and world-leading EO capacity.

The low number of USA-based authors relative to the total number of papers published about the country itself (58%) represents our third anomaly. This result, somewhat unexpected, may be a consequence of many USA “Address” fields listing US States only, rather than the

country itself. As such, several in-country authors may have been excluded from the analysis.

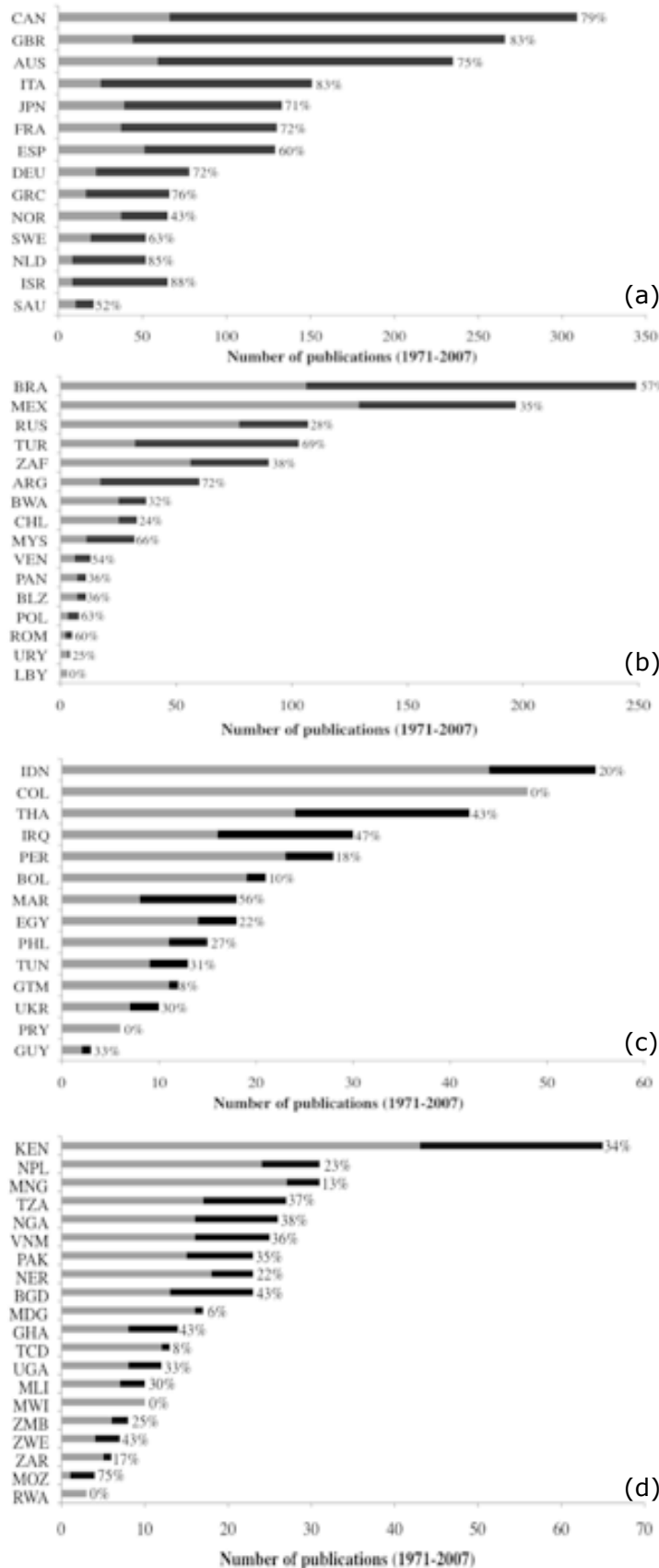


Figure 3.1 Number of publications for a) high income, b) upper-middle income, c) lower-middle income and d) low income countries. Total bar length indicates the total number of publications about the country. The black section indicates the number of papers with the country listed in the author address field. The percentage of in-country affiliated authors compared to the total number publications about that country is given at the end of each bar. Publications written about high and upper-middle income countries have a higher proportion of in-country authors compared to papers written about lower-middle and low-income countries.

Table 3.1 Selected 68 countries and associated country codes (in alphabetical order).

ARG	Argentina	GHA	Ghana	MOZ	Mozambique	RWA	Rwanda
AUS	Australia	GRC	Greece	MUS	Mauritius	SAU	Saudi Arabia
BGD	Bangladesh	GTM	Guatemala	MWI	Malawi	SWE	Sweden
BLZ	Belize	GUY	Guyana	MYS	Malaysia	TCD	Chad
BOL	Bolivia	IDN	Indonesia	NER	Niger	THA	Thailand
BRA	Brazil	IND	India	NGA	Nigeria	TUN	Tunisia
BWA	Botswana	IRQ	Iraq	NLD	Netherlands	TUR	Turkey
CAN	Canada	ISR	Israel	NOR	Norway	TZA	Tanzania
CHL	Chile	ITA	Italy	NPL	Nepal	UGA	Uganda
CHN	China	JPN	Japan	PAK	Pakistan	UKR	Ukraine
COL	Colombia	KEN	Kenya	PAN	Panama	URY	Uruguay
DEU	Germany	LBY	Libya	PER	Peru	USA	United States
DRC	Democratic Republic Congo	MAR	Morocco	PHL	Philippines	VEN	Venezuela
EGY	Egypt	MDG	Madagascar	POL	Poland	VNM	Vietnam
ESP	Spain	MEX	Mexico	PRY	Paraguay	ZAF	South Africa
FRA	France	MLI	Mali	ROM	Romania	ZMB	Zambia
GBR	United Kingdom	MNG	Mongolia	RUS	Russian Federation	ZWE	Zimbabwe

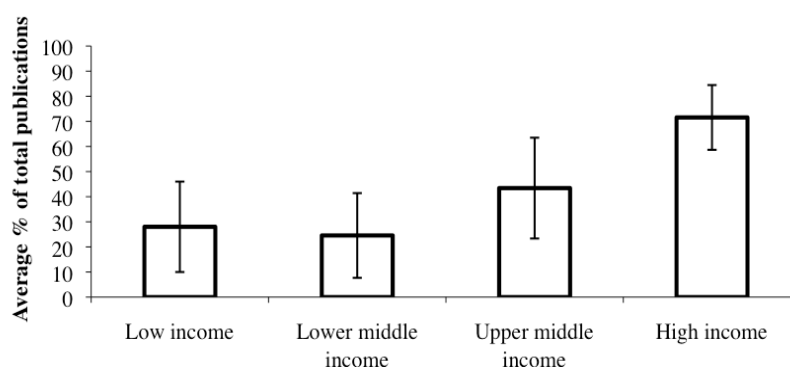


Figure 3.2 Average (with standard deviation) proportion of articles with in-country authors grouped by World Bank income class. High-income countries are almost twice as likely to have an in-country author as low and lower-middle income countries.

The results highlighted by Approach A are further reinforced by those of Approach B (section 3.3.2). Between 2005 and 2010, 44% of EO forest-related research sampled was conducted about developing countries (figure 5.3). However, authors affiliated with developing country institutions account for only 20% of total authorships. These figures drop to 29% and 3% respectively if India, China and Brazil are excluded. When first authorship alone is considered, less than 1% of authors are affiliated with developing country institutions.

Our Approach B results also show Brazil as an anomaly, alongside India and China. Brazil was the country of focus for 9% of research studies sampled, and accounts for 5% of total authors, a proportion dramatically higher than most developing countries. We did not investigate whether a particular author was writing about a particular country, but this does seem to suggest that at least some of the research papers written about Brazil had a Brazilian author, a situation that is not repeated in any other developing country. The consistent efforts, funding and collaborations spearheaded by INPE (National Institute of Space Research) have placed Brazil's EO community well above those of other developing, and some developed, countries, and have led to the prominence of Brazilian scientists within EO research.

For 1990-1995, developing countries represented 25% of countries researched, but only 8% of first authorships. If India, China and Brazil are excluded these figures drop to 12% and zero. Figure 3.3 clearly shows that there has been a change in emphasis about where EO research has been conducted over the last 20 years, with a much greater shift towards southeast Asia, Latin America and Africa. While research conducted between 2005-2010 studies a greater range and proportion of developing countries, developing country researchers still represent a small fraction of the total number of authors. This trend in under-representation has

not altered over the past 20 years. Figures 3.3a and 3.3b highlight a noticeable dearth in Africa and south-east Asia. Despite the rise in the importance of CD, there seems to have been no corresponding rise in authorship from developing country researchers (while based in their home institution) over this period. It is acknowledged that figure 3.3c perhaps overstates how much research was being conducted in Africa during this period, as the countries in West Africa are all from one paper that conducted a region-level analysis, while the African countries represented in figure 3.4b are all from different studies. Nonetheless the numbers remain striking.

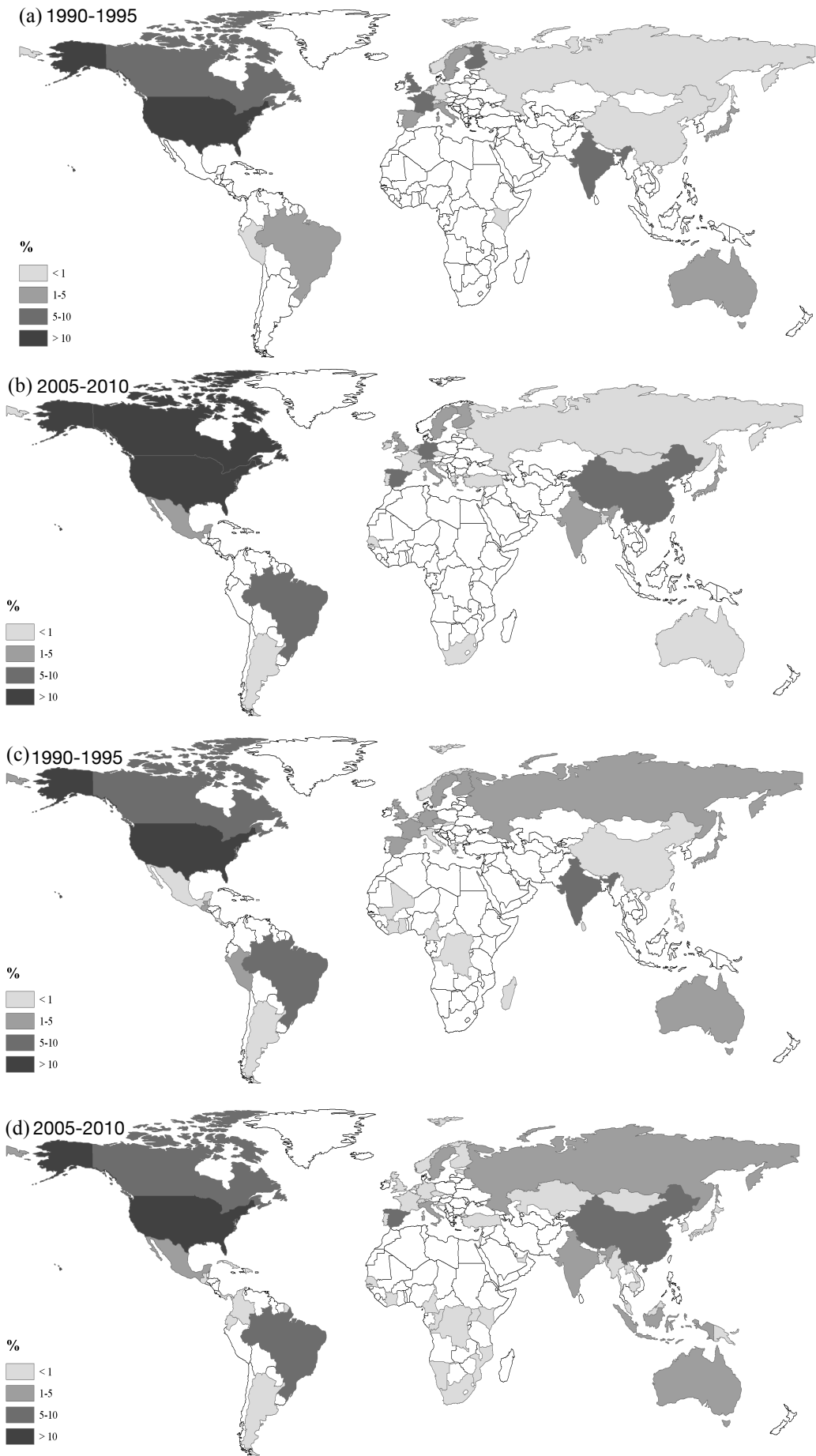


Figure 3.3 Country affiliation of authors for a) 1990-1995 and b) 2005-2010. Geographical location of research conducted c) 1990-1995 and d) 2005-2010. USA dominates EO research with 30% and 50% of total authorships (1990-1995 and 2005-2010 respectively). Overall, gaps in authorship are clearly noticeable over Africa and southeast Asia, despite the increase in the number of countries in these regions where research is conducted.

3.5. Discussion and recommendations

3.5.1 Educational research partnerships, capacity building and international development assistance

For established researchers in the Global North to best contribute to the development of those countries that lack EO expertise it is essential that they compel themselves to partner with local researchers. Such partnerships must form at the beginning of a research project and continue throughout the research process. There is a need to develop indigenous capacity to stop the culture of dependency on foreign institutions. The strong emerging economies (e.g. Asian Tigers) have invested heavily in scientific and technical education and training (Green 1999, Morris 1996) and this is partly apparent in our results. In recent years, about a quarter of donor aid, more than US \$15 billion per year, has gone into technical co-operation, the bulk of which is aimed at CD (OECD 2006). However evaluation results confirm that development of *sustainable* capacity continues to be one of the most difficult areas of international development practice (FAO 2010b, Lusthaus et al. 1999, Horton 2002, Horton et al. 2003, Görgens-Albino et al. 2009).

With so much emphasis on access to basic education throughout the developing world, investment has often been funnelled away from secondary and tertiary education to support these goals. It has been argued that basic education gives a better return on investment than higher education (Psacharopoulos 1972, Psacharopoulos and Patrinos 2002). However, there are now immediate challenges in many developing countries that need to be addressed. Increased investment in research at tertiary institutions (and the subsequent training of students in research skills) would have knock-on effects in many areas of sustainable development and poverty alleviation including environmental degradation. Without a basis in sound research, effective management strategies can neither be designed nor implemented. This is illustrated by the current state of environmental and natural resource management

activities in Africa, which note huge capacity gaps across scales of natural resources management (Folke et al. 2002, Nelson 2010). Research capacity development will contribute to national development by addressing the knowledge gap between the global North and South, with the eventual aim of enabling more balanced South-North partnerships.

However, it seems from the results presented here, that EO research still has a long way to go before the necessary level of equality in research is obtained to allow countries the necessary level of in-country expertise to conduct this research themselves. It also seems that we still have a situation where research is mostly done *about* developing countries, not *by* developing countries. The following section offers some practical approaches to address this issue.

3.5.2 Strategies for Promoting Collaborative EO Research

There are a number of practical steps that can be taken by all EO professionals and their institutions to encourage and engage with developing country researchers. These are designed for those working in developing countries, require little economic outlay (other than time) and have the potential to increase the likelihood of meaningful results. They are by no means exhaustive, and are designed to provoke wider discussion of these issues in a practical context.

Strategy 1: Focused Networking

The importance of networking should never be underestimated as one of the leading means of building capacity in the developing world. Society membership and conference attendance is a luxury that few can afford on a regular basis.

Action: Encourage Researchers to use Free Networking Tools

Online professional networking sites are becoming increasingly common among EO professionals. For instance, LinkedIn

(<http://www.linkedin.com>) is a free networking site that has an EO Network. At the time of writing this article, this network had attracted over 2,400 members worldwide, many of whom are in developing countries. This service allows one to build up personal networks of current and former colleagues or contacts. It has been especially popular amongst financial professionals in the USA, but has expanded now to more than 30 million experienced professionals from around the world, representing 150 industries.

This action recommends that institutions encourage staff to use these free networking tools, and to especially encourage contacts from the developing world to join.

Strategy 2: Engage teams in the complete process from an early stage

Effective collaboration is an effective means of sharing expertise, skills, data and knowledge. Beyond this, it also allows for institutional capacity building and development. The most effective capacity building is not from training courses, but from being involved with hands-on projects. Any projects or other initiatives should aim to collaborate with local institutions, and do so from the very earliest stage – that is, from the initial proposal stage. Academic researchers in developing countries are just as eager to publish as those in developed countries, and often have similar institutional and personal pressure to do so (Sawyer 2004). In this context, we recommend taking a proactive strategy to include local researchers involved with the collaboration as joint authors on papers. The Swiss Commission for Research Partnerships with Developing Countries (KFPE, 1998) outlines 11 principles for successful research partnerships, which serve as a useful framework for defining the ‘rules of the game’ when developing research collaborations (table 3.2).

Table 3.2. Eleven principles of research partnerships (KFPE, 1998)

-
1. Decide on the objectives together
 2. Build up mutual trust
 3. Share information; develop networks
 4. Share responsibility
 5. Create transparency
 6. Monitor and evaluate the collaboration
 7. Disseminate the results
 8. Apply the results
 9. Share profits equitably
 10. Increase research capacity
 11. Build on achievements
-

Strategy 3: Promote an “Open” Culture

“Open source” software is made available to everyone to use, modify and improve. “Freeware” is software that is free to use but the source code is not available to edit. “Open access” (OA) journals are online publications that allow free access to readers but may charge authors a fee to publish.

Action: Publish results in open access journals

Journal access is expensive. In developing countries it is usually prohibitively expensive, and online journals are available only through donor subscriptions. Relying on donated subscriptions is not a long-term sustainable solution. One alternative solution is to encourage researchers to submit their work to electronic open-access journals. Unfortunately, there is a chicken-egg situation with OA journals in environmental sciences – they tend to have lower impact factors and therefore fewer good works tends to be submitted. However, with a concerted effort, this may change over time and perhaps emulate the incredible success that biomedical sciences have had with OA journals. There is now an OA remote sensing journal (Remote Sensing, <http://www.mdpi.com/journal/remotesensing/>) that has been running since March 2009, and many others that publish applied remote sensing

research, for example Carbon Balance and Management (<http://www.cbmjournal.com>) and Environmental Research Letters (<http://erl.iop.org>).

Two points should be noted. First, while this paper is clearly written from the perspective of researchers from a developed nation working in a developing nation, many of the same principles apply generically to an EO project, whoever is conducting the research. Second, these guidelines are tailored for projects where the location country is not expected to necessarily gain from the outputs – such as terrestrial carbon dynamics, ecology, or biodiversity. The project outcomes may have secondary value to the host country, but the main purpose (and particularly the scientific justification that led to it being funded) is not country-specific. Projects aimed at addressing local user needs are more likely to be sensitive to such issues, and in particular require a much greater input from local stakeholders.

Ultimately, the work presented here is, in the first instance, aimed at influencing individual and institutional policy on working in developing countries, and secondly, influencing policy related to funding agencies who have an obligation to consider these issues in the context of the international agreements outlined above.

3.6 Conclusions

The importance of EO for combating current environmental problems is well recognized. By supporting the development of relevant skills, data access and processing tools, EO researchers can enhance the ability of developing countries to assess their vulnerabilities and evaluate options for adaptation. Developing countries are too reliant on external actors for conducting EO research in their own countries. From the research presented here, it appears that there are a much greater number of papers written about developing countries rather than by developing

country researchers. In one example field of EO study (namely, forests) there has been no significant change in this pattern over the last 20 years, despite the increased awareness of the importance of CD within the international development community as a whole. Capacity development in academic EO research is key for encouraging and engaging developing country researchers within the global community, and needs to become imbedded as best practice across all disciplines that conduct research in developing countries.

3.7 Acknowledgements

Funding for this research was provided through GC's PhD studentship from the Natural Environment Research Council and the Moss Centenary Scholarship. The authors wish to thank Jarret Mhango and Dalo Njera, Mzuzu University, who contributed to the ideas expressed in this paper.

4. Assessing the suitability of global land cover products for mapping forests at a national scale in Malawi

Gemma Cassells, Iain H. Woodhouse, Casey Ryan

School of GeoSciences, University of Edinburgh

REDD+ is currently a key driver behind sustainable forest management activities around the world. However there has been little work on whether or not REDD+ can reach an economic break-even point in a particular country, based on that country's particular forest characteristics. I begin by investigating the factors that influence whether or not this economic break-even point can be reached in Malawi. I then examine whether or not global mapping products can provide the necessary forest metrics, at the accuracy and cost levels required to reach this break-even point.

I developed the initial idea for this paper, conducted the data analysis and wrote the manuscript.

Submitted to Proceedings of the National Academy of Sciences.

Abstract

Reduced Emissions from Deforestation and Degradation (REDD+) has become a key item in recent international climate change discussions, and it certainly has the potential to contribute to reducing greenhouse gas emissions and improving livelihoods in developing countries.

However, there has been little discussion to date on whether a particular country could benefit economically from any potential REDD+ activities.

This paper presents the results of a calculation specifically for Malawi based on an existing formula. The results indicate that the most important factors governing whether or not Malawi could successfully implement economically viable REDD+ projects are the accuracy of forest area estimates (which appears to be more important than the actual loss rate, as long as the loss rate falls within 'best guest estimates'). Data products need to be low cost or free if they are going to be used by Malawi's under-funded and under-resourced Department of Forestry. Therefore this paper assesses the usefulness of coarse-resolution optical imagery for providing forest and forest cover change maps. Results indicate that inter-annual variability limits the usefulness of both the MODIS datasets investigated here, making it difficult to know if the trends being seen in a particular dataset are due to changes in the biophysical properties of the surface or whether they are due to other surface changes, or noise in the datasets themselves.

4.1 Introduction

Reduced Emissions from Deforestation and Degradation (REDD+) has become a key item in recent international climate change discussion, and it certainly has the potential to contribute to reducing greenhouse gas emissions and improving livelihoods in developing countries (Lederer 2011, Isenberg 2010). It seems reasonable to assume that REDD+ is most likely to be optimised for those countries with the largest voice on the international stage, such as Brazil and Indonesia, and those countries with large forest stocks such as the Democratic Republic of Congo (DRC). However, there are other developing countries with lower deforestation rates, or lower carbon stocks that are not centre stage in the development of REDD+ and may not be able to benefit as greatly from REDD+. One example, and the broader topic of this paper, are those countries whose dominant woodland type is savanna. While savannas have lower carbon stocks per hectare than rainforests, their large areal extent does make them an important carbon stock (Grace et al. 2006, Murphy and Bowman 2012). The savanna nations, sub-Saharan Africa outside of the Congo basin, and parts of Central and South America, are all developing countries and could all benefit from the extra income that REDD+ credits could provide.

There has been little work to date on examining whether or not specific countries could reach a break-even point with regards to REDD+ implementation. Plugge et al. (2012) have given a methodology which can be used to estimate how much of a country's forest area needs to be given over to REDD+ schemes in order to reach a break-even point for estimated measurement error levels and total monitoring costs. The Plugge et al. approach combines forest loss rates, total area of forest, total volume of forest carbon (and consequently carbon loss) in a particular country, with estimates for the fixed and variable monitoring costs for monitoring that forest, at different error levels (regarding estimates of forest area, carbon stock and loss rates) with an estimated carbon price in

order to estimate how much of a country's forest area would need to be included in a potential REDD+ project in order to reach a break-even point.

This method provides a useful tool for determining if REDD+ is cost-effective for a particular country, and can also be used to determine what carbon pricing or monitoring, reporting and verification (MRV) measurement error would be acceptable for reaching a break even point. The current study focuses on Malawi, a small landlocked country in southeast Africa, that faces challenges balancing the demands of a largely rural population for forest products that is outstripping supply (Mayers et al. 2001). This paper uses the Plugge et al. approach using estimated values of Malawi's forest area and deforestation rate from published estimates from the United Nations Food and Agriculture Organisation's (UN FAO) Forest Resources Assessment 2010 (FRA 2010) (FAO 2010a), and from grey literature produced by the Malawian Department of Forestry. Calculating the break-even point for Malawi (table 4.1) is seen as a first step to assessing what the key factors are that determine whether or not Malawi could make REDD+ cost effective.

Table 4.1 Results of the Plugge et al. (2012) approach for calculating the amount of forest cover necessary to be included in a REDD+ project in order for a particular country to reach its break even point. BL = baseline (10 years) rate of deforestation. Total error is the sum of all the errors associated with monitoring, reporting and verification of carbon stocks and rates of change. Results based on a carbon price of US\$10 per tC. Variable monitoring costs are calculated by multiplying the forest area (in hectares) by the price of monitoring per hectare. Results more than 100% (which indicate REDD+ cannot be cost effective in Malawi) are highlighted in bold. The 47 tC/ha value is the FAO average carbon stock for Malawian woodlands, while the 19tC/ha estimate is based on fieldwork values for miombo woodland only, which is Malawi's dominant woodland type.

Department of Forestry estimates				
BL = -28%		tC/ha = 47.5		
Variable monitoring costs (US\$/ha)	Total error (from measurements of carbon stock and change)			
	1%	2%	5%	10%
0.01	2.6	5.26	13.54	28.58
0.1	2.62	5.27	13.56	28.6
1	2.75	5.41	13.7	28.76
5	3.35	6.02	14.35	29.48
FAO FRA estimates				
BL= -9%		tC/ha = 47.5		
Variable monitoring costs (US\$/ha)	Total error			
	1%	2%	5%	10%
0.01	10.24	20.66	53.24	112.37
0.1	10.29	20.71	53.3	112.44
1	10.82	21.25	53.87	113.08
5	13.18	23.66	56.43	115.93
BL= -9%		tC/ha = 19		
Variable monitoring costs (US\$/ha)	Total error			
	1%	2%	5%	10%
0.01	10.27	20.7	53.28	112.37
0.1	10.41	20.83	53.42	112.44
1	11.73	22.18	54.86	113.08
5	17.65	28.23	61.29	115.93

4.1.1 Is REDD+ feasible in Malawi?

Based on the results of the Plugge et al. (2012) calculations, it appears that the error involved in estimating forest area, forest cover change, and carbon stocks that has the largest impact on whether or not Malawi can make REDD+ projects economically viable. If Malawi has a lower rate of forest loss, as estimated by the FRA 2010, then minimising the error in forest measurements is the key factor in determining the potential economic viability of REDD+ in Malawi. If the deforestation rate is higher, then this can compensate for the reduced income associated with larger errors. For example the Department of Forestry forest loss estimates of 2.8% per year (Nkwanda et al. 2008, although the process for obtaining figure unclear), means that any reasonably accurate (less than 20% total error, based on the results in table 4.1) estimate of forest cover change is sufficient to produce an economic return from REDD+, although more forest will need to be included in REDD+ schemes at higher error levels to reach the break even point.

Malawi needs to balance this need for the accuracy required to make REDD+ economically viable with the constraints currently faced by the Department of Forestry with regards to both finances and current staff capacity to conduct regular remote sensing analysis. Malawi needs remote sensing data products to be free or low cost, with enough consistency to enable sufficient monitoring coverage on an at least yearly basis. The Department of Forestry has a very tight budget that does not currently include much remote sensing data, so the funds for new data would either need to be raised from donors or by reducing funding of existing activities. The data also needs to be able to be analysed using low cost (for example freeware or open source software) or currently available software, given the budget restrictions mentioned above. The Department of Forestry has some ArcGIS licences, but currently has no access to specific remote sensing software. This is even more important when considering the different tiers used for generating carbon credits, if the model currently used by the Kyoto Protocol is adopted (Obersteiner et al.

2009, Köhl et al. 2009). These calculations assume a carbon price of US\$10 per ton of carbon. Only qualifying for lower tier credits could reduce potential payments for carbon credits significantly, which could greatly impact Malawi's break-even point, making accuracy even more important.

Under the Kyoto Protocol, there are three tiers of carbon credit, based on the methods used to assess the carbon stock, and its change over time (UNFCCC 2011). It is possible that any future mechanisms could use a similar system (Obersteiner et al. 2009, Manitis and Mollicone 2010). Tier 1 methods are designed to be the simplest to use, and are based on globally available sources of country specific data, for example global land cover maps (UNFCCC 2011). The data is usually spatially and temporally coarse. Tier 2 uses the same methodological approach as Tier 1, but applies country- or region-specific data on the most important land use, or carbon emissions (UNFCCC 2011). Tier 3 uses more sophisticated models and inventory measurement systems that are tailored to particular national circumstances, repeated over time and driven by high-resolution activity data (UNFCCC 2011). The higher tier methods provide greater certainty when estimating carbon stocks than the lower tiers, and therefore provide higher payments for carbon credits.

There are numerous global land cover products available that all map global process, and could be used to satisfy Tier 1 and 2 requirements (with suitable in-country data for Tier 2). What is less certain is the reliability and accuracy of these datasets for mapping sub-national scale trends. These global maps can provide useful comparisons when looking at relative differences between countries for a particular year relative to each other, however there has been little work done on assessing their accuracy over smaller areas, either over small countries such as Malawi, or at a subnational scale. Along with many other countries in the developing world (Cassells et al. 2011, Romijn et al. 2012), Malawi has a

lack of trained remote sensing scientists to conduct forest mapping, which makes global products a useful starting point for this kind of analysis.

It is for this reason that this paper attempts to use globally available remote sensing products that would be available to Malawian researchers to map forest cover change, to assess whether the required level of accuracy can be achieved with these products. We are investigating the use of data products from the NASA MODerate Imaging Spectrometer (MODIS) instruments for mapping forest cover, and forest cover change. There have been numerous other studies using various MODIS products to map forest cover, most frequently the Enhanced Vegetation Index (EVI) (a variant on the Normalised Difference in Vegetation Index (NDVI)) and the Vegetation Continuous Fields (VCF) product which was developed by Hansen et al. (2003) (for more details see next section). Previous work using the MODIS VCF products to determine deforestation rates have been successful in the Brazilian Amazon, where the deforestation patterns were typically clear felling, with the sensor being best able to determine areas of deforestation larger than 3 ha (Morton et al. 2005). Examples of using the EVI data to map forest loss include Pettorelli et al. (2005) and Cabral et al. (2011). VCF data is only produced on a yearly basis, so MODIS EVI data is also investigated here, as this data is available at 16-day intervals.

There are other, higher resolution optical sensors, such as Landsat, that are also free to users. While Landsat is a very useful mapping tool for smaller study areas and has a long historical archive, it can be more difficult for national mapping as it can be challenging to get sufficient cloud-free imagery in the same year or season. Because of this, is often used as a sampling tool to complement coarser resolution data (Hansen et al. 2008, Cabral et al. 2011). For example, in Brazil, MODIS imagery is used to detect areas of potential change, which are then surveyed in more detail using Landsat imagery (Morton et al. 2005). Because Landsat has a smaller scene size, and more unpredictable acquisitions than MODIS,

Landsat scenes from multiple seasons or years are needed in order to generate sufficient coverage. The failure of the Landsat 7 EMT+ Scan Line Corrector in 2003, meaning multiple scenes are needed in order to generate a complete scene, and, prior to its failure, the intermittent coverage of Landsat 5 compounded this problem.

