Monitoring Tropical Forest Degradation and Deforestation in Borneo, Southeast Asia

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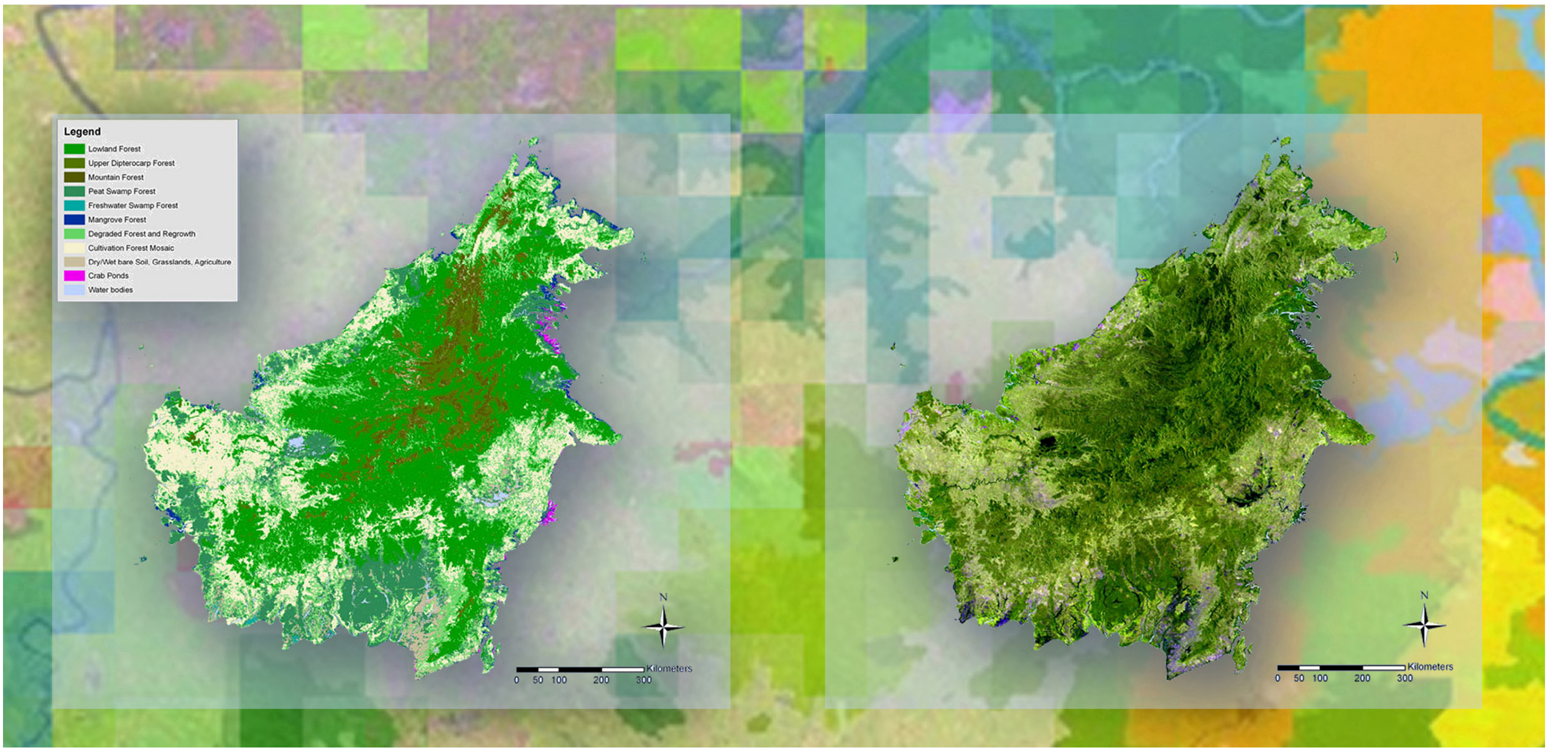

RIGOROSUM

Das Rigorosum fand am Freitag, den 03. April 2009 um 15:00 Uhr, im Biozentrum der Ludwig-Maximilian-Universität München statt.

Die Prüfungskommission setzte sich aus folgenden Gutachtern zusammen:

Herr Prof. Siegert	(GeoBio Center)	(Vorsitz)
Herr Prof. Diehl	(Ökologie)	
Herr Prof. Gemperlein	(em., Zoologie)	
Herr Prof. Uhl	(BIZ)	(Protokoll)

ABSTRACT

Though the forests of the world are vital for all humans, their area is decreasing. While boreal forests even grow in size, tropical forests are severely threatened by deforestation. The elevated deforestation rates of the tropics have severe impact on the global climate as approximately 20% of the total human-induced greenhouse gas emissions stem from deforestation processes. Furthermore, the humid tropics are among the most species-rich ecosystems of the world and the proceeding deforestation severely threatens their high biodiversity. To observe and analyze tropical deforestation satellite based monitoring is mandatory and the only possibility due to the vast and often inaccessible study areas. In comparison to radar systems, optical sensors provide more detailed information to distinguish different types of vegetation. However, the principal limitation of optical imaging systems is that they cannot penetrate clouds, which are quite frequent in the humid tropics. Multitemporal compositing can be used to derive cloud-free mosaics but depending on the revisit time of the satellite not all sensors can be used for the purpose of monitoring larger areas in the humid tropics. Possible solution is the use of low or medium resolution systems, which have shorter orbit repeat cycles, thus acquiring imageries at a higher frequency. This PhD thesis deals with the applicability of different techniques to monitor the fast deforestation activities in the humid tropics, as well as a detailed analysis of the deforestation processes and their underlying causes. Main focus was put on the tropical forest ecosystems of Borneo, as Southeast Asia shows the highest deforestation rate of all humid tropics and Borneo, still having the largest remaining area of tropical rainforest in that realm, is representative for many processes leading to deforestation in the region.

In a first step the ability of multispectral change detection analysis was tested to quickly detect land cover changes. This study was carried out both in Central Africa and Borneo to investigate various satellite sensor systems such as Landsat, MODIS, MERIS and SPOT VEGETATION in different tropical regions with their prevailing land use patterns. Under ideal conditions such as no atmospheric disturbances the use of multispectral change detection analysis based on optical data is a promising approach to quickly monitor changes in the forest cover. Most important advantage of this technique is the omission of the classification step, thus providing much faster results. However, applying this system in the humid tropics implicated pivotal limitations. The frequent cloud coverage of the humid tropics prevents from monitoring larger areas as optical satellite data interfere with clouds or haze. Thus, cloud-free composites had to be used. Depending on the algorithm, these composites either show artifacts due to the selection of single pixels and thus cannot be used as input for multispectral change detection, or when applying compositing methods, which reduce the amount of artifacts considerably, the advantage of easily detecting changes are lost due to the higher number of single images and the longer period of data acquisition. Thus, owing to these limitations inherent to the humid tropics the concept of quickly detecting changes by applying multispectral change detection analysis in these areas is not feasible in an operational way – irrespectively in Central Africa or Borneo.

Therefore another approach was analyzed. The next studies showed that a post classification methodology based on cloud-free composites derived from an average composition method can be successfully used for land cover mapping in the humid tropics. This approach provides more detailed information about the land cover than the multispectral change detection analysis. Based on medium resolution MODIS surface reflectance data it was possible to classify the land cover of Borneo, discriminating 11 land cover classes, also including 6 different forest types. In 2002 about 57% of the land was covered with forests and between 2002 and 2005 the annual deforestation rate was 1.7%. The forest areas of the island are dominated by 74% of dipterocarp and more than 23% of the carbon rich peat swamp forests - the latter one showing an increased deforestation rate of 2.2%. The analysis of the spatial pattern of deforestation showed, that deforestation usually does not start in the middle of closed forests. Almost 98% of all deforestation occurred within a range of 5 km to the forest edges. Causes of deforestation are manifold, such as conversion to farmland, legal and illegal logging for timber supply and fire, which is often linked to deforestation because it is the cheapest means in land preparation. In fact 98% of all forest fires were detected in the same 5 km buffer zone, showing that fire is the major driver of forest degradation and deforestation. Fires inside closed forests, which were observed by active fire detecting sensors, indicate the existence of human access such as small-scale infrastructure, which cannot be detected using medium or low resolution surface reflectance data alone. 94% of all fires detected in a peat swamp forest in Central Kalimantan were located closer than 1 km to existing small-scale logging infrastructures. As fire is one of the major causes of deforestation, the spatial and temporal pattern of all fires detected between 1997 and 2006 was investigated. No single sensor is completely covering the investigation period, therefore several sensors for active fire detection such as AVHRR, ATSR and MODIS had to be combined to analyze the fires retrospectively. About 16.2 Mha, corresponding to 21% of the land surface of Borneo, have been affected by fire at least once and 6% more than one time. During El Niño years with their prolonged droughts the impact of the forest fires increased considerably, affecting about 1 Mha, which is more than 3 times larger than in non-El Niño years. Although ecosystem and land use are similar, there is a pronounced difference in fire occurrence across the different countries of Borneo. In normal years the percentage of the fire affected area in Kalimantan was almost 5 times larger than in the non-Indonesian part of Borneo. During El Niño driven droughts this percentage almost doubled in Indonesia, while the El Niño phenomenon seemed to have no influence on fire occurrence in Brunei and the Malaysian part of the island. This suggests, that El Niño related droughts are not the only cause of increased fire occurrence and do not necessarily lead to a higher number of fires.

The results of this PhD thesis both provide crucial information concerning monitoring techniques based on optical satellite data in the humid tropics and improve the understanding of the drivers of deforestation – information decisive to better protect the remaining rainforests and an essential contribution regarding global climate change.

ACKNOWLEDGEMENTS

This study was conducted at the GeoBio Center at the Ludwig-Maximilians-University (LMU) of Munich, Germany as well as the Remote Sensing Solutions (RSS) GmbH, Munich, Germany and the Department of International Studies, Graduate School of Frontier Sciences, at the University of Tokyo, Japan. I am very grateful to these institutions for providing me the research facilities and the time to work on this study.

In Munich I would first like to thank Prof. Dr. Florian Siegert, who offered me the opportunity to do my PhD thesis on deforestation and their causes mainly focusing on the tropical forests of Southeast Asia. He advised this thesis and mentored me throughout my time at the LMU and RSS GmbH. His broad knowledge and deep insights have been an important resource to my accomplishment. Besides the fact that I enjoyed working on such interesting and complex topic as the analysis of different satellite sensor systems and monitoring techniques of the deforestation processes in that region, this work also had fundamental impact on my whole life as I met my later wife Atsuko during my field work studies on Borneo – some fortunate coincidence for which I am absolutely grateful. Beyond, I would like to thank all colleagues without whom the whole work would not have been half productive and fun as it was. Especially I would like to express my gratitude to Dr. Dr. Shengli Huang, who is now working at the NASA Ames Research Center in the United States, and to Dipl.-Geogr. MSc (GIS) Olaf Kranz, now working at the German Aerospace Center (DLR) in Oberpfaffenhofen, Germany, for their crucial help in many aspects concerning technical questions related to GIS and Remote Sensing. I also would like to thank Dr. Jukka Miettinen who worked as visiting researcher at the RSS GmbH. Since last year November he is coordinating the environmental and natural resource studies in CRISP (Centre for Remote Imaging, Sensing and Processing), National University of Singapore. His short but intensive cooperation resulted in two articles, one of which is part of this study. Furthermore, I would like to thank the many colleagues and former colleagues at the RSS GmbH as well as the LMU Munich such as Claudia Roeben, Tanja Deml, Ruth Leska, Jasmin Horn, Annette Bechteler, Julia Jaenicke, Maria Licht, Dr. Claudius Mott (who is now Technical Marketing Manager at the Earth Observation and Mapping (EOMAP) GmbH & Co.KG), Florian Moder, Uwe Ballhorn, Christian Hamberger, Peter Mamberer for being my colleagues and also for enjoying some private time together.

During my PhD thesis in Munich, I was involved in several very interesting projects, such as STRAPEAT, RESTORPEAT, GEOLAND and AsiaLink where I was able to meet with other scientists in the scope of cooperation, course training, ground survey and academic conference. In this context I would like to express my thanks to the following people: Angelika Heil at the Max Planck Institute for Meteorology in Hamburg, Germany (The Atmosphere in the Earth System); Dr Susan Page, Department of Geography at the University of Leicester, United Kingdom; Prof. Dr. Jack Rieley, School of Geography, The University of Nottingham, United Kingdom; Prof. Dr. Etienne Bartholomé at the Joint Research Centre of the European Commission (Global Environmental Monitoring Unit, Institute for Environment and Sustainability (IES)) in Italy; Dr. Suwido Limin at the University of Palangka Raya, Centre for International Co-operation in Sustainable Management of Tropical Peat, Indonesia; Prof. Olavi Luukkanen and Dr. Eshetu Yirdaw at the Viikki Tropical Resources Institute (VITRI), Department of Forest Ecology, Faculty of Agriculture and Forestry, University of Helsinki, Finland. Besides these people I would also like to thank all (post) PhD students, who were also involved in these projects, and whom I met during my project work.

Before finishing the compiling of my PhD thesis in May 2007, Prof. Dr. Mikiyasu Nakayama from the University of Tokyo (Department of International Studies, Graduate School of Frontier Sciences) offered me the possibility to join his research group funded by a JSPS (Japan Society for the Promotion of Science) fellowship. I am totally thankful for his help and support in Japan as he always encouraged me to finish this PhD thesis and therefore he even provided me the possibility to work for my PhD thesis besides my other project work under his supervision.

Last but definitely not least, many thanks to my family, relatives and friends. As I mentioned above it was the research for this PhD thesis which made me meet my wife. I would like to thank Atsuko for her genuine love, her unselfish support and for encouraging me in finishing the compiling work of this PhD. Many thanks also to my mother and father for their continuous unconditional support and encouragement during this project. Further I would also like to thank all my friends for their help and encouraging words.

I dedicate this thesis to my wife, our whole family and friends for their love and support. May all the nice people who are acknowledged here be happy every day!

STATEMENT

This PhD thesis has been supervised by Prof. Dr. Florian Siegert according to §6 promotion regulations. I herewith declare that this dissertation has not been submitted (as a whole or in parts) to any other commission and that I did not try to pass any other doctoral examination without success.

DECLARATION OF HONOR

I herewith assure that this dissertation was written exclusively by myself without the help of any illegal additives.

Tokyo, January 24, 2009 A. Langner

Date Andreas Langner

CONTRIBUTION OF CO-AUTHORS

Chapter I–IV form the body of my PhD thesis and I was the responsible author in all these chapters. In the following paragraphs I describe the contribution of the co-authors per single chapter:

Chapter I:
Prof. Dr. Etienne Bartholomé participated in the planning phase and introduced the methodology applied for the multispectral change detection analysis. Prof. Dr. Florian Siegert helped me to plan the study.

Chapter II:
Dr. Jukka Miettinen was responsible for producing the 2005 MODIS cloud-free composite of Borneo and to derive some part of the land cover change statistics. He further helped me to write the manuscript. Prof. Dr. Florian Siegert participated in planning the study and also revised the manuscript on several occasions before submission.

Chapter III:
Prof. Dr. Florian Siegert helped me to revise the manuscript.

Chapter IV:
Prof. Dr. Florian Siegert helped me to plan the study and revised the manuscript on several occasions before submission.

Date	
Tokyo, January 24, 2009	
Date	Andreas Langner
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Date	Dr. Jukka Miettinen
Ispra, January 24, 2009	
Date	Prof. Dr. Etienne Bartholomé
Munich, January 24, 2009	
Date	Prof. Dr. Florian Siegert

LIST OF ORIGINAL ARTICLES

First Author:

Chapter I:

Andreas Langner, Etienne Bartholomé, Florian Siegert, Monitoring Deforestation in the Humid Tropics using a Multispectral Change Analysis Technique, *Manuscript*

Chapter II:

Andreas Langner, Jukka Miettinen, Florian Siegert, Land cover change 2002 – 2005 in Borneo and the role of fire derived from MODIS imagery, *Global Change Biology*, 13, 11, 2329-2340, 2007

Chapter III:

Andreas Langner, Florian Siegert, Using low and medium resolution MODIS data to screen for forest degradation in Borneo, *Manuscript*

Chapter IV:

Andreas Langner, Florian Siegert, Spatiotemporal fire occurrence in Borneo over a period of 10 years, *Global Change Biology*, 15, 48–62, doi: 10.1111/j.1365-2486.2008.01828.x, 2009

Parts of the work of this PhD thesis were furthermore published here:

Andreas Langner, Florian Siegert, The role of fire on land cover changes in Borneo, *Proceedings of 4th International Wildland Fire Conference, Wildfire2007*, Seville Spain, May 13-17, 2007

Susan Page, Agata Hoscilo, Andreas Langner, Kevin Tansey, Florian Siegert, Suwido Limin, Jack Rieley, T*ropical Peatland Fires in Southeast Asia*, in M.A. Cochrane, ed. *Tropical Fire Ecology: Climate Change, Land Use and Ecosystem Dynamics*. Springer-Praxis, Heidelberg, Germany, in press

PROJEKT WORK

GEOLAND:

The GEOLAND project was funded by the EU 6th Framework Program. The GEOLAND project was carried out in the context of GMES, a joint initiative of the EC and ESA, which aimed to build up a European capacity for Global Monitoring of Environment and Security. The objective of the Global Land Cover & Forest Change Observatory was to serve two priority areas identified in the GMES/EC action plan (i.e. Africa and Boreal Eurasia). Products were a set of indicators of vegetation growth and vigour, and indices of disturbances possibly leading to land degradation as well as indices of land cover conversion at continental scale. These indicators were then integrated into a higher level processing loop to identify significant ecological processes and human activities. The users of this project were mainly public services of the EC and EU member states; in particular those involved in the environmental dimension of foreign relationships, and UN environmental agencies with a mandate in the field of environmental management and monitoring. Our contribution to the GEOLAND project was the analysis of methodologies for products related to change detection on spectral signals.

STRAPEAT:

The STRAPEAT project was funded by the EU 5th Framework Program. The project aimed to promote wise use of tropical peat lands by integrating biophysical, hydrological and socio-economic data within strategies for sustainable management. It specifically focused on the implementation of strategies once they have been formulated for practical use in the critical peat land areas in Borneo. Local research capability should be strengthened enabling peat land managers to better understand and address the different, interrelated processes operating in tropical peat lands. The project contributed positively to poverty alleviation, protection of the environment, improvement of the quality of life and diminishing health risks.

RESTORPEAT:

The RESTORPEAT project was funded by the EU 6th Framework Program and is the successor of the STRAPEAT project. The project aimed at research and development of new methods on the sustainable restoration of disturbed tropical peat lands and peat swamp forest ecosystems. The implementation involved a range of measures including blocking of channels and drains, restoration of hydrology and ecological functions, rehabilitation of peat swamp forest and its biodiversity, identification of alternative funding mechanisms to promote sustainable livelihoods and formulation of guidelines for sustainable agriculture and forestry. These were linked to a better understanding of the socio-economic base of local people and their communities by determining the nature and degree of their dependence on renewable natural resources and how this has been affected by major land development projects and fire. The problems of fire and inappropriate land use planning were addressed by developing a model fire hazard warning and control system based upon remote sensing and operated by local communities through promotion of fire awareness, prevention and suppression. Stakeholder platforms and skills transfer to the developing countries were focal activities to provide ownership of the project outputs to the bottom levels and, through partnership with local governments, empowered local people to become guardians of their own environment and its resources.