4.2 Methodology

Two MODIS products covering Malawi were downloaded through the USGS Reverb data portal (<http://reverb.echo.nasa.gov/>). The data were reprojected into Universal Transverse Mercator (UTM) using the MODIS Reprojection Tool (USGS) and analysed using ENVI 4.8 (Excelis Visual Information Solutions). These were 250 m, 16-day composite Enhanced Vegetation Index (EVI), part of the MOD13Q1, Vegetation Indices, and the yearly, 500 m resolution Vegetation Continuous Fields (VCF) (MOD44B).

4.2.1 MODIS EVI

The MODIS EVI (Enhanced Vegetation Index) 250 m resolution, 16-day composite products for the period 2001-2011 (part of MOD13Q1) were used to produce maps of vegetation cover. EVI is calculated following the equation:

$$EVI = G \times \frac{(NIR - RED)}{(NIR + C1 \times RED - C2 \times BLUE + L)} \quad (1)$$

where NIR, red, and blue are atmospherically-corrected or partially atmosphere corrected (Rayleigh and ozone absorption) surface reflectances, L is the canopy background adjustment that addresses non-linear, differential NIR and red radiant transfer through a canopy, and C1 and C2 are the coefficients of the aerosol resistance term, which uses the blue band to correct for aerosol influences in the red band. The coefficients adopted in the MODIS-EVI algorithm are; L=1, C1 = 6, C2 = 7.5, and G (gain factor) = 2.5 (Huete et al. 2002).

The quality bands present in the EVI product were used to remove values that failed the quality test. A summary quality layer is included with the MODIS EVI product. This layer contains a ranking describing the quality of each pixel. A value of 0 represents good data; 1 is data that may be useful, but a further check of the full quality data is needed; 2 represents pixels where ground cover was impacted by snow or ice; and 3 represents pixels impacted by cloud cover. Any pixel that ranked 1, 2 or 3 was replaced with a non-numerical fill value, and not used as part of the yearly average.

Imagery from August to October was averaged to produce an average EVI value over the late dry season for each year. The idea behind this averaging is to even out the effects of phenological changes that occur over the course of the season to enable more accurate inter-annual comparisons. Variations in tree greenness or the amount of understory vegetation (primarily caused by changes in rainfall), could lead to an overestimation of forest in a wet year as compared to a dry year (Zhang et al. 2003). Late dry season imagery was used as this is the period when the trees still have their leaves, but the understory grasses have died back and there should be little to no signal from agricultural activities which could effect the tree signal in the data. EVI was selected over the NDVI product also produced as EVI was optimised to improve vegetation monitoring, by reducing the impact of the ground signal relative to vegetation as well as reducing atmospheric influences (Huete et al. 2002). This is particularly important in Africa, where red soils can impact NDVI results (Nicholson and Ferrar 1994). The variability of water bodies (due to turbidity and water level fluctuations) tended to compound change detection analysis, so they were masked out to reduce errors.

The EVI products were then used to undertake change detection of forest area for the period 2002-2011. The methodology used has been used in

previous papers (for example Morton et al. 2005, Mitchard et al. 2009a). A normalised difference index is calculated using the following equation:

$$Change = \frac{EVI_{new} - EVI_{old}}{EVI_{new} + EVI_{old}} \quad (2)$$

This produces an image with values between -1 and +1. After performing a Shapiro-Wilk test for normality, the image was classified according to standard deviation (sd). Areas within ± 1 sd were classified as no change, with areas above ± 2 sd as statistically significant change at a 95% confidence interval. Areas above ± 3 sd were also classified in the imagery to show areas of extreme change.

4.2.2 Vegetation Continuous Fields

Percentage tree cover data was obtained from the VCF product, which is produced yearly for the period 2000-2010. It is produced using a model-based regression tree algorithm developed by Hansen et al. (2003), which incorporates 40-day averaged MODIS data, as well as metrics derived from MODIS products such as maximum and minimum NDVI. This dataset was developed to be able to assess differences in forest cover between different countries and regions, using a continuous forest cover scale. Interestingly, Hansen et al. pick out Malawi's comparative lack of forest cover, relative to neighbouring countries as one of the initial findings of this dataset. The VCF data is potentially one of the most useful forest mapping datasets, as it produces an estimate of forest cover percentage at 500 m resolution. For countries that currently lack any up to date forest cover information, the VCF data is theoretically an important resource, despite the fact it is only produced yearly, making it unsuitable for rapid monitoring. Previous studies using VCF data to map deforestation have usually been conducted over the Amazon (for example Morton et al. 2005, Giri et al. 2005) where the distinction between forest and non-forest is much stronger than in Malawi, and forest cover loss is

primarily clear felling (deforestation), rather than degradation or selective logging, which is more prevalent in Malawi.

Two forest cover change images were produced, first using the whole range in the dataset and second with areas that have more than 20% forest cover. Using 20% tree cover is a relatively common way of defining forest, and has been used in other studies looking at forestry-related issues in Malawi before (see Bandyopadhyay et al. 2011). Malawi's national forest definition is based on 10% forest cover, however using this threshold to investigate change includes many areas that would not be thought of as forest under a REDD+ definition. Also, at the resolution of the VCF data, the changes seen using the 10% threshold are more likely to be influenced by land cover changes other than changes in forest area. By using a 20% threshold, changes in areas of more denser forest cover can be investigated. Both of these change images were produced using the same methodology described for the EVI data, by classifying the results using standard deviation.

4.2.3 Additional satellite products

Two Landsat 5 Thematic Mapper scenes centred over Kasungu National Park, central Malawi were obtained through the USGS Earth Explorer portal (earthexplorer.usgs.gov/). Both scenes had a cloud cover of less than 10%, and were obtained during late September, with one acquisition being taken in 2001 and the second in 2011. The digital number products were converted to Top Of Atmosphere (TOA) reflectances, by first converting each band to radiance using:

$$L_{\lambda} = \text{gain} * \text{DN} + \text{bias} \quad (3)$$

Where:

L_{λ} is the cell value as radiance ($\text{Wm}^{-2}\text{sr}^{-1}\mu\text{m}^{-1}$)

DN is the cell value digital number

gain is the gain value for a specific band bias is the bias value for a specific band.

Radiance values were then converted to TOA reflectances using:

$$\rho_{\lambda} = \pi * L_{\lambda} * d^2 * ESUN_{\lambda} * \cos\theta_s \quad (4)$$

Where:

ρ_{λ} = Unitless TOA reflectance

L_{λ} = spectral radiance (from earlier step)

d = Earth-Sun distance in astronomical units

$ESUN_{\lambda}$ = mean solar exoatmospheric irradiances

θ_s = solar zenith angle.

Calibration values were taken from the supplied metadata.

Image-based atmospheric correction was then undertaken using the dark object subtraction (DOS) method described by Chavez (1989) to obtain surface reflectances. The DOS method assumes that if there are areas in an image with very low actual reflectance values (such as water bodies or surfaces such as tarmac), any apparent reflectance should be due to atmospheric scattering effects, and this information can be used to calibrate the rest of the image. The simplest form of DOS simply converts the path radiance observed as result of haze over the dark object to at-sensor reflectances and subtracts it from the entire image (also converted to at-sensor reflectances). It is unlikely that most images contain entire pixels that are true black, so a correction is applied that assumes a 1% actual reflectance of these areas. A new starting haze value (SHV) must be calculated for each band (Chavez 1988). Once these corrections had been applied to the data, they were then used to calculate the EVI for each scene. A ratioed difference image was then produced in the same way as the MODIS EVI data.

Additionally, 30-day averaged rainfall data from the Tropical Rainfall Measuring Mission (TRMM) satellite was downloaded from NASA (<ftp://trmmopen.gsfc.nasa.gov/pub/merged>) over the period 2000-2010. This rainfall data was used to produce monthly and yearly rainy season average, maximum and minimum rainfall estimates.

4.3 Results

4.3.1 Forest cover change maps using EVI

The changes shown in EVI over the period 2002-2011 show small, but widespread reductions in EVI over large areas of Malawi (figure 4.1). If it is assumed that all these changes are due to a loss in forest cover (which is unlikely), Malawi experienced a forest loss of -3.1% per year. Landsat imagery from late September 2001 and 2011, centred over Kasungu National Park was used to validate the changes shown in the MODIS imagery (figure 4.1). Kasungu was selected because the MODIS data indicates a reduction of EVI inside the boundaries of the national park, which is unexpected, and also something that is not observed in the VCF data (see next section). The Landsat imagery does show the same widespread low-level reductions in EVI that are present in the MODIS EVI data, and also shows a similar pattern of deforestation in the eastern side of Kasungu National Park. The rate of loss over this area is calculated at -2.8% per year using the MODIS data, but only -1.7% using the Landsat data. This discrepancy seems to be due to the increases in EVI seen in the Landsat imagery that are not present in the MODIS imagery.

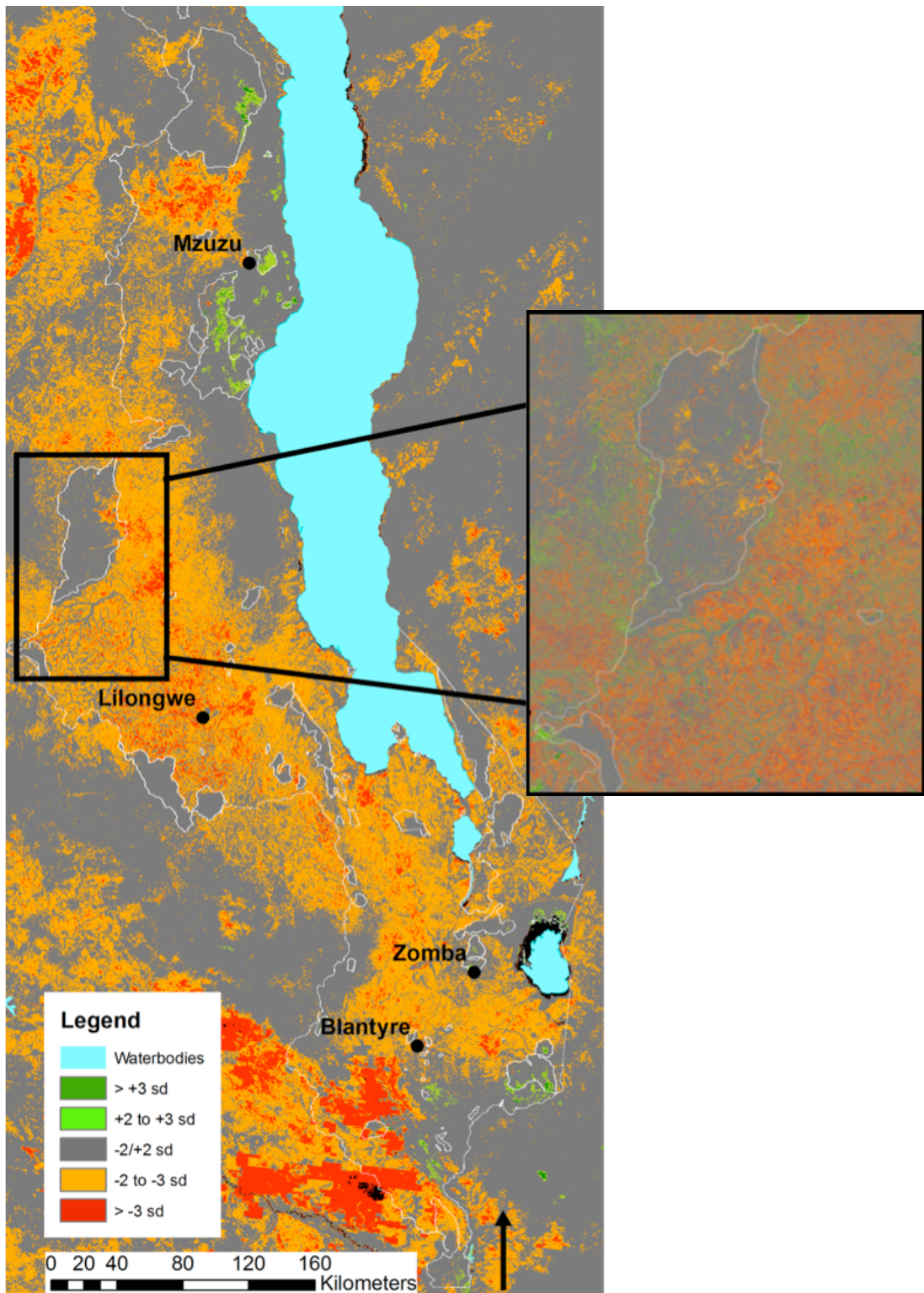


Figure 4.1 EVI changes over the period 2001-2011. There are widespread low-level reductions in EVI being recorded across Malawi, as well as in bordering areas of Mozambique and Zambia. Inset shows a change map from Landsat-derived NDVI from late September 2001 and late August 2011, classified in the same way.

Figure 4.2 shows EVI changes over the period 2001-2011 for different land cover types. Each of these land cover scenarios was identified from knowledge of the region and from Landsat imagery. A total of 25 pixels that best represented each scenario were averaged, to even out site-specific trends. However, given the 250 m resolution, every pixel will contain a mix of land cover types. The bare ground values were obtained using pixels known to have unpaved roads in them, which also contained bare ground along the verges, to minimise the effects of agriculture as far as possible. The deforestation scenario is from a known deforestation event where a forest reserve was cleared to make way for a hospital. The felling started in 2008 and continued into 2009, and this is clearly shown (figure 4.2). The EVI values do not fall to the values of bare ground due to the forest cover remaining around the cleared area. The degradation scenario is the most uncertain. It was identified by visual analysis of Landsat imagery, which showed a gradual reduction in forest cover over the time period. The degraded areas were often on the edges of larger patches of woodland, which is why the starting EVI values are lower than for undisturbed woodland. One of the main problems estimating degradation seems to be highlighted, and that is the fact that areas of degradation, where loss rates may be quite small, often look very similar to the variations in EVI that occur in forest where no change is occurring. This is also complicated by large variability seen in this time series. Assessing forests that did not change is also difficult, as natural woodland gains biomass over time. It is possible that the forest areas that did not show signs of obvious change are also woodlands undergoing degradation, just at a slower rate.

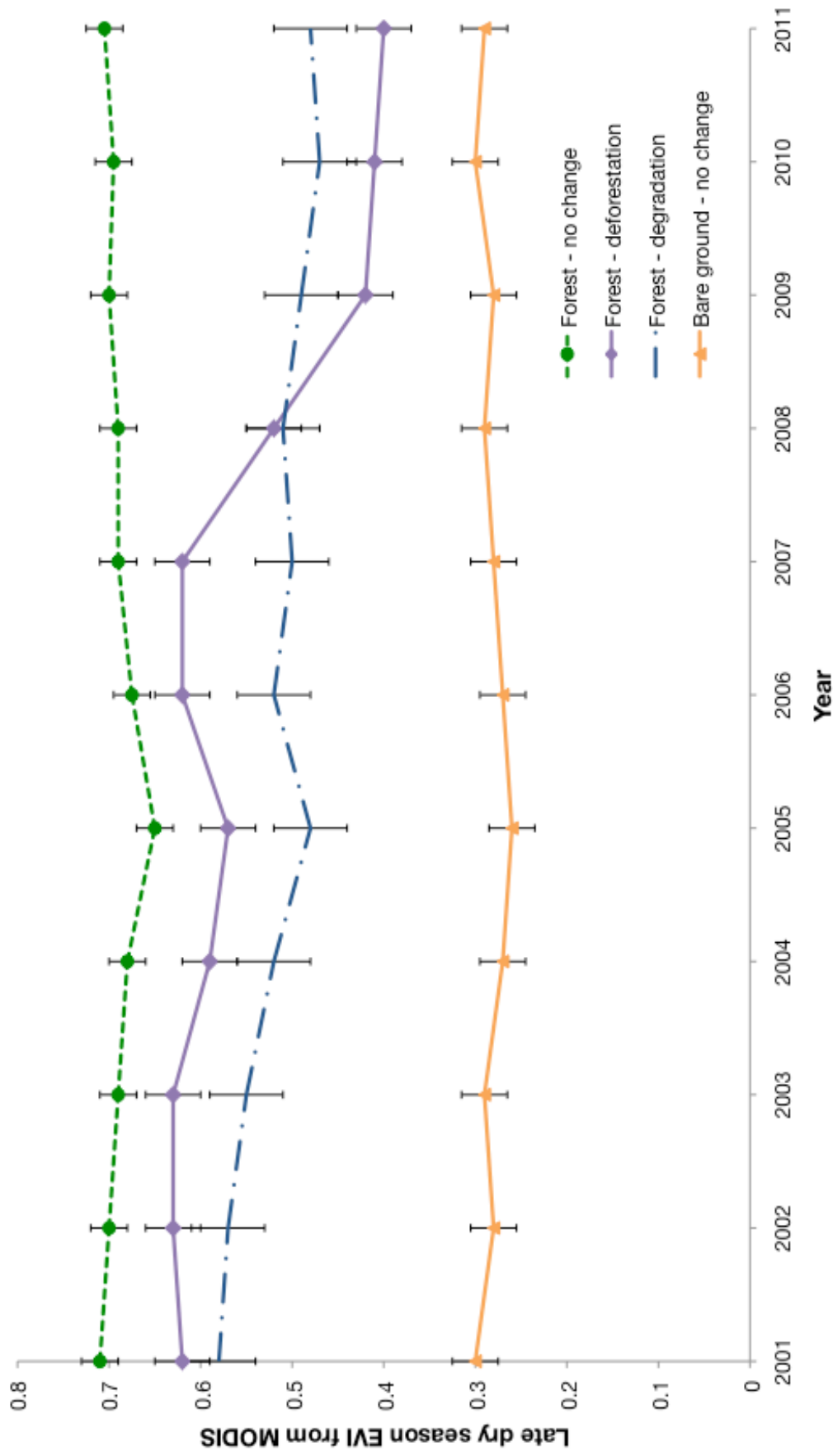


Figure 4.2 EVI changes over the period 2001-2011 for different land cover scenarios: forest - no change; forest - deforestation; forest - degradation; bare ground - no change. Error bars show the standard deviation of each point. It appears that the variability of a particular time series is more a result of the land cover type and change being monitored, rather than inter-annual variations. While the EVI data does clearly show the deforestation event that occurred in 2008/09, the inter-annual variability means it is more difficult to extract trends for degradation and static forest cover.

Despite averaging 8 EVI images per year, there is still some inter-annual variability due to phenological changes, particularly in 2005, where all EVI values show a dip. This means that despite correcting for phenological changes as far as possible, there is still some residual signal, probably due to low rainfall, that has not been accounted for. Using TRMM satellite data, monthly and yearly rainfall averages over Malawi for the period 2000-2010 were calculated (figure 4.3). While monthly maximum and minimum rainfall for the 2004/5 rainy season is approximately the same as other years, the total volume of rainfall is less, with only 804 mm of rain falling, compared to an average of 919 mm over the 2000-2010 period. Given that miombo woodlands are in resource-poor environments (Frost 1996, Chidumayo 1997), it seems reasonable to conclude that this lack of rain is having an effect on how many leaves the trees produced, and how long the trees are keeping their leaves during the dry season. The above average rainfall of 2005/6 and 2006/7 wet seasons seems to have allowed the trees to recover strongly, although it is also possible that this increase in EVI over the subsequent dry seasons in these years is also due to a stronger response from grasses that have greater access to water.

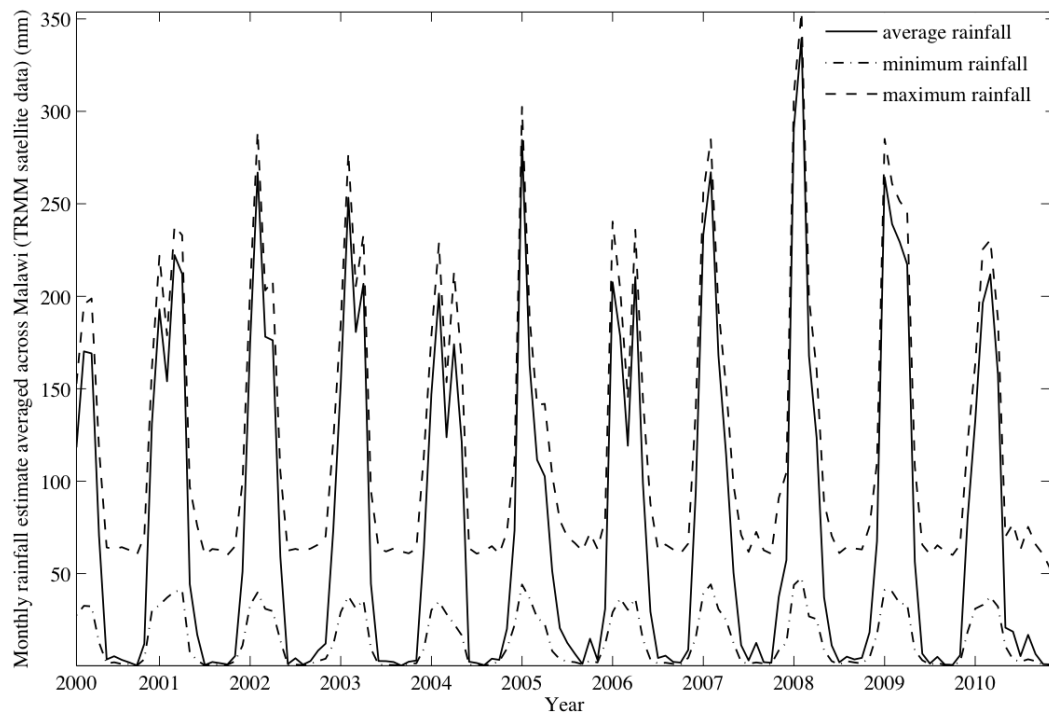


Figure 4.3 Average, minimum and maximum monthly rainfall estimated from TRMM satellite data. The data peaks are associated with the rainy season (Oct-March, with the peak in Dec/Jan) and the troughs are the dry season (March-Sept). The maximum and minimum values remain consistent throughout the period, there is some small changes seen in the average rainfall that correspond to larger changes in the total volume of rainfall throughout the rainy season, with the 2004/05 rainy season having the lowest total rainfall over the decade.

4.3.2 Percentage tree cover

The VCF percentage tree cover data estimates a net deforestation rate across Malawi of 0.91% per year for the period 2000-2010 (figure 3.4).

This is less than a third of the deforestation rate predicted using EVI alone. The forest cover change shown by the VCF datasets for the period 2000-2010 shows quite different trends to those of the EVI data. The VCF data does show trends that are in-line with those expected, with the bulk of forest cover loss occurring in southern and central Malawi, where the bulk of the country's population is located (figure 1.2). However, the widespread increase in forest cover across northern Malawi is contrary to expected trends, and the EVI results, with in-country experts claiming they are seeing an increase in deforestation in northern Malawi (Mhango, *pers. comm.*), particularly around Karonga. Karonga has experienced a

huge population boom in recent years to the opening of a uranium mine in 2008 near the town.

Another key area of difference between the datasets was over Kasungu National Park. Both the MODIS EVI and Landsat-derived EVI show a decrease in EVI over the study period. However the VCF data shows only increase in woody cover over Kasungu for the same time period. Although the Landsat data also shows some areas of increase in EVI, it is not widespread enough to result in a positive overall trend. This difference clearly highlights a need for more validation data for both the EVI and VCF data in order to conduct a thorough accuracy assessment on both datasets. This would require national-scale forest mapping using other satellite sensors, ideally with spatial resolution of less than 30 m, as this would allow an examination of finer changes in forest areas.

When looking at forest cover change in areas with more than 20% forest cover, there is a net loss of 0.76% of forest per year (figure 4.4). Defining forest in this way substantially reduces the area of Malawi being investigated, and removes almost all areas of community forestland from consideration. Instead figure 4.4 highlights only changes in areas, which are almost exclusively protected areas, including forest reserves, national parks, commercial timber plantations and private game reserves. The driving forces for forest cover change are likely to very different in these areas compared to customary land, as in theory most of the forest in this map should be in areas that are protected from logging activities and woody cover should be at least static, if not increasing over time. Therefore the fact there is a loss being recorded at all is actually quite important, and may indicate that pressure for forest resources means people are illegally turning to protected areas to meet their resource needs.

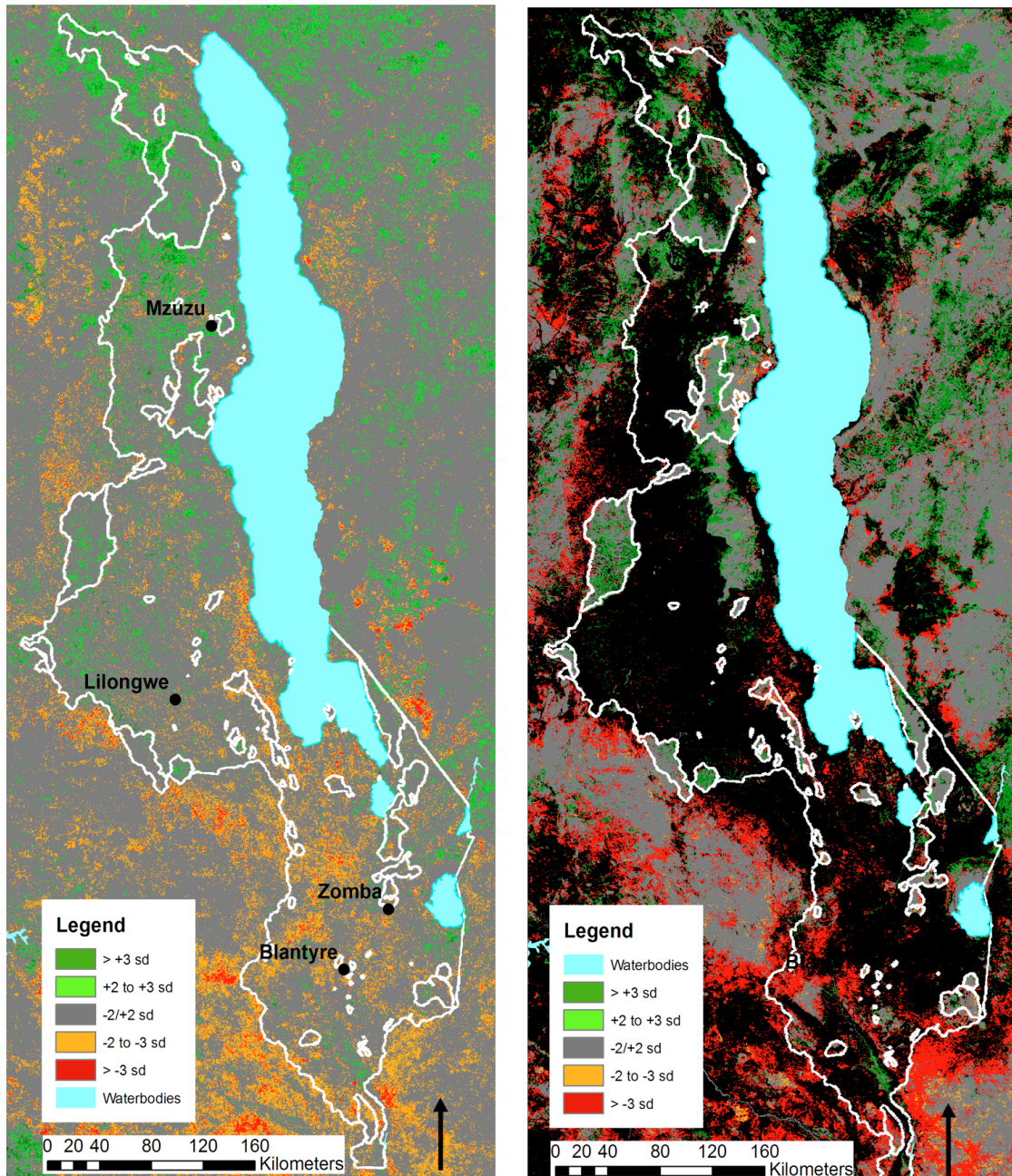


Figure 4.4 Left: Change in forest cover, from VCF data 2000-2010. Most of the loss in forest cover is occurring in southern and central Malawi, which is expected given that most of Malawi's population is concentrated in these regions. The VCF data shows much stronger trends in forest gain than the EVI data, particularly in the northern region. **Right:** Change in forest cover from VCF data 2000-2010, for areas with more than 20% forest cover in 2000. Most of Malawi falls below the 20% threshold (black areas), which is commonly used for defining a forest, with protected or privately owned areas almost exclusively meeting the criteria. The dramatic changes in forest cover highlighted as being most significant are most likely a response to these pixels reaching the 20% tipping point, rather than representing large changes in forest cover.

To investigate the effects of inter-annual variability on the VCF data, histograms of forest cover were plotted for each year (figure 4.5). These histograms show considerable variability in the VCF data is year on year. For example, in 2000 57.4% of Malawi had less than 20% tree cover, with 8% of Malawi having more than 50% tree cover, while in 2005, 56.9% had less than 20% tree cover, but only 2.9% of Malawi had tree cover greater than 50%. This variability makes it difficult to calculate forest cover change occurring each year. By using a long baseline for the change detection conducted here, it is hoped that there is a better chance of seeing actual trends in the dataset. Given a lack of alternative datasets, either remote sensing or ground data, to conduct validation of the VCF data, it is difficult to draw conclusions about which of the two datasets is the more accurate. However, the fact that the differences exist, and are as large as they are, is a potential cause for concern for countries such as Malawi, who face a large knowledge gap about the state of their forest resources.

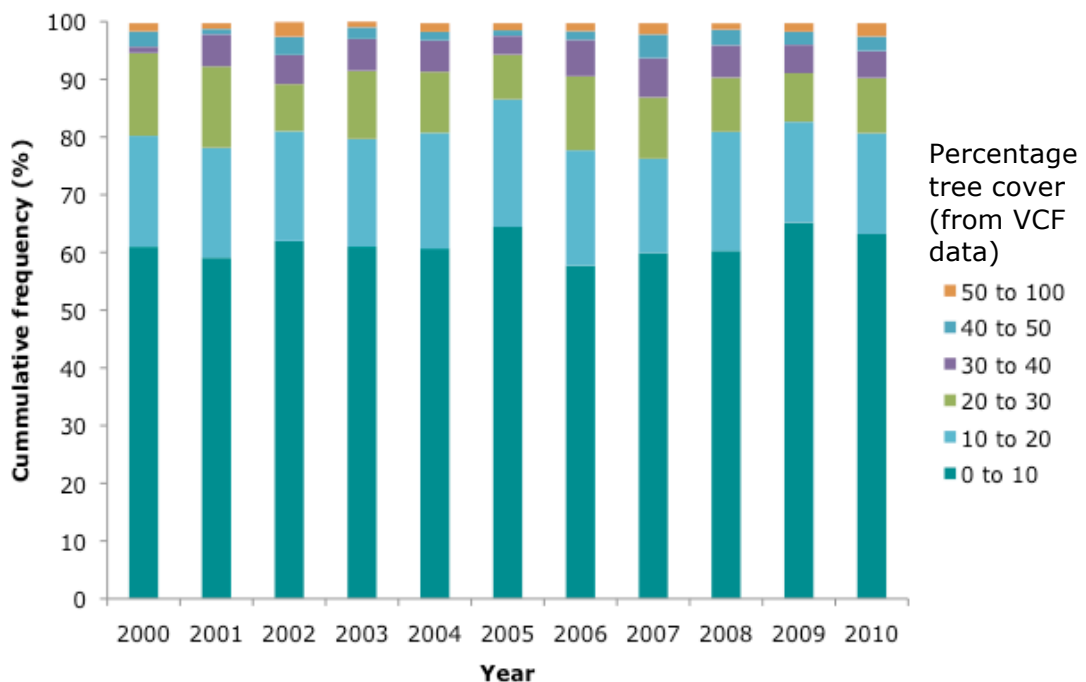


Figure 4.5 Bar graph examining inter-annual variability in the MODIS VCF data over Malawi's land surface area. The VCF data has been classified into 6 broad classes in order to examine inter-annual variability within the VCF dataset. On average, less than 2% of Malawi has more than 50% tree cover, which is why the top class has such a large range. The apparent decrease in forest area in 2005 can be seen here as an increase in the amount of land with less than 20% tree cover.

4.4 Discussion

4.4.1 Making REDD+ economically viable

One of the key debates surrounding forest and carbon stock mapping for REDD+ is how to balance the need for measurements to be as accurate as possible, with the costs that this poses (Defries et al. 2007, Obersteiner et al. 2009, Romjin et al. 2012). The datasets used to estimate forest cover change here are freely available, so the only significant costs associated with using them are staff time. Additionally, as these datasets are products, rather than raw data, much of the processing has already been done, which speeds up the time taken to create the required maps, even for inexperienced users. This means that these datasets are one of the lowest cost options available for mapping forest cover change. However, from the Plugge et al. calculations for Malawi, it appears that monitoring costs, for the modelled values of monitoring costs (up to US\$5 per hectare), are less significant in determining whether or not REDD+ is cost-effective than accuracy in forest loss measurement.

Reducing errors from 10% to 5% makes REDD+ reach the break-even point in Malawi for all simulations. This means that it is worth investing in more accurate mapping, if resources and capability allow. A lack of independent datasets to validate the results produced here, means that a quantitative assessment of their accuracy is not possible. Therefore, it is difficult to quantify the errors involved in producing these maps. For Malawi, producing estimates of carbon stock change with only 5% error is going to be the real crux of the problem, as the Department of Forestry currently has limited institutional and individual capacity to conduct large scale remote sensing monitoring of forests in Malawi. It is hoped that the results presented here can be used to help provide developing countries a stronger footing for arguing for REDD+ scenarios that will be beneficial to them, by providing an easy tool for understanding if different REDD+ scenarios result in them reaching their break even point.

Combining the results of the Plugge et al. approach with currently

available remote sensing datasets could help countries with a lack of internal funding and capacity to conduct remote sensing research into forest cover change that are struggling with meeting their REDD+ readiness goals.

There are certain requirements for baseline and future monitoring, reporting and verification (MRV) datasets that countries wishing to consider REDD+ need to meet. Malawi faces a severe lack of knowledge about the state of its forest resources; the last national forest and land cover maps produced in 1991. Any potential MRV procedures will require some input from remote sensing data (Goetz and Dubayah 2011, Gibbs et al. 2007, Holmgren et al. 2008, Herold and Johns 2007). In-country capacity with remote sensing is one of the key indicators of REDD+ readiness, and one of the major challenges faced by many developing countries (Romijn et al. 2012, Umekiya et al. 2010, Herold and Skutsch 2011). To the best of the authors' knowledge, there has only been one other study utilising remote sensing to map forest cover in Malawi using optical imagery, by Hudak and Wessman (2000), who estimated forest loss for a region of southern Malawi using Landsat imagery between 1981 and 1992. Malawi also lacks up to date field measurements to estimate both forest cover and forest cover change in most of its forest environments.

From the MODIS VCF data, 58% of Malawi's land area with more than 20% tree cover is in forest reserves or national parks. Under all but one of the scenarios where Malawi reaches a break-even point, the amount of forest required could come solely from government-controlled forest areas, which could simplify REDD+ introduction in Malawi by easing issues over land tenure. However, these areas are still utilised by local communities and many forest reserves are managed in conjunction with local communities under community-based natural resource management agreements, so benefits-sharing mechanisms would still need to be in place.

A higher rate of forest loss can compensate for the reduced income associated with larger measurement errors. For example the Department of Forestry forest loss estimate is 2.8% net loss per year, and means that any estimate of forest cover change with less than 20% error is sufficient to produce an economic return from REDD+. However, using the FAO deforestation rate of 0.9% means REDD+ only becomes viable in Malawi with 5% or better measurement error. Based on the results obtained using the MODIS data products, it seems likely that Malawi's deforestation rate is higher than that given in by the FAO, although this is not certain as we have only been able to narrow down a range of estimates of net forest loss to between 0.7-3% per year over the last decade.

4.4.2 Mapping forest cover using global land cover products

Fritz et al. (2011) show that care needs to be taken when conducting change detection with the MODIS land cover products, as the errors in classification for producing the yearly products can on the same magnitude (or even greater) than any changes being detected. This has been the experience of using both the EVI and VCF datasets, which have both needed some correction for inter-annual variation, and in the case of the EVI data, averaging of multiple datasets to get a more consistent yearly average for the late dry season. When NDVI or EVI has been used to map deforestation previously, it has usually been used in areas that are comparatively free from human activity. For example Mitchard et al. (2009a) successfully used NDVI derived from SPOT imagery, to map deforestation across a forest-savanna boundary in Cameroon, using the same methodology as that used here, and Anaya et al. (2009) have mapped deforestation in Columbia using VCF data. One of the main problems in Malawi is that forest loss is usually in the form of degradation, which is more difficult to detect than deforestation. This problem is further compounded by the fact that much of Malawi's

woodland ecosystems are naturally heterogenous savanna woodlands, as well as already being quite degraded.

The MODIS VCF product has been used in a number of studies as a way to understand forest dynamics. Hansen et al. (2003) used Malawi as an example of how this data can be used to investigate national and regional scale trends, and the differences between Malawi's forest cover and that of neighbouring countries can be clearly seen. While the VCF data is useful for comparing global and regional trends at a particular point in time, and indeed may even be useful for estimating change at a regional or global scale (given sufficient averaging of local trends in the datasets), it does seem that it is much more difficult to use these global datasets for national and sub-national scale mapping activities, particularly in heterogeneous savanna environments where forest loss is usually in the form of degradation rather than deforestation. The VCF datasets were initially used and developed with tropical rainforests in mind (DeFries et al. 2000, Hansen et al. 2003), and seem to perform much better at detecting deforestation in these environments, where the difference between forest and non-forest is much more marked, for example moving from 80%+ tree cover to less than 20%. However in Malawi, the changes between forest and non-forest are much smaller, with most of Malawi's forest cover averaging less than 30% tree cover, and agricultural areas often having a signal suggesting 5-10% forest cover. This makes detecting forest cover change in Malawi much more difficult than may be the case in other higher forest cover countries.

The MODIS VCF data does provide a useful first step for investigating changes in forest cover, particularly in Malawi where spatially explicit forest data is mostly unavailable. The same is true of the EVI data, which does have an improved resolution of 250 m, but still needs to have multiple acquisitions averaged to smooth out annual variability. VCF or EVI data can be used for calculating the potential economic possibilities of REDD+ in Malawi, as well as providing estimates for future work to

refine. For example, it now seems more likely that Malawi's deforestation rate lies between 0.7 to 3% per year, and that forest area falls somewhere between 15-25% of Malawi's total land area. We would argue that care needs to be taken when using vegetation indices such as EVI for mapping forests, given that it is so responsive to rainfall and despite taking as many precautions as possible to make sure tree cover is the strongest signal in the image data, trees will not be the only vegetation causing a response.

One other point for those involved in sustainable forest management activities in Malawi to consider is that all the datasets examined here also show that this loss is more severe in the central and southern regions of the country. This is particularly significant when taken together with calculations of Human Appropriated Net Primary Productivity (HANPP) produced by Imhoff et al. (Imhoff et al. 2004), which show that parts of southern Malawi in particular are using 80-100% of the potential energy produced by the environment to meet current needs. This situation will be exacerbated by population growth, which currently stands at around +3.2% per year (United Nations 2012).

4.2.1 Impacts of rainfall

Rainfall is one of, if not the key driver of phenological variability in miombo woodlands (Zhang et al. 2005, Chidumayo and Gumbo 2010). Fluctuations in Southern Africa's seasonal rains are linked to the El Niño Southern Oscillation Phenomenon (ENSO). ENSO can manifest itself as either El Niño or La Niña associated with warm and cool sea surface temperatures respectively in the tropical Pacific. Research has suggested two regions of ENSO related precipitation in Southern Africa: Eastern equatorial Africa, which during an El Niño is likely to receive above average rainfall and South Eastern Africa, which may experience below average rainfall (Stige et al. 2006, Plisnier et al. 2000). Both 2005 and 2009 were moderately strong El Niño years effecting Malawi (Manatsa et al. 2011). A La Niña event is likely to result in the opposite impacts. It is

important to note that these findings represent average impacts. Malawi sits in an area of transition between the two effects of El Niño variations witnessed in south eastern and eastern equatorial Africa (Jury and Mwafulirwa 2002). Malawi's El Niño response is not consistent with either eastern or southern African trends, and instead varies by sometimes being drier and other times wetter, which makes predicting the effects of El Niño on vegetation responses in Malawi very difficult (Jury and Mwafulirwa 2002).

Note, however, that both the MODIS datasets show a lower response to forest cover in 2005. This raises a potential issue for countries that can only conduct forest mapping infrequently. The drop in 2005 is likely to be due to an ENSO event, causing reduced rainfall and a slightly different seasonal rainfall pattern, rather than an actual decrease in forest cover. Furthermore, given the increase in both rainfall and forest cover the next year, it would suggest that datasets that were either using 2005 forest cover without knowledge of the prevailing trends could lead to significant underestimates of forest cover (with the converse being true for wetter years). Ingram and Dawson (2005) found a strong correlation between NDVI and ENSO events in Madagascar. Calculating a similar El Niño vegetation impact index for Malawi could be beneficial for quantifying the trends observed here. The impacts of ENSO could be particularly important when looking at global datasets, for example in the GlobCover land cover mapping over Malawi for 2005, forest cover is much lower than expected, and fits with the trends observed in the MODIS datasets. If the datasets like GlobCover were to be used as baseline data for Malawi without knowing the wider context of vegetation trends due to climatic influences, it could cause under- or over- estimates of forest cover.

4.5 Conclusion

In order for Malawi to benefit from any potential REDD+ projects it is vital that Malawi has accurate monitoring, reporting and verification

procedures in place. It is the error involved in estimating forest area, forest cover change, and carbon stocks that has the largest impact on whether or not Malawi can make enough money from REDD+ projects for them to be economically viable. Doubling measurement errors from 5% to 10% doubles the amount of forest needed to be included in a REDD+ project to reach a break-even point, while increasing monitoring costs from \$0.01 to \$5 per hectare only increases the amount of forest required by 2-10%. Reducing errors from 10% to 5% gave REDD+ the potential to be cost-effective in Malawi for all simulations. If Malawi has a lower rate of forest loss, as estimated by the FRA 2010, then minimising the error in forest measurements is the key factor in determining the potential economic viability of REDD+ in Malawi.

Coarse resolution optical datasets have potential to add greatly to knowledge about the dynamics occurring Malawian woodlands, while avoiding a lot of the challenges that other higher resolution datasets may present such as higher cost, less frequent or less complete coverage, and the need for more pre-processing. However, both of the MODIS datasets investigated here have significant problems with inter-annual variability, making it difficult to know if the trends being seen in a particular dataset are actually due to changes on the ground, biophysical changes that we have not accounted for, or due to noise in the datasets themselves.

Although these results do not present a coherent picture of how fast forest loss is occurring in Malawi, they all confirm that some level of net forest cover loss has been occurring over the last decade (between 0.7-3%), and until now the only evidence for this was anecdotal. These datasets can be used as a starting point for improving forest cover maps in Malawi, and as way to start investigating trends between population dynamics and forests to help develop suitable, targeted mitigation strategies.

5. Use of ALOS PALSAR for mapping forest cover change in savanna woodlands in Malawi

Gemma Cassells, Iain Woodhouse, Casey Ryan, Mike Chirwa

School of GeoSciences, University of Edinburgh, Edinburgh, UK
Forestry Research Institute of Malawi, Zomba, Malawi

Aboveground biomass, in the form of carbon, is the key metric of interest to REDD+. ALOS PALSAR has been used in many previous studies to produce these biomass maps. This paper investigates whether or not these approaches can be successfully applied to Malawi. It also investigates the use of a generic backscatter-biomass relationship developed by Mitchard et al. (2009) for African woodlands. We found no regression between our field-measured forest parameters and backscatter explained enough of the relationship to be used to develop empirical relationships between the variables. This has significance for the future of the REDD+ process, as if a particular mapping approach is going to be expected to be used globally to produce carbon stock estimates there may be cases where particular countries may not benefit fully from REDD+ as these methodologies do not work provide accurate estimates of their carbon stocks.

I organised and led the field data collection, and conducted the data analysis for both field and remote sensing data. I wrote the manuscript.

Abstract

Malawi is one of the poorest and most densely populated countries in the world, with a predominantly rural population largely dependent on forest resources. Currently, scientists and policymakers have to rely on out-of-date information on extraction rates and locations of forest cover change to estimate the magnitude of this problem. This paper examines the development of empirical relationships between ALOS PALSAR L-band synthetic aperture radar (SAR) and field-based forest metrics including biomass and basal area. No correlations between any field-based forest metric and ALOS PALSAR backscatter explained enough of the variability in the datasets to be used to develop empirical relationships between the variables. The accuracy of a generic backscatter-biomass regression developed by Mitchard et al. (2009) is assessed over Malawi, and found to have a similar biomass distribution to that observed in the field data, but poor point-for-point accuracy. Two different methods of assessing forest cover change were also undertaken. The first used a normalised HH/HV ratio to delineate areas of forest, and assess changes around the Lake Chilwa area of southern Malawi from 2007-2010. The second looked for significant land use change by thresholding the predicted AGB maps produced by the Mitchard et al. regression. These results were compared to a forest cover change map produced using MODIS Vegetation Continuous Fields percentage tree cover data. Both the normalised HH/HV ratio change map and the MODIS VCF change map independently found net forest loss rates of 2.5% per year for this area. The predicted AGB change map found a lower loss rate of 1.6%, which is probably because it uses a more strict forest threshold than the other methods.

5.1 Introduction

Malawi, a landlocked country in southeast Africa, is the sixth poorest country in the world (World Bank 2000). Malawi is one of the most densely populated countries in sub-Saharan Africa, with an average of 168 people per km², around 10 times higher than its three neighbours (Zambia, Tanzania and Mozambique). Approximately 10 million people live in rural areas, and almost 8 million live on less than US \$2 per day (National Office of Statistics 2010, McConnell et al. 2007). The links between forest resources and poverty are well established in Malawi (see for example Bandyopadhyay et al. 2011, Fisher et al. 2005, Kamanga et al. 2009a, Conroy et al. 2006), and there is the long history of concern over unsustainable forest resource use in Malawi (French 1986, Bandyopadhyay et al. 2011, Mayers et al. 2001, Zulu 2010). However, because of a lack of data, there are a number of uncertainties concerning the spatial distribution and exact magnitude of deforestation. Scientists and policymakers are forced to rely on out-of-date information, with current deforestation rates extrapolated from data collected and analysed in the early 1990s, and from timber supply and use estimates, which have large uncertainties due to the informal nature of Malawi's fuelwood and charcoal industries (Mayers et al. 2001).

Satellite remote sensing provides an opportunity to map forest cover change on spatial and temporal scales not otherwise possible. There is now a vast range of different satellite platforms and data types to choose from when conducting land cover mapping. SAR (Synthetic Aperture Radar) is particularly appropriate for use in the tropics as persistent haze and cloud cover often limit the use of optical imagery. Due to the direction of the prevailing winds, Malawi's topography and the location of Lake Malawi, it is very difficult to find cloud-free passive optical imagery over much of Malawi, even in the dry season when cloud free passes can routinely be expected for the rest of southeastern Africa. SAR systems

such as the ALOS (Advanced Land Observing Satellite) PALSAR (Phased Array L-band SAR) instrument have the potential to assess not just areas of forest cover change, but they are also sensitive to above ground biomass due to their ability to penetrate deeper into the forest canopy (Imhoff et al. 1995, Le Toan et al. 1992, Broily and Woodhouse, 2013).

Most of the previous estimates of forest cover change in Malawi have had some remote sensing component, usually passive optical imagery such as Landsat (for example see Hudak and Wessman 2000, and Chapter 4). Many previous studies, such as (Imhoff et al. 1995, Le Toan et al. 1992, Kellndorfer et al. 2004, Le Toan et al. 2004, Morel et al. 2011, Mette et al. 2004), have shown the potential of SAR for estimating biomass, but there has been very little work done on this in Africa, and even less for use at sub-nation scales. For three examples of an otherwise sparse literature see Mitchard et al. (2009b), Mitchard et al. (2011b), and Ryan et al. (2011a). This study aims to investigate the suitability of ALOS PALSAR for biomass and forest cover mapping in Malawi. First, we will investigate what, if any, correlation is present between field-measured forest parameters and ALOS PALSAR backscatter. We then assess the accuracy of a generic backscatter-above ground biomass (AGB) relationship developed by Mitchard et al. (2009) using from field data across a number of different African savannas. Thirdly, change detection is also undertaken to assess the accuracy of ALOS PALSAR for mapping forest cover change, by using a normalised HH/HV polarisation ratio (explained in section 5.2.2 and 5.3.3). Another change detection is also conducted using the results of the predicted AGB from the Mitchard et al. equation, to investigate areas of significant forest change.

5.1.1 State of Malawi's forest resources

Approximately a third of Malawi is considered forest³ (the Department of Forestry estimate based on unidentified data is 26% (Nkwanda et al. 2008), and the reported United Nations FAO Forest Resources Assessment 2010 (FRA 2010) estimate is 34%). Malawi relies heavily on its timber resources to generate vital government revenue. Plantation forests have increased from 285,000 ha in 2000 to 365,000 ha in 2010 (FAO 2010a), with Malawi having the second largest plantation forest area in Africa. However, while the area of plantation forests has increased, Malawi's natural miombo woodland is under considerable pressure from the largely rural, impoverished population. By analysing timber use estimates, Mayers et al. (2001) calculate that annual consumption of forest products is 15 million m³, while the sustainable supply is less than 8 million m³. However, given the largely informal nature of Malawi's forest economy these estimates may not be accurate. Projections based on primary forest loss experienced between 1990 and 2005 suggest that all primary forest in Malawi will be degraded or deforested by 2020 (Mayers et al. 2001). This forest loss is attributed to agricultural expansion, and biomass use for fuelwood, charcoal production, tobacco curing, and brick making, among others (Jumbe and Angelsen 2007, Kamanga et al. 2009b, Orr and Mwale 2001). Over 90% of Malawi's total energy demand is met by biomass use, primarily in the form of charcoal, despite the fact that all charcoal production currently occurring in Malawi is illegal (Zulu 2010, Kambewa 2007).

Previous estimates of nationwide deforestation rates vary between 1-2.8% per year, with localised areas showing higher rates (Hudak and Wessman 2000, FAO 2010a, Nkwanda et al. 2008, Chapter 4). This is equivalent to

³ Forest is being used here as a shorthand for a tree-dominated ecosystem. Malawi's official definition of a forest is an area of land of at least 0.5 ha with at least 10% canopy cover, which includes most savanna ecosystems as well as those usually thought of as forest.

forest loss of around 4,000-7,000 hectares a month, an area about the size of Manhattan. This makes protecting Malawi's forests a priority for both the local communities that rely on them to meet their basic livelihood needs as well as the national government. The range of these deforestation estimates, and the lack of information on the spatial and temporal trends in deforestation and degradation across Malawi also raises problems for effective management and monitoring of the forest resource, which desperately need addressing in order to move towards implementing a more sustainable forest management programme in Malawi.

5.2 Methodology

5.2.1 Forest Inventories

Field data was collected from four sites in Malawi; the Thazima region of Nyika National Park (NNP) (10°33'S, 33°50'E), Mkuwazi Forest Reserve (MFR) (11°72'S, 34°05'E), Kaning'ina Forest Reserve (KFR) (11°26'S, 34°03'E) and Malosa Forest Reserve (MaFR) (15°11'S, 35°19'E). These 197 inventories include plots ranging in size from 0.1-1.25 ha. Historical data from 30 0.25 ha permanent sample plots (last surveyed in 2007) in Liwonde Forest Reserve (LFR) (15°08'S, 35°18'E) were obtained from the Forest Research Institute of Malawi. The inventories cover a total area of 31.2 ha of forest, and include measurements from 14,103 individual trees. The NNP and MFR inventories were stratified to include representative samples for all the different land cover types in these areas, included plots located outside the reserve boundary, on adjoining cropland. The KFR and MaFR sites were randomly sampled. The inventories include all standing trees >5 cm diameter at breast height (dbh), and recorded dbh, height (using either a Haglöf Vertex III hypsometer or a clinometer) and species, along with plot coordinates using a handheld GPS (Trimble GeoXH or Garmin GPSmap 60Cx).

These sites are predominantly miombo woodland, dominated by *Brachystegia* species. More degraded areas are dominated by secondary miombo species, usually *Uapaca kirkiana*. Although a stratified sampling technique was not employed, field sites also included several forest and woodlands types with a more limited spatial extent, including evergreen deciduous forest, acacia savanna, riverine forest and a small area of pine plantation. They represent a diverse cross section of Malawi's major ecosystems, including mountain plateaus, the lakeshore and plains, and incorporate some geographic variability between the northern and southern regions of Malawi.

These forest inventories were converted to plot-level estimates of AGB using appropriate allometric equations depending on the dominant forest type of the plot. There is no locally developed allometry available for any of the field sites, indeed there are very few allometric equations developed specifically for miombo (Frost 1996, Chidumayo 1997, Ryan et al. 2011b) and those found all deal with miombo woodlands as a whole rather than on an individual species level. The allometric equation used in this study was developed for miombo woodland in Mozambique by Ryan et al. (2011b) after finding that the other available equations did not accurately predict the growth curves they observed in their sample plots. For the other areas of woodland covered by this field survey, other allometric equations from published sources were used including a generic equation for dry tropical forests from Brown (1997) for evergreen and riverine forest.

5.2.2 Satellite data

Nine Fine Beam Dual (FBD) mode images from the ALOS PALSAR sensor were obtained from the European Space Agency, covering the fieldwork locations, five from 2009 and two from 2007 and 2010 over the same area. These dates were chosen to most closely coincide with the respective dates of fieldwork campaigns in these areas. All images were acquired on the ascending pass, have an incidence angle centred on 34.3°,

and were provided with a 12.5 m pixel size, with 4 looks. All images are from the late dry season (August-October), to minimise the effects of environmental conditions such as soil moisture, which is known to influence L-band backscatter (Rignot et al. 1994, Pulliainen et al. 1999, Magnusson et al. 2007, Santoro et al. 2012, Lucas et al. 2010), changes to understory vegetation or sensor calibration drift. Tropical Rainfall Measuring Mission (TRMM) data was analysed for the week preceding the acquisition to make sure no rainfall events had occurred that would have changed the dielectric properties of the surfaces.

These images were processed using the Alaska Satellite Facility's MapReady software v2.3.6 (ASF, 2010), combined with 90 m resolution elevation data from the Shuttle Radar Topography Mission (SRTM). Each image was converted from digital numbers to backscatter (σ^0) using the calibration coefficients of Shimada et al. (2009), and a geometric and radiometric terrain correction was applied. The images were resampled to 25 m, 50 m and 100 m pixel sizes using nearest neighbour resampling, giving 16, 64, and 256 equivalent looks, respectively. The σ^0 images were resampled using arithmetic means of the real values (not dB). To maintain consistency with previously published graphs, data were convert back to dB for the scatter plots.

The original data were also processed a second time to correct geolocation only, to produce a duplicate set of images that had not been terrain corrected to enable analysis of the impacts of terrain correction on the backscatter-forest parameter regressions. Comparison with optical imagery (Landsat and 10 m resolution SPOT) showed that the resulting images were well geolocated (~1 Landsat pixel, and 1-2 SPOT pixels, ie, 10-30 m) compared to prominent landscape features, such as roads and an airstrip. The images were very closely geolocated to each other, with no geolocation differences visible between the 2007 and 2010 images. In order to produce accurate change detection maps, the scenes were calibrated against each other using areas that are known to have

remained unchanged in both images, such as the central areas of Lake Chilwa, and areas of a pine plantation that were known to have remained unlogged.

5.2.2.1 Empirical relationships between forest parameters and backscatter

The backscatter values for both terrain corrected and non-terrain corrected images at 25 m, 50 m and 100 m resolution were extracted over the plot location, and compared to various field-based forest parameters, including plot estimates of AGB, basal area, and the Biomass Consolidation Index (BCI) developed by Smith-Jorgensen et al. (2007). Both HH and HV channels were considered, even though HV is known to be the most sensitive to forests (Le Toan et al. 1992, Mitchard et al. 2009b).

5.2.2.2 Comparing a generic backscatter-biomass equation and field-estimated AGB

A generic backscatter-biomass equation developed by Mitchard et al. (2009b) was applied to the 25 m resolution images to produce a predicted AGB map. The predicted AGB estimates from the Mitchard et al. equation were compared to the plot estimates of AGB. In order to obtain as large a sample as possible, the forests surrounding the locations of the field plots, rather than just the field plots themselves, was extracted from the imagery, to give a total of just over 10,000 pixels for analysis. A probability density function of predicted and field data-estimated AGB was plotted, as the Mitchard et al. relationship is known to contain large errors of $\pm 20\%$, due to the fact that radar backscatter is interacting with the forest structure, rather than being directly sensitive to biomass (Saatchi and Moghaddam 2000, Woodhouse 2006b, Broly and Woodhouse 2012, Woodhouse et al. 2012), and this would give an indication how the spread of the results compared, even if the measured and predicted values for specific pixels did not correlate exactly.

5.2.2.3 Change detection

The use of ALOS PALSAR for change detection is also investigated through two different methods using 2007 and 2010 imagery, which covers the southern fieldwork sites. Firstly, a change detection map was produced for areas of significant land cover change, by thresholding the predicted AGB map to look only at area with AGB of $> 20 \text{ tC ha}^{-1}$ in the 2007 image. Using this threshold increases the likelihood that only forested pixels are being examined. This map was produced by computing a normalised difference image, which was then classified based on standard deviations of this ratio, to look for areas with positive and negative change. A second change detection was computed by calculating a normalised HH/HV ratio $(\text{HH}-\text{HV}/\text{HH}+\text{HV})$ for each year, and then identifying the forest/non-forest threshold from this data, and producing a normalised difference image. The use of a ratio to define change is appropriate with SAR imagery, as ratioing SAR images (in real number terms) is generally preferred to differencing because of the multiplicative noise-like characteristics of speckle (Rignot and van Zyl 1993, Radke et al. 2005, Mitchard 2011).

Given a lack of alternative datasets for comparing the results of these change detection methodologies, the change maps produced using both of these methodologies were compared to change maps produced using the percentage tree cover data from the Moderate Imaging Spectrometer (MODIS) Vegetation Continuous Fields (VCF) product.

5.3 Results

5.3.1 Regression of backscatter and field-measured plot variables

We investigated both linear and nonlinear regression analysis on a number of different backscatter relationships with field-derived variables, namely AGB, basal area and BCI. All the datasets used for analysis passed a Shapiro-Wilk normality test. Nonlinear regression, specifically

logarithmic curves, provided the best model of fit. The best-fit curves for each regression are shown in figures 5.1-5.4.

No regression was found to be statistically significant enough to be used on its own to develop an empirical relationship between ALOS PALSAR backscatter and any field-derived forest metrics (figures 5.1-5.4). Basal area has the best correlation with backscatter with R^2 values between 0.37-0.39, but still does not explain enough of the relationship between the variables to be useful in building an empirical relationship. The 50 m resolution data also seems to have the smoothest relationships, with all datasets showing a small increase in R^2 , compared to 25 m or 100 m ALOS PALSAR data. This is likely to be a consequence of smoothing out some of the remaining speckle present in the imagery, as well as smoothing some of the heterogeneity in the vegetation, but not smoothing to such an extent that sensitivity is lost.

The datasets appear to lose sensitivity (reach saturation) at less than 15 tC ha⁻¹. This indicates that there are problems with the regression relationships, and that this dataset has an unusually large variability, as most published relationships reach saturation for L-band SAR at around 60+ tC ha⁻¹ (Imhoff et al. 1995, Luckman 1997, Hoekman and Quiriones 2000, Le Toan et al. 1992).

Terrain correction does appear to have some impact on the relationships observed in the data, improving regression significance in all cases (figures 5.1 and 5.2). Given the improvement in the results, it would be beneficial to obtain a higher resolution DEM (50 m postings or less) to assess how this improves regression accuracy. Malawian topography is highly variable, particularly in the northern region, and along the lake shore, with many steep sided valleys, and this complexity is not fully captured by SRTM 90 m data. Although much of the central and southern region is flatter, these areas have long been cleared of trees, and it now forests and woodlands can only be found on steeper, more inaccessible

slopes. This presents a particular problem for the use of SAR in Malawi because of the side-looking nature of the system.

The data from the larger plots (> 0.25 ha) has marginally better regression coefficients (improving R^2 up to 0.05), compared to using the entire dataset (data not shown). This is understandable, given the errors associated with estimating AGB from small field plots (Chave et al. 2004). This could be due to the fact that there are significantly reduced scaling errors when estimating AGB from larger plots (Chave et al. 2004, 2005, Zianis and Mencuccini 2004, Ketterings et al. 2001, Clark and Gelfand 2006). However there are also fewer large plots (47, out of a total sample of 227), which sample a smaller variety of woodland types, leading to less variation in the estimated AGB values. For example the total dataset has a mean (all means quoted \pm one standard deviation) of 48.6 ± 42.7 tC ha⁻¹, because of the variety of woodland environments surveyed, while the larger plots, which are all from similar miombo forest reserves and surrounding customary land, have a mean of 25.7 ± 8.6 tC ha⁻¹. There are undoubtedly large errors associated with estimating AGB for dense forests from 0.1 ha plots, for example riverine forests have a high biomass, but a limited extent, leading to estimates of more than 300 tC ha⁻¹, when the actual extent of the forest patch may actually be less than 1 ha. Some of the noise in the data will also be due to poor geo-location of ALOS data, as the scale of error (10-30 m) is on the scale of some of the smallest plots. Even though savanna environments are heterogeneous, given that most of the field plots were located inside forest reserves or national parks, and purposely located within areas of similar vegetation, away from vegetation boundaries, this effect is likely to be relatively small.