TABLE OF CONTENTS

ABBREVIATIONS

ALOS	Advanced Land Observation Satellite
ASTER	Advanced Space borne Thermal Emission and Reflection Radiometer
ATSR	Along Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
BRDF	Bidirectional Reflectance Distribution Function
CO_2	Carbon dioxide
CSP	Core Service bio-geophysical Parameter
EC	European Commission
Envisat	Environmental Satellite
EOS	Earth Observing System
ERS	European Remote Sensing Satellite
ESA	European Space Agency
ESRIN	European Space Research Institute
ETM+	Enhanced Thematic Mapper Plus
EU	European Union
FAO	Food and Agriculture Organization
FRA	Global Forest Resources Assessment
GIS	Geographic Information System
GLC2000	Global Land Cover of the year 2000
GLOBCOVER	Global Land Cover Map
GMES	Global Monitoring for Environment and Security
HRVIR	High-Resolution Visible Infrared
IFFM	Integrated Forest Fire Management
IGBP-DIS	International Geosphere-Biosphere Programme Data and Information System
IPCC	Intergovernmental Panel on Climate Change
IR	Infrared
IRS	Indian Remote Sensing Satellite
JERS	Japanese Earth Resources Satellite
LIDAR	Light Detection and Ranging
MERIS	Medium Resolution Imaging Spectrometer
MODIS	Moderate Resolution Imaging Spectroradiometer
MRP	Mega Rice Project
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index

NGO	Non Governmental Organization
NOAA	National Oceanic and Atmospheric Administration
RADAR	Radio Detection and Ranging
RADARSAT	Radar Satellite
REDD	Reducing Emissions from Deforestation and Degradation
RIL	Reduced Impact Logging
RS	Remote Sensing
SPOT	Satellite Pour l’Observation de la Terre
TM	Thematic Mapper
TREES	TRopical Ecosystem Environment Observations by Satellites
TRMM	Tropical Rainfall Measuring Mission
UN	United Nations
US	United States (of America)
VCC	Vegetation Cover Conversion

1 STATUS OF THE FORESTS

As the world's forests are in a direct or indirect way interrelated to the livelihood of all human beings, even to all life on earth, it is crucial to preserve these fundamental ecosystems.

According to the FRA 2005 of the FAO (FAO, 2006) the world's forests covered approximately 3,952 Mha in 2005 which corresponds to about 30% of the total land area. The majority of 1,833 Mha is found in the tropics with 47% of the total forest area. About 33% are situated in the boreal zone, 11% in temperate areas and 9% in the subtropics (FAO, 2000). The total area of all pristine forests of the world is decreasing with an estimated deforestation rate of 14.6 Mha per year during the period 1990–2000, mainly by conversion to agricultural land. At the same time, forest planting as well as natural expansion of forests has reduced the net loss of forest area to about 9.4 Mha per year – an area still larger than Venezuela (FAO, 2000).

Generally forests are defined as areas which are covered with trees taller than 5 meters height and at least 10% canopy cover. This definition includes both pristine forests and anthropogenic forest plantations. In the subtropical and tropical zones, a 10-40% canopy cover defines open canopy forest, and 40-100% canopy cover is classified as closed canopy forest (FAO, 2000; Matthews *et al.,* 2000). Forests are threatened by forest degradation and deforestation, whereby forest degradation is often a precursor for deforestation (Asner *et al*., 2005). While deforestation describes the total removal of forest cover to less than 10% (Mayaux *et al.*, 2005), forest degradation is characterized by a significant reduction in either tree density or in the proportion of forest cover from closed forests to open or fragmented forests (Karjalainen *et al.*, 2003; Achard *et al.*, 2004; DeFries *et al*., 2007).

1.1 Deforestation in the Tropics

Pressure on forests is not homogenous throughout the world. While boreal forests even show a slight increase in their net pristine forest area, the situation for the pan-tropical forests is quite different. Tropical deforestation increased tremendously in the past two decades (Achard *et al*., 2002; Fuller, 2006). Due to the slight increase of non-tropical forests, which mitigates the net change area of the world's forests, tropical forests show an even larger area of forest loss in comparison to the total of the world's forests. Based on statistics from the FRA 2000 main report, the tropics suffered under a net loss of natural forests of 12.3 Mha per year during 1990 – 2000 (FAO, 2000). The pan-tropical forests consist of three ecological zones: the tropical dry forests with more than six dry months, the tropical moist deciduous forests with three to six dry months and the tropical rain forests with no or only a short dry season (FAO, 2000). Concerning the tropical humid or rain forests of the earth the TREES study showed that about 5.8 ± 1.4 Mha of forest were lost each year between 1990 and 1997. Additionally an area of 2.3 ± 0.7 Mha of humid tropical forests was degraded annually (Achard *et al.*, 2002; Mayaux *et al.*, 2005). Forest degradation by logging and fire is often a precursor to complete deforestation (Nepstad *et al*. 1999; Achard *et al*., 2004).

1.1.1 Southeast Asia

Examining the annual tropical deforestation rates per continent showed, that the humid tropical forests of Southeast Asia are most severely threatened. While Latin America and Africa have an annual deforestation rate of 0.4 to 0.5% respectively, the net loss of forest area for Southeast Asia increased from annually 0.83% between 1990 -2000 to annually 0.98% for the period 2000 – 2005 (FAO, 2006). Other independent studies show similar values (Achard *et al.*, 2002; Mayaux *et al.*, 2005). According to FAO (2006) only 33.4% of the land area of South and Southeast Asia are covered by forest nowadays. Indonesia and Malaysia, the largest countries of Insular Southeast Asia, experience one of the highest deforestation rates in the whole world with annual change rates of 1.3% (FAO, 2000; Marcoux, 2000; Achard *et al.*, 2002; FWI & GFW, 2002; Holmes, 2002). From the originally 162 Mha of forest in Indonesia in 1950, only 98 Mha are left 50 years later (FWI & GFW, 2002). And the deforestation rate is increasing. Expressed in hectares per year, Indonesia showed an annual loss of forested area of 1 Mha in the 1980s, 1.7 Mha in the first part of the 1990s and about 2 Mha annually since 1996 (FWI & GFW, 2002; Holmes, 2002).

1.1.1.1 Borneo

In comparison to all other Indo-Malaysian forests, Borneo still has one of the largest tropical rainforests remaining in Southeast Asia, with a large variety of unique ecosystems ranging from mangrove forests along the coast, large areas of peat swamp forests in the alluvial flats and freshwater non-peaty swamps, heath forests, lowland dipterocarp forests and various mountain forests (MacKinnon *et al.*, 1996). However, these forests are under severe pressure by the vast deforestation processes, which are typical for the region (Achard *et al.*, 2002; Curran & Trigg, 2006; Fuller, 2006; Trigg *et* *al*., 2006; Chambers *et al*., 2007). The lowland rainforests are expected to become extinct within the next decade (Rautner *et al.*, 2005). Major drivers of deforestation in insular Southeast Asia are linked to human activities, such as shifting cultivation, governmental resettlement activities (transmigrasi), logging of natural forests and establishment of plantations and industrial timber estates (Christanty, 1986; Sunderlin & Resosudarmo, 1996; Barber & Schweithelm 2000; Boehm & Siegert, 2001; McMorrow & Talip, 2001; FWI & GFW, 2002; Schroeder-Wildberg &Carius, 2003; Goldammer, 2007). For all of these activities fire is used for land clearing. In comparison to mechanical or manual methods, burning is by far the cheapest means for land preparation (ASEAN, 2003; Suyanto *et al*., 2004; Dennis *et al*., 2005).

2 OBJECTIVE AND STRUCTURE OF THE STUDY

In the context of climate change and the conservation of biodiversity the protection of forests, especially of the large tropical rain forests is regarded to be very important (Brown *et al*., 2002; Houghton, 2002; Niles *et al*., 2002; IPCC, 2007). The forest ecosystems of Borneo are severely threatened by different human induced activities and scientists expect that most of the lowland forests of the island will disappear shortly after 2010 (Holmes, 2002). Land cover change detection and monitoring of deforestation derive decisive information, which is crucial to be able to take measures within the framework of the Kyoto protocol and its successors. Therefore, the purpose of this study was both to find appropriate techniques to monitor land cover changes in the humid tropics as well as to analyze the extent of forest degradation and deforestation on Borneo and its possible underlying causes. For this sake the study was divided into four chapters I – IV.

In chapter I multispectral change detection was tested for its usability in fast monitoring land cover changes in the humid tropics. Though the study was carried out both in tropical Africa and Borneo, the results can also be applied to any other humid tropical forest as the atmospheric conditions and cloud cover are comparable. In chapter II special emphasis was put on the question how to reduce the impact of atmospheric disturbances such as haze or clouds for land cover monitoring. This chapter concentrated on the analysis of the actual status and land cover changes of the different ecosystems on Borneo to elaborate patterns of deforestation and their major drivers using a post classification approach. Chapter III dealt with the combined application of medium and low resolution satellite data to screen for small-scale forest disturbances which are normally only detectable using high resolution data. Chapter IV analysed the spatial and temporal impact of fire as one of the most important drivers of deforestation in Borneo. The annual fire events in the humid tropics release tremendous amounts of carbon into the atmosphere and hence have an enormous impact on the global climate – therefore special emphasis was put on the analysis of these fires. For that sake, active fire detections, so-called hotspots, were used to analyze the role of fire in the loss of forest and forest degradation. Specific questions to be investigated in this phase were: 1) which are the major land cover types affected; 2) what are the effects of El Niño; 3) is there a correlation between land use and fire and 4) how well are National Parks protected from fire. Finally the major drivers of fire were analyzed in order to better understand the processes leading to fire in tropical rainforest ecosystems and to foster improved fire management in the future. The purpose of this chapter was to deepen the understanding of the processes responsible for the ongoing forest degradation and deforestation in that area.

Altogether this study is expected to serve as sound foundation for further studies in that region to provide crucial information about the complicated processes of the proceeding deforestation on Borneo. Furthermore, the research about the application of monitoring techniques as well as the precise results of the status of Borneo’s rainforests could make an essential contribution regarding the current topic of global climate change.

3 STUDY AREA

3.1 Geography and Climate

After Greenland and New Guinea, Borneo is the third largest island in the world, covering more than 74.6 Mha. Almost three quarters of the island is Indonesian territory, known as Kalimantan, which is divided into the four administrative provinces of East Kalimantan (Kalimantan Timor), South Kalimantan (Kalimantan Selatan), Central Kalimantan (Kalimantan Tengah) and West Kalimantan (Kalimantan Barat). The rest of Borneo is shared by the two largest states of Malaysia (Sarawak and Sabah) and the independent sultanate of Brunei Darussalam in the northern part of the island (MacKinnon *et al.*, 1996; Rautner *et al.*, 2005).

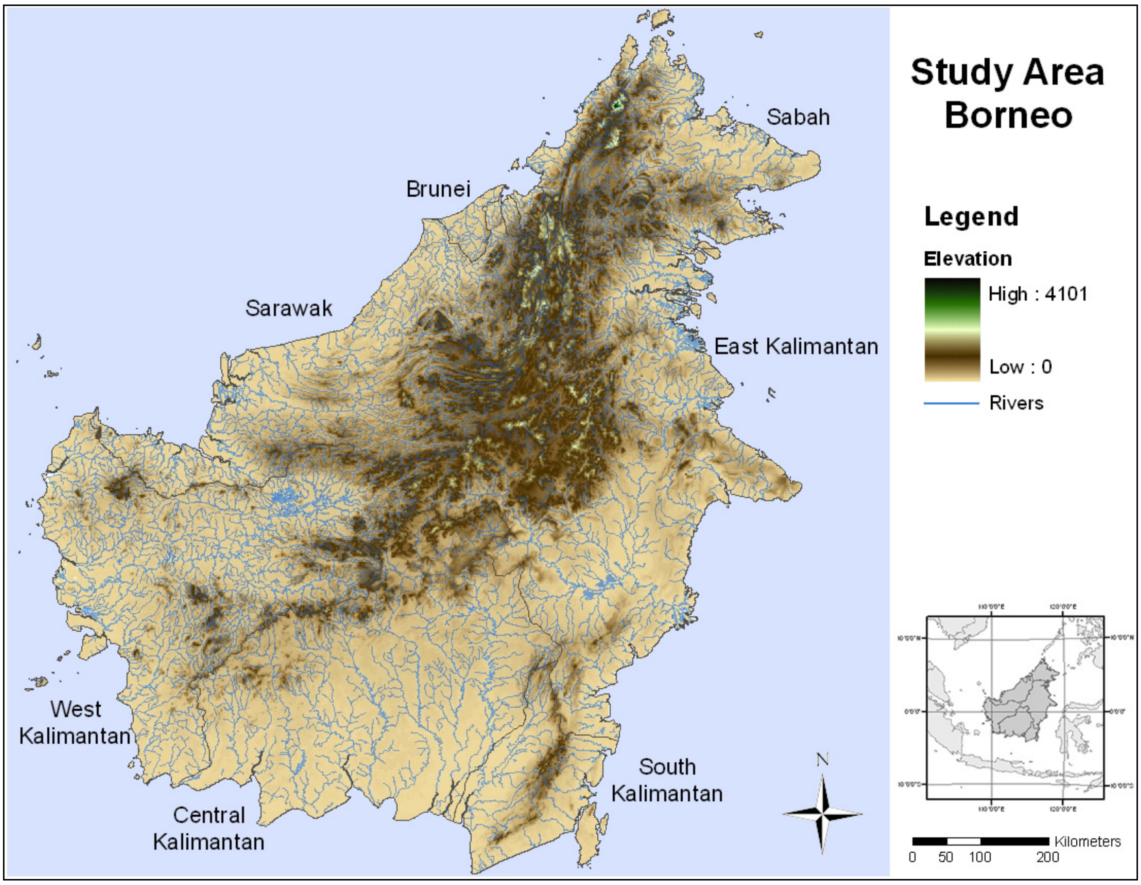

Figure 1: Island of Borneo with an elevation model as well as superimposed rivers and province names.

Borneo is dominated by shallow areas, especially in the south vast areas along the coast and river plains are flat. More than half of the island does not exceed 150 m in altitude.

Several great rivers run from the interior of the island to its coasts (Figure 1). Mountain chains cross the centre of Borneo from north to south. The highest peak is Mount Kinabalu in Sabah, reaching 4,101 m while almost all other mountains do not exceed 2,000 m. Several large rivers constitute the main transport routes. The longest are the Kapuas (1,143km) flowing to the west coast, the Barito (900 km) flowing south and the Mahakam (775 km) whose estuary is on the east coast (Rautner *et al.*, 2005; MacKinnon *et al.*, 1996).

Due to its geographical position at the equator, Borneo experiences a moist and tropical climate, which is characterized by frequent rainfall and high temperatures between 25^0C and 35^0C throughout the year, responsible for the luxuriant vegetation of this region. The pattern of rainfall is mainly affected by the “dry” southeast monsoon from May to October and the “wet” northwest monsoon from November to April, resulting West and Central Borneo to be the wettest areas while parts of East Borneo are substantial drier (MacKinnon *et al.*, 1996; Rautner *et al.*, 2005). Occasionally the normally short annual drier periods are unusually long. Such prolonged droughts happened periodically even in historical times and are related to the El Niño Southern Oscillation and the Indian Ocean Dipole (Field & Shen, 2008). The El Niño is a periodic climatic phenomenon, occurring every 2 to 7 years, which is caused by interaction between the unusually warm surface water in the eastern Pacific Ocean off the coast of South America and the atmosphere. While the El Niño phenomenon is a global and natural part of the Earth's climate, whether its intensity or frequency may change as a result of global warming is an important concern. It is assumed that the greenhouse effect might aggravate the impacts of El Niño events (Vellinga & van Verseveld, 2000). The last strongest El Niño events which became notorious due to their impact on the ecosystems of Borneo in combination with severe fire events happened in 1982/83 and 1997/98, but also in 1987, 1991, 1994, 2002 and 2006 the droughts were more severe than normally (Dennis, 1999; Barber & Schweithelm, 2000; Langner & Siegert, 2009).

3.2 Flora

In terms of flora the most species rich forests of the world are found in Borneo and Sumatra with 10,000 to 15,000 flowering plants and at least 3,000 tree species with 267 species of the dipterocarp family (Ashton, 1988; Appanah & Turnbull, 1998; Glover & Jessup, 1999; Rautner *et al.*, 2005). The commercially most important timber trees are ironwood (*Eusideroxylon zwageri*) and dipterocarps such as Meranti (*Shorea spp.*), Merawan (*Hopea spp.*), Kapur (*Dryobalanops spp.*), Keruing (*Dipterocarpus spp.*), Ramin (*Gonystylus bancanus*), and legumes (*Intsia bijuga*; *I. palembanica*; *Pericopsis mooniana* and *Pterocarpus indicus*) (Rhee *et al*., 2004). In comparison to the other Sunda Islands, Borneo experiences the highest levels of endemism with about 34% of all plants (MacKinnon *et al.*, 1996) and the forests of this island include a variety of different forest types (Rautner *et al.*, 2005):

Mangrove forests are found on river deltas and along shallow coastal areas. To deal with the special conditions in this muddy environment, mangroves have particular characteristics such as mechanical adaptations for fixation in loose soil, breathing roots which are known as pneumatophores for gas exchange in the waterlogged and oxygen-poor soils as well as specialized mechanisms to deal with excess salt concentrations. Beside their importance for coastal protection as well as nursery and spawning ground for many coastal and offshore fish species, mangrove forests also provide timber and further forest products for local communities. Peat swamp forests are situated along the flat coastal areas but also occur on the shores and flood zones of rivers and lakes. Peat lands are formed due to the partial decomposition of organic deposits. There are several conditions that have to be met to promote the accumulation of organic matter formation of peat. The area should be a topographically flat water impounded landscape with high precipitation and humidity and the soil has to be nutrient poor and highly acidic, with a reduced biological activity of decomposers (Rieley & Page, 2005). Thus, peat accumulated up to 20 meters thick (Page *et al*., 2002). Peat swamp forests are called ombrogenous because they receive their water supply only via rainfall, thus having little input of organic materials. Peat swamp forests are much less rich in species compared to the other forest types of Borneo. Another forest type which is well adapted to waterlogged conditions is the freshwater swamp forest. It can be found along the coastal areas and on flood zones of rivers and lakes. Freshwater swamp forests are composed under the influence of fluctuating levels of river flood water and they are referred to as topogenous. Thus, freshwater swamp forests receive a much higher amount of organic nutrients in comparison to peat swamp forests and therefore are more species-rich. Lowland dipterocarp forests can be found further inland from the swampy coastal areas, normally growing on well-drained land. The nomenclature of this forest formation is derived from the dominating tree family of the Dipterocarpaceae. Lowland dipterocarp forests are commercially the most important forest type in Borneo, because of the combination of height and low weights of its trees. The dipterocarp family are well known for their rare and irregular flowering at intervals of 5 to 9 years. Droughts caused by the El Niño are most probably responsible for triggering the mass fruiting events of this tree family (Ashton, 1988; Appanah & Turnbull, 1998; Curran *et al*., 2004). Another tree species to be often found in lowland rainforests is the Borneo ironwood or Belian (*Eusyderoxylon zwageri*). Its timber is very durable and dense and therefore it often used for building bridges and houses. Borneo exhibits the largest heath forests of whole Southeast Asia. Heath forests or Kerangas belong to the lowland rainforest formations and predominantly grow along the coastal areas as well as further inland on sandstone plateaus. As their soils, which are often described as white sand soils, are poor in bases and extremely acidic, heath forests show own structural and vegetation characteristics with a reduced species richness. So trees are generally much smaller in comparison to other lowland rainforest types and heath forests only have a low and uniform single-layered canopy structure. The vegetation types of mountains change according to the altitude because of different climatic conditions. Thus, distinct vegetation zones with particular species and appearance prevail. These vegetation zones are not dictated by elevation alone. Depending on the altitude of the mountain, the vegetation zones show different magnitudes. On lower isolated mountains these zones are narrower, while on higher isolated mountains or in the central part of a mountain range these zones are broader. This is called Massenerhebung effect (MacKinnon *et al.*, 1996). According to Whitmore (1984) the altitude starting from 800 meters is dominated by different dipterocarp species of the genus *Shorea*. Above an altitude of 1,200 meters other tree families such as Fagaceae and Lauraceae and even higher Ericaceae and Myrtaceae are most dominant. In this study, forests situated in the zone between 800 m and 1,200 m are summarized as upper dipterocarp forests and above as mountain forests.