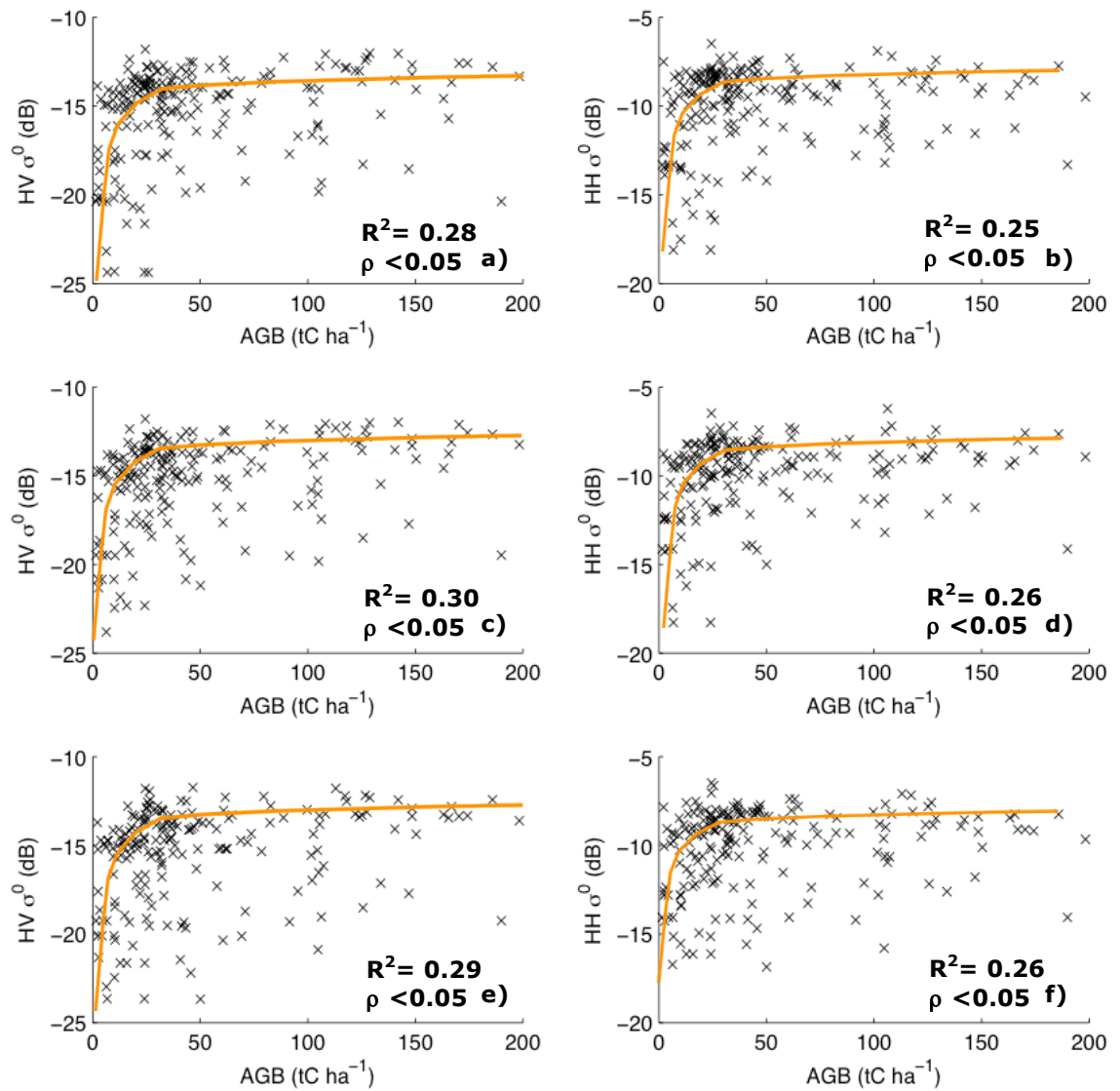


Figure 5.1 Regression of backscatter from terrain corrected ALOS PALSAR data (using ASF's MapReady software) and fieldwork-derived AGB estimates from 227 0.1-1ha plots across Malawi, for both HV polarisation, at 25 m (a), 50 m (c) and 100 m (e) resolution and HH polarisation, at 25 m (b), 50 m (d) and 100 m (f) resolution.

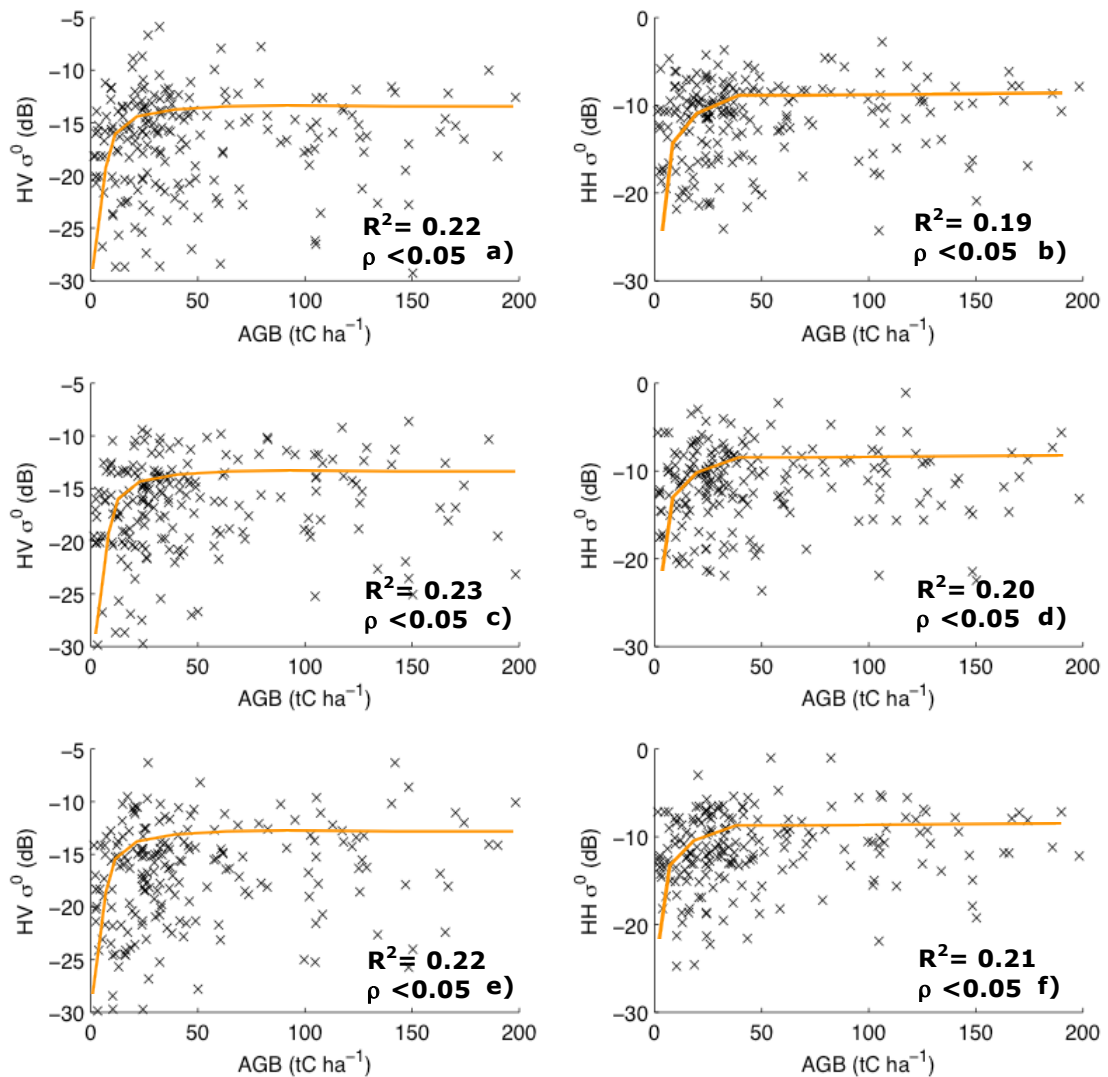


Figure 5.2 Regression of backscatter from non-terrain corrected ALOS PALSAR data and fieldwork-derived AGB estimates from 227 0.1-1ha plots across Malawi, for both HV polarisation, at 25 m (a), 50 m (c) and 100 m (e) resolution and HH polarisation, at 25 m (b), 50 m (d) and 100 m (f) resolution. Some of the noise in this data is due to relatively poor geo-location (1-2 Landsat pixels), which is on the scale of the plot size for some of this data.

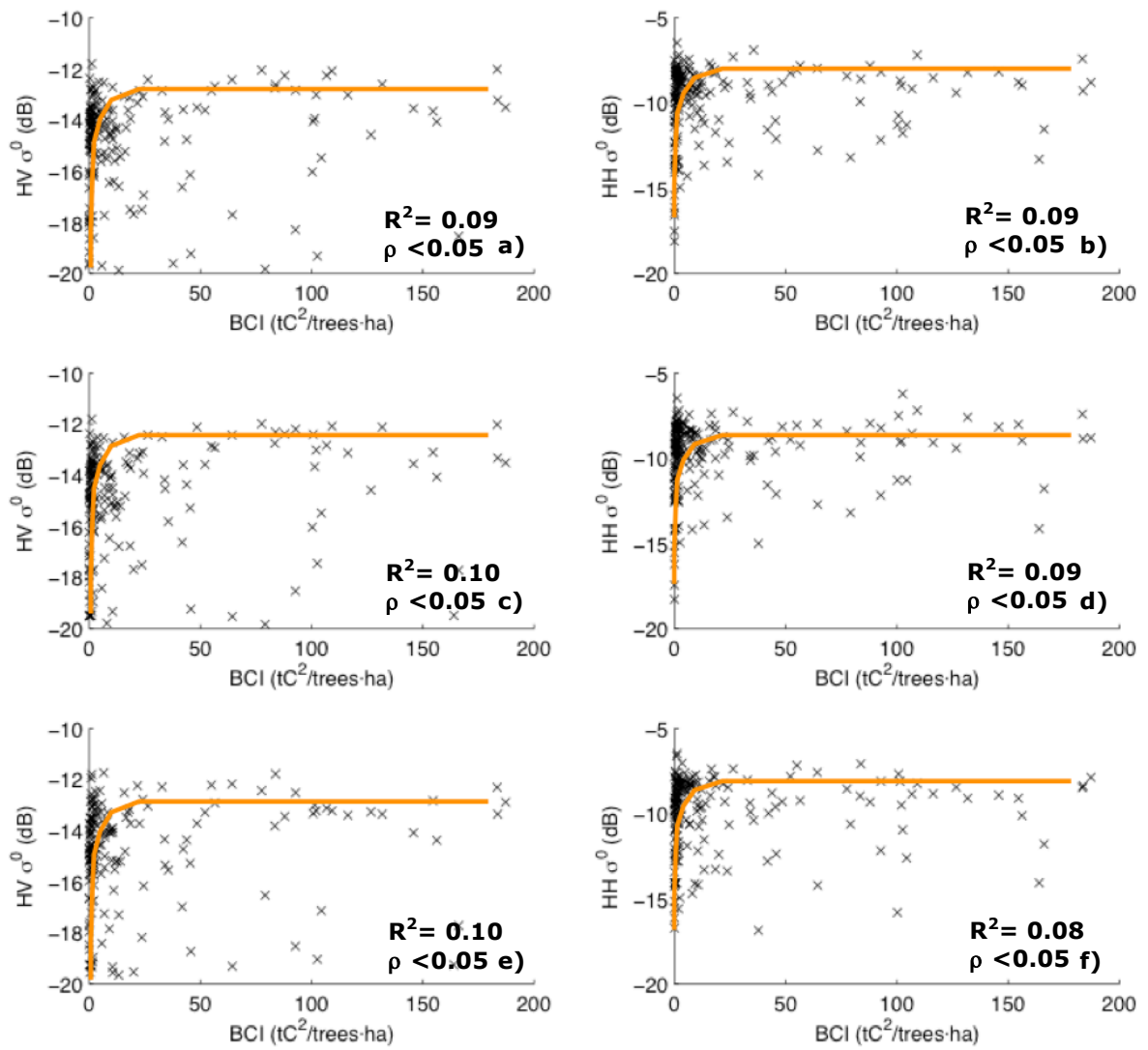


Figure 5.3 Regression of backscatter from terrain corrected ALOS PALSAR data and BCI (Smith-Jonforsen et al. 2007) from 227 0.1-1ha plots across Malawi, for both HV polarisation, at 25 m (a), 50 m (c) and 100 m (e) resolution and HH polarisation, at 25 m (b), 50 m (d) and 100 m (f) resolution.

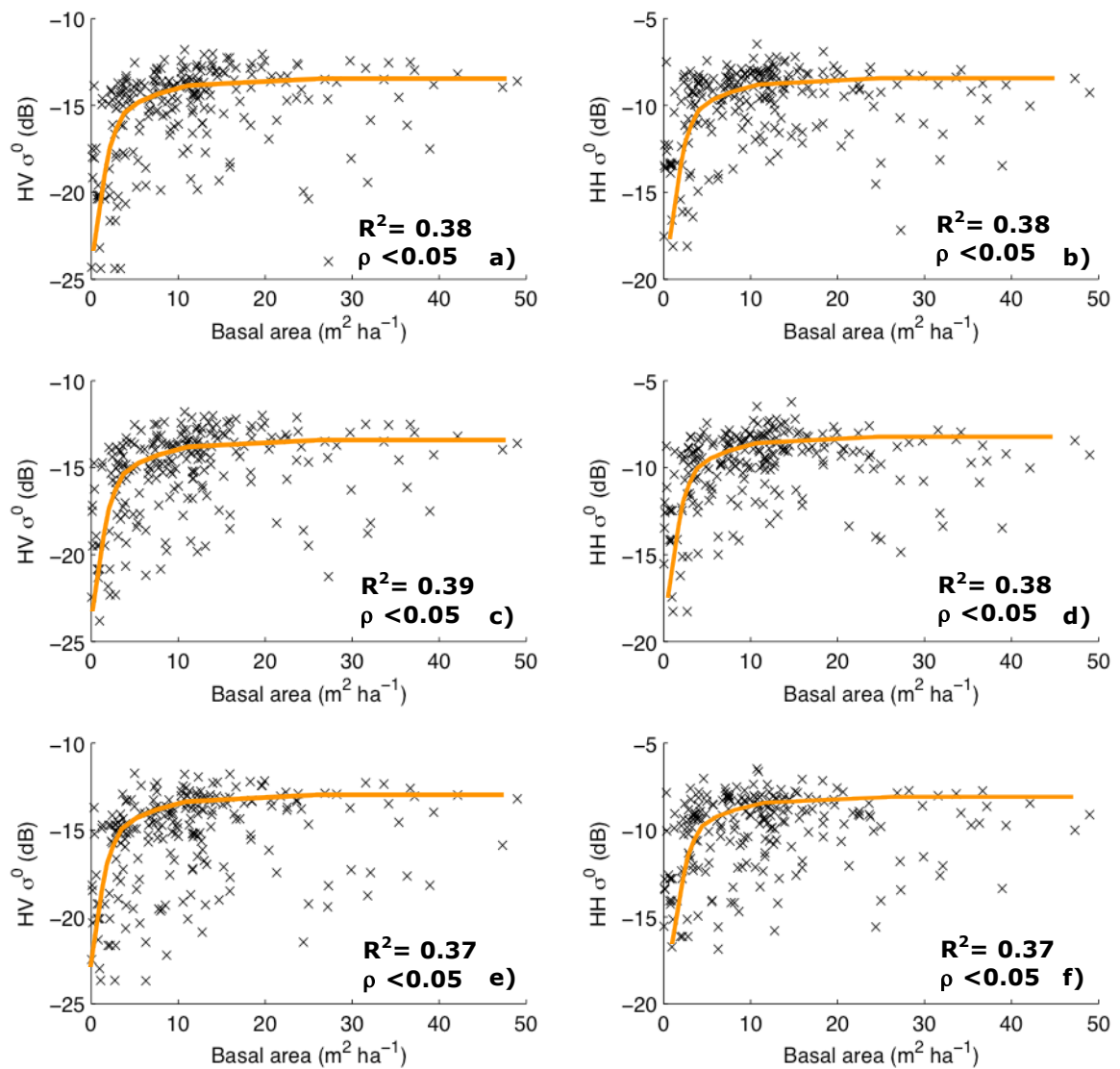


Figure 5.4 Regression of backscatter from terrain corrected ALOS PALSAR data and basal area from 227 0.1-1ha plots across Malawi, for both HV polarisation, at 25 m (a), 50 m (c) and 100 m (e) resolution and HH polarisation, at 25 m (b), 50 m (d) and 100 m (f) resolution.

5.3.1.1. Impact of allometric equations on regression

In order to assess what, if any, impact the selection of allometric equations and consequent plot-level biomass estimates were having on backscatter-biomass regressions, and the lack of correlations observed, the regressions were repeated using AGB estimates from a number of different equations, including two of the most widely used generic dry tropics allometric equations from Brown (1997) and Chave et al. (2005), as well as 2 other miombo-specific allometric equations from Abbot et al. (1997) and Frost (1996), in addition to the allometric equation developed by Ryan et al. (2011). Figure 5.5 shows how these allometric equations vary in predicting biomass.

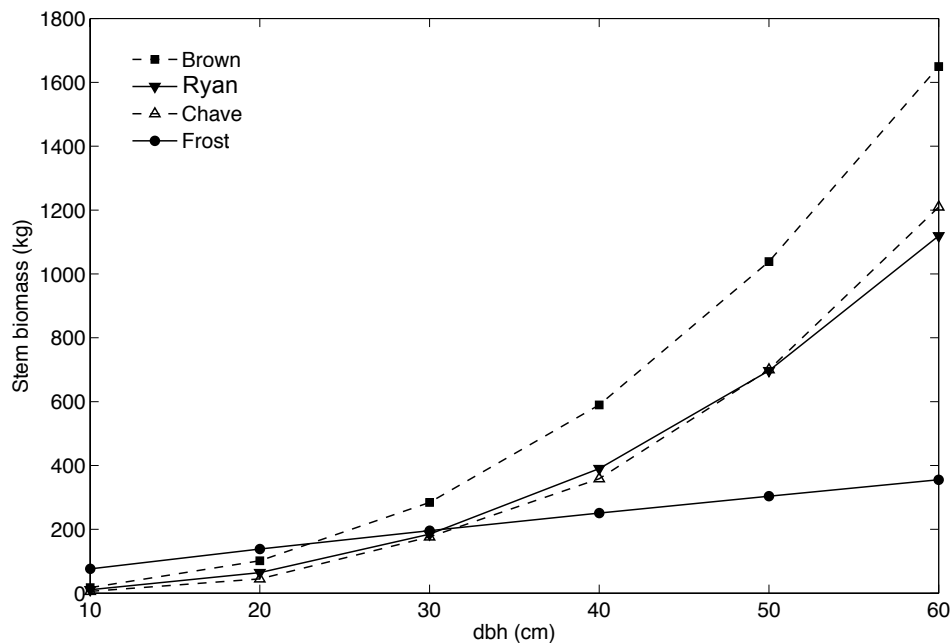


Figure 5.5 Comparison of four different allometric equations from Brown et al. (1997), Frost (1996), Ryan et al. (2011), and Chave et al. (2005), which shows how AGB estimates could vary significantly depending on which allometric equation was selected to convert from field measurements to AGB. The Chave et al. (2005) and Brown et al. (1997) equations are two widely used pan-tropical allometric equations, while the Ryan et al. (2011) and Frost (1996) are miombo-specific equations.

For the Chave et al. (2005) pan-tropical optimum allometric equations, the moist tropical forest equation was used for forest species, and the dry forest equation was used for savanna species. These equations use dbh,

height and wood density. Wood density data were taken from the Global Wood Density Database (Zanne et al. 2009). Where species-specific data was not available, the average value for African members of the same genus were used. For the Brown et al. (1997) equations, the moist tropical forest equation was used for forest species and the dry forest equation was used for savanna species.

The backscatter-biomass regressions were examined for the different biomass estimates, but little change was found in any of the statistics from those obtained using the Ryan et al. (2011) equation. However it is interesting to note that basal area had the strongest relationship with backscatter. This could indicate that allometry is having an impact on the AGB-backscatter regressions, and that improved allometry could improve the relationship. Future work on backscatter-biomass regression may need to take the differences in AGB estimates produced by different allometry into account, as the results from just 4 equations here show how much biomass estimates can vary based on the allometry used.

5.3.2 Using a generic backscatter-biomass regression to predict AGB

Since the attempts to find a site-specific correlation between backscatter and field-derived metrics of forest cover failed to produce statistically significant results, alternative methods for estimating biomass from backscatter were attempted. We assessed the accuracy of an AGB map produced using the generic regression developed for Africa by Mitchard et al. 2009, by comparing AGB estimated using the Mitchard et al. (2009) regression (now referred to as “predicted AGB” for concision) with field-derived AGB. The Mitchard et al. regression estimates AGB as dry biomass in Mg ha⁻¹, so these values were multiplied by 0.44 to obtain equivalent values of plot biomass in tC ha⁻¹. There was no significant correlation between field-derived estimates of AGB and predicted AGB estimates at the plot level. This is unsurprising, based on lack of success in finding a site-specific backscatter-AGB regression, and considering the

errors inherent in the Mitchard et al. regression, with an estimated accuracy of $\pm 20\%$ AGB.

In order to assess the accuracy of this regression more widely, areas of the forest surrounding the field plots were extracted, giving a total sample of 10,000 pixels (compared to 227 plot locations). This allows the overall accuracy of the predicted AGB values to be better assessed. Probability density functions were produced to compare the distribution of AGB averages with field estimates of AGB (figure 5.6). Due to the differences in the number of points sampled, both probability density functions have different bins (the optimum number was calculated using the formula from Freeman and Diaconis 1981). There seems to be a reasonably close match between the two histograms, although the Mitchard et al. equation predicts a smoother distribution of values, with a single peak around 15-25 tC ha⁻¹. The field estimates seem to show two peaks (one at 20-30 tC ha⁻¹ and another, smaller peak at around 100 tC ha⁻¹), which seem to correspond roughly to the averages expected from miombo woodland, and those expected for the higher biomass areas of dry tropical forest.

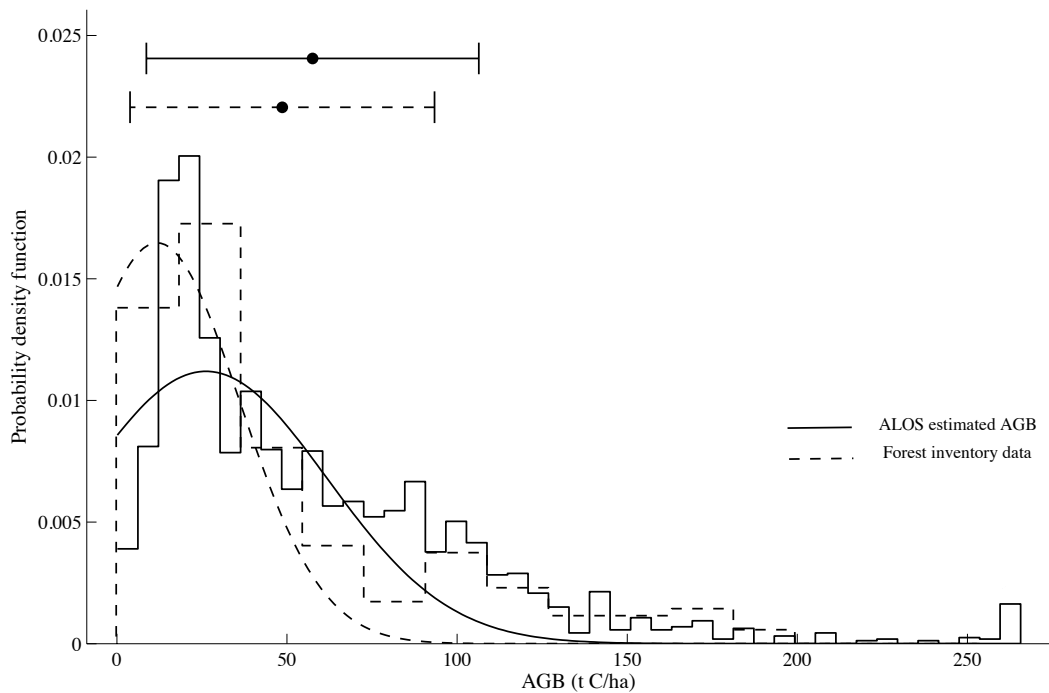


Figure 4.6 Probability density functions of fieldwork-derived above ground biomass estimates from 227 sites (dashed line) and estimates from ALOS PALSAR using the generic regression from Mitchard et al. (2009) for a sample of 10,000 pixels from the forests surrounding the fieldwork locations (solid line). Non-centred Gaussian trends lines are fitted to both histograms. Lines above show mean (solid dot) and standard deviation. Means are 57 tC ha⁻¹ from the ALOS estimates and 48 tC ha⁻¹ from forest inventory data. This is also close to the UN-FAO estimated average for Malawi of 44 tC ha⁻¹.

There are some key differences in the distribution of dbh, and its contribution to biomass (figure 5.7), which may also be causing some of the differences observed in the probability density functions.

For the Malawi field plots, 62% of trees inventoried had a dbh of < 10 cm, which accounted for 11% of AGB, while a sample of the field data that was used to develop the Mitchard et al. equation from Mbam Djerem National Park in Cameroon, has 40% of trees with a dbh < 10 cm, which account for 4% of AGB. When considering only the savanna plots in the inventory, 44% of trees having a dbh < 10 cm, which accounted for 5% of total biomass. For larger trees, the Mitchard et al. dataset has 4% of trees inventories with a dbh > 40 cm, which account for 41% of AGB estimates, while in the Malawi field plots, 0.5% of trees with a dbh > 40 cm, accounted for 19% of AGB estimates.

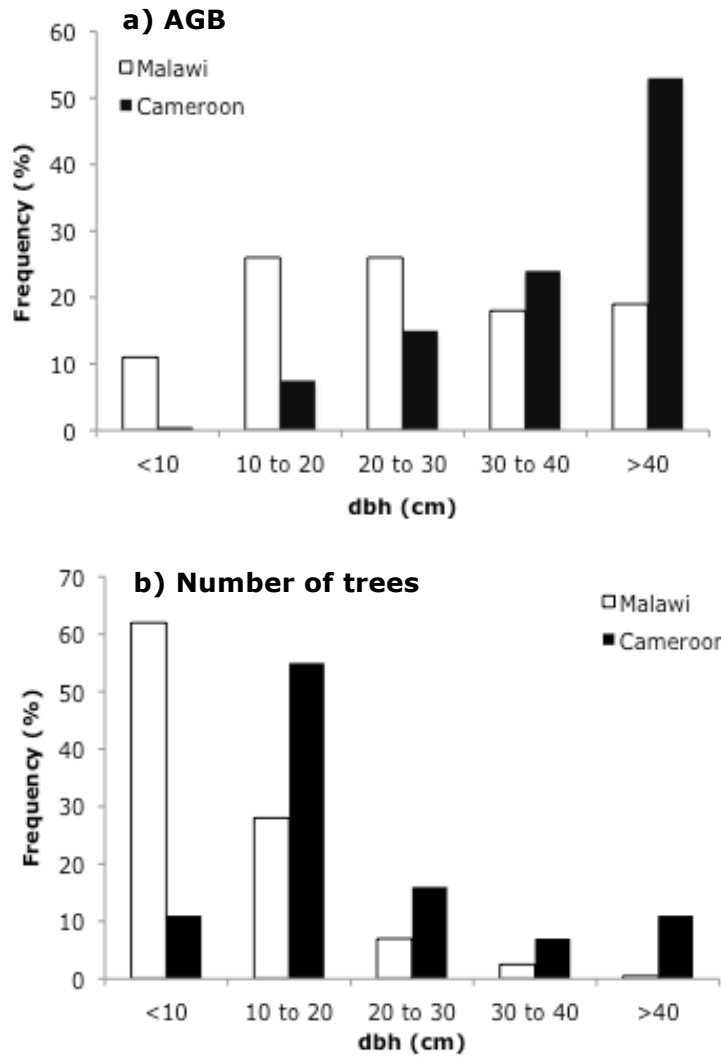


Figure 5.7 AGB by dbh class (top), and the distribution of the number of trees by dbh class (bottom) for all 14 103 trees inventoried in Malawi, and for a sample of field data from Mbam Djerem National Park in Cameroon (n = 996 stems) to produce the Mitchard et al (2009) generic backscatter-biomass regression. Data for these figures used with permission of Mitchard et al.

5.3.3. Forest cover change detection for southern Malawi

From visual analysis of the imagery, forest areas are well delineated despite the lack of success finding a backscatter-biomass regression. This section therefore evaluates whether ALOS can be used to produce forest cover change maps despite being unable to produce biomass maps.

A normalised HH/HV ratio ($(HH-HV)/(HH+HV)$) was calculated. This ratio seems to be a sensitive predictor of forest cover, closely mirroring trends seen in the original imagery (Dong et al. 2012, Sarker et al. 2012, Walker

et al. 2012, Mitchard et al. 2012). A threshold of 0.35 was chosen as it qualitatively appeared to be most accurate in delineating the forest/non-forest transition, with lower values (darker areas of figure 4.8) being forest. This value was selected based on the previous experience of Mitchard et al. (2012), and from visual analysis of the imagery. All values between 0.2-0.4 (to 2 decimal places) were considered, and then visually compared to Landsat and high resolution imagery on GoogleEarth to see which corresponded best to areas of known forest cover. Forest cover maps for 2007 and 2010 using this threshold were produced, and then used to produce a forest cover change map (figure 5.8). The tree cover in this region is predominantly miombo, with the bulk of the forest cover that remains in the area in government-managed forest reserves.