3.3 History of Humans on Borneo

Very first human colonization on Borneo can be dated back about at least 40,000 years ago, when Australoid races crossed dry land ridges connecting the Asian mainland with the Sunda Islands during the interglacial periods of the Pleistocene (MacKinnon *et al.*, 1996). About 28,000 years ago people subsisted by gathering forest food plants and hunting wildlife. At that time they also started to harvest the hill sago palm *Eugeissona utilis*. Later waves of migration of the ancestor's of today's Dayak came from the southern mainland of China and reached Borneo about 4,500 years ago, replacing the Australoid races (Rautner *et al.*, 2005). Besides trading these early Dayak tribes also cultivated rice using systems of shifting cultivation which were well adapted to the tropical forest environment. Typical for these indigenous farming systems is the fact that they are based on community rules and consensus. Over the whole island of Borneo several hundred of different ethnic groups are summarized under the term Dayak, each of them with distinct culture, social organization and language. Beside the Dayak groups there are also the Penan, which are comparable few in numbers. While all Dayak groups settled down and live on agriculture, the Penan people still have their hunter-gatherer existence. In the 3rd and 4th centuries Chinese Buddhist pilgrims on their way to India most probably established first coastal settlements on Borneo. A system of trade relations inaugurated between them and the Dayak in the interior of the island. Trading posts at the mouths of each tributary stream were established to enable exchange with seagoing traders from China, India and Arabia. Starting from the 14th century the religion of the Islam entered Borneo via these ports, becoming dominant in the 16th century. At the same time regular trade between Portugal and Brunei developed. The following centuries were dominated mainly by European colonialism till the second half of the 20th century. Right after colonialism the new governments of Indonesia and Malaysia established land rights for the indigenous people of Borneo which got undermined shortly after by additional laws making the local people powerless against the deterioration of their livelihood. There have been increasing protests of Dayak and Penan communities against the deforestation activities of the governments giving large logging concessions to international companies. However, their protests have been ignored to a large extent till nowadays (Rautner *et al.*, 2005).

Since colonialism the population of Borneo increased steadily. In 1980 the population reached 9 million people. Nowadays, there are about 17 million people living on Borneo, which corresponds to a population density of 22 people per km^2 (MacKinnon *et al.*, 1996; Rautner *et al.*, 2005). Even though the human population on Borneo is still small in comparison to other Southeast Asian islands, anthropologic activities had dramatic and far reaching effects on the ecosystems of Borneo. In the last 30 years a lot of development has taken place to exploit the island’s rich tropical forests and other natural resources.

3.3.1 Human Impact on Forest

Before the spread of human influence in the post-Pleistocene about 8,000 years ago, most of Borneo was covered by forest (Billington *et al.*, 1996). Mainly due to low soil fertility the population densities of the first humans on Borneo stayed very low with almost no pressure on the forests and other natural resources (Rautner *et al.*, 2005). Until the middle of the 20th century only few forest dwelling people subsisted from the forests of Kalimantan, gathering food and natural products and practicing shifting cultivation. Shifting cultivation or swiddening was used over thousands of years as original agricultural system which is based on a cycle of forest clearing, cultivation and fallowing (Barber & Schweithelm, 2000). Starting with colonialism the situation began to change. Mainly the agricultural expansion, to meet the local and global demand for rice *Oryza sativa*, rubber *Hevea brasiliensis*, oil palm *Elaeis guineensis* and cocnut *Cocos nucifera*, was responsible for the first large-scale deforestation activities in that region starting from the 19th century. In the second half of the 20th century the increasing demand for timber triggered the proliferation of commercial logging activities (Flint, 1994, Holmes, 2002; Sodhi *et al*., 2004). Major causes for deforestation in Southeast Asia are the expansion of agricultural activities, the conversion of forests into oil palm and pulp wood plantations and the degradation of pristine forests due to logging (Thompson, 1996; Casson, 1999; WRM, 2000; Curran *et al*., 2004; Christanty, 1986; Sunderlin & Resosudarmo, 1996; Barber & Schweithelm, 2000; FWI & GFW, 2002; Schroeder-Wildberg &Carius, 2003; Goldammer, 2007). In their study, Geist and Lambin (2002) detected large-scale timber extraction, agricultural expansion and infrastructure development as the major drivers of tropical deforestation. Illegal logging also accounts to a large extent for the vast deforestation taking place in Borneo. According to a WWF report about 40% of all wood-based products, imported into the European Union from Southeast Asia and China in 2006, probably originate from illegal logging. And almost half of this amount comes from Indonesia alone (Hirschberger, 2008). It includes all forestry practices or activities connected with wood harvesting, processing and trade that do not conform to law. There are two kinds of illegal logging. One is carried out by legitimate operators who violate the terms of their licenses. The other involves outright timber theft, whereby trees are felled by people who have no legal right to cut trees at all (Aden *et al*., 2001; Schroeder-Wildberg & Carius, 2003; Tacconi *et al.*, 2003). Illegal logging occurs all over in Borneo, with a dramatic increase of 44% since the onset of the Asian economic crisis in the mid-1997 and after the fall of the Soeharto regime (Sunderlin, 1999b; Sunderlin *et al.*, 2000; Casson & Obidzinski, 2002; Dudley, 2004; Rautner *et al.*, 2005). Currently, an estimated 73-88% of all timber logged in Indonesia is illegal (Schroeder-Wildberg & Carius, 2003). Transmigration to the Indonesian part of Borneo (transmigrasi) and poorly planned development projects such as the MRP (Sunderlin, 1999a) strongly contributed to the loss of natural forest ecosystems and resulted in increased fire activities (Hoffmann *et al*., 1999; Jepson *et al*., 2001; Page *et al*., 2002; Dennis *et al*., 2005) (Figure 2).

Figure 2: Devastated peat swamp forest on the area of the former MRP in Central Kalimantan (September 2005). Due to extensive drainage by various larger and smaller canals vast areas burnt during the 1997/98 El Niño event.

3.3.2 Fire in the Humid Tropics

Deforestation is often linked to fire and several studies have shown that fire is the most important factor accelerating forest degradation and deforestation in the tropics, in particular in the Amazon and Southeast Asia (Uhl & Kauffman, 1990; Taylor *et al*., 1999; Siegert & Hoffmann, 2000; Siegert *et al*., 2001; Page *et al*., 2002; Cochrane, 2003). Usually in tropical closed canopy forests fires are very seldom due to high air humidity and little amounts of fuel (Uhl & Kauffman, 1990; Siegert *et al*., 2001; Rieley & Page, 2005). However, if a forest has been logged and affected by fire once, the probability for recurrent fires increases dramatically (Cochrane, 2003). Especially damaging are fires in intensely logged forests, where large amounts of potential fuel such as buttresses and treetops are left in the forest after the logging process (Goldammer, 2007). Recurrent fires eventually lead to complete deforestation transforming the forest vegetation into fire prone alang-alang grasslands (Goldammer, 1993; Asner *et al*., 2005). Depending on the situation of forest policies in the particular country, either mechanical techniques or fire or a combination of both is used for land clearing. Especially in Indonesia, fire is used most frequently because it is the cheapest means for clearing the land (Suyanto *et al*., 2004) and policies regulating the use of fire are poorly supported by the government (Sargeant, 2001; FWI & GFW, 2002; Tacconi, 2003). Land speculation, and poorly planned developmental projects have led to devastating fire events in Borneo during the last decade (Page *et al*., 2002; Siegert *et al*., 2001; Goldammer, 2007).

Fire is an essential part of both traditional shifting cultivation as well as all other modern ways of land use – especially in Indonesia. It has to be mentioned that the role of shifting cultivation as dominant cause of forest fires has been overrated by several studies (Brookfield & Byron, 1990; FWI & GFW, 2002), as shifting cultivation farming is sometimes confused with other farming methods, which also use slash and burning activities (Sunderlin, 1997). The original swiddening is regarded sustainable if the time period between the burning events is long enough, i.e. more than 20 or 30 years and the swidden plots are small (Marten, 1986; Brookfield & Byron, 1990). In comparison to mechanical or manual methods, burning is a much cheaper means in land preparation for industrial oil palm and cash crop plantations, as well as for smallholder communities (Suyanto *et al.,* 2004; Dennis *et al*., 2005; ASEAN, 2003). Oil palm plantations have been singled out to be one of the major causes of fire in Indonesia because estate companies use fire after removing all valuable timber and leaving behind only fire-prone debris (Barber & Schweithelm, 2000; Glastra *et al.*, 2002; Holmes, 2002; Casson, 2003). In comparison to clearing land for oil palm plantations with the help of fire, zero burning practices are more expensive (FWI & GFW, 2002) increasing the costs by US$50 to US$150 per ha (Guyon & Simorangkir, 2002). As even government institutions use fire to acquire land for large-scale agricultural, tree-crop or forestry development programmes, local people feel forced to also use fire to claim their rights to their traditional lands – not to lose the land in a race against migrants and big estate companies (Byron & Shepherd, 1998).

Beside its use to clear the land, fires can also be lit due to political reasons, such as expressing a complaint or settling old scores for perceived injustices, especially among poor rural people who have few other means of redress. Main reasons for these grievances are land tenure conflicts between local communities and large plantations. When allocating land for forest concessions or for the establishment of new plantations the companies often violate the customary land rights of the indigenous people (Byron & Shepherd, 1998; Barber & Schweithelm, 2000; Wakker, 2000; FWI & GFW, 2002; Brown & Jacobson, 2005; Suyanto, 2007).

Several devastating fire events have been recorded in Indonesia over the past 10 years which were connected primarily with land speculation, and developmental projects (Siegert *et al*., 2001; Page *et al*., 2002; Goldammer, 2007). According to Fuller and Murphy (2006), fires in Southeast Asia are especially devastating during El Niño seasons, which cause prolonged droughts in the region. In Kalimantan several Mha of forests were lost during two El Niño episodes in 1997-98 and 2002 (Siegert *et al*., 2001; Fuller *et al*., 2003; van der Werf *et al*., 2008).

4 MONITORING DEFORESTATION

Essential protection of the remaining forests of Borneo needs exact and detailed knowledge about the current extent and status of the different ecosystems.

4.1 The Role of Remote Sensing

There are various methods of monitoring forest ecosystems. Monitoring techniques simply based on field studies show severe restrictions as only punctual data can be obtained, thus providing no direct information about whole areas. Statistical methods have to be applied to interpolate the data to achieve two-dimensional information.

Using RS it is possible to directly obtain information in the second dimension. The term of "Remote Sensing" was first introduced in 1960 by Evelyn L. Pruitt of the United States Office of Naval Research. According to Lillesand *et al*. (2004) RS is the "science and art" of obtaining information about an object through the analysis of data acquired by a device that is not in physical contact with the object under investigation. However, the history of aerial photography is dating back till 1858 when Gaspard Felix Tournachon (later known as "Nadar") captured the first recorded aerial photograph from a balloon tethered over the Bievre Valley. Later manned and unmanned kites as well as pigeons were also used. Systematic aerial photography was developed for military surveillance and reconnaissance purposes beginning in World War I. The development of satellites in the second half of the 20th century allowed RS to progress to a global scale and sensors provided global measurements of various data for civil, research, and military purposes. As the land area under threat of deforestation is vast and inaccessible on the ground such as the tropical forests of Borneo, satellite RS offers the most feasible way of assessing land cover changes and deforestation rates on a regional scale (Tucker & Townshend, 2000).

The principle of the RS process is to detect electromagnetic energy which got reflected from earth surface features. There are many forms of electromagnetic energy such as radio waves, microwaves, terahertz radiation, infrared radiation, visible light, ultraviolet radiation, X-rays and gamma rays (Figure 3).

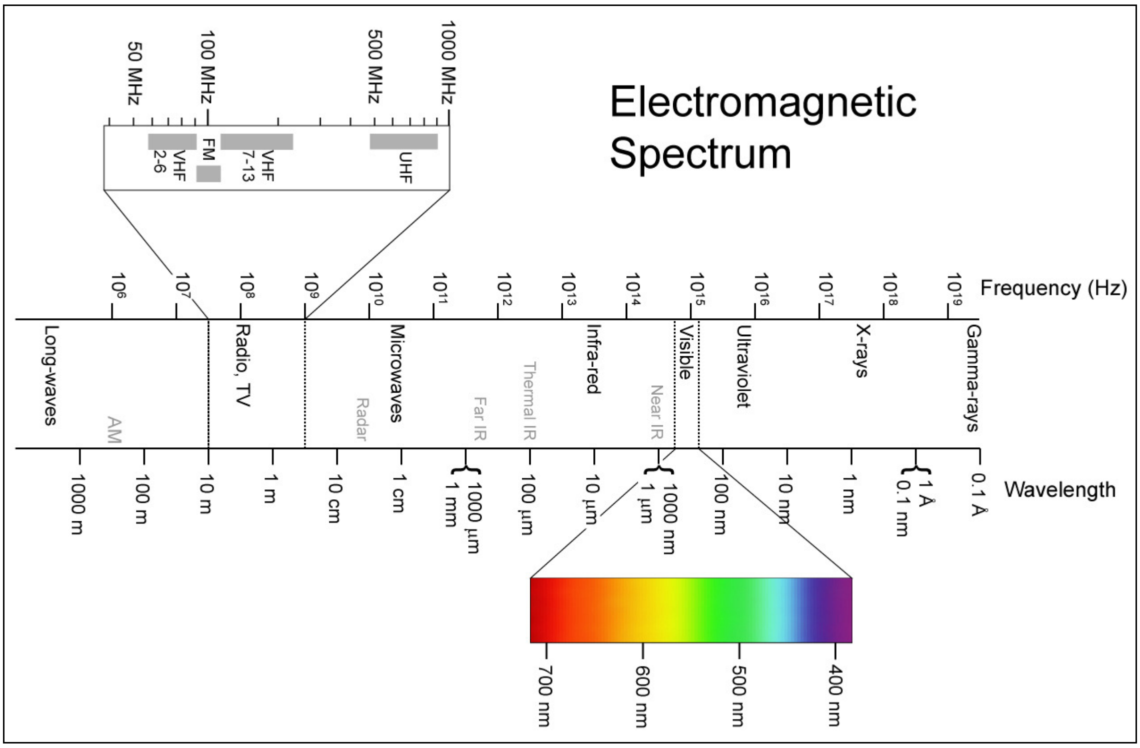

Figure 3: The electromagnetic spectrum (courtesy of Louis E. Keiner – Coastal Carolina University; Wikipedia – The Free Encyclopedia).

All energy detected by satellite sensors has to pass the atmosphere at least one time. Depending on the path length through the atmosphere, the magnitude of the energy signal, the prevailing atmospheric conditions and the involved wavelengths, the atmosphere has varying effects on the intensity and spectral composition of radiation reaching the sensor. These effects are caused principally through the mechanisms of atmospheric scattering and absorption. While atmospheric scattering is the unpredictable diffusion of radiation by particles in the atmosphere, atmospheric absorption results in the effective loss of energy to the atmosphere.

All satellite sensors can be characterized according to their spatial, spectral, radiometric and temporal resolution. The spatial resolution refers to the size of a pixel that is recorded in a raster image - typically pixels may correspond to square areas ranging in side-length from several decimeters to 1,000 meters or more. The spectral resolution refers to the number of different frequency bands recorded. Usually, this is equivalent to the number of sensors carried by the platform. Radiometric resolution refers to the number of different intensities of radiation the sensor is able to distinguish. The temporal resolution is simply the frequency of satellite overpasses, and is only relevant in time-series studies or those requiring an averaged or mosaic image. The various number of sensor systems can be summarized in active and passive sensor types. While active sensors such as RADAR or LIDAR supply their own source of energy, passive electronic-optical systems only sense naturally available energy.

4.2 Technical Problems of Land Cover Monitoring in the Tropics

4.2.1 Frequent Cloud Cover

Due to their multispectral sensing capabilities passive electronic-optical sensor systems offer the highest accuracy to distinguish different types of vegetation. However, one of the principal limitations of the use of optical imaging systems is that these technologies cannot penetrate clouds due to atmospheric scattering and absorption, persisting over many parts of the humid tropics such as Borneo during the wet season or throughout the whole year (Fuller, 2006) (Figure 4). As a consequence, this effectively reduces the number of satellite passes suitable for monitoring the tropical forest, as only cloud-free scenes can be processed.

Active radar systems with their cloud penetrating sensing capabilities proof great advantage in comparison to optical data, especially in the humid tropics with their frequent cloud cover. The ability of achieving images at regular intervals is considered as very important for monitoring the extent of forest cover in such areas. However, radar data does not provide as much detailed information in comparison to optical imagery to be able to distinguish different land cover or vegetation classes (Podest & Saatchi, 2002; Fuller, 2006). Therefore, the land cover classifications in this thesis were based on optical data alone. However, SRTM data (http://srtm.usgs.gov/), which was derived from a specially modified radar system acquiring interferometry radar data that flew onboard the Space Shuttle Endeavour during an 11-day mission in February of 2000 (Rodriguez *et al.*, 2005), was used to discriminate different mountain forest types with similar spectral properties according to their elevation.

Before being able to monitor land cover and land cover changes in the humid tropics using optical satellite data, it is necessary to remove clouds and haze. Generally this is done by applying an empirically derived set of rules on the single imageries. However, the process of removing clouds and cloud shadows results in images with areas of missing data. A combination of multitemporal datasets can help to fill in these gaps of missing data as described under 4.2.3.

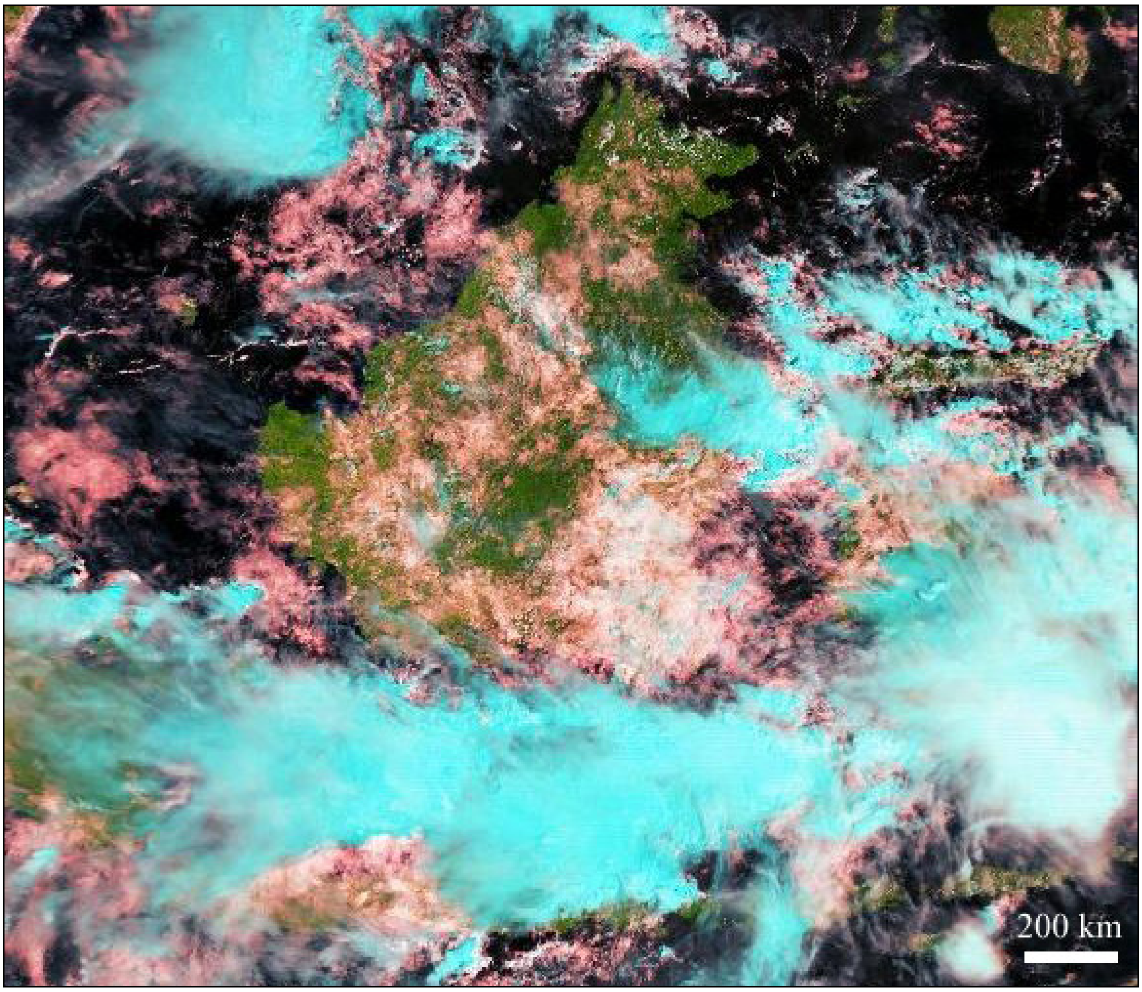

Figure 4: Subset of single day MODIS scene dating from 2002-12-29 covering Borneo (middle of picture) and parts of the Philippines, Sumatra, Java, Sulawesi and some smaller Indonesian islands (courtesy of CRISP). The white and light blue patches are different types of clouds.

4.2.2 Atmospheric Effects

Besides clouds there are also atmospheric disturbances which can be problematic for some kind of monitoring processes. The electromagnetic radiation collected by the satellite sensors in the solar spectrum are modified by scattering and absorption by gases and aerosols while travelling through the atmosphere (Figure 5 A).

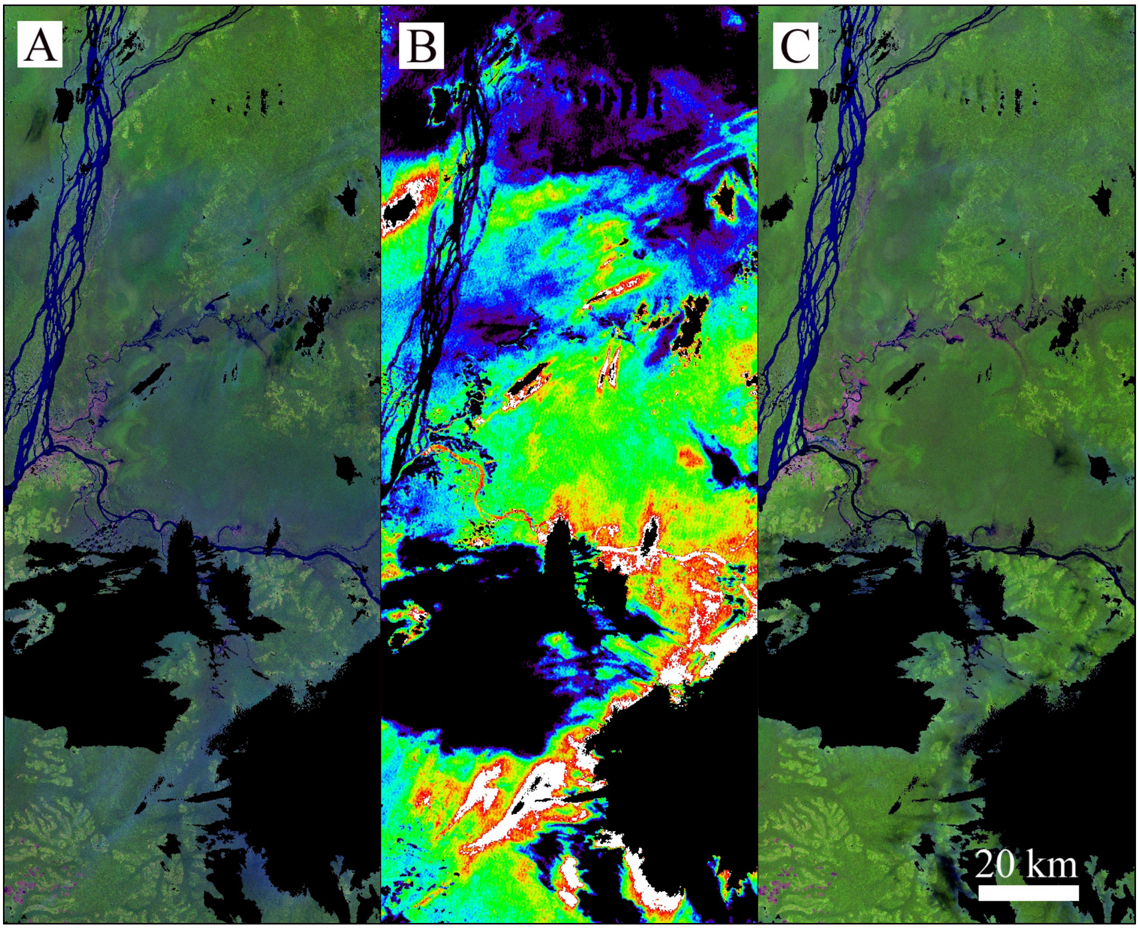

Figure 5: A) Subset of a Landsat 7 ETM+ scene (06.08.2001) of the Congo basin after cloud removal (black areas) but before atmospheric correction (band combination MIR, NIR, Red). Atmospheric influence is visible as transparent blue color over the vegetation. B) Atmospheric influence on the short-wave band 1 of Landsat. Color ramp from dark blue to white indicate low to high atmospheric influence. C) Same subset after atmospheric correction showing a stronger signal of the vegetation.

However, not all data derived from optical sensors has to be corrected for atmospheric effects. It mainly depends on the information desired and on the analytical methods used to extract the information. As long as the training data and the data to be classified are in the same relative scale there is no need to correct for atmospheric effects. In other circumstances, as for example multispectral change detection analysis, where the spectral characteristics over all available bands are analyzed without classifying each single image, atmospheric correction is mandatory (Conghe *et al.,* 2001). Using such kind of analysis, change maps derived without any kind of atmospheric correction would show the results from a mixture of different factors, such as artifacts due to different atmospheric conditions of the two images to be compared and real land cover changes. There are various kinds of atmospheric correction methodologies available, but most of them require additional information other than that provided by the imagery itself (Chavez, 1989; Coppin & Bauer, 1994; Ekstrand, 1994; Liang *et al.,* 1997; Michener & Houhoulis, 1997; Schott *et al*., 1988; Spanner *et al.,* 1990). According to Conghe *et al.* (2001) relative atmospheric correction is most recommended for change detection applications because no additional information concerning the atmospheric conditions of both images is needed. However, it has to be noted that a complete removal of all atmospheric influences is impossible (Figure 5 B, C).

4.2.3 Mosaiking Artifacts of Multitemporal Datasets

After removing clouds, cloud shadows and haze the images show areas of missing data values. For monitoring the whole study area it is therefore necessary to combine several images thereby filling up the areas of missing data. According to the high frequency of cloud coverage over Borneo, a large number of satellite images are necessary to derive satisfying results.

There are numerous algorithms of processing satellite images in order to achieve cloud-free composites. An important prerequisite for composing multitemporal images is a precise geolocation of the single imageries. Standard practice is to select pixels per single imagery on the basis of high observation coverage, low view angle, the absence of clouds or cloud shadow, and aerosol loading using the minimum-value rule (Cihlar, 2000; Fuller *et al*., 2003). Other selections are based on minimum values in the short-wave and near IR spectral bands or maximum value of the NDVI, providing a maximum discrimination between forest and non-forest (Stibig *et al*., 2002; Stibig & Malingreau, 2003). Due to BRDF effects and different prevailing atmospheric conditions corresponding pixels of various satellite overpasses show different reflectance properties. Owing to the composition processes, selecting single pixels according to the above mentioned rules, the cloud-free composites often show artificial structures similar to a rag rug, which are irrespective to the actual land cover (Figure 6 A, B).

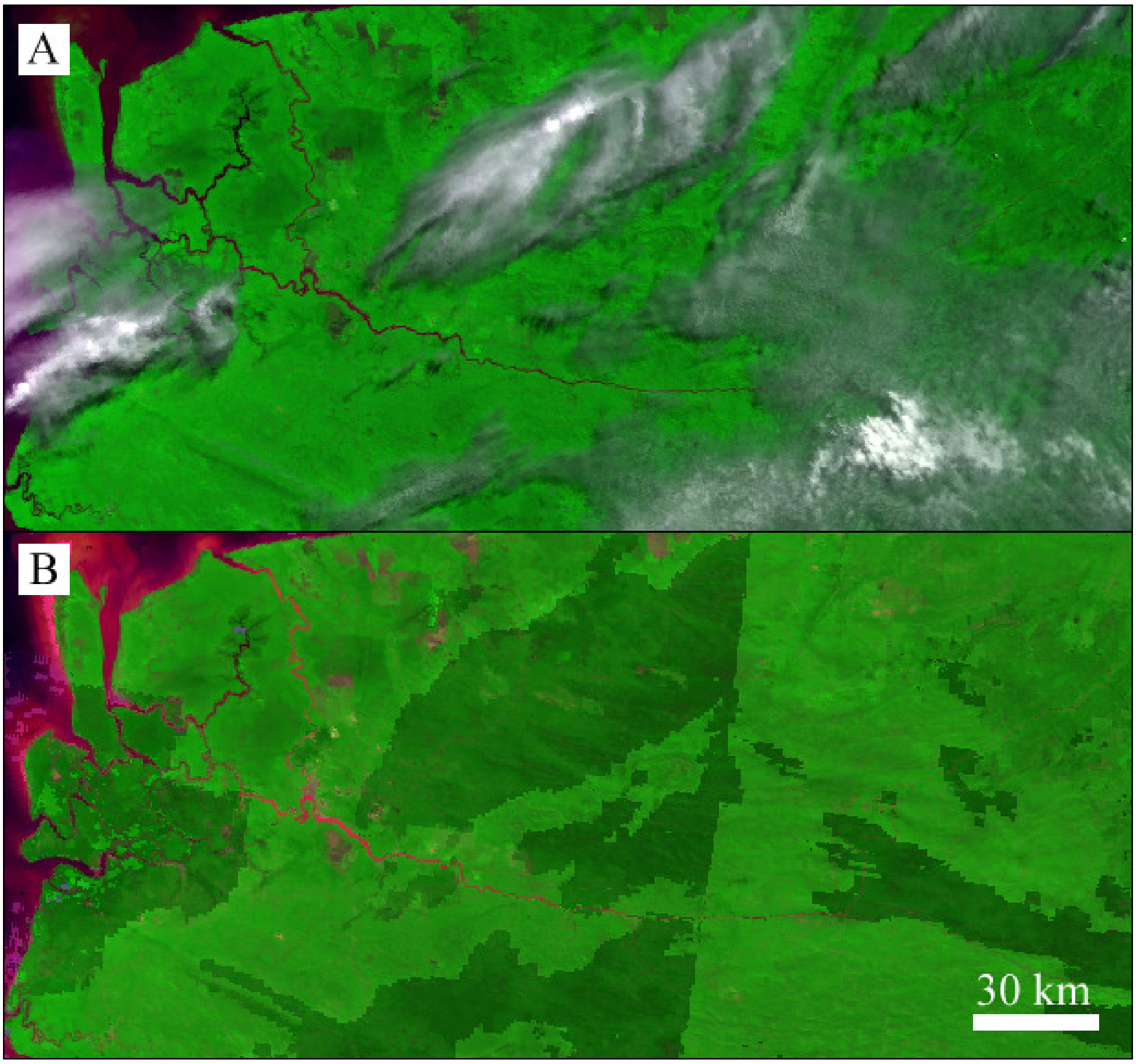

Figure 6: A) Subset of MODIS single day reflectance data (14.08.2002) over Sarawak. The scene shows comparable little cloud and haze impact. B) MODIS 8-day composite (13.-20.08.2002) with artifacts due to the cloud removal process.

This is also obvious in figure 7 (A, B), which shows a subset area in the Congo basin of Central Africa recorded by the SPOT VEGETATION sensor. It has to be noted that this problem also exists in other tropical areas with comparable atmospheric conditions. This artificial heterogeneity caused by these composition algorithms complicates the automatic interpretation of such composite images.

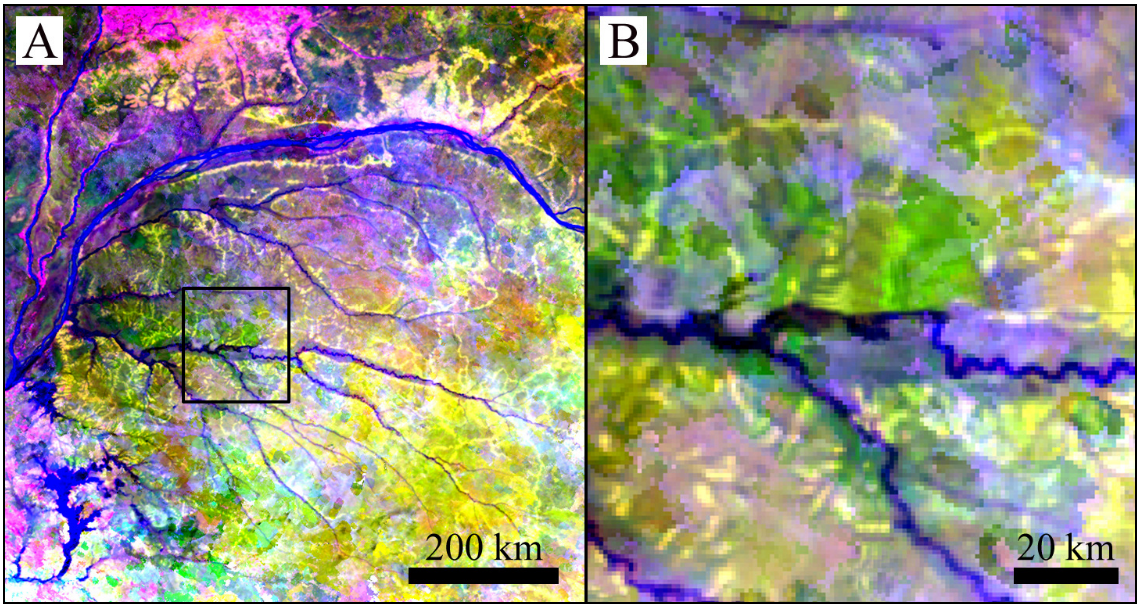

Figure 7: A) SPOT VEGETATION monthly composite of the surface reflectance product (January 2003) of the Congo basin, processed by the CSP in the scope of the GEOLAND project (http://www.gmes-geoland.info/index.php). B) Subset of the scene (black rectangle) showing clearly the artifacts of mosaiking the single cloud-free images.

4.3 Technical Problems due to incomplete Data Continuity

Fire is one of the most important drivers of forest loss and subsequent carbon dioxide emissions. A detailed analysis of a time series of fire events on Borneo over several years might reveal crucial information concerning the impact and the drivers of the fires, as well as possible counteractions. However, analyzing the spatial pattern of fire in relation to land cover and land use in Borneo over several years is problematic due to deficiency of a consistent high quality database covering a longer period of time. The first question which has to be answered is what kind of satellite data can be used for such substantial analysis. An annual detection of all burnt areas is not possible because there are not enough high resolution satellite images to cover the whole island each year. Reasons are frequent cloud coverage, narrow swath, and long orbit repeat cycles beside the increased costs for these high resolution data. Mapping all burnt areas with the help of low or medium resolution data is also not possible as the data is either not available for each year or has too coarse spatial resolution to resolve the small fire scars (Miettinen *et al.*, 2007). The only feasible way to monitor fire activity offer active fire detecting systems, which deliver coordinates of active fires, so called hotspots. Unfortunately there is not a single sensor system which would cover the full 10 years period, thus different sensors have to be combined. Each of the satellite systems has different terms of acquisition such as different spectral properties, sensitivities and orbit repeat cycles, which make it difficult to compare the number of fires of different years (Siegert and Ruecker, 2000; Li *et al*., 2001; Justice *et al*., 2002). Deriving burnt areas from active fire detections is also error-prone, as the detected hotspots do not provide information about the actual burnt area (Stolle *et al*., 2004; Miettinen *et al*., 2007). It has to be noted that the factual size of the actual burnt area is unknown. The actual size of a fire saturating the sensor element can be as small as 10 m^2, as gas flames on oil platforms are also detected. High resolution satellite imagery would be necessary to calibrate each sensor for different years, different land cover and land use types but this data is not available on a larger scale (Miettinen *et al*., 2007).

4.4 High versus Low Resolution Sensors for Tropical Forest Monitoring

For detailed mapping of forest cover while discriminating different types of vegetation, optical sensor systems still offer higher accuracies than radar data (Podest & Saatchi, 2002; Fuller, 2006). Depending on their revisit cycle, optical systems with a low temporal coverage can become virtually useless for periodic monitoring, for deriving the status of an ecosystem at a certain date or for monitoring fast land cover changes. This especially applies to sensors with a higher spatial resolution (<100 m) such as ETM+, SPOT HRVIR or ASTER as there is a correlation between the spatial and the temporal resolution (Fuller, 2006). The Landsat TM and ETM+ sensors (Table 1) for example have orbit repeat cycles of 16 days. The higher the spatial resolution of a sensor, the more land cover details can be resolved. The higher spatial detail is obtained at the expense of a narrower swath width of the satellite and thus a smaller area monitored per overpass. As the swath width of the satellite is smaller, more orbits are needed to cover the whole globe, thus the time of the sensor to pass the same spot on the ground is longer. The trade-off can be summarized as follows: the higher the spatial resolution of a sensor, the longer the orbit repeat cycle. Low spatial resolution systems (>500 m) such as NOAA AVHRR, SPOT VEGETATION (Table 1) and MODIS on the other hand provide daily coverage, which is required to cope with the cloud problem, but their low resolution limits the ability to resolve smaller scale land cover details. A good compromise is offered by medium resolution sensor systems such as MERIS but also MODIS (Table 1) with a spatial resolution between 250 and 500 m (Cihlar, 2000; Fuller, 2006; Huang & Siegert, 2006). In addition to an improved spatial and spectral resolution, these satellites also have a better sub-pixel geometric registration with superior calibration, cloud screening and atmospheric correction (Achard *et al.*, 2007;

Friedl *et al*., 2002; Fuller, 2006). In comparison to MERIS, the MODIS sensor shows a longer history of data records since 1999, provides a higher temporal resolution of two acquisition periods during daytime and it is readily available free of charge.

Table 1. Wavelengths (nm) of SPOT VEGETATION, MERIS, MODIS Surface Reflectance and Landsat 7 ETM+ data, which were used in this study.

Band	SPOT VEGETATION	MERIS	Terra MOD09GQK / Aqua MYD09GQK	Landsat 7 ETM+
1	430-470 (1,000 m)	407.5-417.5 (300 m)	620-670 (250 m)	450-520 (28.5 m)
2	610-680 (1,000 m)	437.5-447.5 (300 m)	841-876 (250 m)	530-610 (28.5 m)
3	780-890 (1,000 m)	485-495 (300 m)	459-479 (500 m)	630-690 (28.5 m)
4	1,580-1,750 (1,000 m)	505-515 (300 m)	545-565 (500 m)	780-900 (28.5 m)
5		555-565 (300 m)	1,230-1,250 (500 m)	1,550-1,750 (28.5 m)
6		615-625 (300 m)	1,628-1,652 (500 m)	10,400-12,500 (57 m)
7		660-670 (300 m)	2,105-2,155 (500 m)	2,090-2,350 (28.5 m)
8		677.5-685 (300 m)		520-900 (14.25 m)
9		700-710 (300 m)		
10		750-757.5 (300 m)		
11		758.75-761.25 (300 m)		
12		767.5-782.5 (300 m)		
13		855-875 (300 m)		
14		885-895 (300 m)		
15		895-905 (300 m)		

4.5 Major Land Cover Products

The studies of this PhD thesis were undertaken to derive more precise information about the land cover and deforestation patterns of the tropical forests of Borneo than previous land cover products could offer due to their pan tropical or global approaches. The TREES studies initiated in the early 1990s is one example of a global assessment of the status of the world’s humid tropical forest cover using high resolution Landsat TM data (Achard *et al*., 2002). Due to the above described problems of using high resolution optical sensor data in the humid tropics, most other regional and global forest cover mapping surveys such as the IGBP-DIS (DISCover) product, the UMd land cover map, TREES I and II, GLC2000 and the MODIS global land cover product were based on low resolution optical satellite data (Malingreau *et al*., 1989; Achard & Estreguil, 1995;

Mayaux *et al*., 1998; Eva *et al*., 1999; DeFries *et al*., 2000; Loveland *et al*., 2000; Friedl *et al*., 2002; Fuller *et al*., 2003; Bartholome & Belward, 2005; Stibig *et al*., 2007). However, low spatial resolution systems are limited in their ability to resolve small-scale land cover details. Using the MERIS sensor, a first global land cover map at a medium resolution of 300 m was produced in the framework of the ESA GLOBCOVER project in March 2008 (Bicheron *et al*., 2006).