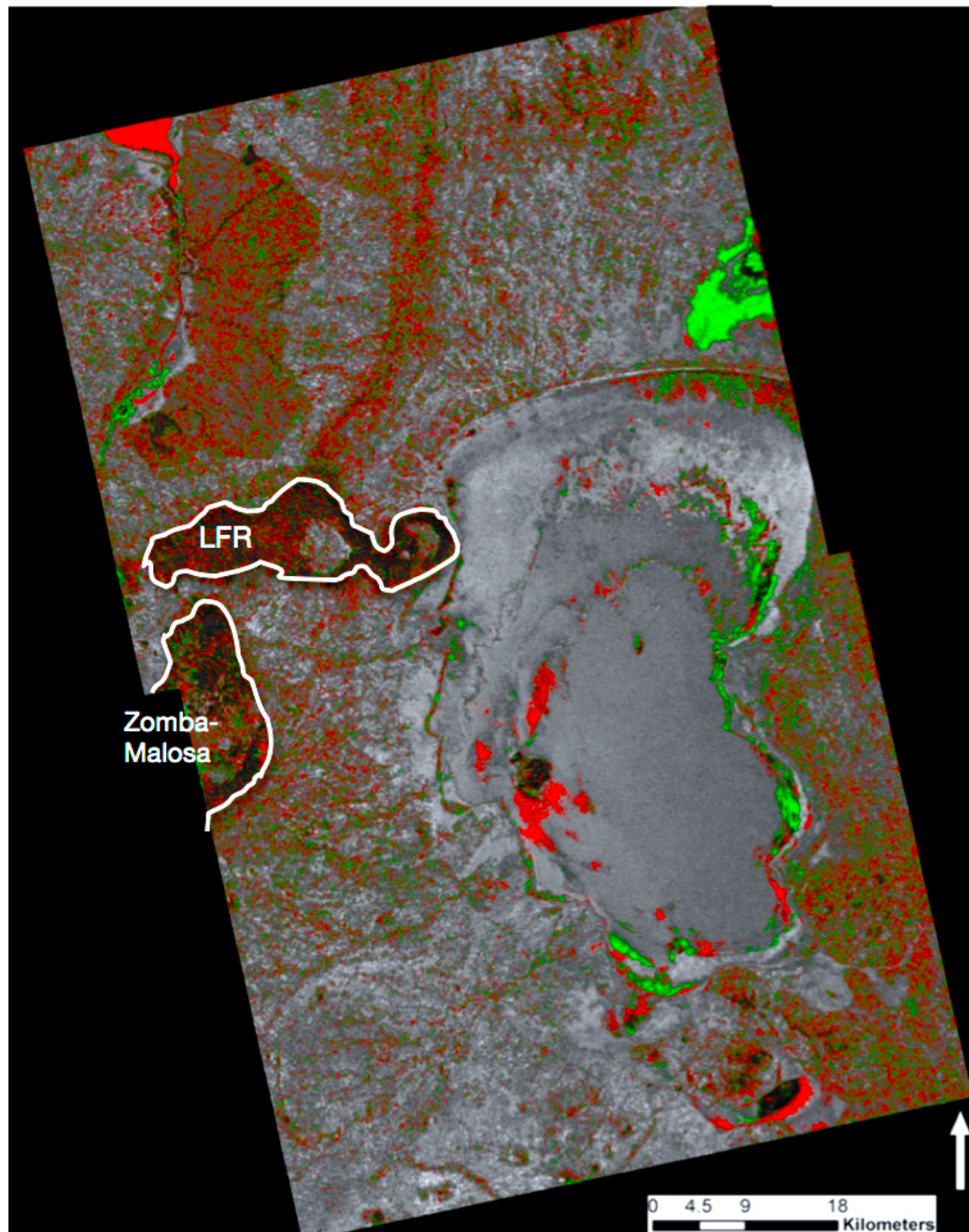


Figure 5.8 2007-2010 change in the normalised HH/HV ratio for areas with a starting value of 0.35 or lower (areas that were below the threshold in 2007, and above it in 2010 (forest gain) are in green, with the reverse (forest loss) shown in red), overlaid on the normalised HH/HV ratio for 2010 to aid interpretation (darker areas are more forested). The ratio appears to be quite sensitive in obtaining estimates for forest cover, including almost completely ignoring changes in marsh and swamp areas surrounding Lake Chilwa (centre of the image), with are picked up much more strongly when using estimated AGB for change detection (figure 4.9). However, there are still areas (areas around the lakeshore, and the areas of green on the far right, and red at the top left) that are responding to changing river/lake levels between the two images, rather than changes in forest cover.

Figure 5.8 shows quite a fragmented pattern of forest cover change, including picking up some non-forest changes, associated with changes in swamp and marsh extent around the shores of Lake Chilwa (centre of the image). There is also a smaller area of marshland that formed as a small lake experienced very low lake levels in 2010 (top right of the image), which shows as a strong gain in forest. Despite these mis-classifications, the map does appear to show some anecdotal trends regarding forest cover loss inside the supposedly protected LFR and Zomba-Malosa Forest Reserves.

Due to the similarity of the two probability density functions, change detection was also attempted using the predicted AGB map. In order to look for areas of significant land cover change, only pixels with $> 20 \text{ tC ha}^{-1}$ in the initial image were examined. A normalised change image was produced, with the magnitude of change categorised by standard deviation (figure 5.9). This map shows similar trends to that produced using the normalised HH/HV ratio, with regard to showing loss of biomass from inside the forest reserves closest to the major towns in the area (Liwonde and Zomba). This map also picks up more false positives associated with changes along the lakeshore than the normalised ratio map.

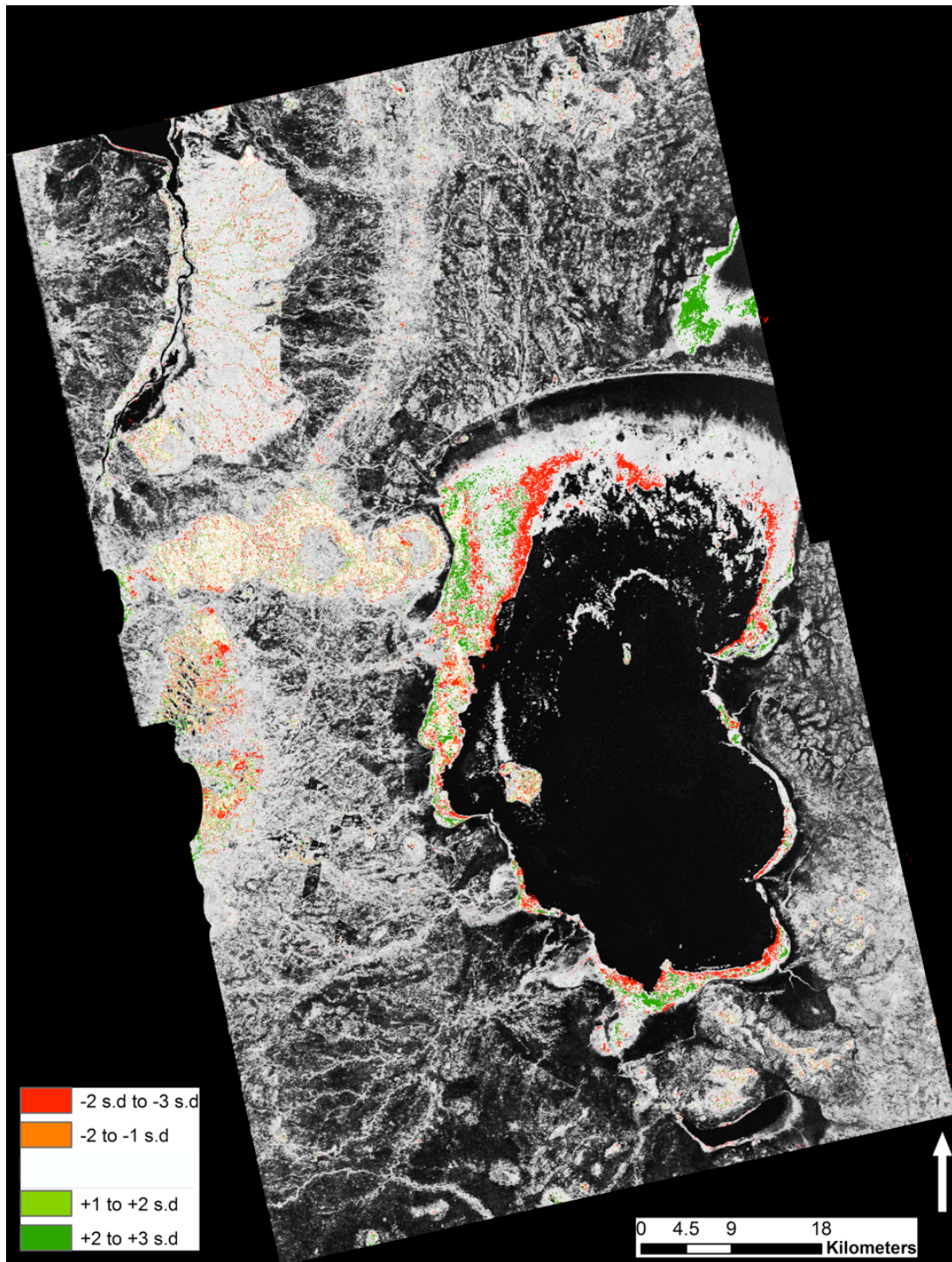


Figure 5.9 Normalised change in AGB from 2007 and 2010 for the Lake Chilwa basin area, southern Malawi, overlaid on the estimated AGB map for 2010 produced from the Mitchard et al (2009) regression (whiter areas are higher biomass). Magnitude of change is categorised by standard deviation. Despite thresholding the data to look for significant change (only areas with a starting AGB of $> 20 \text{ MgC ha}^{-1}$ were analysed), non-forest changes are still detected in areas surrounding Lake Chilwa, caused by changes in marsh and swamp extent.

The forest cover change estimates produced from the above methods were compared to a forest cover change map produced using MODIS Vegetation Continuous Fields (VCF) percentage tree cover data from 2007 and 2010. A threshold of 20% has been previously used in Malawi for delineating forest areas (Bandyopadhyay et al. 2011), and for this region, a threshold of 20% appears to be most consistent in selecting the same areas of forest as the normalised HH/HV ratio image. Using a lower forest definition (for example 10%, in line with Malawi's official forest definition) causes some mis-classification of forest areas and forest loss at the resolution of the MODIS products. The major problem with using MODIS data to compare to the ALOS data is the difference in resolution, as the MODIS VCF data has a 500 m resolution while the ALOS data was analysed at 25 m resolution. The trends picked up at these different resolutions are understandably different, but do provide an indicator of reliability of the estimates as there are currently no other ways to assess this for Malawi. Areas of known mis-classification in the PALSAR-derived maps along the lakeshore were manually masked out when producing the forest cover change estimates as a practical heuristic.

Both the ALOS and MODIS change maps show trends of net forest cover loss, even over the short baseline of 2007-2010. The images have a kappa coefficient of 0.61, indicating that both methods interpreted similar patterns of forest cover change. The largest areas of mis-classification were along the edges of Lake Chilwa, where the MODIS imagery showed less change than was picked up in the ALOS imagery. The ALOS imagery also identified smaller patches of change inside the forest reserves, probably due to the sensor's finer resolution. From the normalised HH/HV ratio image, in 2007 the area mapped had approximately 20% forest cover, but this had dropped to 12% by 2010. The estimated change rate from the normalised ratio data is a net forest loss of 2.5% per year over the 3-year period, while the MODIS VCF data showed a loss of 1.8% per year over the same period. From the predicted AGB change map, less than 10% of the image had an AGB of $> 20 \text{ tC ha}^{-1}$ in 2010. The area

experienced a loss of almost 11% and a gain of 6% in areas with $> 20 \text{ tC ha}^{-1}$. This gives a net change of -1.6% per year, which is the same as the rate obtained using the MODIS VCF data. This is expected as both of these methods used much narrower criteria for looking at forest cover change, and consequently missed the smaller changes that will be picked up in the normalised ratio image.

5.4 Discussion

5.4.1 Establishing empirical relationships

Globally, there is an understanding that there is some relationship between radar backscatter and biomass, up to a saturation level dependent upon the wavelength used, with longer wavelengths typically saturating at higher biomass values (for example Imhoff et al. 1995; Le Toan et al. 1992; Kellndorfer et al. 2004; Le Toan et al. 2004; Morel et al. 2011; Mette et al. 2004). There have even been relationships developed in neighbouring countries using the same methodologies (Mitchard et al. 2009b, Ryan et al. 2011a). Despite this, we were unable to establish any statistically significant empirical relationships between backscatter and forest parameters. Only one other published study has found difficulties establishing a correlation between ALOS backscatter and biomass (Maniatis et al. 2011).

Malawi represents a confluence of many of the conditions that SAR finds most difficult to accurately work with, including highly variable topography, and heterogenous vegetation, and these will be discussed now. However, there are a number of possible causes for the lack of correlation found here, and it is likely a combination of these factors is responsible, rather than one specific uncertainty.

The areas of Malawi where forests remain tend to be steeper land that is currently less attractive for agriculture. These areas have highly variable topography with steep valleys. Attempts to correct the data for layover

and the effects of terrain on the imagery did show some improvement in the regression statistics, but the effects of terrain can still be seen in the imagery, indicating that the backscatter responses are being driven by factors other than AGB. Radar responds to slope more than to AGB in mountainous landscapes and areas with high topology (Smith and Ulander 2000). Slopes tilted towards the radar increase the backscatter, while slopes tilted away reduce it (Le Toan et al. 2004). Topography also interferes with the conversion of the imagery from slant-range to ground range causing geolocation errors, and in more extreme cases cause foreshortening, and loss of data due to layover and shadow (Woodhouse 2006a). The field data used in developing the backscatter-biomass relationship in Mitchard et al. (2009b), used in Ryan et al. (2011a) was all collected on flat or gently undulating ground. It would be beneficial to obtain a higher resolution DEM to see if this improves the results.

Most of the plots sampled here were miombo, and this heterogeneous savanna environment also causes challenges for SAR. Paradzayi and Annegarn (2012) recognise the need for larger field plots in order to account for the heterogeneity of savanna environments when using ALOS PALSAR. Regression coefficients increased marginally when using plots larger than 0.25 ha to investigate empirical relationships. This could indicate a need for even larger plots, or a greater number of these larger plots (there were only 47 plots larger than 0.25 ha, out of a total of 227 field plots). The speckle inherent in radar data causes more problems in heterogeneous environments as area averages are not as reliable as proper multi-looking. Although speckle should be reduced as the data is resampled to coarser resolutions, we found this did not have a noticeable impact on the different correlations. It is possible that the plots were too small to fully take advantage of this smoothing.

From the analysis presented here, Malawian miombo woodland broadly follows trends identified by Brown et al. (1995), who found that 3% of trees in Amazonia rainforest contained 50% of the biomass. Despite very

different forest structure and composition, in miombo woodland the largest 3% of trees account for 37% of the biomass. Additionally, trees with a dbh > 20 cm account for only 10% of trees, but 63% of AGB. This could be a useful statistic for conducting future forest inventories, as trees smaller than 10 cm dbh form the bulk of trees sampled (62%), but only have small contribution to overall biomass (11%). Field campaigns to collect new forest inventories could possibly be made more efficient by concentrating only on measuring the largest trees in the plot, which could allow a wider area to be sampled as a result.

While the issue of allometry did not make much of an impact in this study (probably because the errors associated with the allometry were only a small factor in why no significant relationship was found between radar backscatter and biomass) we believe that allometry needs to be carefully considered when conducting these regressions. There has been little work done at a global level on how the choice of allometric equation can influence the result of the backscatter-biomass regression, or change influence comparisons between regionally developed regressions. Given the variability shown between different allometric equations, and the improved relationships between backscatter and basal area, it is conceivable that the backscatter-AGB relationship could be improved with improved allometry.

5.4.2 Change detection using ALOS PALSAR

Change detection in Malawi is complex due to the fragmented nature of the ecosystem. This is compound by the fact that the dominant form of forest loss is due to degradation rather than clear-fell. Both of the change detection techniques investigated here produced quite scattered patterns of forest cover loss, which seem to indicate this. The normalised HH/HV ratio seems to be more sensitive to smaller, possibly less significant changes in forest cover as it is not restricted to higher biomass or forest cover areas like the predicted AGB map or the MODIS VCF data.

The results presented here indicate the potential of using SAR for forest cover change mapping. The change maps produced using ALOS data show the same trends in net forest loss as the MODIS VCF data. Estimates from the normalised HH/HV ratio show a loss of 2.5% yr⁻¹, or approximately 765 km² over the 3-year baseline, with an estimated gain of 298 km². Estimates using a stricter forest definition using the predicted AGB map show a net loss of 1.4%, and matches that estimated using the MODIS VCF data. Previous attempts at producing forest cover change estimates for Malawi have found deforestation rates of between 0.9-3.5% per year, depending on both the spatial and temporal variation of the sites being studied (Hudak and Wessman 2000, FAO 2010b, Nkwanda et al. 2008, Cassells et al. *in prep.*). All the estimates obtained here fall within this range, and are close to the official estimates from the Department of Forestry of -2.6% yr⁻¹ (Nkwanda et al. 2008), which is based on an unknown dataset. This indicates the potential of this dataset for investigating forest cover change in Malawi, even if direct estimation of AGB is not possible.

5.4.3 Management implications

From the results presented here, it is clear that there are parts of southern Malawi, which are known to be the most deforested in the country as well as the most populated, that are now reaching very low levels of forest cover. Even the forest reserves appear to be experiencing forest cover loss, as these are almost the only remaining sources of wood in the region. There is anecdotal evidence that most areas of woodland in southern Malawi are now in graveyards and forest reserves (Mhango *pers. comm.*). This has implications for any future management programmes, and means that even supposedly protected areas cannot be ignored when creating programmes aimed at poverty reduction and environmental management. For example, the Lake Chilwa Climate Change Adaptation Programme (Government of Malawi 2010) highlights the vulnerability of rural populations to climate change in the area, and much of this is centred on ensuring the sustainability of natural

resources, particularly forests, but there are very few trees left in Village Forest Areas in the catchment.

5.4.4.3 Developing methodologies for using SAR data for forest monitoring in Malawi

Additional work is needed in order to develop any operational methodology for using SAR data to map biomass in Malawi. The results of forest cover change mapping show the potential of using SAR in Malawi, although care needs to be taken to make sure that any changes detected are validated as both the methodologies used here presented some areas of false detection, both positive and negative. The similarities between the probability density functions found between the AGB predicted by the Mitchard et al. regression and the field estimates of AGB indicate a possibility for using this equation as technique to estimate biomass, if a wide enough area is sampled. Any estimates of change produced from this regression will need to be thresholded at some level, which will mean losing some of the detail for lower level biomass estimation, but will reduce the risk of attributing changes in biomass to causes other than forest loss.

If SAR data is to be useful for mapping forest cover change in Malawi, the data needs to be easily analysed to produce consistent results by personnel who may have had little to no training or experience in handling SAR data. Additionally, if a methodology to map forest cover change is going to have any lasting impact, it needs to be consistently repeated to build up a long-term time series to allow effective change detection and monitoring, which means there is a need to seek out free data sources and open source or open access software, in order to remove dependency on donated software licences which are often linked to specific projects, and finish at the end of the project's funding cycle. This would increase both the use and utility of SAR data for forest monitoring in Malawi, and would allow government personnel and academics greater

access to SAR data to fully evaluate its utility in a Malawian context, which is necessary from both a forest management and capacity development perspective. There are some existing examples suitable of open access/open source software currently available including MapReady (ASF 2010), which is a great tool that converts ALOS data from its proprietary format, into one which can more easily be loaded in GIS packages (specific remote sensing software is almost universally lacking in Malawi), as well as enabling terrain correction, geo-correction and resampling of ALOS data. Open source GIS and remote sensing programmes are also starting to gain increasing sophistication, giving a more user-friendly experience, and could provide great solutions of increasing the use of SAR data for forest cover change mapping in Malawi.

5.5 Conclusions

Malawi is highly dependent on its forest resources. Effective sustainable management strategies are difficult to implement due to a lack of knowledge about how the forest resource is changing. Despite significant evidence from other studies conducted around the world, it appears that Malawi represents a more challenging and complex environment for using SAR to support sustainable forestry. We find only that no regression between ALOS PALSAR backscatter and field-based forest metrics including AGB, BCI, and basal area is enough on its own to be used to develop an empirical relationship between the variables, despite following the methodologies followed by previous studies, and other recommendations in the literature, including resampling to coarser resolutions and terrain correction. While it is possible to observe visual trends in the data that indicate it is able to detect differences between forest and non-forest landscapes, we have had no success in producing a statistically significant method of detecting these trends using regression based on field plots. This is likely to be due to a combination of factors including geo-location errors in the PALSAR data, the speckle inherent in

SAR data, variable topography, plot size and the heterogeneity of the vegetation.

All change detection methodologies show that the study area has experienced forest loss over the period 2007-2010. The HH/HV ratio appears to be sensitive to forest cover, and a useful way of detecting forest cover change, even in more degraded ecosystems. This has value from a management perspective, as ALOS PALSAR is not subject to the same limitations as optical data with respect to cloud cover and atmospheric haze. There are steps that need to be taken to ensure that the PALSAR data is correctly geo-referenced, and terrain corrected but there are relatively simple solutions that can be implemented using open source software, so this should not deter attempts to use SAR data for forest mapping in Malawi.

There is also good similarity between predicted AGB estimates from a generic regression for African woodlands produced by Mitchard et al., and field estimates of AGB when averaged over larger areas, despite a poor one-to-one correlation. This would need to be verified for more areas across Malawi, but could provide a useful methodology for producing national biomass estimates from only one remote sensing dataset. As there are currently no Malawi-specific biomass estimates, this could help development of REDD+ activities and management plans until alternative methodologies are developed.

5.6 Acknowledgements

Fieldwork was funded through a combination of GC's NERC PhD studentship, the Moss Centenary Scholarship, and a Natural Resources Foundation International travel grant. Data collection was undertaken with help from the staff and students of Mzuzu University, the Forest Research Institute of Malawi and the Department of Forestry.

6. Discussion

This thesis has examined the use of both optical and SAR remote sensing data for mapping forests and forest cover change in Malawi, as well as examining global trends in the level of engagement of developing country researchers with the global academic remote sensing community. The original questions I set out to answer with this thesis is ‘can remote sensing be used to support sustainable forestry in Malawi?’.

As stated in section 1.6, the aims of this thesis are to:

- (1) Assess the potential of different remote sensing data for mapping forest cover in Malawi, including both optical and radar data, and make a recommendation on which approach is most appropriate for Malawi.
- (2) Evaluate how REDD will work in Malawi given results of (1), or at best, make recommendation on how Malawi could implement EO monitoring of forests.
- (3) Consider the issue of in-country EO capacity and how that is important to (1) and (2) actually happening.

This thesis has looked at preparedness for REDD+, in the wider context of supporting sustainable forestry in Malawi. While REDD+ has brought considerable international attention to forestry issues, it is worth remembering that sustainable forest management is going to be a key part of Malawi’s development strategy for many years to come, especially given the current dependence on charcoal, which is predicated to remain the country’s dominant energy source for the next 15-20 years (Government of Malawi 2009). The particular focus of this thesis has been on the MRV (monitoring, reporting and verification) requirements for REDD+, as this is the area that remote sensing will be most useful.

This thesis has critically evaluated which methods, if any, will work for forest cover and carbon stock mapping, given the capacity and economics of a particular situation, namely Malawi. By looking at specific elements relating to applying remote sensing approaches for forest mapping in Malawi, and at capacity building, including what needs to change in a global context to encourage in-country remote sensing capacity building, I have built up a case for arguing that care is needed when attempting to use standardised methodologies or data products and trying to apply them to all situations. Additionally, I have linked the role of the economics of REDD+ to the MRV requirements and shown the importance of making sure estimates of forest loss and carbon stocks have measurement errors below 10% if REDD+ is going to be cost-effective in Malawi.

With regards to the first aim, this thesis assessed the use of both optical and radar data for mapping forest cover in Malawi, specifically L-band SAR and MODIS and Landsat optical data. The following section will draw out some of the general trends encountered while investigating different remote sensing options for this thesis. With regards to the second aim, the results presented in this thesis have started the process of identifying a suitable forest cover monitoring solution for Malawi. Despite inconclusive results of the approaches examined here, I still believe that remote sensing will have a roll to play in allowing a greater understanding dynamics of Malawi's forest resources because there is a need for nationwide accurate, validated forest maps that can be repeated at least on a yearly basis, and without the resources to conduct large scale national ground inventories each year remote sensing will still have a roll to play. With this in mind, I will outline the main criteria for assessing the suitability of a remote sensing forest mapping solution for Malawi. I will finish this chapter with recommendations about the direction future work on forest mapping in Malawi could pursue.

6.1 Using remote sensing to map forests in Malawi

This thesis has provided insights into the difficulties that Malawi faces using remote sensing to map forest cover change, even when using methodologies and data products that have been successfully applied elsewhere.

From a policy perspective, remote sensing has been linked to the implementation of UNFCCC objectives as part of the MRV requirements for the Kyoto Protocol (Rosenqvist et al. 2003, Patenaude et al. 2005). The technology for mapping land cover dynamics from space has improved considerably over the last 15 years, and it is likely that our current monitoring capabilities will inform REDD+ design and implementation. As the exact implementation of REDD+ is still being decided, there is a vigorous on-going debate about how remote sensing will be involved in the MRV process (for example Gibbs et al. 2007, Defries et al. 2007, Goetz et al. 2009, Goetz and Dubayah 2011, Bucki et al. 2012, De Sy et al. 2012). There is a large amount of funding currently being focused on forestry activities, which is leading some stakeholders to look for “the answer”, not ‘an answer’ to forest mapping using remote sensing. From the results presented in this thesis, this will be a real challenge to the success of REDD+. REDD+ implementation could be compromised if some countries will not be able to undertake REDD+ projects because the methods used to assess forest loss or carbon stocks are “standardised” at a global level or they are expected to be able to use approaches that have been successful in other countries without issue, and they do not work in that particular country. The results from this thesis show that SAR is not going to work easily, and that freely available products such as MODIS can work to some extent, but there are still issues that need to be addressed or limitations that need to be accepted as part of the dataset. Added to this is the fact that higher resolution data, or lidar is too expensive to be used for routine monitoring.

One of the main uses for remote sensing is to extrapolate trends across large areas (for example Ehlers 1996, McRoberts and Tomppo 2007, Collins et al. 2009, Gibbs et al. 2007, Brink and Eva 2009, Baccini et al. 2008). However, when dealing with an environment that is highly variable and heterogeneous, such as savanna, the initial data used to build up an understanding of the landscape needs to be more detailed than that used in other, more homogenous areas, and any products developed need to be able to take this variability into account (Rocchini et al. 2012, Hill et al. 2011). Using ground data or knowledge from a particular forest environment, and then extrapolating those characteristics globally can cause difficulties when trying to use these products in areas that experience forest characteristics that are different from those used to produce the original datasets (for example Mitchard et al. 2011). While there are many reasons⁴ for particular remote sensing methodologies or products not working as expected in Malawi, they are all likely to be compounded by the heterogeneous nature of Malawi's dominant forest ecosystem (miombo savanna), and the fact that much of Malawi's woodland is already largely degraded, meaning that differences between a forest and non-forest signal are much smaller than they would otherwise be. Additionally, forest cover change detection is made more difficult by the fact that the main form of forest loss being degradation rather than deforestation.

When a global dataset is produced, it is impossible for it to include representative data for every type of land cover scenario. While the remote sensing data interpretation (or product) that is extrapolated from

⁴ These reasons include Malawi's hilly topography which has significant impacts on SAR, and the presence of Lake Malawi, which means that even dry season optical imagery is often affected by problems with cloud cover. Other factors include SAR-specific problems such as the impact of speckle in areas with heterogeneous vegetation, and some possible problems with the size of plots being used to develop the backscatter-biomass relationships. With regards to optical imagery, the coarse resolution imagery used here has difficulties detecting small-scale changes (ie degradation) in heterogeneous environments. This is exacerbated by Malawi's high population density, as it is difficult to detect differences between scattered trees in agricultural environments and the scattered trees of a miombo savanna.

a handful of key, but broad, land cover types may average out to a suitable representation of trends and processes occurring on a global scale, there may be local level variations that this particular remote sensing product smooths out, or even worse, misses completely, because the training data used does not accurately represent these local scale changes. A common theme from all the remote sensing datasets examined as part of this thesis is that Malawi seems to represent a more challenging environment for mapping forests using remote sensing than may at first be expected. Malawi appears to encounter difficulties that other countries do not seem to face when attempting to use current standard processes for mapping AGB using SAR data, or using optical data or global land cover products. The following sections will examine the use of SAR and optical data in more detail.

6.1.1 Radar

Despite using the standard methodology for both obtaining ground data and processing ALOS PALSAR imagery, there was no usable correlation between field-measured metrics and SAR backscatter. There have been studies that successfully established and applied an empirical backscatter-AGB relationship in Mozambique, using the same methodology and also working in miombo woodland (Mitchard et al. 2009b, Ryan et al. 2011a). Even though Mozambique and Malawi share the same dominant woodland ecosystem (miombo) that is floristically similar across the whole ecosystem, as it is defined by the dominance of 3 species (*Brachystegia*, *Julbernardia* and *Isoberlina*), there are differences in structure and composition due to the different environments and different resource pressures placed on forest resources in both countries. Malawi's high population density (averaging 168 people per km² - for comparison, Mozambique's population density averages 28 people per km²) (United Nations 2012), and high rate of consumption of forest products (Mayers et al. 2001) means that there are very few areas of undisturbed woodland remaining in the country. Many of the current protected areas (forest reserves and national parks) have only been

created within the last 30-50 years, with woodland in these areas still showing signs of previous human use prior to their creation. For example, in Nyika National Park, an area of miombo woodland that used to surround a village that was moved when the national park was created still retains evidence of coppicing with plots in the area containing up to 1200 stems per hectare. Results from Luoga et al. (2004) back up the persistency of coppicing in miombo species. This is different to both Mozambique and Zambia, where there are still large tracts of miombo that have been minimally impacted by human activity.

There has been an understanding in the remote sensing community when using SAR that there is an underlying causal relationship with forest structure, and therefore biomass (Imhoff et al. 1995, Le Toan et al. 1992, Woodhouse 2006b). However, from the results presented here, it appears that this relationship may be more complex than previously imagined. Work on SAR backscatter-AGB relationships has focused primarily on temperate plantation forests and rainforest. As mentioned previously, there have been studies that have successfully found a backscatter-AGB relationship in savanna woodland, notably by Mitchard et al. (2009b) and Ryan et al. (2011a). Mitchard et al. also produced a generic backscatter-AGB relationship that was used in Chapter 4 to try and map AGB in Malawi, but there was no success with this either.

There are several reasons why these studies have managed to find successful backscatter-AGB relationships using the same methodologies that have failed in Malawi. Firstly, the dataset used by Mitchard et al. contained larger plot sizes, covered a savanna-forest transition zone (where changes in forest structure were occurring in addition to changes in biomass), and the bulk of the plots were located on flat ground. The same field data used by Ryan et al. also had larger plot sizes and was on flat ground. However, even when looking at only the plots greater than 0.25 ha for Malawi, there was still no relationship with backscatter. SAR is known to have problems with areas with highly variable topography

(Bayer et al. 1991, Woodhouse 2006a), and despite using MapReady software to perform terrain correction, there were still some visible terrain artefacts in the ALOS PALSAR data. Almost all areas of significant forest cover remaining in Malawi are on or surrounded by steeply sloping terrain. This is probably one of the most significant problems with finding a correlation between radar backscatter and AGB.