Beside these various land cover products describing the status of the forest ecosystems to a certain single date, there are only few studies such as the VCC product (Zhan *et al*., 2002; Hansen *et al*., 2003) or the MODIS land cover and land cover change product (Zhan *et al*., 2000) investigating change detection using medium-resolution MODIS or MERIS imagery.

5 PAPERS

5.1 Chapter I

Monitoring Deforestation in the Humid Tropics using a Multispectral Change Analysis Technique

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Abstract

The ability of a multispectral change detection method was tested to quickly detect land cover changes in the humid tropics. Therefore, the absolute value of difference between each corresponding spectral band of the images to be compared was calculated. These absolute differences were summed up over all bands to receive the information about all changes that occurred between both scenes. This study was carried out in Central Africa and on the Southeast Asian island Borneo but its results can also be applied to other humid tropical areas with comparable atmospheric conditions. Under ideal conditions such as no frequent cloud cover the use of this multispectral change detection method is a very good approach to quickly monitor changes in the forest cover. Most important advantage of this technique is that it does not require the classification of the images to be compared, thus providing much faster results. However, implementing this system in the humid tropics implicated pivotal limitations. The frequent cloud coverage of these areas prevented from monitoring larger areas as optical satellite data interfere with clouds or haze. Thus, cloud-free composites had to be used. Depending on the algorithm, these composites either showed artefacts due to the selection of single pixels and thus could not be used as input for multispectral change detection, or when applying average compositing methods, which reduced the amount of artefacts considerably, the

advantage of easily detecting changes was lost due to the longer period of data acquisition because a higher number of single images had to be processed. Thus, owing to these limitations inherent to the humid tropics the concept of quickly detecting changes over larger areas by applying this multispectral change detection technique is not feasible in an operational way.

Keywords: multispectral change, monitoring, land cover change, rainforest, deforestation

Introduction

Tropical deforestation and forest degradation increased tremendously in the past two decades (Achard *et al*., 2002; Fuller, 2006). Based on statistics from the FRA 2000 main report, the tropics suffered under a net loss of natural forests of 14.2 Mha per year during 1990 – 2000 (FAO, 2001). Concerning the humid tropical forests of the earth the TREES study showed that about 5.8 ± 1.4 Mha of forest were lost each year between 1990 and 1997. Additionally an area of 2.3 ± 0.7 Mha was degraded annually (Achard *et al.,* 2002; Mayaux *et al.,* 2005). Therefore, adequate monitoring techniques, which are able to quickly resolve deforestation events, became necessary.

The detection of land cover changes based on the direct analysis of the spectral properties of optical satellite imageries derived from two different acquisition dates without classifying the images themselves is called radiometric change detection analysis. Changes in land cover can be detected due to the fact that changes of objects on the ground result in spectral changes of these specific objects. An example is the signal coming from the bare soil after a clearing took place which totally differs from the signal coming from a pristine forest. The ability of this technique to quickly detect land cover changes in the humid tropics was tested. This study was carried out in Central Africa and on the Southeast Asian island Borneo but its results can also be applied to other tropical areas with comparable atmospheric conditions. The objective of this study – in contrast to techniques based on spectral categorization (classification) of the input data and post classification comparison (delta classification) – was to directly identify changes in the spectral properties (radiometric change) that might indicate a change in land cover between two acquisition dates. Major advantage of this system is therefore the faster response to changes in land cover because of a reduced processing time due to the lack of the classification steps before and after the change. This study aimed to analyze the suitability of different kind of satellite data from high to low spatial resolution such as Landsat, MERIS, MODIS and SPOT VEGETATION for radiometric change detection analysis.

Several approaches for radiometric change detection have been discussed in the literature mostly using high-resolution data such as Landsat (Coppin *et al.,* 2004). Univariate image differencing (Weismiller *et al*., 1977; Singh, 1986; Muchoney & Haack, 1994; Green *et al*., 1994; Chavez & Mackinnon, 1994) is the most widely applied change detection algorithm. While the image differencing method involves subtracting one date of original or transformed imagery such as vegetation indices from a second date that has been precisely registered to the first, image rationing divides two co-registered images to produce a new change image (Singh, 1989; Yuan *et al*., 1999; Mas, 1999). The Principal Component Analysis can also be used for change detection by comparing two corresponding bands (before and after the change occurred). The second component shows the temporal change (Byrne *et al*., 1980; Richards, 1984; Ingebritsen & Lyon, 1985; Fung & Ledrew, 1987; Jiaju, 1988; Muchoney & Haack, 1994; Chavez & MacKinnon, 1994; Mas, 1999; Chavez & Kwarteng, 1989).

To be able to compare the reflectance signal of two corresponding pixels the images must be georeferenced with high accuracy. The absolute geolocation of the SPOT VEGETATION data is better than 300 m while temporal superimposition is about 325 m (Sylvander *et al.,* 2000), showing little pixel-size augmentation at the borders of the image with increasing viewing angle. In comparison to the low resolution systems of NOAA AVHRR, MERIS and MODIS provide an improved spatial and spectral resolution. Furthermore, these satellites also have a better sub-pixel geometric registration with superior calibration, cloud screening and atmospheric correction (Achard *et al*., 2007; Friedl *et al*., 2002; Fuller, 2006). According to Defourney et al. (2007) MERIS has a relative accuracy of 51.6 m and an estimated absolute accuracy of 77 m. The data to be compared should be obtained under similar seasonal conditions, which is less important in the humid tropics. Furthermore, some important precondition for radiometric change detection is that the two pictures to be compared should optimally contain no cloud contamination. However, the persistent cloud cover of the humid tropics proofed to be highly problematic. It was therefore necessary to remove all clouds, cloud shadows, and haze by defining adequate thresholds. When applying single date scenes the number of available scenes with little or no cloud/haze coverage was therefore severely restricted. This was especially true for the Landsat sensor but in this paper we also analyzed single date MERIS data. When using multitemporal datasets it was possible to derive cloud-free composites using different mosaiking algorithms. As far as possible both images had to be corrected for atmospheric influences to ensure the direct comparability of the reflectance values of the corresponding pixel locations.

In contrast to the above mentioned and common change detection methodologies, which only make use of a subset of their spectral bandwidth such as single bands or band combinations, the idea of this research was to process the information of all available bands of the sensor devices – thus performing a multispectral change detection analysis. Therefore, the absolute value of difference between each corresponding spectral band of the images to be compared was calculated. These absolute differences were summed up over all bands to receive the information about all changes that occurred between both scenes. The higher the absolute value of change the higher the quality of the change, as the spectral difference between the two images is directly reflected in the product of the absolute values. With respect to all other factors, which also cause spectral change, variations in radiance due to land cover change must be large enough to be identified as real change. Applying this algorithm, conversions from forest to non-forest, such as transformations from forest to clear-cuts and forests to agricultural areas and vice versa should be identified. Besides, the ability of this multispectral change analysis to detect changes in the agricultural domain from natural vegetation to agriculture and between different crop types should be analyzed.

Materials and methods

Study areas

Both study areas are situated in the humid tropics along the equator and are characterized by frequent rainfall and high temperatures throughout the year. In Africa a subset area of the Congo basin was chosen as it contains mainly pristine rain forest with only small-scale disturbances. As a result of its equatorial location, the Congo experiences large amounts of precipitation with an annual rainfall of up to 2,000 mm and has the highest frequency of thunderstorms on Earth. The climate is typically continental equatorial, hot and humid with a slightly drier season from June to August. The climate of Borneo is affected by the ‘dry’ southeast monsoon from May to October and the ‘wet’ northwest monsoon from November to April. The study area in Central Kalimantan was chosen because it shows the transition zone between one of the last vast areas of peat swamp forests of Southeast Asia and a highly degraded area due to the establishment of a large-scale transmigration project – the so called Mega Rice Project (MRP). In contrast to the African study site with its small-scale land cover changes, the study area in Borneo shows rather large-scale disturbances, typical for the Southeast Asian region.

Satellite data

Two spatial high resolution Landsat 7 ETM+ scenes, showing little cloud coverage, were selected in Central Africa and Central Kalimantan respectively. This data was used for different purposes such as the analysis of the multispectral change detection algorithm on high resolution datasets, the calibration of the medium and low resolution datasets for change threshold definition and for accuracy assessment. As far as possible, the scenes were selected contemporary to the medium and low resolution satellite data.

Table 1. *Wavelengths (nm) of SPOT VEGETATION, MERIS level 2 full resolution, MODIS Surface Reflectance and Landsat 7 ETM+ data, which were used in this study.*

Band	SPOT VEGETATION	MERIS	Terra MOD09GQK / Aqua MYD09GQK	Landsat 7 ETM+
1	430-470 (1 km)	407.5-417.5 (300 m)	620-670 (250 m)	450-520 (28.5 m)
2	610-680 (1 km)	437.5-447.5 (300 m)	841-876 (250 m)	530-610 (28.5 m)
3	780-890 (1 km)	485-495 (300 m)	459-479 (500 m)	630-690 (28.5 m)
4	1,580-1,750 (1 km)	505-515 (300 m)	545-565 (500 m)	780-900 (28.5 m)
5		555-565 (300 m)	1,230-1,250 (500 m)	1,550-1,750 (28.5 m)
6		615-625 (300 m)	1,628-1,652 (500 m)	10,400-12,500 (57 m)
7		660-670 (300 m)	2,105-2,155 (500 m)	2,090-2,350 (28.5 m)
8		677.5-685 (300 m)		520-900 (14.25 m)
9		700-710 (300 m)		
10		750-757.5 (300 m)		
11		758.75-761.25 (300 m)		
12		767.5-782.5 (300 m)		
13		855-875 (300 m)		
14		885-895 (300 m)		
15		895-905 (300 m)		

While the images for the scene path 180 / row 060 in Africa were dating from 2000-02-25 and 2001-08-06 respectively, the images in Central Kalimantan (118/062) were derived on the 2003-01-14 and 2005-10-02. The latter scene was recorded in Scan Line Corrector (SLC)-off mode with stripes of missing data. Image data from medium resolution MODIS and MERIS sensors as well as the low resolution VEGETATION sensor were analyzed for their suitability for multispectral change detection. Table 1 shows the spatial and spectral properties of the different sensor systems. While the Landsat sensor has an orbit repeat cycle of 16 days, the medium or low resolution systems show a much higher temporal resolution. SPOT-4 VGT reflectance datasets at 1 km spatial resolution were derived on daily basis. To produce cloud-free surface reflectance composites the VGT datasets were processed using the mean compositing algorithm (Vancutsem *et al.*, 2007b) and provided by the Research Laboratory in Environmetrics and Geomatics of the Université catholique de Louvain in Belgium. The MERIS sensor, which is located on the ENVISAT satellite, allows a global coverage of the whole earth within 3 days. The single day MERIS level 2 full resolution data at 300m spatial resolution, dating form 2004-07-01 and 2006-04-30, covering the southeastern part of Borneo were ordered directly via the Earthnet OnLine Interactive Stand Alone (EOLI-SA) of the ESA (http://earth.esa.int/object/index.cfm?fobjectid=5035). Besides the SPOT VGT and MERIS data Surface Reflectance 8-day L3 MODIS composites, acquired in March 2000 and February 2001, were also analyzed for the purpose of multispectral change detection. The data of the study area in Africa, which was recorded from the MODIS sensor on the Terra satellite at 500 m resolution, was downloaded with the help of the USGS Global Visualization Viewer (http://GloVis.usgs.gov/BrowseBrowser.shtml) from the Earth Resources Observation and Science Center (EROS).

Data pre-processing

In a first step clouds, cloud shadows and haze had to be removed from all images. Most of the clouds, cloud shadows and haze of the Landsat images of Africa and Borneo were masked using empirically derived thresholds based on the short-wavelength band 1. Besides removing the clouds and cloud shadows, the stripes of missing data had also to be masked. In a second step the masks of the corresponding images were combined and the resulting mask was filtered using a 3 x 3 median filter. The single day MERIS level 2 full resolution data, used for analyzing deforestation in Central Kalimantan, was processed alike. The 8-day MODIS composites were created selecting single pixels associated with the maximum NDVI value recorded during that period (Cihlar, 2000; Fuller *et al.*, 2003). Hence, the composites contained artificial heterogeneity caused by this compositing algorithm, which often complicates the interpretation of such composite images. These artefacts as well as remaining clouds were on purpose not masked before further processing to analyze their effects on the multispectral change detection algorithm. The surface reflectance composites of the SPOT VGT data, which were created using a mean compositing algorithm (Vancutsem *et al.*, 2007b), did not show much remaining cloud contamination and thus were used without any further processing.

To reduce atmospheric disturbances the short waved bands 1 and 2 were excluded from the analysis of the Landsat data over both study sites (Foody *et al.*, 1996; Collins & Woodcock, 1994). In Africa it was also possible to reduce the influence of atmospheric disturbances using some modification of a relative atmospheric correction model. A moving window of 10 x 10 pixels was used to correct for these disturbances by calculating the median over the kernel size of both images to be compared. For atmospheric correction, all bands of the chronologically younger scene (image of time 1 was acquired chronologically before image of time 2) were calibrated according to the corresponding bands of the master scene using the following equation (1) while masked areas, such as clouds and cloud shadows, were excluded from this calculation:

Equation 1:

$$\text{Adjustment of band}^{\,n\text{Time }2} = \text{band}^{\,n\text{Time }2} + \left(\text{MEDIAN band}^{\,n\text{Time }1} - \text{MEDIAN band}^{\,n\text{Time }2}\right)$$

Thus the digital number (DN) values of all bands in the corrected image (time 2), which did not experience land cover changes, represented comparable reflectance values as the radiometric master scene (time 1). However, this algorithm did not perform an absolute atmospheric correction (Chavez & Mackinnon, 1994) and was only applied to the Landsat data of the Congo basin. Concerning the medium and low resolution datasets, no relative atmospheric correction was applied as well as all available spectral bands were used for multispectral change detection.

Multispectral change detection analysis

The multispectral change detection analysis itself consists of several single processing steps. First, the absolute value of difference between each corresponding spectral band of the two images to be compared had to be calculated. In a next step these absolute differences were summed up over all bands to receive the information about all changes that occurred between both scenes (Equation 2).

Equation 2:

$$\text{Sum of differences over band}^{n} = \sum_{k=1}^{n} \mid \text{Image 1 band}^{k} - \text{Image 2 band}^{k} \mid$$

As third step the results had to be normalized to better define thresholds for change detection. Therefore, the sum of these differences was divided by the sum of the maximum value per corresponding band of both images and multiplied by the factor 100 to derive percentile values. As there are no negative reflectance values, the sum of the maximum single pixel values over each corresponding band of both images can be the maximal difference between both data sets to be compared (Equation 3).

Equation 3:

$$\text{Percentil} = \frac{\text{Sum of differences over all bands}}{\sum_{k=1}^{n} \text{MAX (Image 1 band}^{k} - \text{Image 2 band}^{k})}$$

Though providing information about the quality of change there is no information about the direction of the land cover changes such as deforestation or natural forest regrowth. For that sake the Normalized Differenced Vegetation Index (NDVI) was calculated. Vegetation can best be discriminated using the red and the NIR band, because chlorophyll in leaves absorbs most energy in the red spectrum whereas it reflects most in the NIR part of the spectrum. Both bands are used to calculate the NDVI according to the following formula (4):

Equation 4:

$$\text{NDVI} = \frac{(\text{NIR} - \text{red})}{(\text{NIR} + \text{red})}$$

As the NDVI has the best sensitivity to changes in areas of higher vegetation cover such as the tropics it is preferentially used to derive the status of tropical vegetation (Kriegler *et al.*, 1969; Rouse *et al.*, 1973). To obtain information about the direction of change, the difference of the NDVI values of both input images was calculated (Equation 5):

Equation 5:

$$\Delta \text{NDVI} = \text{NDVI}^{\text{Time 2}} - \text{NDVI}^{\text{Time 1}}$$

From this result the algebraic sign was derived, which was used to mask the change detection analysis; whereas positive values implied a gain in vegetation cover and negative values represented vegetation cover loss.

Change threshold definition

The multispectral change analysis results in images showing varying amounts of changes. Besides for the Landsat scenes for Central Africa an atmospheric correction was not feasible. Therefore, spectral differences in the image pairs represent a mixture of real land cover changes as well as noise due to different atmospheric conditions of the two input images. By defining applicable thresholds to quantify reflectance changes we tried to separate the actual changes from the noise. Therefore a workable definition of "change" for each sensor system had to be defined. As no ground truth information from GPS readings was available for the different study sites, the appropriate threshold values were defined by the repeated empiric comparison of various threshold settings for each sensor and the results of the medium and low resolution sensors were also compared with the corresponding Landsat scenes, which served as reference data. In a final step the change maps were filtered to remove all polygons smaller than 4 pixels as they mainly display noise.

Accuracy assessment

Owing to lack of ground truth reference data, the two Landsat scenes per study area were classified according to their forest cover and agricultural areas. To reduce the impact of atmospheric disturbances as remaining haze only the Landsat bands 3, 4, 5 and 7 were used, only covering the red to the short wavelength Infra Red (IR) spectrum which contains the most relevant information for detecting vegetation cover. Using an unsupervised ISODATA algorithm with 10 iterations, 10 clusters were assigned to three classes by visual inspection. For the African study area the land cover classes were water, forest and shifting cultivation mosaic. The study site on Borneo was classified in water, forest and a mixed class of agricultural fields with fern regrowth and artificial surfaces. The classification results were filtered to remove noise by a median filtering process with a kernel size of 3x3 pixels. These maps were used to validate only the

Landsat based change detection results. To avoid some conflict between calibration activities (change threshold definition) and accuracy assessment we used different subset areas of the reference data for both purposes.

As there was a temporal shift between the acquisition dates of the Landsat scenes and other medium and low resolution datasets, the Landsat based land cover classifications were not applied for accuracy assessment of the other sensors change detection results. The validation was carried out by the visual interpretation of 350 randomly selected points. However, the Landsat classifications served as reference to cover the two important land cover classes with enough sample points. Both the forest and agricultural land cover classes were validated using 100 randomly selected locations and an additional 100 points to take into account the varying extent of both land cover types. As land cover changes from forest to agricultural land or vice versa were comparatively seldom in the African study site, another 50 points were set manually by visual comparison of the Landsat reference images to secure enough samples for better statistical analysis. As the land cover changes of the study area in Borneo were much larger in comparison to the African study site, all points were set using a random selection algorithm. Finally the Landsat based validation points were superimposed on the multispectral change results from the Landsat, MERIS, MODIS and SPOT VEGETATION sensors to evaluate the accuracy of the different sensor systems, taking into account their different spatial resolutions. For this sake the overall accuracy, the errors of omission and commission as well as the kappa coefficient, accommodating for effects of chance agreement, were calculated (Cohen, 1960; Foody, 2001). For statistical analysis we used the statistic module of Mackinnon (2000) to derive the kappa coefficient and to test the significance of the results on a 95% confidence interval.

Results

Landsat sensor

Our analysis of the Landsat data in Central Africa showed that a threshold value of ±3.0% is most fitting to separate atmospheric noise from real changes, which resulted in the loss or regrowth of vegetation. Almost all changes in the land cover in tropical Africa were rather small- than large-scale with a mean size of 0.5 ha – independently if they occurred in the forest or the agricultural domain. The overall accuracy of the multispectral change analysis of the two corresponding high resolution Landsat scenes over the African study site was 96.0% with a k-coefficient of 0.8878 (Table 2). As the kappa coefficient represents the chance corrected proportion of agreement with the reference data, the obtained value indicates almost perfect agreement. Of the total, 2.3% were severe errors and 1.7% was slight errors. The severe errors consisted of reductions in vegetation cover, which were erroneously interpreted as increases in vegetation cover. No single vegetation regrowth was misclassified as vegetation loss. Slight errors occurred when the ground-truth data showed no changes while the multispectral change analysis either detected a gain or a loss in vegetation cover and vice versa (Figure 1 A-C).

The study area on Borneo experienced much larger-scale modifications of the land cover with a mean size of 20 ha (Figure 1 G-E). For that region threshold values below -10.0% were regarded as vegetation loss while values above +3.2 were considered as gain of vegetation cover. The overall accuracy of the Landsat scenes in Borneo was lower in comparison to the African study site with 85.1% with a k-coefficient of 0.5639 (Table 2). As all wrong assignments consisted of slight errors (14.9%), no severe errors were observed.

Table 2. *Accuracy assessment of the different high, medium and low resolution sensors over both study sites in Africa and Borneo.*

Sensor type Study site	Overall acc. Kappa	Type of error	Increase in vegetation cover	Reduction of vegetation cover	No change in land cover
Landsat 7 ETM+ Africa	96.0% 0.8878	Omission Commission	0.0% 35.7%	17.9% 4.2%	1.4% 0.7%
MODIS Africa	46.3% -0.0379	Omission Commission	55.6% 95.0%	97.2% 91.7%	44.5% 23.8%
Landsat 7 ETM+ Borneo	85.1% 0.5639	Omission Commission	14.8% 42.5%	41.7% 43.2%	11.5% 7.0%
SPOT VGT Borneo	81.4% 0.1703	Omission Commission	77.8% 45.5%	91.7% 70.0%	3.8% 16.1%
MERIS Borneo	58.0% 0.2888	Omission Commission	38.5% 84.8%	26.8% 52.3%	45.5% 8.2%

MERIS sensor

Based on the change detection analysis of the MERIS data values below –4.5% and above +6.5% were assigned as land cover changes. The overall accuracy of the multispectral change detection analysis was 58.0% with a k-coefficient of 0.2888 indicating fair agreement to the reference data (Table 2). The total of the 42% of the incorrect assignments can be divided into a large part of 38.6% slight errors and only 3.4% of severe errors (Figure 1 J-L).

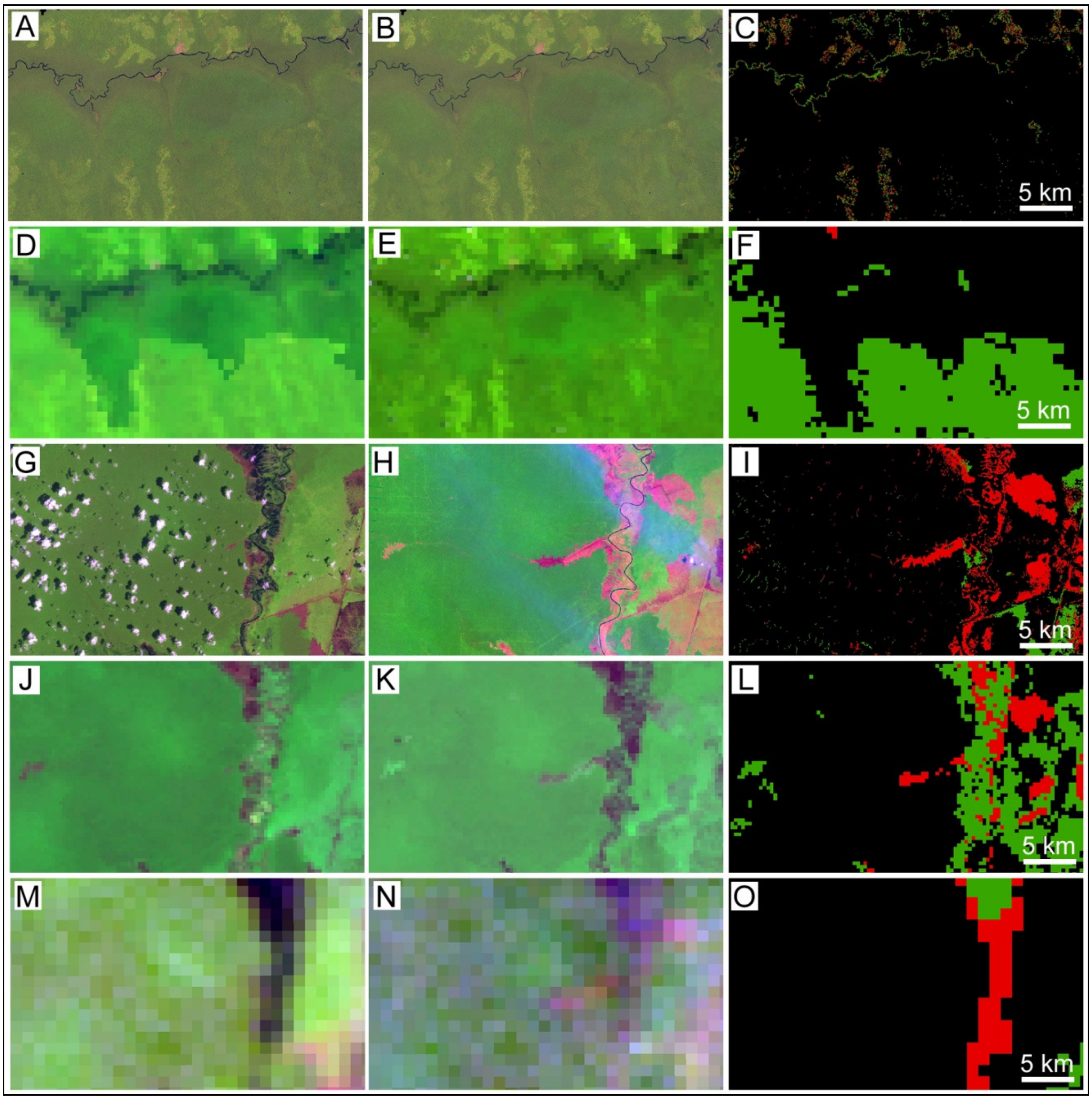

Figure 1:

(A-C) Subset of Landsat scene in Central Africa, Congo basin dating from 2000-02-25 (A), 2001-08-06 (B) and the result of the multispectral change detection analysis (C).

(D-F) Subset of Surface Reflectance 8-day L3 MODIS composites in Central Africa dating from 2000-03 (D), 2001-02 (E) and the result of the multispectral change detection analysis (F).

(G-I) Subset of Landsat scene in Central Kalimantan, Indonesia dating from 2003-01-14 (G), 2005-10-02 (H) and the result of the multispectral change detection

analysis (I).
(J-L) Subset of MERIS level 2 data in Central Kalimantan, Indonesia dating from 2004-07-01 (J), 2006-04-30 (K) and the result of the multispectral change detection analysis (L).
(M-O) Subset of SPOT-4 VGT composites in Central Kalimantan, Indonesia dating from 2003-01 – 2003-4 (M), 2006-01 – 2006-4 (N) and the result of the multispectral change detection analysis (O).
Colors in the figures C, F, I, L, O: black = no change; red = loss of vegetation cover; green = increase in vegetation cover.

MODIS sensor

Even though the multispectral change detection result based on the MODIS 8-day surface reflectance data over Central Africa with threshold values of −1.8% and +1.7% obtained an overall accuracy of 46.3%, the kappa coefficient showed a value of -0.0379 (Table 2). The negative kappa value indicates below chance agreement with the Landsat reference data. From 53.7% of incorrect assignments when using MODIS 8-day surface reflectance data for multispectral change detection the larger part (49.1%) showed only slight errors and 4.6% were severe errors (Figure 1 D-F).

SPOT VEGETATION sensor

The analysis of the SPOT VEGETATION data in Borneo revealed, that a threshold value of less than −8.1% best indicated a loss in vegetation cover, while values above +9.7% showed a gain in vegetation cover. Even though the overall accuracy of the multispectral change detection analysis was quite high with 81.4%, the kappa coefficient of 0.1703 showed only slight agreement (Table 2). The total of the 18.6% of the incorrect assignments consisted almost of slight errors (18.3%) and only 0.3% of severe errors (Figure 1 M-O).

Discussion and conclusion

In this study a multispectral change detection algorithm was tested for its suitability to identify land cover changes in the humid tropics, based on different kind of high, medium and low resolution optical satellite data, such as Landsat, MERIS, MODIS and SPOT VEGETATION. Two study sites in Africa and Southeast Asia were selected because of their totally different land use patterns. It has to be noted that deforestation events were more small-scale in Africa (Figure 1 C), where most changes occurred mainly due to shifting cultivation activities of local farmers, in comparison to Borneo, where we focused on the transition zone between one of the last and largest peat swamp forest areas of Southeast Asia of the highly degraded land cover of the former Mega Rice Project (MRP) (Figure 1 I). The MRP project, which was initiated by President Suharto in 1995, had the aim of developing one million ha of peat land for rice cultivation (Rieley & Page, 2005). Between 1996 and 1998 more than 4,600 km of irrigation channels have been built (Boehm & Siegert, 2001). The project was finally stopped in early 1999, because it was not possible to establish sustainable agriculture on the chosen nutrient poor and acidic peat lands (Rieley & Page, 2005).

Before applying this multispectral change detection technique all kind of clouds, cloud shadows and haze (as far as possible) have to be masked from the imageries – irrespective of the sensor system. As optical sensor systems also interfere with any kind of atmospheric disturbance due to scattering and absorption by gases and aerosols (Lillesand *et al.*, 2004), change maps derived without any kind of atmospheric correction show results from a mixture of different factors, such as artefacts due to different atmospheric conditions of the two images to be compared, various kind of composition artefacts (if image composites were used) and real land cover changes. To separate the actual land cover changes from the artefacts it was necessary to correct for the atmospheric conditions of both input images – at least in the cases where it was feasible. There are various kinds of atmospheric correction methodologies available, but most of them require additional information other than that provided by the imagery itself (Chavez, 1989; Coppin & Bauer, 1994; Ekstrand, 1994; Liang *et al.,* 1997; Michener & Houhoulis, 1997; Schott *et al*., 1988; Spanner *et al.,* 1990). The simplest way to reduce atmospheric disturbances is to exclude the short waved bands, therefore we only processed band 3, 4, 5 and 7 of the Landsat data over both study sites (Foody *et al*., 1996; Collins & Woodcock, 1994). According to Conghe et al. (2001) relative atmospheric correction is most recommended for change detection applications because no additional information concerning the atmospheric conditions of both images is needed. This method is based on the assumption of a linear correlation between corresponding image bands, which can be determined from radiometric measurements over pseudo-invariant features (PIFs), which have to be known before analysis (Conghe *et al*., 2001). As our study aimed to evaluate a multispectral change detection methodology to quickly detect land cover changes in humid tropical areas, where less or no information about the actual conditions on the ground are available, we did not apply algorithms depending on such kind of ground truth information. However, due to the obviously very small-scale land cover changes in the African study site with a mean size of 0.5 ha, it was possible to perform a relative atmospheric correction in this region without detailed radiometric ground truth information. Therefore, the bands of the chronologically younger Landsat scene were adapted to the corresponding bands of the master scene. It has to be noted that land cover changes also occurred in the period between the acquisition dates of the two scenes, which should not be removed by the correction process. Therefore, it was necessary to differentiate between pixels just showing atmospheric disturbances and those also including actual land cover changes, such as deforestation or reforestation events. As atmospheric disturbances are not uniformly distributed across the image, a moving window of 10 x 10 pixels was used to correct for these disturbances of the African study site by calculating the median over the kernel. This was done for every single band as atmospheric disturbances have varying impact over the electromagnetic spectrum, depending on the wavelength and the particle size of the aerosols (Lillesand *et al.*, 2004). The size of the window was adapted to the region typical size of the land cover changes to correct for atmospheric differences in spatial detail while preserving real land cover changes. For filtering the median was applied as this algorithm is less susceptible concerning outliers, which have to be preserved because they represent actual land cover changes. In comparison to atmospheric disturbances, real land cover changes such as deforestation events usually cause larger and more abrupt modifications in the reflectance values between two images to be compared. It has to be mentioned that this method did not lead to accurate surface reflectance values, but it best minimized the difference in reflectance values of the corresponding images due to atmospheric disturbances, thus improving the results of the multispectral change detection analysis. Due to the much larger-scale land cover changes of the study site of Borneo with a mean size of 20 ha, the atmospheric correction algorithm using the above described method was not feasible without losing crucial information about the real land cover changes. Therefore no relative atmospheric correction was carried out on this study site. Also the medium and low resolution data were not explicitly processed using this atmospheric correction. The MODIS and MERIS data products, used in this study, were already corrected for atmospheric effects beforehand (Friedl *et al.*, 2002; Fuller, 2006). And as multitemporal composite imageries, such as the MODIS (Figure 1 D, E) and the SPOT VEGETATION data (Figure 1 M, N), are a rag rug of pixels with different atmospheric conditions, they could not be corrected for atmospheric disturbances using the above mentioned algorithm.

Owing to the lack of ground truth data, the visual comparison of high resolution Landsat scenes had to be used as reference for validation. Therefore, a detailed analysis of the magnitude of change was impossible. Without detailed information about the magnitude of change, the exact definition of threshold values, defining the loss of gain of vegetation cover, turned out to be very difficult. Real ground truth information would have essentially improved the change detection analysis. However, as the purpose of this study was to analyze the capabilities to quickly detect land cover changes in the humid tropics with less or no information about the actual ground truth conditions, this study had to cope with the problematic of proper threshold definition.

Besides their purpose as reference data, the Landsat scenes were also used as input data for the multispectral change detection analysis to show the potential of high resolution single imagery data. Though land cover changes in the African study area were small-scale, a multispectral change detection based on high resolution Landsat data was feasible with a very high overall accuracy of 96% in Africa due to the high spectral difference between vegetation and clear cuts. The high kappa coefficient of 0.8878 indicates the almost total exclusion of chance agreement. About 2.3% of the errors in this study area showed an actual loss in vegetation cover, which were incorrectly classified as an increase in vegetation cover. The analysis of these errors indicated that the characteristics of the NDVI algorithm alone accounted for this kind of error because young regrowth shows higher NDVI values as mature vegetation. For the study site in Borneo images, which were derived from the beginning and the middle of the wet season, have been compared. As expected, Borneo experienced much larger-scale land cover changes with an average size of 20 ha. However, the overall accuracy of the change detection analysis was with 85% about 11% lower than the accuracy of the African study site. This can mainly be attributed to the missing atmospheric adjustment of both images. Due to that reason it was very difficult to find the appropriate threshold values to define land cover changes. This became most obvious as the majority of the errors occurred on areas, which were most affected by haze. However, it was possible to detect illegal logging activities inside the Sebangau peat swamp forest, which became National Park in 2004. Beside alterations in the forest cover, changes in the reflectance values can also describe variations in the vegetation cover of agricultural areas. Due to missing ground truth information covering this particular acquisition period we were not able to analyze the capabilities of this multispectral change detection algorithm to detect changes in the agricultural domain, such as changes between different crop types or between grassland and agricultural fields. However, such kind of changes might also be difficult to be detected due to very similar reflectance properties, which hinder appropriate change detection in the agricultural sector while atmospheric disturbances additionally interfere with these marginal differences.

Though high resolution sensors are able to resolve even small-scale changes, such sensor systems are not applicable for monitoring larger tropical forest areas to quickly resolve land cover changes due to several reasons such as high costs, narrow swath, and long orbit repeat cycles (Fuller, 2006). Especially the humid tropics are characterized by frequent cloud coverage, lowering the frequency to obtain an image pair which can be used for change detection analysis. Coppin et al. (2004) identified the low temporal frequency of observations of high spatial-resolution sensors as a serious disadvantage for change detection. Thus, sensor systems with low or medium spatial resolution, which are therefore able to secure images with higher temporal resolution, show better potential for wide-area change detection analysis in tropical areas. The shorter the time of the repeat cycle of the satellite, the higher the possibility to obtain images with less or little cloud contamination. At present only coarse to moderate spatial-resolution sensors ensure the high temporal frequency of observations that is necessary for adequate monitoring. However, for analyzing MERIS data as input for the multispectral change detection analysis, single day data was processed in order to investigate the advantage of the high spectral resolution without negative impacts due to mosaiking artefacts. Though the high spectral resolution with 15 distinct bands in the visible and near IR part of the spectrum, the relative low overall accuracy of 58% resulted most probably from different atmospheric influences as the input imageries were not explicitly atmospherically adjusted to each other using the above described relative correction. Another advantage of moderate spatial-resolution sensors is the possibility to observe large areas with low data costs. However, small-scale changes in land cover make a detection using medium or low resolution satellite data difficult, but depending on the satellite system forest cover changes smaller than the corresponding pixel resolution might be possible to be detected if the signal of the changes is strong enough.

When working with MODIS or SPOT VGT data the high number of available data made it possible to combine the cloud-masked single imageries to derive multitemporal cloud-free composites. This is a crucial step towards an operational application for monitoring larger areas in the humid tropics. This can be done using different kind of algorithms: Single pixel selection algorithms such as maximum value NDVI composites (Mayaux *et al*., 2004) have the advantage that only one single scene is necessary per pixel location, keeping the time period of composition as short as possible – depending only on the prevalent weather conditions and the repeat cycle of the satellite. Using such algorithm, each pixel location represents the actual observed reflectance value of the corresponding pixel. However, it has to be noted that due to this mosaiking process, which selects single pixels of different acquisition dates, a precise temporal allocation is not feasible. Therefore, changes which might have occurred during the acquisition period can be lost – depending if the corresponding pixels are chosen before or after the change occurred. Based on single pixel selections, the resulting composites show artefacts due to different atmospheric conditions of the acquisition days, even though the image products have been atmospherically corrected before. Further reason for artefacts are BRDF effects, which are responsible that same pixel locations show different reflectance properties during various satellite overpasses when viewed under different angles. As the multispectral change detection analysis applied in this study is solely based on differences in the observed reflectance values it is very sensitive concerning any kind of compositing artefacts. Due to that reason cloud-free images derived by compositing methods based on the selection of single pixels are of very limited use as input data for multispectral change detection analysis. This became obvious when analyzing the Surface Reflectance 8-day L3 composites of the MODIS sensor for the study area in Central Africa (Figure 1 D). The multispectral change detection resulted in a very low overall accuracy of 46%. Reasons for this poor accuracy were the artifacts derived by the mosaiking process of the composites, the remaining cloud contamination of the composites (Vermote & Vermeulen, 1999) as well as sensor errors in several bands.

Other methodologies to obtain cloud-free composites had to be applied, which show less compositing artefacts. Instead of selecting and mosaiking the reflectance values of single pixels several cloud-free observations for a single pixel with different viewing and illumination angles were combined by calculating the arithmetic average of these observations to average the reflectance values. This algorithm was described in parallel by Vancutsem et al. (2007a; 2007b) using SPOT VEGETATION and MERIS data as well as by Langner et al. (2007) using MODIS surface reflectance data. The main advantage of this method is that it reduces BRDF effects, haze and shadow artifacts considerably. To avoid unnecessary artifacts it is important not to combine images belonging to different seasons– a problematic, which is less crucial in the tropics, even though images of the dry and wet season should be treated separately due to their different effects on the vegetation. However, there were also some restrictions when applying this compositing method. Similar to the single pixel selection, this methodology also did not provide consistent dates of the images to be compared. As the pixels of the composite show the average mean of several corresponding pixels, which were obtained over a certain period of time, possible changes, which might have occurred during the time of acquisition can be obscured. The higher the amount of single images to derive the cloud-free composite, the more homogenous is the quality of the resulting composite. However, the higher amount of images also prolongates the period of image acquisition, thus losing the advantage of the multispectral change detection methodology in comparison to post classification approaches to quickly derive land cover changes. Despite of the low spatial (1 km) and spectral resolution (4 bands) the analysis of the SPOT VGT data showed a comparable high overall accuracy of over 81%. However, it was impossible to detect small scale changes as new established logging roads or areas of selective logging because of the coarse spatial resolution of 1 km. Only larger structures could be reliably detected. Though the VGT data covered the whole island of Borneo, the accuracy was only tested for the single reference site in Central Kalimantan. The visual comparison of the SPOT scenes revealed a lower quality of the composites in the mountain areas of Borneo. The frequent cloud occurrence of these areas decreased the number of available cloud-free images, which resulted in increased speckle structures using a mean composition method – a problematic which was also described by Langner et al. (2007). Such areas were especially prone to wrong assignments.