6.1.2 Optical

Global remote sensing products provide useful data on global processes, and in this sense perform very well. However when considering using these data or methodologies at smaller scales, for example at national or sub-national levels, there can be issues with accuracy due to the increased heterogeneity being observed, with less area to average over to smooth the results and trends. This is highlighted in Chapter 4, when attempting to use MODIS EVI and VCF datasets to map forest cover change in Malawi. Despite being useful products for assessing global trends and patterns (Hansen et al. 2008, Morton et al. 2005, DeFries et al. 2000, Hansen et al. 2003), the inter-annual variability observed over Malawi made it difficult to accurately assess forest cover change.

Given the current low level of technical remote sensing expertise among Malawian forestry professions, these global products represent a huge resource of potential data as they remove many of the problems with pre-processing the data. As almost all of Malawi fits on one MODIS tile, there is no need for extensive calibration and mosaicing multiple scenes to conduct wall-to-wall mapping. There are a huge number of potential data sources that could be used to provide some insight into the current dynamics occurring in Malawian forests, as long as the errors in each dataset are accounted for, or at least accepted and understood.

With regards to optical imagery, Malawi faces no more than the standard problems; namely cloud cover and haze. However due to the position of Lake Malawi and the direction of the prevailing winds, obtaining cloud

free optical imagery is difficult, even in the long dry season when cloud free imagery can almost be guaranteed across much of the region. This lack of consistent imagery causes problems when trying to use freely available moderate resolution optical imagery such as Landsat. These problems are compounded by the failure of Landsat 7's scan line corrector in 2003, as multiple Landsat scenes are needed to produce a complete image. The upcoming launch of the Landsat Data Continuity Mission in 2013 should help alleviate this and could provide a large new low-cost data resource for Malawi.

6.1.3 Additional data sources

When considering potential remote sensing data sources for supporting sustainable forest management it is easy to focus on satellites that provide images of the Earth's surface, in order to assess land cover, and land cover changes. However satellites such as TRMM (Tropical Rainforest Mapping Mission) can provide useful ancillary data for assessing, in this case, rainfall patterns over a given time period, which may be affecting observed changes in land cover. It can also be useful when selecting dates of other satellite acquisitions, especially SAR, as it has been shown that soil moisture changes the dielectric properties of the ground surface, which can influence radar returns (Lucas et al. 2010, Pulliainen et al. 1999). TRMM can provide useful spatial data on rainfall patterns to make sure the best possible imagery is selected and used for analysis. TRMM data can also provide additional information on the state of the forest ecosystem, by providing seasonal and annual rainfall estimates. One of the trends highlighted in Chapter 4 was how responsive the dry season EVI signal (presumed to be trees) was to the previous year's rainfall.

Other supporting datasets include socio-economic data, such as gridded population data can help understand the causes and drivers of forest cover change (Appendix 1), and could also be investigated alongside remote sensing data. For example, Bandyopadhyay et al. (2011) used

MODIS VCF data to estimate a biomass map for Malawi alongside household survey data on forest use to investigate the impacts of biomass scarcity on rural livelihoods.

6.2 Remote sensing solutions for Malawi

Having discussed the unexpected challenges facing Malawi when using standard remote sensing techniques for mapping forest cover change, I will now draw out the common features that have emerged about the kind of remote sensing imagery that is best suited to mapping forests in Malawi, in an attempt to answer the initial question posed by this thesis ‘can remote sensing be used to support sustainable forestry in Malawi?’. Section 2.1.3 outlined some brief criteria that remote sensing data products would need to meet in order to be a useful tool for sustainable forest management in Malawi. I will now expand on these, with regards to the results presented in the previous chapters.

For Malawi, remote sensing data products ideally need to meet all of the following criteria:

- Results must link to international criteria and standards
 - Estimates of forest area or AGB and change detection need to be produced, as these are the key metrics for SFM and for REDD+. Additionally, these metrics need to meet any accuracy or other criteria demanded by any future REDD+ policies in order to be used for MRV.
- Imagery needs to be free or low cost
 - Malawi relies heavily on donor aid support, which for various political reasons is only just being restarted after being withdrawn 2 years ago. The Department of Forestry does not have the budget to pay for expensive commercial remote sensing data, even though it may be able to do a better job than the datasets examined in this thesis. Academics are similarly constrained by a lack of funds to buy data. However, this is

potentially more serious for the Department of Forestry and FRIM, who are officially tasked with forest cover change mapping in Malawi because they are government departments. Many proposals for free data are restricted to research proposals, so proposals for free data for academic use have to be conducted in conjunction with universities. Encouraging more interaction between academics and policymakers could help enable these collaborations.

- Imagery needs to be available on a yearly basis, preferably every 3-6 months.
 - A yearly baseline would allow change detection for updating forest cover change and changing management priorities. More frequent mapping would allow for more rapid detection and response to changes. This thesis has only investigated mapping savanna in the dry season, as the rainy season poses additional challenges, which would require more research to investigate the extent of these differences and make steps to address them.
- Any system needs to be able to detect degradation in miombo woodland
 - This is probably the most challenging technical aspect, given how difficult it has been to produce any kind of change detection map in Malawi. Mapping degradation using remote sensing is a well-known challenge in remote sensing, and research into this issue is continuing (Goetz et al. 2009, Goetz and Dubayah 2011, Rocchini et al. 2012). The additional challenges posed by savanna also need to be considered in this research.
- Image processing needs to be simple to implement consistently across different operators
 - This requires proper and thorough documentation of the processing steps as well as an easy-to-produce error or uncertainty quantification for each product. It also needs to take into account potential differences in computer literacy, and

software access. There also needs to be suitable access to data storage and archiving.

- Results need to be obtainable on free or open source software
 - Using freeware would reduce Malawi's dependence on pirated/cracked software, or donated licenses. It would mean that GIS/RS software could be installed on every machine, rather than one or two, making GIS/RS available to a wider audience.

There is a large range of different types of remote sensing data products available, all of which are potentially useful for forest cover change mapping. The key issues involve trade offs between resolution, time between acquisitions, cost, and the user's computational skills. Defries et al. (2007) summarise the different methods available for monitoring deforestation, and outline some of the key choices influencing methodology selection, including the costs of data, and technical abilities of those who undertake data analysis, the overall size of the country and forest area, clearing size and patterns of deforestation, seasonality of the forest. No previous attempt has been made at categorising the ease of use of these different remote sensing data products, probably because of the sheer number of factors that go into making such a value judgement, which by its very nature is subject to change and differences in interpretation. Usability will have a different meaning for a developing country civil servant tasked with producing forest maps, perhaps with little or no practical experience of using GIS or remote sensing software and limited internet access or colleagues to ask for support than a Western university-based researcher, with extensive postgraduate training, focusing on a very specific technique or problem. Table 6.1 presents an initial attempt to categorise some of the common remote sensing data sets for monitoring forests for use in Malawi.

If remote sensing data is to be useful in Malawi, and indeed in other developing countries, then it needs to be able to be adapted to local

proficiencies. Developing an ease of use rating requires a number of factors to be considered, which all vary depending on the type of imagery being considered and the type of analysis required to answer a particular research question, and it is difficult to account for all possible scenarios.

The ease of use criteria used in Table 6.1 are:

1. Imagery requires specialist commercial software to open and/or analyse.
 - Data requires several preprocessing steps, which may require additional software.
2. Imagery requires specialist software to open and/or analyse, for which there are freeware or open source alternatives to commercial software, but multiple freeware software packages are required.
 - Data requires atmospheric, terrain, or geometric correction prior to use.
3. Imagery can be viewed using standard image or photo viewing software (such as the ERDAS Viewer), but analysis requires simple specialist software for which there are freeware or open source options.
 - Data may require some simple preprocessing prior to use (for example minor geocorrection), particularly if being used in conjunction with other datasets.

The aim of the ease of use rating is to provide a first glance guide to some of the main remote sensing data sources and products, so that an in-country scientist/researcher can select the technique that offers them the best trade off between their ability level, software availability, cost and monitoring goals. The factors considered when developing this ease of use rating are discussed in the following section.

Table 6.1 Some of the most common remote sensing products used in forest mapping. This table summarises the key information necessary for deciding which remote sensing products are best suited to a particular project.

Sensor	Ease of use	Cost of acquisition	Resolution	Date active	Source	Type (R/P)	Uses	Notes
ALOS PALSAR	1	Commercial costs are approximately US\$ 500 a scene Reduced costs for research institutions through scientific use scheme (varies depending on which node covers study area, around €50/scene).	Supplied at 12.5 m, usable is 25-50+ m	2006 - 2011	JAXA	R	<ul style="list-style-type: none"> Land cover classification Empirical relationships between forest parameters and backscatter can be attempted to estimate AGB Change detection 	<p>Nonfunctional since Dec 2011. Currently no L-band SAR system in orbit</p> <p>Free 50m mosaics are available over the central tropics. Global coverage of these mosaics is planned as part of the Kyoto and Carbon initiative.</p>
SPOT 1,2,4,5	2	Commercial costs are €1900-8700 per scene, depending on resolution. Limited imagery grants available through Planet Action	2.5 m-20 m NIR, R, G, B bands	1986-present	Astrium	R	<ul style="list-style-type: none"> Land cover classification Vegetation indices (eg EVI) Change detection 	Planet Action data requests are limited to a maximum of 10 scenes and require a developing country partner organisation

Landsat	2/3	Free for all users	Landsat 5 TM = 30 m Landsat 7 ETM+ = 28.5m	1972- present	USGS/ NASA	R	<ul style="list-style-type: none"> Land cover classification Vegetation indices (eg EVI) Change detection Calibration and geocorrection of other satellite products 	<p>Landsat 7 EMT+ scan line corrector failed in 2003, leading to a loss of data in every scene obtained since.</p> <p>Landsat 5 suspended data downlinks in November 2011, and although work continues to restore it, it is unlikely due to the age of the satellite (it was launched in 1984).</p> <p>The Landsat Data Continuity Mission is due for launch in 2013.</p>
MODIS daily data	2/3	Free for all users	250 m	2000- present	NASA	R	<ul style="list-style-type: none"> Land cover classification Vegetation indices (eg EVI) Change detection 	
MODIS LAI	2/3	Free for all users	1 km	8 day composites from 2000- present	NASA	P	<ul style="list-style-type: none"> Canopy cover assessments (needs to be used in conjunction with field data) Change detection 	
MODIS Land cover classification	3	Free for all users	500 m	Yearly composites 2000- present	NASA	P	<ul style="list-style-type: none"> Contains global classified land cover data Change detection 	
MODIS Vegetation Indices	3	Free for all users	250 m	8 day composites 2000- present	NASA	P	<ul style="list-style-type: none"> Phenology Agriculture Forest area assessment 	Includes NDVI and EVI

MODIS Vegetation Continuous Fields	3	Free for all users	250 m	Yearly composites 2000- present	NASA	P	<ul style="list-style-type: none"> • Forest area estimation • Bare ground estimation 	Care should be taken when using this product for change detection, as many factors can cause inter-annual fluctuations in percentage tree cover
IKONOS	2	Archive data is US\$10/sq km commercially, imagery grants are available GeoEye Foundation	2-4 m < 1 m panchromatic	1999 - present	GeoEye	R	<ul style="list-style-type: none"> • Land cover classification • Vegetation indices (eg NDVI) • Change detection • Calibration and geocorrection of other satellite products 	Commercially through GeoEye (www.geoeye.com) Imagery grants available through GeoEye Foundation (www.geoeyefoundation.org)
DMC	2/3	£0.03-0.09 / km sq for 22-32 m multispectral data		2005 - present	DMCii (www.dmcii.com)	R	<ul style="list-style-type: none"> • Land cover classification • Vegetation indices (eg NDVI) • Change detection 	Large image size (up to 660 km x 4100 km)
Radarsat-2	1	Commercial costs are €2540- 5910/scene Free through some research use agreements	3-100 m	2007 - present		R	<ul style="list-style-type: none"> • Land cover classification • Forest area estimation can be attempted • Change detection 	C-band fully polarimetric SAR

TerraSAR-X	1	Commercial costs are €1375-3375/scene for archive data. Discounted prices are available at €200/scene for scientific use proposals	3-16m depending on product type	2008 - present	Commercial data through Infoterra Research data through DLR	R	<ul style="list-style-type: none"> • Land cover classification • Forest area estimation can be attempted • Change detection 	X-band fully polarimetric SAR
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The factors used to develop the ease of use rating come from a number of different concepts that stem from the concept of usefulness. The concept of usefulness breaks down into two concepts, usability and utility (Beyer and Holtzblatt 1997). Utility refers to the ability of the product to perform a task or tasks. The more tasks a product is designed to perform, the more utility it has (Beyer and Holtzblatt 1997). Usability is a measure of how easy it is to use a product to perform prescribed tasks (Beyer and Holtzblatt 1997). When using image analysis software, there is usually a necessary trade off between utility and usability. Simple image viewing software, such as the ERDAS Viewer, offers less utility than full image processing software, such as the full version of ERDAS, but may offer more usability because it is easier for the user to perform particular tasks. However, increased familiarity with a particular software package will often increase usability, as the operator becomes more confident in performing basic tasks and moves onto more complex ones, making utility a more important consideration, if the operator has the patience and confidence to gain this initial experience (Singhroy et al. 1996). However, even an experienced user of a certain software package will have some problems when using a new system, but the problems are increased by an order of magnitude for novice users (Ehlers 1996).

The attempt to categorise software requirements tries to account for an additional component of usefulness, by assessing the technical proficiency required by the user. In an ideal world, the most useful (easiest to use) methodology would also be the most accurate and the most precise. However, as with all remote sensing options there are some trade offs that need to be made. These mostly have to do with how accuracy is defined. An estimate of forest cover change using MODIS data may be accurate, at the limits of that sensor's resolution and within the confines of the particular methodology used. However, a higher resolution sensor may be able to pick up changes that the MODIS sensor does not. This does not make one more accurate than the other, but can increase

precision, if precision is understood as a function of resolution. This does not necessarily mean Malawi needs to invest in the most accurate and precise forest cover mapping available. Given the current lack of up-to-date information about key forest metrics in Malawi, any methodology that can provide these estimates helps to narrow down potential value ranges, helping to improve both accuracy and precision.

Another factor to consider when assessing the usefulness of a particular remote sensing dataset is how much preprocessing is required. When using remote sensing data, several preprocessing stages are usually required to provide an image with a physical meaning, which can then be used to extract information about an area. These stages include orthorectification or geocorrection (particularly important for change detection, or when comparing different datasets over the same area), radiometric corrections, to convert the product supplied to a physical value, and mosaicing or subsetting imagery (Lillesand et al. 2008). The steps in the processing chain differ according to the type of data, adding more confusion for inexperienced users. These steps may involve using more than one software package, as some data products have (usually free) tools designed to help with this preprocessing, which may add to confusion if users are not aware of them.

MODIS products are a move towards increasing the usability of remote sensing data. They provide users with products that are instantly downloadable, in most cases with all preprocessing already completed (in some cases some small inter-annual calibrations may still be needed), allowing users to start using the data straight away, with little chance of inexperienced users introducing errors into the processing chain.

However, the trade off for this improvement in usability is the coarse resolution of the MODIS sensor (250 m to 1 km) and the variability inherent in many of the products developed. The user also loses access to the original data by using these products (although it is also available if the user wishes). SAR requires more preprocessing and more

understanding on the part of the user to correctly interpret, but also offers finer resolutions and the potential to overcome problems facing optical data such as cloud cover. There is no one correct remote sensing solution that will meet all of Malawi's forest mapping requirements. The most appropriate solution will be the one which best balances all the criteria, including intended outcomes, user expertise, software availability and funding for data.

Based on the considerations discussed above, I will now make some recommendations about areas for future work, including potential remote sensing data and techniques, and ideas for encouraging capacity development in key areas associated with using remote sensing to support SFM in Malawi.

6.3 Recommendations

Despite the challenges encountered during this thesis, remote sensing still remains as one of the only options for conducting countrywide forest mapping in Malawi. It is also necessary to use remote sensing in order to obtain historical deforestation estimates, in order to implement REDD+ projects. There are a number of areas that could be focused on, in order to continue the development of remote sensing to support SFM in Malawi. Many of the recommendations made here have impacts for both policy and research, given the importance of forests for meeting livelihood needs in Malawi and the number of technical challenges still remaining to obtain accurate and updatable forest maps of Malawi.

6.3.1 Capacity development

This thesis has focused on trying to find remote sensing mapping solutions based on the constraints faced by forest management agencies and researchers in Malawi. Given the seemingly unique challenges being faced in Malawi, the best chance of developing a forest mapping methodology will come from in-country researchers who are most familiar

with the nuances of Malawi's ecosystems. This means there is a clear need to raise the institutional, technical and individual capacity of those involved in forest management who wish to use remote sensing as a management tool. Following the recommendations outlined in Chapter 3 would go a long way to helping develop this capacity. For example, both academics at Malawian universities and staff at the Department of Forestry and FRIM would benefit from increased in-country networking opportunities, as there is a growing body of expertise and experience in Malawi surrounding forestry and remote sensing, as well as many projects operating in-country with similar aims. Being aware of these activities could provide more strategic direction to Malawian forestry research.

When considering the future of remote sensing for forest cover change mapping in Malawi, by Malawians, there are a number of areas that need to be developed in order for in-country professionals to conduct research into the most appropriate type of remote sensing data for Malawi to use to monitor forest cover. These areas include human, institutional and technical capacity to conduct remote sensing research, as well as development of potentially novel techniques applicable to the circumstances faced in Malawi. Software and hardware development have to be accompanied by "brainware" development so that the end users can actually use them to achieve their intended goals (Ehlers 1996). Encouraging more research collaborations between Malawian forestry professionals, both in-country and externally will help enable the development of suitable forest mapping solutions. It is only by testing solutions and data products in Malawi that a suitable methodology for forest mapping will be developed.

The lack of internet connectivity means that even free data sources, or resources for software or information are not exploited as fully as they could be. This would be one of the most beneficial changes for Malawi as there is a growing repository of free data, or data that is available free of

charge for scientific use, or through imagery donation schemes that could be utilised. Malawi has a growing fiberoptic broadband network but uptake has been slow due to the cost of the service. Providing support for funding internet connectivity, even working with donor agencies to ensure this in place, would greatly benefit many aspects of in-country remote sensing research in Malawi, by allowing easier access to both data and the wider remote sensing community.

6.3.1.1 Open access software

There is a need to build technical capacity with regards to access to remote sensing software. This is not a problem unique to Malawi. Defries et al. (2007) argues that a key constraint to developing countries using remote sensing to monitor deforestation is access to data at a reasonable cost and the technical infrastructure (hardware, software, internet connection) to properly make use of this data. One of the main problems facing remote sensing research in Malawi is a lack of suitable software, and a lack of knowledge about alternatives to commercial software. The Department of Forestry at University of Malawi, Bunda College only obtained licences for ERDAS Imagine in 2011, and is the only institution in the country to have access to remote sensing software. The Government Department of Forestry only has access to ArcGIS on a limited number of machines. Given the dramatic improvements in open source or freeware alternatives to remote sensing software, these alternatives are now strong competitors to commercial software programmes (Steiniger and Hay 2009). One of the most well used programmes is GRASS (Graphical Resources Analysis Support System) (<http://grass.fbk.eu>) (often used in conjunction with Quantum GIS (<http://www.qgis.org>), which provides a more user-friendly interface).

Many forestry professionals in Malawi have had little or no exposure to remote sensing software other than ArcGIS. Open source alternatives can be intimidating to new users, and while many have online documentation or help forums, a lack of internet access can cause problems when

accessing this documentation. For example, while ArcGIS and GRASS have much of the same functionality, the help menus in ArcGIS mean that it can seem less intimidating to new users. Also, given that open source software is community developed, it can lack a cohesive approach.

6.3.2 Remote sensing data and techniques

Given that attempts to map forest cover in Malawi using free (or cheap) data products have not worked as well as expected, it would be beneficial if other data types that were not investigated here because they were thought to be too expensive to be used for long term monitoring were investigated. These include the possibilities for forest mapping using lidar and other SAR systems such as TerraSAR-X. Viergever (2008) showed the potential of using x-band SAR to map forest cover in savannah and this would be worth examining in Malawi. Given the success of using fully polarimetric data to estimate deforestation in Malawi (Cloude et al. 2009, Appendix 3), the fully polarimetric capabilities of both TerraSAR-X and the upcoming ALOS-2 will be interesting areas for investigation. As ALOS suffered catastrophic failure in 2011, there are currently no other spaceborne L-band SAR systems, so further investigations into the relationships between L-band SAR and AGB will have to wait until the launch of ALOS-2 in 2013. Preliminary results presented by Cloude et al. (2009), who mapped AGB using fully polarimetric ALOS PALSAR data showed more promise than those presented here using simpler decompositions of only the HV or HH bands. Fully polarimetric ALOS data was only an experimental mode, and did not have the necessary coverage to provide wall-to-wall mapping, so was not explored in this thesis. However, it does have the potential to reduce errors by extracting more information from the radar signal, and may offer a better solution for mapping AGB in Malawi.

There will be challenges finding funding for these data products. A recent remote sensing user survey of 377 respondents from over 30 African countries, that found the majority of respondents believed that they had

an adequate amount of remote-sensing expertise and capability but that they needed a greater number of accessible geospatial data sets (Johnson 2009). It is hoped that the results of this thesis will give Malawian researchers, and partner organisations a stronger case when applying to funding organisations, given the difficulties experiences here using predominantly free or discounted data. Additionally, given the results of the Plugge et al. (2012) calculations (Chapter 4) showing how important error reduction was for allowing Malawi to reach a break even point for REDD+, this increased accuracy could offset the increase in monitoring costs by increasing the potential for REDD+ payments.

The findings in this thesis have shown the difficulties of using radar to map AGB, which was unexpected, given the almost universal agreement in the published literature about the presence of the backscatter-AGB relationship. We do not yet truly understand the response of radar to vegetation, and while empirical relationships between AGB and backscatter have been established in forests around the world, this thesis is constrained in understanding why these approaches failed to work in Malawi, making an understanding of the fundamental physics underlying the radar response to forests critical. Currently there is a disagreement about which type of scattering mechanism dominates, and why saturation occurs (Imhoff et al. 1995, Lin and Sarabandi 1999, Woodhouse 2006b, Broily and Woodhouse 2012), and resolving this is critical for understanding precisely why the empirical relationship between AGB and backscatter breaks down over Malawi.

From a management perspective, ALOS PALSAR imagery does have some value in mapping forests in Malawi as it is not subject to the same limitations as optical data with respect to cloud cover and atmospheric haze. There are steps that need to be taken to ensure that the PALSAR data is correctly geo-referenced, and terrain corrected but these steps are relatively simple solutions that can be implemented using open source software and should not deter attempts to use SAR data for forest

mapping in Malawi. There is good similarity between predicted AGB estimates from a generic regression for African woodlands produced by Mitchard et al. (2009), and field estimates of AGB, when averaged over larger areas, despite a poor one-to-one correlation. This would need to be verified for more areas across Malawi, but could provide a useful methodology for producing national biomass estimates from only one remote sensing dataset. As there are currently no Malawi-specific biomass estimates, this could help development of REDD+ activities and management plans until alternative methodologies are developed.

With regards to optical data, it would be worthwhile investigating Malawian savanna ecology, in order to better understand how inter-annual variability is impacting vegetation indices. It would be beneficial to investigate how changes in rainfall patterns resulting from ENSO oscillations impact estimates of tree cover the following year, in order to provide better data to conduct inter-annual calibrations of optical data and vegetation metrics derived from them. Another area of research would be to investigate how high resolution optical imagery compares to coarse and moderate resolution data in estimating forest loss in miombo woodland. Cabral et al. (2011) found much higher estimates of deforestation in savanna woodland using Landsat imagery than using MODIS imagery, given the finer scale detail and smaller scale losses being observed in the Landsat imagery. It would be interesting to see if these trends are observed in Malawi.

Lidar was only mentioned briefly in the introduction to this thesis, and was not used in any of the data analysis. Airborne lidar could provide valuable data on canopy height, and to a certain extent three-dimensional structure of forests. There is currently no spaceborne lidar, following the failure of the Geoscience Laser Altimeter System instrument onboard ICESat. This allows accurate estimates of biomass to be produced (Asner et al. 2010). Lidar data is very expensive and time-consuming to collect and process and therefore not easily applicable to Malawi's monitoring

requirements. Lidar data can also be used to help calibrate and validate carbon stock and change estimates developed using radar or optical data (Zhao et al. 2009, Lucas et al. 2008, Asner et al. 2010, Goetz et al. 2009), which could help build a larger dataset to develop other methodologies.

On a final note, developing remote sensing solutions in conjunction with in-country researches will give the best possible opportunity for developing Malawi-specific remote sensing solutions to forest mapping challenges.

7. Conclusions

7.1 Key findings

This thesis has presented work assessing the use of remote sensing for supporting sustainable forestry in Malawi. One of the main ways remote sensing can support sustainable forestry in Malawi is by producing maps of forest cover and assessing how forest cover has changed over time, in order to help those involved in forest management assess which areas are under greatest threat, or whether mitigation activities are having the desired impact. Remote sensing will also have a key role to play in the MRV process in any potential REDD+ schemes, by providing a baseline estimate of forest area, forest cover loss and carbon stocks. Carbon stocks can either be estimated by applying average values to particular land cover types or possibly be directly estimated by using L-band SAR. Up to date forest cover maps are an important first step to help those responsible for forestry issues in Malawi to make informed decisions about which areas are under greatest threat, and in conjunction with other socio-economic data, draw conclusions about why this is the case so suitable mitigation strategies can be put in place.

7.1.1 Chapter 3 findings

In this chapter, we make a novel investigation into the extent to which the EO academic research community is engaged in capacity development. The importance of Earth Observation (EO) for addressing current environmental problems is well recognized. Most developing countries are highly susceptible to environmental degradation, however the capacity to monitor these changes is predominantly located in the developed world. Using the Web of Knowledge publication database (<http://wok.mimas.ac.uk>), we examined the geographical distribution of published EO related research (a) by country, as object of research and (b)

by authors' country of affiliation. Our results show that while a **significant proportion of EO research (44%) has developing countries as their object of research, less than 3% of publications have authors working, or affiliated to, a developing country** (excluding China, India and Brazil, which are not only countries in transition, but have well established EO capacity). These **patterns appear consistent over the past 20 years**. Capacity development in academic EO research is key for encouraging and engaging developing country researchers within the global community, and needs to become imbedded as best practice across all disciplines that conduct research in developing countries.

We suggest the following 3 recommendations for increasing capacity development:

- Focused networking, including making use of free online tools such as LinkedIn.
- Engage all collaborators in the research process from an early stage.
- Promote an “open” culture by encouraging publishing in open access journals, and the development of free and open source software.

7.1.2 Chapter 4 findings

This chapter presents the results of a calculation based on an previously published formula, for Malawi. Based on the results of this calculation, it appears that the most important factors governing whether or not Malawi could successfully implement economically viable REDD+ projects are the **accuracy of forest area estimates** (which appears to be more important than the actual loss rate, as long as the loss rate falls within ‘best guest estimates’). Reducing the total errors associated with estimating forest loss and carbon stocks halves the amount of forest

needed for REDD+ to reach a break-even point. **Data products need to be low cost or free** if there are going to be used by Malawi's under-funded and under-resourced Department of Forestry. Coarse resolution optical datasets have potential to add greatly to knowledge about the dynamics occurring Malawian woodlands, while avoiding a lot of the challenges that other higher resolution datasets may present such as higher cost, less frequent or less complete coverage, and the need for more pre-processing. Therefore this paper assesses coarse-resolution optical imagery for providing forest and forest cover change maps. It appears that **inter-annual variability limits the usefulness of both the MODIS datasets investigated here**, making it difficult to know if the trends being seen in a particular dataset are actually due to changes on the ground or whether they are due to noise in the datasets themselves. However, both datasets show that **Malawi is experiencing forest loss**, and has helped narrow down the range of values to between -0.7 to -3.1% per year.

7.1.3 Chapter 5 findings

This chapter examined the use of ALOS PALSAR for estimating AGB, firstly by attempting to extract a site-specific relationship between backscatter and field-measured forest variables including AGB, basal area and BCI. Non-linear regression provided the best fit, but **no correlations explained enough of the relationship between the variables to be used to develop empirical relationships on their own**, despite following the methodologies followed by previous studies, and other recommendations in the literature, including resampling to coarser resolutions and terrain correction. There are a number of different explanations for this, and it is likely to be a combination of factors including geolocation errors in the PALSAR data, the speckle inherent in SAR data, variable topography, and the heterogeneity of the vegetation.

The accuracy of a generic backscatter-biomass regression developed by Mitchard et al. (2009) is assessed over Malawi, and found to have a similar biomass distribution to that observed in the field data. Two different methods of assessing forest cover change were also undertaken. The first used a normalised HH/HV ratio to delineate areas of forest, and assess changes around the Lake Chilwa area of southern Malawi from 2007-2010. The second looked for significant land use change by thresholding the predicted AGB maps produced by the Mitchard et al. regression. These results were compared to a forest cover change map produced using MODIS Vegetation Continuous Fields percentage tree cover data. **Both the normalised HH/HV ratio change map and the MODIS VCF change map independently found net forest loss rates of 2.6% per year for this area. The predicted AGB change map found a lower net loss rate of 1.6% per year,** which is probably due to the fact that it uses a more strict forest threshold than the other methods.

From a management perspective, ALOS PALSAR imagery does have some value in mapping forests in Malawi as it is not subject to the same limitations as optical data with respect to cloud cover and atmospheric haze. There is good similarity between predicted AGB estimates from a generic regression for African woodlands produced by Mitchard et al., and field estimates of AGB, when averaged over larger areas, despite a poor one-to-one correlation. This would need to be verified for more areas across Malawi, but could provide a useful methodology for producing national biomass estimates from only one remote sensing dataset.

7.2 Overarching conclusions/Research applications

Global remote sensing products provide useful data on global processes, and in this sense perform very well. However when considering using these data or methodologies at smaller scales, for example at national or

sub-national levels, there can be issues with accuracy due to the increased heterogeneity being observed, with less area to average over to smooth the results and trends. **Malawi appears to be a much more complicated and challenging environment for conducting forest mapping using remote sensing than may have been previously assumed.** While one of the main goals of remote sensing is to extrapolate data from a small area to a larger one, in the case of Malawi this may cause problems due to the heterogenous nature of Malawi's forest ecosystems, and the nature of the forest loss currently occurring.

This thesis has examined both optical and SAR data for mapping deforestation in Malawi and found no dataset can provide a definitive answer of the current rate of forest loss in Malawi. However, all of these datasets do agree that some level of deforestation is occurring in Malawi, and helps narrow down the current range of national deforestation estimates to between -0.7 and -3.1%. Although this is a large range, there is now compelling data that the deforestation rate is much higher than previously thought, even if in only localised areas, particularly in southern Malawi. It also gives a 'working range' for estimates of deforestation in Malawi for future studies to refine.