It is important to note that this kind of multispectral change detection analysis does not provide any information about the land cover type affected. Therefore, forest maps such as the GLC2000 map of Africa and Southeast Asia (Bartholomé & Belward, 2005; Mayaux *et al*., 2004; Stibig *et al*., 2007) or existing local maps have to be used to assign the underlying land cover status to the corresponding changes. However, existing large scale land cover maps still do not show that much spatial detail and local maps are often unreliable or non-existent, which necessitates the classification of the satellite data used for change detection or other data of a similar time period. This additional processing further prolongates the time to quickly recognize land cover changes.

In summary we have to state that the large-scale operational use of multispectral change detection analysis in tropical rainforests using single day imageries is not feasible due to the frequent cloud coverage in these areas. Cloud-free composites, based on single pixel selection techniques, are not usable due to compositing artefacts. Averaging composition techniques, which result in spatially more homogeneous cloud-free images with greater radiometric stability, can be used for multispectral change detection in the humid tropics. However, this technique loses its benefit of being able to quickly detect land cover changes due to the higher number of input images and thus the longer acquisition period. Due to these reasons, multispectral change detection analysis might perform better in non tropical areas with less cloud problematic. Owing to the limitations inherent to the humid tropics we regarded the concept of quickly detecting changes by applying this multispectral change detection technique as not feasible in that area in an operational way. Some further constraint of the multispectral change detection method is that it provides no information about the affected land cover type. Post classification approaches on the other hand might show better performance in detecting land cover changes in the humid tropics as they also provide information about the land cover type affected. According to our evaluation an operational application in the humid tropics, only based on this kind of multispectral change detection is not advisable but a combined product between multispectral change detection analysis and post classification approach might be more promising.

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References

Achard F, Eva HD, Stibig H-J, Mayaux P, Gallego J, Richards T, Malingreau J-P (2002) Determination of Deforestation Rates of the World's Humid Tropical Forests. *Science*, **297**, 999-1002.

Achard F, DeFries R, Eva H, Hansen M, Mayaux P, Stibig H-J (2007) Pan-tropical monitoring of deforestation. IOP Publishing, Environmental Research Letters, 2, doi:10.1088/1748-9326/2/4/045022.

Bartholomé E, Belward AS (2005) GLC2000: a new approach to global land cover mapping from Earth observation data. *International Journal of Remote Sensing*, **26**, 9, 1959–1977.

Boehm H-DV, Siegert F (2001) Ecological Impact of the One Million Hectare Rice Project in Central Kalimantan, Indonesia, using Remote Sensing and GIS, *22nd Asian Conference in Remote Sensing*, Singapore, 05-09.11.2001.

Byrne GF, Crapper PF, Mayo KK (1980) Monitoring land-cover change by principal component analysis of multitemporal Landsat data. *Remote Sensing of Environment*, **10**, 175-184.

Chavez PS, (1989) Radiometric calibration of Landsat Thematic Mapper multispectral images. *Photogrammetric Engineering and Remote Sensing*, **55**, 1285–1294.

Chavez PS, Kwarteng AY (1989) Extracting spectral contrast in Landsat Thematic Mapper image data using selective principal component analysis. *Photogrammetric Engineering and Remote Sensing*, **55**, 339-348.

Chavez PS, Mackinnon DJ (1994) Automatic detection of vegetation changes in the southwestern United States using remotely sensed images. *Photogrammetric Engineering and Remote Sensing*, **60**, 571-583.

Cihlar J (2000) Land cover mapping of large areas from satellites: status and research priorities. *International Journal of Remote Sensing*, **21**, 1093–1114.

Cohen J (1960) A coefficient of agreement for nominal scales. *Educational and Psychological Measurement*, **20**, 37–46.

Collins JB, Woodcock CE (1996) An assessment of several linear change detection techniques for mapping forest mortality using multitemporal Landsat TM data. *Remote Sensing of Environment*, **56**, 66–77.

Conghe S, Woodcock CE, Seto KC, Lenney MP, Macomber SA (2001) Classification and Change Detection Using Landsat TM Data: When and How to Correct Atmospheric Effects? *Remote Sensing of Environment*, **75**, 230-244.

Coppin PR, Bauer ME (1994) Processing of multi-temporal Landsat TM imagery to optimize extraction of forest cover change features. *IEEE Transactions on Geoscience and Remote Sensing*, **32**, 918–927.

Coppin P, Jonckheere I, Nackaerts K, Muys B (2004) Digital change detection methods in ecosystem monitoring: a review. I*nternational Journal of Remote Sensing*, **25**, 9, 1565-1596.

Defourney P, Vancutsem C, Bicheron P, Nino F, Brockmann C, Schouten L, Leroy M (2007) Towards a 300 m global land cover product – the GLOBCOVER Initiative. *Proceedings of the 2nd Workshop of the EARSeL Special Interest Group on Land Use and Land Cover*, 28-30 September 2006, Bonn, University of Bonn, Germany, 226.

Ekstrand S (1994) Assessment of forest damage with Landsat TM: correction for varying forest stand characteristics. *Remote Sensing of Environment*, **47**, 291-302.

FAO (2001) Global Forest Resources Assessment 2000 – Main Report. *FAO Forestry Paper*, **140**, ISSN 0258-6150.

Foody GM (2001) Status of land cover classification accuracy assessment. *Remote Sensing of Environment*, **80**, 185–201.

Foody GM, Palubinska G, Lucas RM, Curran PJ, Honzak M (1996) Identifying terrestrial carbon sinks: classification of successional stages in regenerating tropical forest from Landsat TM data. *Remote Sensing of Environment*, **55**, 205–216.

Friedl MA, McIver DK, Hodges JCV et al. (2002) Global land cover mapping from MODIS: algorithms and early results. *Remote Sensing of Environment*, **83**, 287–302.

Fuller DO, Jessup TC, Salim A (2003) Loss of forest cover in Kalimantan, Indonesia, since the 1997–1998 El Niño. *Conservation Biology*, **18**, 249–254.

Fuller DO (2006) Tropical forest monitoring and remote sensing: A new era of transparency in forest governance? Singapore Journal of Tropical *Geography*, **27**, 15-29.

Fung T, Ledrew E (1987) Application of principal components analysis to change detection. *Photogrammetric Engineering and Remote Sensing*, **53**, 1649-1658.

Green K, Kempka D, Lackey L (1994) Using remote sensing to detect and monitor land-cover and land-use change. *Photogrammetric Engineering and Remote Sensing*, **60**, 331-337.

Hansen MC, DeFries RS, Townshend JRG, Carroll M, Dimiceli C, Sohlberg R (2003) Global percent tree cover at a spatial resolution of 500 meters: first results of the MODIS vegetation continuous field algorithm. *Earth Interactions*, **7**, 1–15.

Ingebritsen SE, Lyon RJP (1985) Principal components analysis of multitemporal image pairs. *International Journal of Remote Sensing*, **6**, 687-696.

Jiaju L (1988) Development of principal component analysis applied to multitemporal Landsat TM data. *International Journal of Remote Sensing*, **9**, 1895-1907.

Kriegler FJ, Malila WA, Nalepka RF., Richardson W (1969) Preprocessing transformations and their effects on multispectral recognition. Proceedings of the Sixth International Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, MI, 97-131.

Langner A, Miettinen J, Siegert F (2007) Land cover change 2002 – 2005 in Borneo and the role of fire derived from MODIS imagery, *Global Change Biology*, **13**, 11, 2329-2340 (12).

Liang S, Fallah-Adl H, Kalluri S, JaJa J, Kaufman YJ, Townshend JRG (1997) An operational atmospheric correction algorithm for Landsat Thermatic Mapper imagery over the land. *Journal of Geophysical Research*, **102**, 173–186.

Lillesand TM, Kiefer RW, Chipman JW (2004) Remote sensing and image interpretation, 5th Edition, *John Wiley & Sons Ltd*, ISBN 0-471-15227-7.

Mackinnon A (2000) A spreadsheet for the calculation of comprehensive statistics for the assessment of diagnostic tests and inter-rater agreement. *Computers in Biology and Medicine*, **30**, 3, 127-134.

Mas J-F (1999) Monitoring land-cover changes: a comparison of change detection techniques. *International Journal of Remote Sensing*, **20**, 139-152.

Mayaux P, Bartholomé E, Fritz S, Belward A (2004) A new land-cover map of Africa for the year 2000. *Journal of Biogeography*, **31**, 861–877.

Mayaux P, Holmgren P, Achard F, Eva H, Stibig H-J, Branthomme A (2005) Tropical forest cover change in the 1990s and options for future monitoring. *Philosophical Transactions of the Royal Society*, **360**, 373-384.

Michener WK, Houhoulis PF (1997) Detection of vegetation changes associated with extensive flooding in a forested ecosystem. *Photogrammetric Engineering and Remote Sensing*, **63**, 1363–1374.

Muchoney DM, Haack BN (1994) Change detection for monitoring forest defoliation. *Photogrammetric Engineering and Remote Sensing*, **60**, 1243-1251.

Rieley JO, Page SE (2005) Wise Use of Tropical Peatland: Focus on Southeast Asia. ALTERRA - Wageningen University and Research Centre and the EU INCO - STRAPEAT and RESTORPEAT Partnership. ISBN 90327-0347-1. *Report*.

Richards JA (1984) Thematic mapping from multitemporal image data using the principal components transformation. *Remote Sensing of Environment*, **16**, 35-46.

Rouse JW, Haas RH, Schell JA, Deering DW (1973) Monitoring vegetation systems in the Great Plains with ERTS, Third ERTS Symposium, NASA SP-351, 1, 309-317.

Schott JR, Salvaggio C, Volchok WJ (1988) Radiometric scene normalization using pseudoinvariant features. *Remote Sensing of Environment*, **26**, 1–16.

Singh A (1986) Change detection in the tropical forest environment of northeastern India using Landsat. *Remote sensing and tropical land management*, 237-254.

Singh A (1989) Digital change detection techniques using remotely-sensed data. *International Journal of Remote Sensing*, **10**, 6, 989-1003.

Spanner MA, Pierce LL, Peterson DL, Running SW (1990) Remote sensing of temperate coniferous forest leaf area index: the influence of canopy closure, understory vegetation and background reflectance. *International Journal of Remote Sensing*, **11**, 95–111.

Stibig H-J, Belward AS, Roy PS, Rosalina-Wasrin U, Agrawal S, Joshi PK, Hildanus, Beuchle R, Fritz S, Mubareka S, Giri C (2007) A land-cover map for South and Southeast Asia derived from SPOTVEGETATION data. *Journal of Biogeography*, **34**, 625–637.

Sylvander S, Henry P, Bastien-Thiry C, Meunier F, Fuster D (2000) VEGETATION Geometrical Image Quality. *Proceedings of the VEGETATION 2000 conference*, Belgirate, Italy, 3–6 April 2000, Saint, G.Ed, CNES, Toulouse & JRC, Ispra, 33–44; http://www.spotvegetation.com.

Vancutsem C, Bicheron P, Cayrol P, Defourney P (2007a) An assessment of three candidate compositing methods for global MERIS time series. *Canadian Journal of Remote Sensing*, **33**, 6, 492-502.

Vancutsem C, Pekel J, Bogaert P, Defourney P (2007b) Mean compositing, an alternative strategy for producing temporal synthesis. Concepts and performance assessment for SPOT VEGETATION time series. *International Journal of Remote Sensing*, **28**, 22, 5123-5141.

Vermote EF, Vermeulen A (1999) MODIS Algorithm Technical Background Document ATMOSPHERIC CORRECTION ALGORITHM: SPECTRAL REFLECTANCES (MOD09). *NASA contract NAS5-96062, University of Maryland, Dept of Geography*, Version 4.0, April 1999.

Weismiller RA, Kristof SJ, Scholz DK, Anuta PE, Momin SA (1977) Change detection in coastal zone environments. *Photogrammetric Engineering and Remote Sensing*, **43**, 1533-1539.

Yuan D, Elvidge CD, Lunetta RS (1999) Survey of multispectral methods for land cover change analysis. *Remote sensing change detection. Environmental monitoring methods and applications*, 21-39.

5.2 Chapter II

Land cover change 2002–2005 in Borneo and the role of fire derived from MODIS imagery

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Abstract

Borneo has experienced heavy deforestation and forest degradation during the past two decades. In this study the Moderate Resolution Imaging Spectroradiometer was used to monitor land cover change in Borneo between 2002 and 2005 in order to assess the current extent of the forest cover, the deforestation rate and the role of fire. Using Landsat and ground observation for validation it was possible to discriminate 11 land cover classes. In 2002 57% of the land surface of Borneo was covered with forest of which 74% was dipterocarp and more than 23% peat swamp forest. The average deforestation rate between 2002 and 2005 was 1.7% yr^{-1}. The carbon-rich ecosystem of peat swamp forests showed a deforestation rate of 2.2%. Almost 98% of all deforestation occurred within a range of 5 km to the forest edge. Fire is highly correlated with land cover changes. Most fires were detected in degraded forests. Ninety-eight per cent of all forest fires were detected in the 5 km buffer zone, underlining that fire is the major driver for forest degradation and deforestation.

Keywords: deforestation, fire, forest degradation, hotspots, Indonesia, land cover change, MODIS, peat swamp forest, rainforest, Southeast Asia

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Introduction

The world's humid tropical forests are under considerable pressure, resulting in high deforestation rates and increasing degradation of pristine forests. The global rate of tropical forest loss is about 0.52% yr^{-1} and with 0.91% it is highest in Southeast Asia (FAO, 2000; Achard *et al*., 2002). Major causes for deforestation in Southeast Asia are the expansion of agricultural activities, the conversion of forests into oil palm and pulp wood plantations and the degradation of pristine forests due to logging (Thompson, 1996; Casson, 1999; WRM, 2000; Curran *et al*., 2004). In their study, Geist and Lambin detected large-scale timber extraction, agricultural expansion and infrastructure development as the major drivers of tropical deforestation (Geist & Lambin, 2002). Illegal logging increased dramatically in Indonesia since the end of 1998 after the fall of the Soeharto regime (Casson & Obidzinski, 2002; Dudley, 2004). Transmigration to the Indonesian part of Borneo and poorly planned development projects such as the Mega Rice Project (MRP) (Sunderlin, 1999) strongly contributed to the loss of natural forest ecosystems and resulted in increased fire activity by shifting cultivation activities (Hoffmann *et al*., 1999; Jepson *et al*., 2001; Page *et al*., 2002; Dennis *et al*., 2005). Several studies have shown that fire is the most important factor accelerating forest degradation and deforestation in the tropics, in particular in the Amazon and Southeast Asia (Siegert & Hoffmann, 2000; Siegert *et al*., 2001; Page *et al*., 2002; Cochrane, 2003).

Because the land area under threat of deforestation is vast and often inaccessible on the ground, satellite remote sensing is the only way of assessing land cover change and deforestation on a regional scale. Low- and moderate-resolution satellite data such as National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer (NOAA AVHRR), Satellite Pour l'Observation de la Terre (SPOT VEGETATION), MODIS and MEdium Resolution Imaging Spectrometer (MERIS) have been widely used for regional and global forest cover mapping surveys (Malingreau *et al*., 1989; Achard & Estreguil, 1995; Mayaux *et al*., 1998; Eva *et al*., 1999; DeFries *et al*., 2000; Loveland *et al*., 2000; Fuller *et al*., 2003). Sensors with high spatial resolution such as the Enhanced Thematic Mapper Plus (ETM1), SPOT High-Resolution Visible Infrared (HRVIR) or Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) allow much more detailed forest cover assessments [e.g. the Tropical Ecosystem Environment Observations by Satellites (TREES) studies initiated in the early 1990s (Achard *et al*., 2002)]. However, their swath is narrow and the orbit repeat cycle of 20 days and less is of limited use in humid tropical regions as a result of high cloud cover. On the other hand, low-resolution systems such as NOAA AVHRR or SPOT VEGETATION sensors with 1 km spatial resolution provide daily coverage, which is required to manage the cloud problem, but their low spatial resolution limits the ability to resolve land cover details. A good compromise is offered by medium resolution sensor systems such as MERIS and MODIS with 300 and 250/500m spatial resolution, respectively (Cihlar, 2000; Fuller, 2006; Huang & Siegert, 2006). In addition to an improved spatial and spectral resolution, these satellites also have a better sub-pixel geometric registration with superior calibration, cloud screening and atmospheric correction (Friedl *et al*., 2002; Fuller, 2006).

So far there are few studies investigating change detection using medium-resolution MODIS/MERIS imagery as the Vegetation Cover Conversion (VCC) product (Zhan *et al*., 2002; Hansen *et al*., 2003) or the MODIS land cover and land cover change product (Zhan *et al*., 2000). The objective of our study was to investigate the current forest cover in Borneo and its changes between 2002 and 2005 using multitemporal MODIS image composites. We focused on the island of Borneo because it still has the largest remaining area of tropical rainforest in Southeast Asia and at the same time these forests are under severe pressure by logging and fire. Borneo is representative for many processes leading to deforestation processes in the region (Achard *et al*., 2002; Fuller, 2006; Trigg *et al*., 2006). In addition, Borneo has a large variety of unique rainforest ecosystems ranging from mangrove forests along the coast, large areas of peat swamp forests in the alluvial flats and freshwater non peaty swamps, heath forests, lowland dipterocarp forests and various mountain forests ecosystems (MacKinnon *et al*., 1996). We investigated the suitability of MODIS to monitor land cover change and forest degradation because forest degradation is a strong indicator for future deforestation (Asner *et al*., 2005). We investigated different methods to obtain cloud-free image composites from multitemporal MODIS images. In contrast to other studies, we also tried to increase the number of different land cover types such as different forest ecosystems and to discriminate different stages of forest degradation. Finally, we used hotspots detected by MODIS to analyze the role of fire in the loss of forest and forest degradation.

Materials and methods

Study area

The island of Borneo covers more than 746,000km^2. It is the third largest island in the world and the largest land mass in the Sunda Region. Almost three quarters of the island is Indonesian territory, known as Kalimantan; the rest is shared by Malaysia and the independent sultanate of Brunei Darussalam. The climate of Borneo is characterized by frequent rainfall and high temperatures throughout the year. The pattern of rainfall is linked to the 'dry' southeast monsoon from May to October and the 'wet' northwest monsoon from November to April. Until the 1950s almost the whole island was covered by tropical evergreen rain forest consisting mainly of species of the Dipterocarp family of which many are valuable timber species (MacKinnon *et al*., 1996). Besides the well-known lowland rainforest, there exist several other types of rainforest, each of them characterized by a high degree of endemic species. 'Kerangas' or heath forests grow on extremely nutrient-poor and acid substrates. Carbon-rich peat swamp forests are mainly located in the coastal and sub-coastal lowlands of Borneo, while freshwater swamps are found along rivers inland. Mangrove forests grow next to the shore line and cover coastal plains. All natural ecosystems are under pressure by over-exploitation and fire (Page *et al*., 2002; Brook *et al*., 2003; Curran *et al*., 2004; Sodhi *et al*., 2004; van Nieuwstadt & Sheil, 2005; Trigg *et al*., 2006).

Satellite data

The MODIS sensor is mounted on two satellites systems, Terra and Aqua, which pass the equator at 10:00 and 13.30 hours every day.

Table 1. Characteristics of MODIS Surface Reflectance bands

Band	Wavelength (nm)	Resolution (m)
1	620 – 670	250
2	841 – 876	250
3	459 – 479	500
4	545 – 565	500
5	1,230 – 1,250	500
6	1,628 – 1,652	500
7	2,105 – 2,155	500

The MODIS L2G daily surface reflectance product (MOD09GHK/MYD09GHK for the 500m bands and MOD09GQK/MYD09GQK for the 250m bands) (Table 1) provides measurements of the surface spectral reflectance for each band as it would be measured at ground level in the absence of atmospheric scattering or absorption. The data were downloaded from the EOS Data Gateway with bands 1 and 2 in 250m resolution and bands 3–7 in 500m spatial resolution at nadir.