The combination of challenges faced when trying to use remote sensing make Malawi an unexpectedly difficult country to work in. The combination of problems associated with the use of both optical and radar data make no particular sensor or methodology an ideal product. Instead, a careful assessment of the available remote sensing options needs to be made based on the user's required outcomes for a particular project, along with the technical expertise of those conducting the data analysis.

Increasing the use and development of open source GIS and remote sensing software will enable more Malawian researchers to have access to specialised remote sensing software. It is hoped that this will encourage

more in-country research into remote sensing to support sustainable forestry in Malawi. **The best chance of developing a forest mapping methodology will come from in-country researchers who are most familiar with the nuances of Malawi's ecosystems.**

7.3 Future work

Future work on understanding the exact relationship between forest parameters and remote sensing data would help to remove many of the uncertainties encountered here, particularly with regards to vegetation indices developed from optical data. Another interesting avenue for future research would be to investigate how much more accuracy is obtained from higher resolution optical sensors. This could help refine deforestation estimates and may help to highlight areas where trends are most complex. Fully polarimetric L-band SAR data has shown potential to map AGB in Malawi. The launch of ALOS-2 would provide more opportunities to test these more complex decompositions for mapping biomass in Malawi. Lidar data may be able to resolve many of the questions and issues raised with the other datasets, but it is prohibitively expensive. If the funding could be found, it would be worth exploring the use of lidar data in Malawi.

Capacity development needs to be a component of any future work undertaken in Malawi. When considering the future of remote sensing for forest cover change mapping in Malawi, by Malawians, there are a number of areas that need to be developed in order for in-country professionals to conduct research into the most appropriate type of remote sensing data for Malawi to use to monitor forest cover. These areas include human, institutional and technical capacity to conduct remote sensing research, as well as development of potentially novel techniques applicable to the circumstances faced in Malawi.

“A little knowledge is a dangerous thing.

So is a lot.”

- Albert Einstein

Appendix 1: Forests as living environments

Gemma Cassells, Iain H. Woodhouse

The initial idea for this paper was from IHW. I performed the data analysis, and wrote the manuscript.

A1.1 Abstract

Forests are currently at the centre of many global and national political and socioeconomic debates. However the demographic and economic factors associated with forest use and deforestation are poorly understood, partly because of their complexity and partly because of a lack of data available for global analysis. This study presents the results from a comparison of two freely downloadable global datasets, namely the Global Land Cover 2000 map (<http://bioval.jrc.ec.europa.eu/products/glc2000/glc2000.php>) from the European Commission's Joint Research Centre, and gridded population density data (<http://sedac.ciesin.columbia.edu/gpw>.) from the Socioeconomic Data and Applications Centre, at Columbia University. These datasets were analysed to produce a maps of forest with low population density and forests with high population density. These maps were then compared, and major trends for Africa, southeast Asia and South America were identified. We found that while all three of these regions have significant areas of forest cover, the population dynamics of these forests are different. In South America and southeast Asia, it appears that most people live around the edges of forest areas, or in urban centres close to forest areas. However in Africa it appears that the population is distributed more thinly across a much wider forest area. Finally, we place these findings within the wider context of changing patterns of forest use.

A1.2 Introduction

We revisit the figure that approximately 1.6 billion people around the world still rely on forests to meet their basic livelihood needs (FAO, 2006). The methodology for generating this number is not explicit in the FAO report so we applied a methodology that combines two existing data sets available at global scale for 2000. These are a remote sensing derived global land cover map (Global Land Cover 2000 (GLC2000) produced by the European Commission's Joint Research Centre), and gridded population data based on census returns (produced by the Socioeconomic Data and Applications Center (SEDAC) at Columbia University). These data are used to examine the geographical trends of people living in or near forests within the global context of changing demographic trends, including urbanisation, and their impacts on forest use. The results are important for providing an indication of baseline human-forest habitation, and we anticipate that the observed geographic variability may have significant impact on the effectiveness of international policy aimed at reducing deforestation (e.g. the Reduced Emissions from Deforestation and Degradation).

Given the fact that forest resources are often most significant for developing countries, this is the focus of our discussion.

A1.3 The Importance of People and Forests

Forests⁵ have been pushed to the top of the international agenda over the past decade, particularly with the on-going negotiations for a post-Kyoto international climate change agreement. The International Year of Forests (2011-2012) was coordinated by the United Nations Forum on Forests to highlight the essential role that forests play in the lives of billions of people. With somewhere between 6-17% of anthropogenic

⁵ As a clarification, forest is being used as shorthand for tree-dominated ecosystems including forests, woodlands and woody savannas.

carbon emissions coming from deforestation (van der Werf et al. 2009; Eliasch 2008; Baccini et al. 2012), and the costs of mitigating the effects of climate change estimated to reach US\$1 trillion by 2100 (Eliasch 2008), there is a global need to take forest loss seriously. For developing countries that rely on forests to produce vital government revenue, and local populations that rely on those same forest resources to meet basic livelihood needs, forest loss becomes an even more immediate political, social and economic reality. Forests will also play a significant role in realising the Millennium Development Goals 1 and 7 of halving the number of people living in absolute poverty by 2015 and ensuring environmental sustainability (United Nations 2011).

In the developed world, forests are used primarily for recreation or commercial lumber production. However in developing countries, forests are much more of a “lived” environment (Sankaran et al. 2005). Forests are at the heart of multiple political and socioeconomic issues for many developing countries, ranging from decentralisation of resource management (for example Colfer & Capistrano 2005; Hoang et al. 2011; Jenkins 2011), to pro-poor development (for example Liu et al. 2012; Kgathi et al. 2012; Parrotta & Agnoletti 2012), food security (for example Ehrlich et al. 1993; Place 2012; McMichael & Schneider 2011; Godfray et al. 2011), and energy supply (for example Ahrends et al. 2010; B. Fisher et al. 2011; le Polain de Waroux & Lambin 2012). Half the world’s population uses biomass fuels for cooking, and the majority of this is fuel wood or charcoal (World Health Organization 2006).

Demographic and economic factors associated with deforestation are poorly understood, partly because of their complexity, which is both spatially and temporally variable, and partly because consistent and reliable data have not been available for global analysis (Grainger 2008; DeFries et al. 2010). Population pressures are linked to all other underlying causes of deforestation (Cropper & Griffiths 1994). These

links are thought to be so strong that the UN has previously estimated deforestation rates by only using a model of population pressures (UN FAO 1993). Cropper and Griffiths (1994) estimate that as population increases, for every 100 people per 1000 hectares, the deforestation rate increases 0.33% per year.

A1.4 Methods

Population density data was obtained from the Socioeconomic Data and Applications Center, hosted by the Center for International Earth Science Information Network at Columbia University (<http://sedac.ciesin.columbia.edu/gpw>.) for the year 2010. This data set relies on national statistics office estimates of population and an interpolating algorithm based on known locations of roads and settlements to produce gridded global population data (full details available in (Balk et al. 2010)). Because of the data sources used, and the disparate methodologies using in collecting the data, there are known differences between this data and UN population estimates. The majority of these discrepancies are for small island states, due to the difficulty of locating them within the 5 km resolution of the gridded population data.

The Global Land Cover 2000 (GLC2000) map (<http://bioval.jrc.ec.europa.eu/products/glc2000/glc2000.php>) was downloaded from the European Commission's Joint Research Centre. The GLC2000 uses the VEGA 2000 dataset, collected by the VEGETATION instrument on SPOT-4 to produce a harmonised global land cover database. The GLC2000 land cover classes were aggregated into forest or non-forest classes, to produce a global map of forest cover at 1 km resolution. The forest classes included all wet and dry woodlands, including savannas but excluding scrubland. The GLC2000 map was selected because it has better global accuracy than either the GlobCover maps or the MODIS land cover products (Mayaux et al. 2005; Fritz et al..

2011), with the biggest disagreements between the datasets usually over the classification of savanna, scrubland and cropland, particularly in very heterogeneous environments (Giri et al. 2005).

A1.5 Results and Discussion

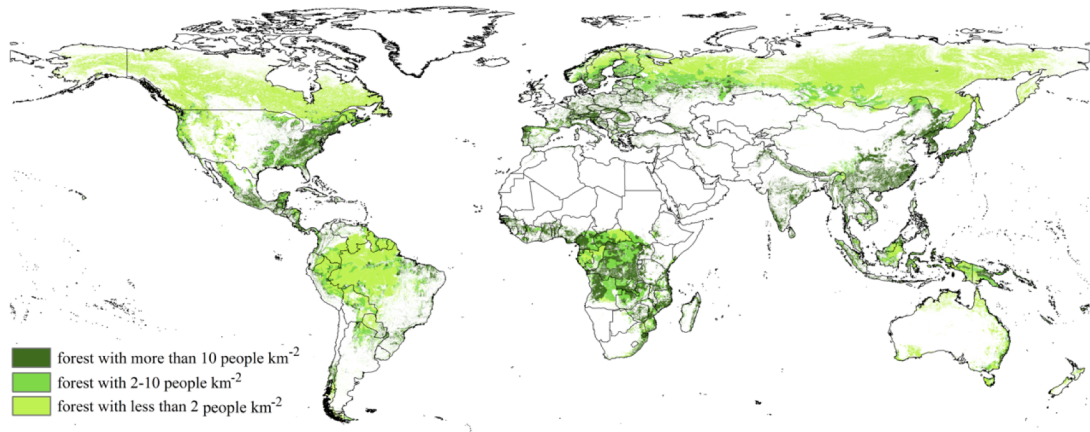


Figure A1.1 Global forest extent, from GLC2000 data, stratified by population density. The GLC2000 classes for all tree dominated ecosystems, including deciduous and evergreen forest and woody savanna were amalgamated to produce a global forest map. The boreal forests of Russia and Canada, and the Amazon are the largest forest areas with low population densities. The high population density of India and China means that most of the forest in these two countries has a large population living close by. Africa stands out from the other forest areas, as it appears that forest areas here coincide with a thinly spread population.

A1.5.1 Global overview

The total global forest area estimated by GLC2000 is 59,955,725 km² (figure A1.1). Global forest area for 2000 estimated from the United Nations Food and Agriculture Organisation Forest Resources Assessment (UN FAO FRA) 2010 data (this data set includes revised totals for forest in 2000 due to an improved methodology) is 53,098,570 km², giving a difference of more than 6 million km² of forest between the two estimates. There are several possible reasons for this difference. Firstly, there are key differences in the methodologies used to produce the estimates, as the FRA 2000 data is based on country reports to the FAO, which can be inaccurate, especially in developing countries that do not have the resources necessary to support national forest monitoring at a consistent standard. Secondly, there is likely to be some differences in what was

classed as forestland between the two estimates. We have used as broad a definition as possible using the FRA 2010, including forest, other forested land and other land with forests in the estimates to account for the inclusion of the “savanna” class in the GLC2000 dataset.

When comparing this global forest map with the population data, it is estimated there are approximately 1.52 billion people living within 5 km of a forest. Because the population data is provided at a 5 km resolution, it is not possible to narrow down the results any further, as there will be some discrepancies at the forest boundaries. This result is close to the figure quoted by the FAO of 1.6 billion people relying on forest resources to meet their livelihood needs, if proximity to forests is assumed to increase their importance to meeting livelihood needs. In fact, the number of people who rely on forests for fuel wood may actually be much higher than those people who live closest to the forests. DeFries et al. (2010) found that increasing urban populations tended to correlate with increasing deforestation in the tropics, even when those urban centres may be at some distance from the deforestation taking place.

A1.5.2 Africa

In 2000, Africa had a total forest cover of 34%, just over 10 million km². Much of this is concentrated in the Congo basin, and the adjacent savanna ecosystems predominantly to the east and south. Sub-Saharan Africa has an approximate total forest cover of 45%, with 8.9 million km² of forest. 208 million, or approximately 21% of Africa’s total population, lives within 5 km of a forest. If just sub-Saharan Africa (minus South Africa) is considered, approximately 197 million people, or a quarter of the population, live within 5 km of a forest. It is clear from figure A1.1 that much of Africa’s forests also coincide with where people live. It appears that Africa has a population that is distributed thinly across almost all of its forest area. However, it should be noted there are some doubts over the population data for several countries in Africa, in

particular the DRC, which has not conducted a census in 30 years, making demographic records unreliable.

Given the dominance of rain-fed subsistence agriculture across Africa, and the reliance on charcoal for heating and cooking for much of the region, this percentage of people living close to a forest actually seems quite low, and may indicate the distances people are travelling to obtain forest products or the reliance on an internal transportation mechanism. As a continent, Africa has the highest proportion of people in poverty, along with some of the lowest yields from staple food crops (Place 2012), which has led to a need to expand crop land in order to increase yields as population increases. This could be one explanation for why the percentage of people living close to a forest appears quite low, given the fact that charcoal is Africa's dominant fuel source (Fisher 2004; Fisher et al. 2011; Ahrends et al. 2010), with Africa accounting for about half of the world's global charcoal production and consumption (Chidumayo & Gumbo 2010). Charcoal is also the dominant fuel source in urban areas (Fisher 2004; Fisher et al. 2011; Ahrends et al. 2010), which means that despite living at some distance from forest resources, these urban populations are still dependent on it.

There have been greater urbanising pressures in southeast Asia, and South America, which has not happened as much in Africa yet, although this is starting to change. In the DRC, the history of insurgency and civil war has meant that the many people feel safer living in the forest, rather than in the cities. Indeed, there are very few cities for them to move to, and little work for them to do if they abandon subsistence farming. However, there is still an increasing urbanising trend in Africa, possibly due to the fact that most aid money is spent on cities, and aid is easier to access in the cities than in rural areas (Van Donge & Henley 2012).

A1.5.3 Southeast Asia

In southeast Asia, 232 million people live within 5 km of a forest, or 37% of the total population of the region. This is possibly due to the high population density in the region, which averages 121 people/km², combined with the region's relatively high forest cover of approximately 34% (2.2 million km²). It is also likely to be influenced by the historically high rates of urbanisation (Hackenberg 1980; Dick & Rimmer 1998; Van Donge & Henley 2012), with many large cities having expanded closer, or even into forested land. The high populations of India and China show similar trends, with seemingly very few forests that are far away from people.

One important distinction in Asia is the importance of plantation forests. According to FRA 2010 data (UN FAO 2010), there was a loss of 3.4 million ha of primary forest from 2000 to 2010, with a gain of 2.2 million ha per year of plantation forests between 2000-2010, implying a net increase in forest cover. However the factors influencing the use of natural forests are likely to be very different from those influencing the use and development of plantation forests.

A1.5.4 South America

In South America, 81.8 million people live within 5 km of a forest, or 21% of the total population. Although almost 60% of South America is covered by forest, it appears that people tend to live around the edges of the forests. This is in contrast to much of Africa, where there seems to be a much more thinly spread population living throughout the forest. While not assessed here, deforestation in the Amazon is well documented (for example (Shukla et al. 1990; Rodrigues et al. 2009; Kirby et al. 2006; Godar et al. 2012)). With this in mind, the findings presented in figure A1.1 indicate that forest loss is continuing despite most people living at some distance to the forest. This is in agreement with the findings of DeFries et al. (2010) and Gloor et al. (2012), who both found that South

America's rapidly urbanising population is causing a shift in forest resource use away from small scale shifting cultivation towards more intensive agricultural production to support a rapidly urbanising population.

Some authors (e.g. Becker 1995) argue that as the urbanisation rate in the Amazon region of Brazil is so high that the term 'urban forest' should be used to describe the area. Dal'Asta et al. (2012) find further evidence of extensive urbanisation in the Amazon, which is not picked up fully in the results seen here. It is possible that this urbanisation is very localised, and consequently there is only a small area of the Amazon with above-average population densities.

Primary forest accounts for 36% of global forest area (UN FAO 2010), but has decreased by 0.4% annual over the last decade (a total of more than 40 million hectares lost since 2000). From the data presented here, it seems likely that much of this is in the Amazon and the boreal forests of Russia and Canada, as the FRA defines primary forest as having no visible indications of human activities, and these areas are the only areas with a low enough population density to meet these criteria.

A1.6 Conclusion

The demographic trends associated with forest use are complex, and not well understood. The results presented here highlight the potential of using existing data to raise awareness, and perhaps address, of some of these macro-scale issues. From the results presented, there are clear differences in patterns of population across forested land in South America, southeast Asia and Africa. For both South America and Southeast Asia, it appears populations are predominantly around the edges of forests. In Africa the situation appears to be different, with a population that is more thinly spread throughout the forest area. This

has interesting implications when the impacts of urbanisation on forest use are considered, as it appears there is now more evidence in support of a global shift in the causes of deforestation from small scale shifting cultivation towards more intensive agricultural production to support urbanising populations.

Appendix Two: Academic and Research Capacity Development in Earth Observation Research

This is the final published manuscript of the paper in Chapter 3.

Academic and research capacity development in Earth observation for environmental management

Gemma Cassells¹, Iain H Woodhouse¹, Genevieve Patenaude¹ and Mavuto Tembo²

¹ School of GeoSciences, The University of Edinburgh, Edinburgh, Scotland EH8 9XP, UK

² Department of Land Management, Mzuzu University, Private Bag 201, Luwingu, Mzuzu 2, Malawi

E-mail: g.f.cassells@sms.ed.ac.uk

Received 10 February 2011

Accepted for publication 23 September 2011

Published 10 October 2011

Online at stacks.iop.org/ERL/6/044002

Abstract

Sustainable environmental management is one of the key development goals of the 21st century. The importance of Earth observation (EO) for addressing current environmental problems is well recognized. Most developing countries are highly susceptible to environmental degradation; however, the capacity to monitor these changes is predominantly located in the developed world. Decades of aid and effort have been invested in capacity development (CD) with the goal of ensuring sustainable development. Academics, given their level of freedom and their wider interest in teaching and knowledge transfer, are ideally placed to act as catalyst for capacity building. In this letter, we make a novel investigation into the extent to which the EO academic research community is engaged in capacity development. Using the Web of Knowledge publication database (<http://wok.mimas.ac.uk>), we examined the geographical distribution of published EO related research (a) by country as object of research and (b) by authors' country of affiliation. Our results show that, while a significant proportion of EO research (44%) has developing countries as their object of research, less than 3% of publications have authors working in, or affiliated to, a developing country (excluding China, India and Brazil, which not only are countries in transition, but also have well established EO capacity). These patterns appear consistent over the past 20 years. Despite the wide awareness of the importance of CD, we show that significant progress on this front is required. We therefore propose a number of recommendations and best practices to ease collaboration and open access.

Keywords: capacity development, Earth observation, best practice

1. Introduction

Sustainable environmental management is one of the key development goals of the 21st century. EO is increasingly recognized as a key tool for providing large-scale, up-to-date data about Earth surface processes to aid management decisions. There is growing awareness of the need for developing indigenous capacity across all nations in the application of satellite remote sensing. The vulnerabilities of developing countries to the impacts of climate change and

environmental degradation have been highlighted many times (e.g. Ayers and Dodman 2010, Patt *et al* 2010, IPCC 2007). Yet many such countries currently lack the necessary scientific and technical capacity within their research communities to fully assess possible future impacts. They are less able to conduct the multi-disciplinary studies needed to fill gaps in understanding climate change impacts at regional and local levels, or to fully take advantage of the global data sets now widely available (DeFries *et al* 2007).

While developing countries face the most pressing threats from environmental degradation, the best EO capacity to monitor these changes lies in the developed world. The aim of this letter is therefore to examine whether this 'capacity versus needs' polarization also occurs in the academic EO literature. This is achieved by exploring publication patterns between developed and developing countries. Notably, we query whether EO research, conducted in or about a given country, involves in-country authors. We first explore this issue broadly by examining the proportion of EO research published about a particular country compared to the proportion of in-country affiliated authors associated with that research. Secondly, by utilizing the field of forestry as a test case, we then explore geographically the patterns of authorship provenance and countries as research focus. Our discussion considers whether (and if so how) EO research has responded to meet the developing world's EO CD needs, and examines wider implications for development and policy-making. We conclude by proposing three strategies for promoting academic and research CD in the EO sector. In section 2, we introduce briefly the development of CD thinking, and discuss the importance of academic-led CD in Earth Observation.

2. What is capacity development?

Capacity is defined as the 'ability or power to do, understand or experience something' (Oxford English Dictionary 2010). 'Capacity building' involves strengthening particular scientific or technical abilities and resources in individuals, institutions or infrastructure (Wignaraja 2009). Some authors and institutions advocate the use of the expression 'capacity development' in recognition of the existing knowledge or infrastructure available (Linnell 2003, Lusthaus *et al* 1999, Wignaraja and Yocarini 2008). Some have argued that both expressions narrow focus to mainstream development strategies (Fisher 2010). In this letter however, CD is intentionally loosely defined to be inclusive of a broad variety of development focused strategies. While most frequently referring to activities conducted in developing countries, CD is not country- nor sector-specific. In this letter, we focus on academic and research CD in the EO sector.

A summary of EO activities pertaining to CD has recently been published (Group on Earth Observation, GEO 2006) and a key highlight of this report is the demonstration that the success of EO related CD depends on the building of capacity in all (not only one) of the following three dimensions: human, institutional and infrastructural. Capacity and performance is a result of the interactions within and between these dimensions. Examples of such successful EO sector CD within the developing world are found in the fields of weather forecasting and disaster monitoring. CD strategies in these fields were primarily driven by the importance of EO technologies for food security and livelihood resilience (Quansah *et al* 2010, Lewis *et al* 2010). The success of projects such as those by Jason *et al* (2010) partly stems from their clear definition of technical yet specific goals, realistic objectives, and perhaps most importantly, from a long-term commitment to projects and associated CD.

Other EO fields have recently received attention, notably that of forest mapping. Such attention has been driven largely by both the United Nation's Food and Agriculture Organization's (FAO) increasing reliance on remote sensing to produce the Forest Resource Assessments (FAO 2010b), and an increased attention to the need to monitor Reduced Emissions from Deforestation and Degradation (REDD) from developing countries. REDD has been proposed as a global policy instrument for mitigating climate change (Gibbs *et al* 2007, Obersteiner *et al* 2009).

Within a given country, CD can be driven by internal and external pressures or incentives. While some instances of internally led CD activities (conducted independently from external donor activity) can be found (Eade and Williams 1995, Baser and Morgan 2008), foreign aid programmes have had a predominant role to play in CD (Caplan 2004). Successes have ensued from such foreign aid programmes, but some associated CD strategies have led many low income countries to become dependent on foreign donors. Results were often constrained by a project's life span, which ultimately led to disempowering the very countries that were meant to benefit from the development (Stephen 2006). Current best practice advocates empowerment: developing countries should design and implement development approaches themselves (Wignaraja and Yocarini 2008, Wignaraja 2009, Brinkerhoff 2009), allowing them to articulate a vision of development that best meets their own situation and beliefs. This shift has taken place largely as a result of the recognition that CD must operate at all levels within a country if donor intervention is to have any lasting long-term impact (OECD 2006, 2008, Wignaraja and Yocarini 2008, Samoff and Carrol 2004).

2.1. Academic and research capacity development

'... Research in and with developing countries should—and indeed must—lead to the strengthening of their research capacity.'

—Swiss Commission for Research Partnerships with Developing Countries (KFPE) (1998).

Academic and research CD, and the associated CD necessary to support it, is key to engaging developing country researchers in global academic discourse, strengthening their own skills and confidence in conducting internationally recognized research (Crossley and Holmes 2001). The GEO Capacity Building Strategy (GEO 2006) has identified a need for close collaboration between countries to strengthen institutions and infrastructures, beyond technological and capacity development in developing countries. This does not simply mean developed and developing country partnerships, but also partnerships between developing countries. For example South Africa, Algeria and Nigeria have greater capacity than most of the rest of sub-Saharan Africa with regards to EO expertise (Jason *et al* 2010, Gottschalk 2010), and could take the lead in partnering with other countries in the region to develop regional EO capacity. Brazil has also taken on a leading role in South–South partnerships in a number of areas including EO research (Peter 2009). This is illustrated by their commitment to providing free EO data to Latin American

Table 1. Selected 68 countries and associated country codes (in alphabetical order).

ARG	Argentina	GHA	Ghana	MOZ	Mozambique	RWA	Rwanda
AUS	Australia	GRC	Greece	MUS	Mauritius	SAU	Saudi Arabia
BGD	Bangladesh	GTM	Guatemala	MWI	Malawi	SWE	Sweden
BLZ	Belize	GUY	Guyana	MYS	Malaysia	TCD	Chad
BOL	Bolivia	IDN	Indonesia	NER	Niger	THA	Thailand
BRA	Brazil	IND	India	NGA	Nigeria	TUN	Tunisia
BWA	Botswana	IRQ	Iraq	NLD	Netherlands	TUR	Turkey
CAN	Canada	ISR	Israel	NOR	Norway	TZA	Tanzania
CHL	Chile	ITA	Italy	NPL	Nepal	UGA	Uganda
CHN	China	JPN	Japan	PAK	Pakistan	UKR	Ukraine
COL	Colombia	KEN	Kenya	PAN	Panama	URY	Uruguay
DEU	Germany	LIB	Libya	PER	Peru	USA	United States
DRC	Democratic Republic Congo	MAR	Morocco	PHL	Philippines	VEN	Venezuela
EGY	Egypt	MDG	Madagascar	POL	Poland	VNM	Vietnam
ESP	Spain	MEX	Mexico	PRY	Paraguay	ZAF	South Africa
FRA	France	MLI	Mali	ROM	Romania	ZMB	Zambia
GBR	United Kingdom	MNG	Mongolia	RUS	Russian Federation	ZWE	Zimbabwe

and Africa as part of the China Brazil Earth Resources Satellite (CBERS) programme (Ferreria and Camara 2008).

As a broad generalization, scientists in developing countries are increasingly becoming concerned about external agencies, institutions and individual researchers operating in their countries with limited regard for local CD or alignment with national and regional development priorities (Samoff and Carrol 2004, Jallade *et al* 2001). Regional or country-specific EO research activities that cover developing nations are often not conducted in partnership with local research groups or institutions. This is understandable given that many EO activities, by definition, are done remotely.

To gauge the extent of this problem, we looked at one aspect of research output, namely research publications in peer-reviewed journals, firstly by searching for papers published by a range of countries defined by their economic status and secondly by investigating the geographical distribution of authors compared to countries of research focus. Notwithstanding the obvious limitation that we only cover published research (much in-country research may not find its way to journals or may be conducted by organizations who have no goals for publishing in this way) we believe this analysis provides a valuable perspective on the effectiveness of EO capacity development.

3. Methodology

3.1. An assessment of publication output

Approach A. Articles containing any of the following terms were extracted from Web of Knowledge (WoK) (<http://wok.mimas.ac.uk>), for the period from 1971 to present (Oct 2010): remote sensing, Earth Observation, satellite image, ALOS, Landsat, and MODIS. Our intent was not to develop an exhaustive database of EO research, but rather to generate a representative overview of EO research. This time period was selected as EO emerged as a discipline around the 1970s. Articles related to meteorology, atmospheric science, oceanography and marine science (using the Boolean NOT option) were excluded.

After these initial search criteria were defined, a list of more than one third of the world's (68) countries was created. Our selection, presented in table 1, aimed at being representative of a broad spectrum of economic development status. Countries falling within each one of the World Bank's 4 economic status categories (World Bank 2010) were selected ensuring a fair distribution of countries in each of the categories (low, low-middle, upper-middle and high income). Once this list was generated, the name of each country was added as the final criteria to the search terms listed above. Using the analysis feature within the WoK, we then quantified the number of articles per country and the number of articles per country with the country's name also appearing within the author(s)' address. This was repeated for all 68 countries.

3.2. Investigating geographic trends

Approach B. While Approach A allows an assessment of the proportion of papers written about a particular country with an in-country author involved, it does not allow to explore changes in practices over time in EO-specific CD, nor does it enable us to investigate and visualize the geographical distribution of authorship (including the division between first and subsequent authors) compared to countries of research focus. To achieve this, a similar selection approach to that described above was adopted, with two differences. (a) Given the size of the database generated, we constrained our search to forestry, a highly topical research area. In addition to the terms listed in Approach A, the terms forest* or woodland* (* as wildcard) were also used to extract articles. All conference proceedings were excluded, our aim being to explore the extent of collaboration occurring throughout the research process (from design to peer-reviewed publication). Irrelevant papers accidentally included (e.g. from chemistry, zoology, medicine) were also manually filtered out. (b) To explore whether CD progress has been made in this area, two time periods were considered. The inclusion of CD within the international development agenda is relatively recent and can be traced back to approximately 20 years ago (Wignaraja and Yocarini 2008, Wignaraja 2009). The periods considered here,

namely 2005–10 and 1990–5 inclusively, were selected to fall well within this timeframe.

Using a random number generator, the selected records were then sampled from the searches, using the record number as a unique reference. A sample size of 20% was generated ($n = 474$ for 2005–10, $n = 87$ for 1990–5). For each record, the following information was recorded (a) the country, countries or region(s) in which the research was conducted (b) all authors' country affiliation (listed in the address field for each author). Where more than one address was listed for an author, the first one was selected. Because remote sensing studies tend to lend themselves to large-scale studies, some papers focused on many countries or even on whole regions or continents. Where papers researched multiple countries, each country was included as an individual entry. The results of these searches were then loaded into ArcMap to allow a visual interpretation of the trends in research patterns (figure 3). Choropleth maps were created using 4 frequency classes: less than 1% (highlights those countries that occur particularly infrequently, maybe only once or twice), 1–5%, 5–10% and greater than 10%. While a 10% threshold may seem low, it actually represents a strong degree of dominance in the results and a significant volume of research output and interest, with very few countries exceeding 10%.

4. Results and discussion

Our selected list of 68 countries is presented in table 1 and our results from Approach A (section 3.1) are presented in figures 1 and 2. Figure 1 presents our results on a country by country basis, while figure 2 shows averages and standard deviations per economic status categories. Both figures show that EO research conducted about a low income or lower-middle income country is much less likely to have an in-country author than research conducted about an upper-middle or high income country. We nevertheless found three anomalous countries: China, India and the USA. While these were excluded from figures 1 and 2, they are further discussed below.

Relative to countries within the same economic status categories, China and India had an anomalously high number of in-country authors relative to the total number of papers published about those countries (79% and 85% respectively). Academically, both China and India stand out compared to other developing countries. They have a significant internal publishing communities illustrated by a healthy number of journals such as the *Journal of the Indian Society of Remote Sensing* or the *Chinese Journal of Atmospheric Sciences*, which target predominantly within country scientists. Most articles in these journals are composed and read almost exclusively by indigenous scholars. The availability of facilities and infrastructure for journal printing and distribution has most likely contributed significantly to the development of these flourishing publishing communities. Also, as countries in transition, both countries have already developed in-house internationally influential and world-leading EO capacity.

The low number of USA-based authors relative to the total number of papers published about the country itself (58%) represents our third anomaly. This result, somewhat

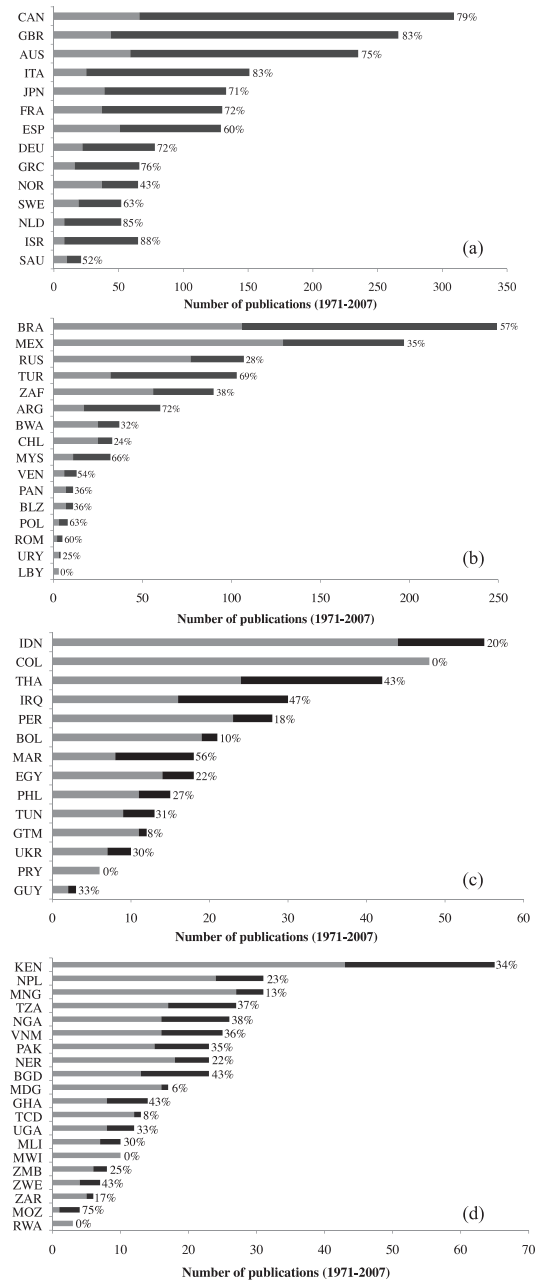


Figure 1. Number of publications for (a) high income, (b) upper-middle income, (c) lower-middle income and (d) low income countries. Total bar length indicates the total number of publications about the country. The black section indicates the number of papers with the country listed in the author address field. The percentage of in-country affiliated authors compared to the total number publications about that country is given at the end of each bar. Publications written about high and upper-middle income countries have a higher proportion of in-country authors compared to papers written about lower-middle and low income countries.

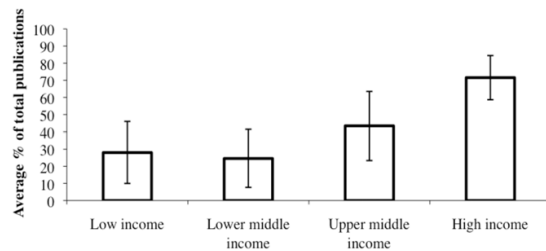


Figure 2. Average (with standard deviation) proportion of articles with in-country authors grouped by World Bank income class. High income countries are almost twice as likely to have an in-country author as low and lower-middle income countries.

unexpected, and may be a consequence of many USA ‘Address’ fields listing US States only, rather than the country itself. As such, several in-country authors may have been excluded from the analysis.

The results highlighted by Approach A are further reinforced by those of Approach B (section 3.2). Between 2005 and 2010, 44% of EO forest related research sampled was conducted about developing countries (figure 3). However, authors affiliated with developing country institutions account for only 20% of total authorships. These figures drop to 29% and 3% respectively if India, China and Brazil are excluded. When first authorship alone is considered, less than 1% of authors are affiliated with developing country institutions.

Our Approach B results also show Brazil as an anomaly, alongside India and China. Brazil was the country of focus for 9% of research studies sampled, and accounts for 5% of total authors, a proportion dramatically higher than most developing countries. We did not investigate whether a particular author was writing about a particular country, but this does seem to suggest that at least some of the research papers written about Brazil had a Brazilian author, a situation that is not repeated in any other developing country. The consistent efforts, funding and collaborations spearheaded by INPE (National Institute of Space Research) have placed Brazil’s EO community well above those of other developing, and some developed, countries, and have led to the prominence of Brazilian scientists within EO research.

For 1990–5, developing countries represented 25% of countries researched, but only 8% of first authorships. If India, China and Brazil are excluded these figures drop to 12% and zero. Figure 3 clearly shows that there has been a change in emphasis about where EO research has been conducted over the last 20 years, with a much greater shift towards southeast Asia, Latin America and Africa. While research conducted between 2005 and 2010 studies a greater range and proportion of developing countries, developing country researchers still represent a small fraction of the total number of authors. This trend in under-representation has not altered over the past 20 years. Figures 3(a) and (b) highlight a noticeable dearth in Africa and southeast Asia. Despite the rise in the importance of CD, there seems to have been no corresponding rise in authorship from developing country researchers (while based in their home institution) over this period. It is acknowledged

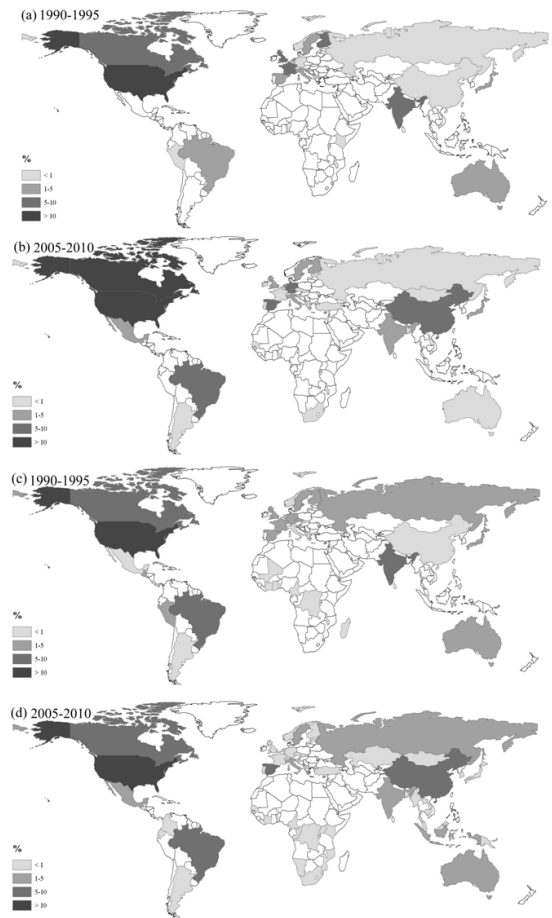


Figure 3. Country affiliation of authors for (a) 1990–5 and (b) 2005–10. Geographical location of research conducted (c) 1990–5 and (d) 2005–10. USA dominates EO research with 30% and 50% of total authorships (1990–5 and 2005–10 respectively). Overall, gaps in authorship are clearly noticeable over Africa and southeast Asia, despite the increase in the number of countries in these regions where research is conducted.

that figure 3(c) perhaps overstates how much research was being conducted in Africa during this period, as the countries in West Africa are all from one paper that conducted a region-level analysis, while the African countries represented in figure 3(b) are all from different studies. Nonetheless the numbers remain striking.

5. Discussion and recommendations

5.1. Educational research partnerships, capacity building and international development assistance

For established researchers in the Global North to best contribute to the development of those countries that lack EO expertise it is essential that they compel themselves to partner with local researchers. Such partnerships must

form at the beginning of a research project and continue throughout the research process. There is a need to develop indigenous capacity to stop the culture of dependency on foreign institutions. The strong emerging economies (e.g. Asian Tigers) have invested heavily in scientific and technical education and training (Green 1999, Morris 1996) and this is partly apparent in our results. In recent years, about a quarter of donor aid, more than US \$15 billion per year, has gone into technical co-operation, the bulk of which is aimed at CD (OECD 2006). However evaluation results confirm that development of sustainable capacity continues to be one of the most difficult areas of international development practice (FAO 2010a, Lusthaus *et al* 1999, Horton 2002, Horton *et al* 2003, Gorgens and Kusek 2009).

With so much emphasis on access to basic education throughout the developing world, investment has often been funnelled away from secondary and tertiary education to support these goals. It has been argued that basic education gives a better return on investment than higher education (Psacharopoulos 1972, Psacharopoulos and Patrinos 2002). However, there are now immediate challenges in many developing countries that need to be addressed. Increased investment in research at tertiary institutions (and the subsequent training of students in research skills) would have knock-on effects in many areas of sustainable development and poverty alleviation including environmental degradation. Without a basis in sound research, effective management strategies can neither be designed nor implemented. This is illustrated by the current state of environmental and natural resource management activities in Africa, which note huge capacity gaps across scales of natural resources management (Folke *et al* 2002, Nelson 2010). Research capacity development will contribute to national development by addressing the knowledge gap between the global North and South, with the eventual aim of enabling more balanced South–North partnerships. However, it seems from the results presented here, that EO research still has a long way to go before the necessary level of equality in research is obtained to allow countries the necessary level of in-country expertise to conduct this research themselves. It also seems that we still have a situation where research is mostly done about developing countries, not by developing countries. Section 5.2 offers some practical approaches to address this issue.

5.2. Strategies for promoting collaborative EO research

There are a number of practical steps that can be taken by all EO professionals and their institutions to encourage and engage with developing country researchers. These are designed for those working in developing countries, require little economic outlay (other than time) and have the potential to increase the likelihood of meaningful results. They are by no means exhaustive, and are designed to provoke wider discussion of these issues in a practical context.

Strategy 1: focused networking. The importance of networking should never be underestimated as one of the leading means of building capacity in the developing world.

Table 2. Eleven principles of research partnerships (KFPE 1998).

1	Decide on the objectives together
2	Build up mutual trust
3	Share information; develop networks
4	Share responsibility
5	Create transparency
6	Monitor and evaluate the collaboration
7	Disseminate the results
8	Apply the results
9	Share profits equitably
10	Increase research capacity
11	Build on achievements

Society membership and conference attendance is a luxury that few can afford on a regular basis.

Action: encourage researchers to use free networking tools. Online professional networking sites are becoming increasingly common among EO professionals. For instance, LinkedIn (www.linkedin.com) is a free networking site that has an EO Network. At the time of writing this article, this network had attracted over 2400 members worldwide, many of whom are in developing countries. This service allows one to build up personal networks of current and former colleagues or contacts. It has been especially popular amongst financial professionals in the USA, but has expanded now to more than 30 million experienced professionals from around the world, representing 150 industries.

This action recommends that institutions encourage staff to use these free networking tools, and to especially encourage contacts from the developing world to join.

Strategy 2: engage teams in the complete process from an early stage. Effective collaboration is an effective means of sharing expertise, skills, data and knowledge. Beyond this, it also allows for institutional capacity building and development. The most effective capacity building is not from training courses, but from being involved with hands-on projects. Any projects or other initiatives should aim to collaborate with local institutions, and do so from the very earliest stage—that is, from the initial proposal stage. Academic researchers in developing countries are just as eager to publish as those in developed countries, and often have similar institutional and personal pressure to do so (Sawyer 2004). In this context, we recommend taking a proactive strategy to include local researchers involved with the collaboration as joint authors on papers.

The Swiss Commission for Research Partnerships with Developing Countries (KFPE 1998) outlines 11 principles for successful research partnerships, which serve as a useful framework for defining the ‘rules of the game’ when developing research collaborations (table 2).

Strategy 3: promote an ‘open’ culture. ‘Open source’ software is made available to everyone to use, modify and improve. ‘Freeware’ is software that is free to use but the source code is not available to edit. ‘Open access’ (OA)

journals are online publications that allow free access to readers but may charge authors a fee to publish.

Action: publish results in open access journals. Journal access is expensive. In developing countries it is usually prohibitively expensive, and online journals are available only through donor subscriptions. Relying on donated subscriptions is not a long-term sustainable solution. One alternative solution is to encourage researchers to submit their work to electronic open access journals. Unfortunately, there is a chicken–egg situation with OA journals in environmental sciences—they tend to have lower impact factors and therefore fewer good works tends to be submitted. However, with a concerted effort, this may change over time and perhaps emulate the incredible success that biomedical sciences have had with OA journals. There is now an OA remote sensing journal (Remote Sensing, www.mdpi.com/journal/remotesensing/) that has been running since March 2009, and many others that publish applied remote sensing research, for example Carbon Balance and Management (www.cbmjournals.com) and Environmental Research Letters (<http://erl.iop.org>).

Two points should be noted. First, while this paper is clearly written from the perspective of researchers from a developed nation working in a developing nation, many of the same principles apply generically to an EO project, whoever is conducting the research. Second, these guidelines are tailored for projects where the location country is not expected to necessarily gain from the outputs—such as terrestrial carbon dynamics, ecology, or biodiversity. The project outcomes may have secondary value to the host country, but the main purpose (and particularly the scientific justification that led to it being funded) is not country-specific. Projects aimed at addressing local user needs are more likely to be sensitive to such issues, and in particular require a much greater input from local stakeholders.

Ultimately, the work presented here is, in the first instance, aimed at influencing individual and institutional policy on working in developing countries, and secondly, influencing policy related to funding agencies who have an obligation to consider these issues in the context of the international agreements outlined above.

6. Conclusions

The importance of EO for combating current environmental problems is well recognized. By supporting the development of relevant skills, data access and processing tools, EO researchers can enhance the ability of developing countries to assess their vulnerabilities and evaluate options for adaptation. Developing countries are too reliant on external actors for conducting EO research in their own countries. From the research presented here, it appears that there are a much greater number of papers written about developing countries rather than by developing country researchers. In one example field of EO study (namely, forests) there has been no significant change in this pattern over the last 20 years, despite the increased awareness of the importance of CD within the international development community as a whole. Capacity

development in academic EO research is key for encouraging and engaging developing country researchers within the global community, and needs to become embedded as best practice across all disciplines that conduct research in developing countries.

Acknowledgments

Funding for this research was provided through GC's PhD studentship from the Natural Environment Research Council and the Moss Centenary Scholarship. The authors wish to thank Jarret Mhango and Dalo Njera, Mzuzu University, who contributed to the ideas expressed in this letter.

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Appendix Three: An Assessment of ALOS L-Band Polarimetry for Land-Use Monitoring in Malawi

S R Cloude, P Lumsdon, G Cassells, I H Woodhouse, M Tembo

I contributed to the data analysis presented in this paper, and provided the field data used here. I also provided background knowledge on Malawi's forest, and contributed to writing the introduction.

AN ASSESSMENT OF ALOS L-BAND POLARIMETRY FOR LAND-USE MONITORING IN MALAWI

S. R. Cloude⁽¹⁾, P. Lumsdon⁽¹⁾, G. Cassells⁽²⁾, I.H. Woodhouse⁽²⁾, M. Tembo⁽³⁾

⁽¹⁾AEL Consultants, SCOTLAND, UK, aelc@mac.com

⁽²⁾School of Geosciences (Geography), University of Edinburgh, SCOTLAND, UK, i.h.woodhouse@ed.ac.uk

⁽³⁾Dept. of Land Management, University of Mzuzu, Bag 2, Mzuzu, MALAWI, tembomd@mzuni.ac.mw

ABSTRACT

In this paper we investigate the advantages of using full quadpol low frequency radar imaging data for large area land-use classification and forest biomass estimation. We employ multiple PALSAR data sets over test sites in Malawi, Africa, where we have extensive in-situ measurements and ground campaigns for validation. We show how L-band PLR modes show great potential for quantitative land use applications and important sensitivity to above ground biomass.

Index Terms— Radar Polarimetry, Biomass estimation, ALOS PALSAR

1. INTRODUCTION

This paper addresses the potential use of the experimental quadpol PLR21.5 mode of ALOS-PALSAR for improved land-use mapping and forest biomass estimation for several test sites located in Malawi. This application links with a much wider program of carbon asset determination for the region. The potential for developing carbon finance projects from the avoided deforestation and conservation of forests in Malawi has been assessed using baseline figures from Mkuwazi Forest Reserve, and the Thazima region of Nyika National Park as examples [1]. The approach used is likely to be suitable for forest conservation projects in National Parks and Forest Reserves throughout Malawi that maintain natural forest cover. Data were collected in collaboration with the communities of Mkuwazi Forest Reserve and the Thazima Region of Nyika National Park, the Department of National Parks and Wildlife (DNPW), Department of Forestry (DF), and Forest Research Institute of Malawi (FRIM), and staff and students from Chancellor College, Malawi and The University of Edinburgh, UK. Satellite imagery, existing literature and land use maps, community consultations, and site visits were used to estimate the areas covered by different land use and land cover classes, estimate past trends in the rates of deforestation and identify the threats present in each of the project areas. Existing carbon stocks were then quantified for the Thazima Region

of Nyika National Park and Mkuwazi Forest Reserve in the Nkhata Bay district of Malawi. Reference Carbon stocks were calculated using standard carbon inventory methods for each identified land use and land cover classes, including aboveground and below-ground woody biomass and deadwood.

The key agents and drivers of deforestation within Mkuwazi Forest Reserve and Nyika National Park, were identified by local communities, DNPW and DF staff. For both project areas key agents included local and distant communities and commercial interests in the forest reserve area. Weak enforcement, population pressure and government policies were identified important drivers of the quantity of deforestation, while key determinants of the areas most at risk of deforestation included proximity to settlements, paths and roads and existing and planned developments and markets. Both Nyika National Park and Mkuwazi Forest Reserve are under encroachment pressure from surrounding areas where suitable land for agriculture and charcoal production is becoming scarce. In both areas initial gazettement resulted in the displacement of communities, which has the potential to cause conflict with any future changes in government.

Estimation of the past trends in rates of deforestation across the whole of Malawi range from 0.9% to 2.8% [1]. Primary forest land, including protected areas are under greatest threat. Predicting future trends in deforestation is a complex and multi-faceted problem because of the diverse nature of the causes and drivers of deforestation. Projection of the losses in primary forest experienced between 1990 and 2005 suggest that all primary forest in Malawi will be degraded or deforested by 2040. The current threats to carbon stocks within Mkuwazi Forest Reserve and Nyika National Park are likely to increase in the future because of the growing demand for woodfuel and charcoal, increasing threats from businesses and infrastructure development, population growth, and development of tobacco and timber markets. For this reason we are investigating the use of satellite radar technology for monitoring land-use change and, if possible, the estimation of forest biomass and biomass change in the

region.

2. METHODOLOGY

We acquired 12 ALOS-PALSAR PLR21.5 data sets for the test sites in Malawi from the JAXA archive (see table I). Notice that some data sets are separated in time by 46 days (the minimum temporal baseline), so enabling POLInSAR studies, while others are separated by more than a year, so enabling a multi-temporal analysis.

Track ID	Date	Mode
ALPSRP067066980	2007/04/28	PLR21.5
ALPSRP140876980	2008/09/15	PLR21.5
ALPSRP067066970	2007/04/28	PLR21.5
ALPSRP140876970	2008/09/15	PLR21.5
ALPSRP067066960	2007/04/28	PLR21.5
ALPSRP060356960	2007/03/13	PLR21.5
ALPSRP140876960	2008/09/15	PLR21.5
ALPSRP064586960	2007/04/11	PLR21.5
ALPSRP071296960	2007/05/27	PLR21.5
ALPSRP138396960	2008/08/29	PLR21.5
ALPSRP067066950	2007/04/28	PLR21.5
ALPSRP140876950	2008/09/15	PLR21.5

Table I: Details of 12 PALSAR data sets used for Malawi

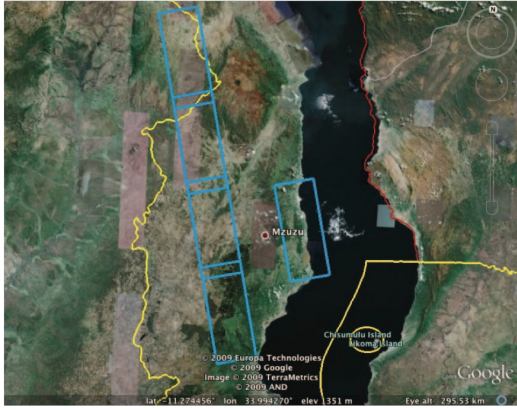


Figure 1: Location of PALSAR data sets, centred around Mzuzu, Malawi, lat/long $-11.46^{\circ}/34.02^{\circ}$

Figure 1 shows the geographic location of the data sets in Google Earth. We see one long strip of data covering a variety of land use types and one coastal scene on the shore of Lake Malawi, where our main forest test area is located. We then used these level 1.1 data sets to develop a range of secondary products based on two main approaches, first the

use of decomposition theory [2] and the POLSARPro toolbox [<http://earth.esa.int/polsarpro/>] to investigate land-use classification and change [3,4] and to provide separability of surface and volume scattering for biomass estimation [5]. In a second phase we employed repeat-pass interferometry to investigate the possibility of tree height estimation, as originally applied by us to airborne data in [6] and later investigated for ALOS PALSAR [5,7]. Previous studies of POLInSAR with ALOS-PALSAR have shown large degrees of temporal decorrelation over the 46-day repeat time of ALOS, [5,7] and this is confirmed in our analysis of the Malawi data sets. For this reason we concentrated on our primary objective, the use of *single pass* quad-polarimetric data for improved land use and biomass studies.

3. BIOMASS ESTIMATION FROM μ

Forest biomass is often estimated directly from backscatter, for example in L-band HV. However, it is possible to retrieve biomass from other parameters, more particularly the ratio of surface-to-volume scattering or μ . This we can estimate as follows. Based on our extensive analysis of PALSAR data sets, the coherency matrix at L-band for forested terrain can be well represented by the following two-component decomposition model [1].

$$\begin{aligned}
 [T] &= [T_s] + [T_v] \\
 &= \begin{bmatrix} m_s \cos^2 \alpha & m_s \cos \alpha \sin \alpha e^{i\phi} & 0 \\ m_s \cos \alpha \sin \alpha e^{-i\phi} & m_s \sin^2 \alpha & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad -1) \\
 &+ \begin{bmatrix} Fm_v & 0 & 0 \\ 0 & m_v & 0 \\ 0 & 0 & m_v \end{bmatrix}
 \end{aligned}$$

where $[T_s]$ is the dominant 'surface' component, modeled as either a single or double bounce contribution, and $[T_v]$ is the volume component, assumed to be azimuthally symmetric. This model is entirely consistent with the RVOG model widely used in POLInSAR. The parameter F is often interpreted, under single scattering, to be the mean particle shape in the vegetation, often $F = 2$ for pine, corresponding to the dipole cylinder cloud model described in [1]. However F can also approach unity in case there is multiple scattering present in the volume (which we have found to often be the case in L-band imagery) and so we keep it as a free parameter. Equation 1 has five unknowns and five observables so can be solved directly from coherency matrix data (although special care needs to be taken in cases when $[T]$ is diagonal, which situations we identify using a special test for azimuthal symmetry as described in [8]). To obtain good estimates of the coherency matrix we employed extensive multi-looking of the radar data (equivalent to

around 100 independent looks), giving an effective resolution of around 100m x 100m on the ground.

For biomass estimation we then seek to choose a polarization that maximizes the ratio of surface-to-volume scattering and hence is most sensitive to the changes in surface scattering caused by the presence of growing vegetation. This maximization problem can be formulated directly in terms of coherency matrix components as shown in equation 2, the solution for the maximum μ is then given by the maximum eigenvalue of $[T_v]^{-1}[T_s]$, which can be explicitly derived in terms of α as shown in equation 3

$$\mu = \frac{\text{surface}}{\text{volume}} = \frac{w^{*T}[T_s]w}{w^{*T}[T_v]w} \rightarrow 0 \leq \mu \leq \mu_{\max} \quad -2)$$

$$\mu_{\max} = \frac{m_{\max}}{m_v} (\sin^2 \alpha + \frac{1}{F} \cos^2 \alpha) \quad -3)$$

Figure 2 shows a sample image for the Malawi data sets. Here we map μ_{\max} (i.e. the surface-to-volume ratio) in a color-coded form as shown between -15dB and +15dB. Hence blue areas are where surface scattering dominates and yellow/red where volume dominates. We see most forested areas are yellow corresponding to a μ_{\max} in the range 0 to -5dB.

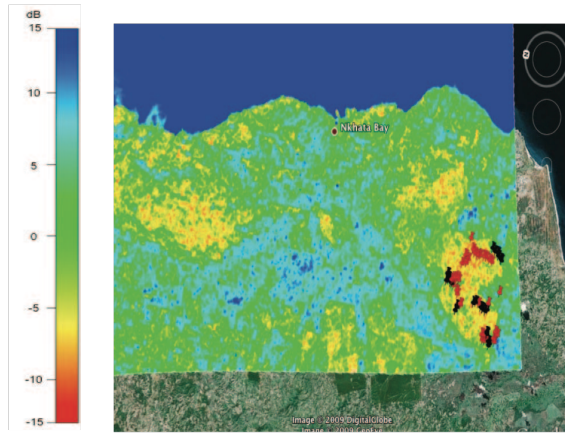


Figure 2: Image of μ_{\max} in dB for Lake Malawi data set showing location of field data points

Also shown in red/black are the locations of our field data points for different woodland types (red= Miombo and black = Evergreen [1]). This intermediate product can now be scaled to biomass as follows. When μ is large, the idea is that biomass is low (due to gaps in the forest or low level vegetation) and when μ is small, biomass is high due to increased volume scattering. This idea has been developed quantitatively using the two-layer approach of surface and

volume scattering in [9]. It leads to a class of relationships between biomass and μ as shown in equation 4

$$B = \frac{0.6}{\beta} \log\left(1 + \frac{R}{\mu_{\max}}\right) \quad R = \frac{\sigma_o^{surf}(\theta)}{\sigma_o^{veg}} \quad -4)$$

The problem is here we have two unknowns, β (a generalized extinction coefficient) and R, being the limiting ratio of scattering from bare surface to closed canopy dense forest. Fortunately estimates of these two for L-band data have been obtained for Scandinavian forest test sites and published in the literature [9]. Note that we can also use regions of high and low μ to obtain an estimate of R directly from the data itself. Using typical values of R=0.5 and $\beta = 0.005$ we can then use μ_{\max} data of figure 2 to obtain a biomass map of Malawi as shown in figure 3.

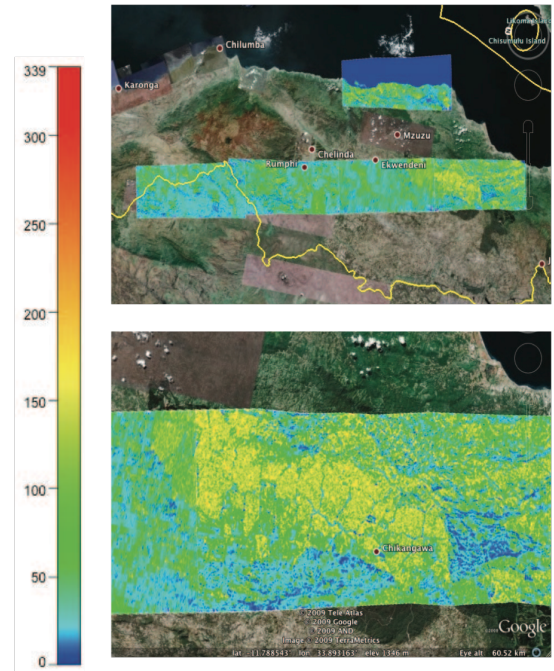


Figure 3 : Polarimetric Radar Biomass Maps (in t/ha) for whole Malawi scene (upper) and for main forested region (lower)

Note that this estimate does not require multi-temporal data as required in [9] and so enables better tracking of temporal changes in biomass. It also does not require external forest/nonforest masks, as the quadpol data provides good discrimination in entropy between forest and non-forest regions.

Such biomass maps can then be used for validation by comparison with plot-level ground estimates, as shown for

example in figure 4. Here we show a comparison (with estimated error bars) of the mean biomass level for 8 important forest environments across the two forest reserves in our study (see [1] for details).

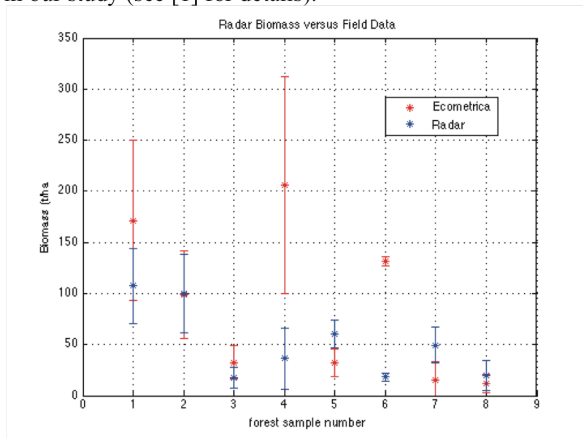


Figure 4 : Comparison of Radar derived Biomass (blue) vs. in-situ data (red) for Mkuwazi/Thazima Forest Reserves [1]

- 1 = Mkuwazi Evergreen forest
- 2 = Mkuwazi Miombo woodland
- 3 = Mkuwazi Customary Land
- 4 = Thazima Evergreen
- 5 = Thazima Miombo Woodland
- 6 = Thazima Riverine Forest
- 7 = Thazima Savannah
- 8 = Thazima Customary Land

We see good agreement for class 2 for example but some differences between the methods for other classes, especially for classes 4 and 6, where the radar predicts much lower biomass than the field data. It is important for application development that the reason for such discrepancies be found and related to either break down of the radar model or to the difficulties in performing field sampling in such heterogeneous forest environments. Such studies are on-going in this program, but it is clear that polarimetric radar data plays an important role in helping resolve these issues and hence build confidence in achieving the right balance between radar technology and field sampling for large area biomass mapping, with obvious implications for the more heavily forested areas outside of the Malawi context.

4. CONCLUSIONS

The PLR mode of ALOS-PALSAR is experimental and not designed to provide global coverage or systematic multi-temporal acquisitions. However, the issue of whether to use quad or dual polarized modes for future radar satellites is of great topical interest and in this study we used the PLR mode of ALOS to investigate this issue for a well calibrated and important African test site. Our test sites in Malawi

provide useful confirmation of the utility of quadpolarized L-band data for improved land-use classification and biomass estimation. Our conclusions comprise three stages. In the first, confirmation of the potential of polarimetry for improved land-use classification. In the second, support for the idea of single-pass biomass estimation using L-band quad-polarimetry and finally confirmation of the limited potential for POLInSAR height retrieval using 46-day repeat data due to the high levels of temporal decorrelation.

5. ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of JAXA, under their international PI program, for providing the data. Thanks also to Ecometrica of Edinburgh, Scotland for their support in providing in-situ data for validation.

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