Compositing algorithm

To obtain images suitable for land cover classification, cloud-free composite images had to be created. For 2002, 57 images collected over a 1-year period from November 2001 to October 2002, and for 2005, 60 images collected between January 2005 and June 2005 were used. Images dating from the dry season showed less cloud cover but were more affected by smoke and haze. In 2002 we only used images from the Terra satellite whereas in 2005 both Aqua and Terra data were used over a shorter period of data acquisition. Owing to the high evaporation rates of tropical forests, large fractions of the images were covered by clouds. Therefore, it was necessary to select this high number of single images for each composite. Furthermore, due to the sensor's characteristics, off-nadir pixels show a reduced spatial resolution and wrong spectral values [bowtie effect due to MODIS whisk broom sensor (Gomez-Landesa *et al.*, 2004)]. The most appropriate images were selected by visual inspection to minimize off-nadir effects and unfavorable cloud conditions (haze and scattered clouds). More than 300 images were rejected for the 2005 composite.

Table 2. Set of rules for cloud, haze and sensor error detection

Condition
1) band n = -28,672
2) band 3 (459 nm – 479 nm) = 0
3) band 3 (459 nm – 479 nm) ≥ 500
4) band 1 (620 nm – 670 nm) ≥ band 2 (841 nm – 876 nm)

Before running the compositing algorithm, an empirically derived set of rules was applied to mask out pixels showing clouds, haze and all kinds of sensor errors. These rules were derived by analyzing in detail the spectral characteristics of the land cover classes to be distinguished in comparison with clouds, haze, cloud shadows and apparent sensor errors. A pixel was rejected if at least one of four conditions was met (Table 2). Condition 1: Pixels in any band showing the value -28 672 (off-nadir pixels or water areas in the surface reflectance products are masked with the value -28 672 by the MODIS science team). Condition 2: Pixels in band 3 showing the data value 0 (sensor errors in band 3 where regions of pixels in band 3 exhibit the value 0 but the other bands show normal reflectance values). Condition 3: Band 3 is sensitive to the blue spectrum of the light, thus being most appropriate for cloud detection. For automated cloud removal a threshold above 500 in band 3 was applied, which was derived by empirically analyzing all images of the 2002 period. Condition 4: Normally in areas of dense vegetation the reflectance value in the NIR wavelength is much higher compared with the reflectance in the red wavelength. Some areas in undisturbed forests in a couple of images showed sensor errors where the reflectance value in band 1 (red wavelength) was higher than the value in band 2 (NIR wavelength). These pixels were removed as well.

All four conditions were combined in a single mask for each image. By evaluating all masks it was possible to calculate the number of useful images per pixel-location. This value was used to calculate the arithmetic mean of each pixel-location.

To create the final composite images, all 500m resolution bands were resampled to 250m spatial resolution using cubic convolution to make use of the higher spatial resolution of the two original 250m bands (red and NIR). After masking out all unwanted pixels that were not suitable for compositing while preserving the useful image information, the mean of each cloud-free pixel-location was calculated. After this step there were still some pixels in the final composites left that were contaminated by slight haze. These single pixel errors were eliminated by a median filtering process with a kernel size of 3x3 pixels.

The seven reflective bands in MODIS are similar to the Landsat ETM+ bands in their spectral properties (Jensen, 2000; Turner *et al*., 2001). Land cover maps based on seven evaluated Landsat images distributed across Borneo served as training sites for classification (Boehm & Siegert, 2001; Boehm *et al*., 2001). The Landsat classification was based on the TRopical Ecosystem Environment observations by the Satellite (TREES) classification scheme: each forest type is divided into four categories: closed high-density forest, closed medium-density forest, open and fragmented forest canopy. Only the first two categories with a crown cover of more than 40% were regarded as forest in this study.

Land cover classification

For the 2002 composite, only bands 2, 5, 6 and 7 were used in the classification process because the other bands had severe sensor errors. For the 2005 composite, all seven bands could be used. Comparing the classification results of unsupervised and supervised classification approaches we obtained better results using the unsupervised ISODATA algorithm. In his study Cihlar showed that for mapping large areas with little ground truth reference data, the unsupervised classification approach is best fitting because no prior information about the land cover types and their distribution is required and the classification algorithm purely relates on spectral characteristics (Cihlar, 2000). The original 100 clusters produced by the unsupervised ISODATA classification (100 iterations) were reassigned into eight different classes using field data, Landsat-based land cover maps and visual interpretation.

The Shuttle Radar Topography Mission (SRTM, http://srtm.usgs.gov/) 90m resolution elevation data were used to discriminate lowland forest from forests in higher altitudes (800–1200 m), which were assigned to upper dipterocarp forests, and those above 1200 m, which were assigned to mountain forests. These forests were otherwise difficult to discriminate.

Validation and accuracy assessment

Owing to lack of any reference data, the 2002 land cover map was validated using 18 Landsat ETM+ images covering all ecological zones of Borneo. The validation was carried out by visual interpretation of 650 randomly selected points. Each land cover class (except water) was validated using 50 randomly selected locations across the island of Borneo and an additional 150 points (corresponding to 30% of 500) to take into account the varying extent of the different land cover types. The combination of these two sampling methods also incorporates the spatial complexity of the landscape, which has major impact on map accuracy (Mayaux *et al*., 2006). In the case of ancillary data about the distribution of the different land cover types (e.g. peat swamp forests would have been available for whole Borneo), this data would have been used as reference data applying the same sampling method. The smallest land cover feature identified in the Landsat scenes was 7 ha corresponding to single MODIS pixel. Finally, the overall accuracy and the k coefficient accommodating for effects of chance agreement (Foody, 2001) of the land cover classification and the discrimination between forest and non-forest were determined. The producer's and user's accuracy was calculated to determine the accuracy of individual land cover types. Slight and severe errors in instance of incorrect allocations were discriminated. Severe errors were pixel locations in the map showing no forest cover but which were forests in the Landsat images and vice versa. Wrong assignments of different forest types (e.g. confusion between pristine and degraded forest classes) were considered as slight errors.

Active fire detection and patterns of deforestation

The MODIS sensor is a well-established system to detect active fires (Justice *et al.*, 2002) at a spatial resolution of 1 km. To analyze the role of fire in land cover change, and especially deforestation, we used all MODIS hotspots acquired during the two MODIS acquisition periods 2002 and 2005. In order to calculate the fire-affected area the hotspot data were buffered with a 1km2 buffer and intersected with the land cover maps of 2002 and 2005. The area of overlapping hotspots was considered burnt only once. It is important to note that the hotspots of 2005 were analyzed on a land cover map, which was derived before the start of the actual fire season of 2005. To investigate the spatial pattern of fire in relation to forest edges, all forest areas were buffered inwards with either a 1km or a 5km buffer. Degraded forests were regarded as non-forested areas. The percentage of hotspots in forests occurring within these buffer zones was analyzed. To study the spatial pattern of deforestation, we also examined the percentage of forest loss in these buffer zones.

Results

Multitemporal composite images

After preliminary tests with the MODIS 8-day composites downloaded from the EOS Data Gateway, we decided to use the MODIS single-day reflectance product because these images contained less-artificial heterogeneity of reflectance values related to BRDF and haze than the MODIS 8-day composites in which cloud-free pixels from different viewing angles are combined using the minimum-value rule (Cihlar, 2000; Fuller *et al.*, 2003). If there were several cloud-free observations for a single pixel with different viewing and illumination angles, we calculated the arithmetic average of these observations to average reflectance values. This significantly improved the result. Such a procedure is feasible for Borneo because seasonal variation of reflectance values is very small in the humid tropics. We found that this algorithm reduced BRDF and atmospheric artifacts significantly resulting in cloud-free and spatially homogeneous composite images over Borneo (Figure 1A and B).

Figure 1E and F shows the number of cloud-free images per pixel-location in the 2002 composite. Although 57 images were used for the 2002 composite, the maximum number of cloud-free images per pixel-location was 42 and 3750 ha (about 0.005% of total area of Borneo) were permanently covered by clouds. The number of available cloud-free observations per pixel-location was correlated to geomorphologic structures. Images from Terra were typically less contaminated by clouds because of an earlier overpass time. At later time frequently cumulus clouds form due to the high evaporation levels in the humid tropics.

Using the multitemporal composites it was possible to discriminate eight different land cover classes, which were refined using SRTM elevation data, resulting in 11 types of different land cover (Table 3 and Figure 1C and D). Forests were separated in 6 different types.

Table 3. Land cover types and derived classes from ancillary data

Land cover classes derived from ISODATA classification	Lowland Forest (> 40% crown cover)
	Degraded Forest (≤ 40% crown cover) and Regrowth
	Peat Swamp Forest
	Mangrove Forest
	Cultivation Forest Mosaic
	Dry/Wet bare Soil; Grasslands; Agriculture
	Crab Ponds
	Water
Land cover classes derived by modifications using SRTM elevation data	Upper Dipterocarp Forest (800 m < forest ≤1,200 m)
	Mountain Forest (forest > 1,200 m)
Land cover class derived by manual modifications	Freshwater Swamp Forest

Land cover in 2002 and 2005

In 2002 lowland dipterocarp forests covered 59.5% of the island's forest area, followed by the peat swamp forests with 23.6%. The remaining forest types consisted of upper dipterocarp forests (almost 10.8%), mountain forests (4.0%), 1.9% of mangrove forests and a small fraction of freshwater swamp forests. In 2005, we obtained very similar results in comparison with the 2002 forest area. Some decrease in the classes of lowland dipterocarp forests (56.2%), upper dipterocarp forests (10.6%), peat swamp forests

(22.0%) and mangrove forests (1.5%) could be monitored whereas mountain forests showed a slight increase (4.4%).

Degraded forests were defined to have a crown cover of less than 40% and also include forest mosaics and forest regrowth. Cultivation forest mosaics integrate a complex pattern of slash-and-burn fields and fallow land with bushes and regenerating forest. The class of dry/wet bare soil, grasslands and agriculture combines a variety of bare soil, urban areas and low vegetation types such as grasslands, bushes and freshly cleared land. The spatial resolution did not allow further refining this land cover class. The areas of all land cover types in 2002 and 2005 are shown in Table 4.

We assumed the validation of the 2002 land cover result to be sufficient because this result in turn served as training data in the ISODATA classification for the 2005 classification and as base map to compare with the 2005 result for deriving the land cover changes. The overall accuracy of the 2002 land cover map was 84.8% with a k coefficient of 0.8290. Of the total, 8.1% were slight errors and 7.1% were severe errors. Forest - non-forest maps were produced by combining all forest types into the forest class whereas all disturbed forests, agriculture and bare soil were combined into non-forests. The overall accuracy of the 2002 forest - non-forest map was 89.2% with a k coefficient of 0.7789 and the map showed that about 57% of Borneo was covered by forest.

Table 4. Land cover and change detection statistics from 2002 to 2005

	2002 (ha)	2005 (ha)	Annual change
Mangrove Forest	804,463	613,269	-7.92%
Freshwater Swamp Forest	85,088	90,813	2.24%
Peat Swamp Forest	9,893,231	9,228,638	-2.24%
Lowland Forest (> 40% crown cover)	24,925,694	23,553,588	-1.83%
Upper Dipterocarp Forest (800 m < forest ≤1,200 m)	4,512,075	4,435,425	-0.57%
Mountain Forest (forest > 1,200 m)	1,676,356	1,825,344	2.96%
Degraded Forest (≤ 40% crown cover) and Regrowth	15,228,238	14,343,831	-1.94%
Cultivation Forest Mosaic	13,219,144	16,671,681	8.71%
Dry/Wet bare Soil; Grasslands; Agriculture	2,726,406	2,188,775	-6.57%
Crab Ponds	275,188	289,944	1.79%

Land cover change 2002–2005

In addition to the land cover statistics for 2002 and 2005, Table 4 shows the results of the change assessment between these 2 years. Altogether more than 18Mha showed changes in the land cover without taking into account the areas where some kind of reforestation occurred. More than 7 Mha were degraded or deforested. Cultivation forest mosaics increased most significantly, mainly owing to further degradation of previously degraded forests. Mangrove forests showed the highest deforestation rate (almost 8%yr^{-1}) mainly due to conversion into crab ponds. The area of peat swamp declined at a rate of more than 2.2% yr^{-1}, while lowland forests had a deforestation rate of 1.8% yr^{-1}. The overall rate of forest loss amounted to 1.7% yr^{-1}.

Besides the change in area, the spatial pattern of change might give important clues about the underlying causes of deforestation. We examined the proportion of deforestation that occurred in a buffer zone of 5 km along the forest outskirts since this area is most easily accessible by farmers and illegal loggers. Our analysis showed that 97.7% of all forest conversion/degradation between 2002 and 2005 occurred in this zone (Figure 2A and B).

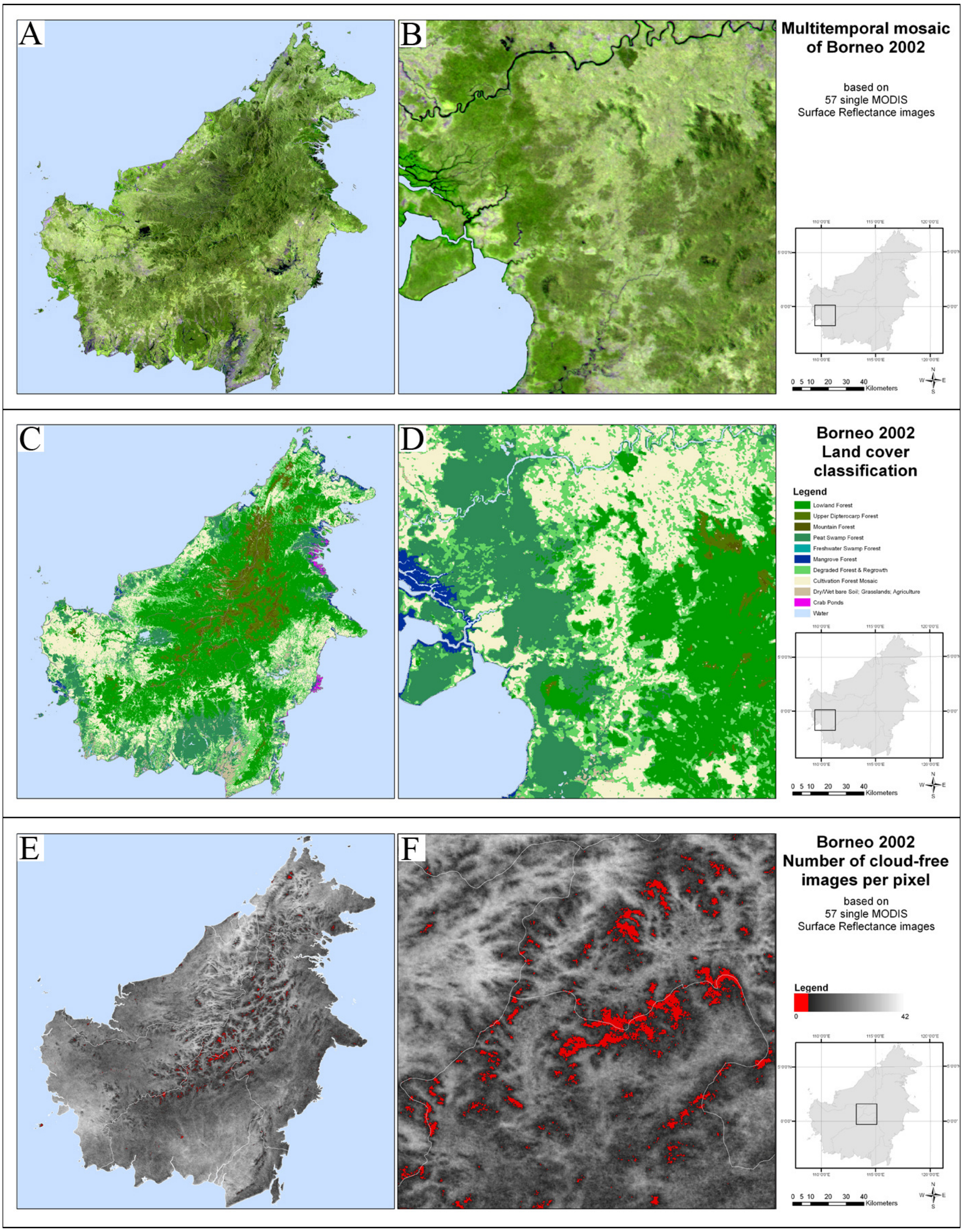

Figure 1:

(A, B) Multitemporal composite of Borneo based on 57 single MODIS Surface Reflectance images obtained in 2002. The subset on the right hand side shows an area in West Kalimantan with some mangrove forest in bright green color, peat swamp forest (further inland) in lush green and the lowland forest in paler green color (on the right

hand side). The area in light grey color is cultivation forest mosaic.
(C, D) Land cover map of Borneo based on MODIS data dating from 2002 with a subset of an area in West Kalimantan.
(E, F) Number of cloud-free images per pixel-location for the 2002 MODIS composite. Values are displayed from black (low number of cloud-free images) to white (high number of cloud-free images). Pixel-locations with 5 or less available cloud-free images were displayed in red because these low values resulted in less homogenous signals.

Land cover change and fire

We started our investigation on the role of fire in land cover change and deforestation by analyzing the spatiotemporal pattern of all hotspots recorded in both 2002 and 2005 regarding the corresponding land cover classifications. In total 44,656 hotspots were detected in 2002, which potentially affected an area of 2.9Mha of which 0.8Mha was forest. In 2005 the number of hotspots amounted to 15,322, potentially affecting an area of 1.1 Mha of which 0.2Mha was forest. Table 5 shows that in 2002, degraded forest and regrowth were the most strongly affected land cover type with more than 33%, followed by cultivation forest mosaics with more than 25%. In 2005, on the other hand, cultivation forest mosaics were most severely affected with 37% followed by degraded forests with 27% of all fire-affected areas. Most fires are linked to the seasonal land clearing activities of shifting cultivators.

Table 5. Distribution of fire-affected area into land cover types

Land cover class	2002 (in %)	2005 (in %)
Mangrove Forest	0.3	0.1
Peat Swamp Forest	20.2	10.7
Degraded Forest ≤ 40% crown cover and Regrowth	33.4	27.1
Cultivation Forest Mosaic	25.3	37.1
Dry/Wet bare Soil; Grasslands; Agriculture	13.5	16.4
Lowland Forest (> 40% crown cover)	6.7	8.1
Upper Dipterocarp Forest	0.1	0.2
Freshwater Swamp Forest	0.5	0.2
Mountain Forest	0	0

Most of the forest fires occurred in the carbon-rich peat swamp forests with 73% (591,816 ha) and 55% (120,377 ha), respectively, for 2002 and 2005 even though the total area of peat swamp forests is less than half of the area of lowland dipterocarp forests. It must be pointed out, however, that forest fires form a minority of all detected hotspots. This can be clearly seen in Table 6, which shows the frequency of fires in relation to forest degradation levels.

Table 6. Distribution of fires in relation to forest degradation

Land cover cluster	2002 (in %)	2005 (in %)
Pristine Forest types	27.8	19.3
Degraded Forest (≤ 40% crown cover) and Regrowth	33.4	27.1
Cultivation Mosaic; Dry/Wet bare Soil, Grasslands, Agriculture	38.8	53.6

Further examination of the spatial distribution of forest fires showed that they were mostly located close to the forest edges (Figure 2C and D). We investigated the spatial pattern of fire occurrence in forests in two different buffer zones: 1 and 5 km from the forest edge. The results were very clear: in 2002, 75% and 98% of all fires detected in undisturbed forests were within a 1 or 5 km distance of the forest edge. In 2005, it was even more evident. Almost 81% and 99%, respectively, occurred within the 1 and 5 km buffer zone.

In order to study the impact of fire on land cover change, we analyzed all hotspots recorded between November 2002 and December 2004 excluding all fires that occurred during the periods when the images for the composites were acquired to make sure that only hotspots were analyzed, which might be responsible for the land cover changes. In total 44,869 hotspots were detected affecting 3.1Mha of Borneo. This area was then intersected with the change map, showing that during this period 50% (22,412) of all fires occurred in areas with land cover change, mainly on agricultural areas, and 20% (8,967) of the hotspots were detected in areas that experienced deforestation during this period of time.

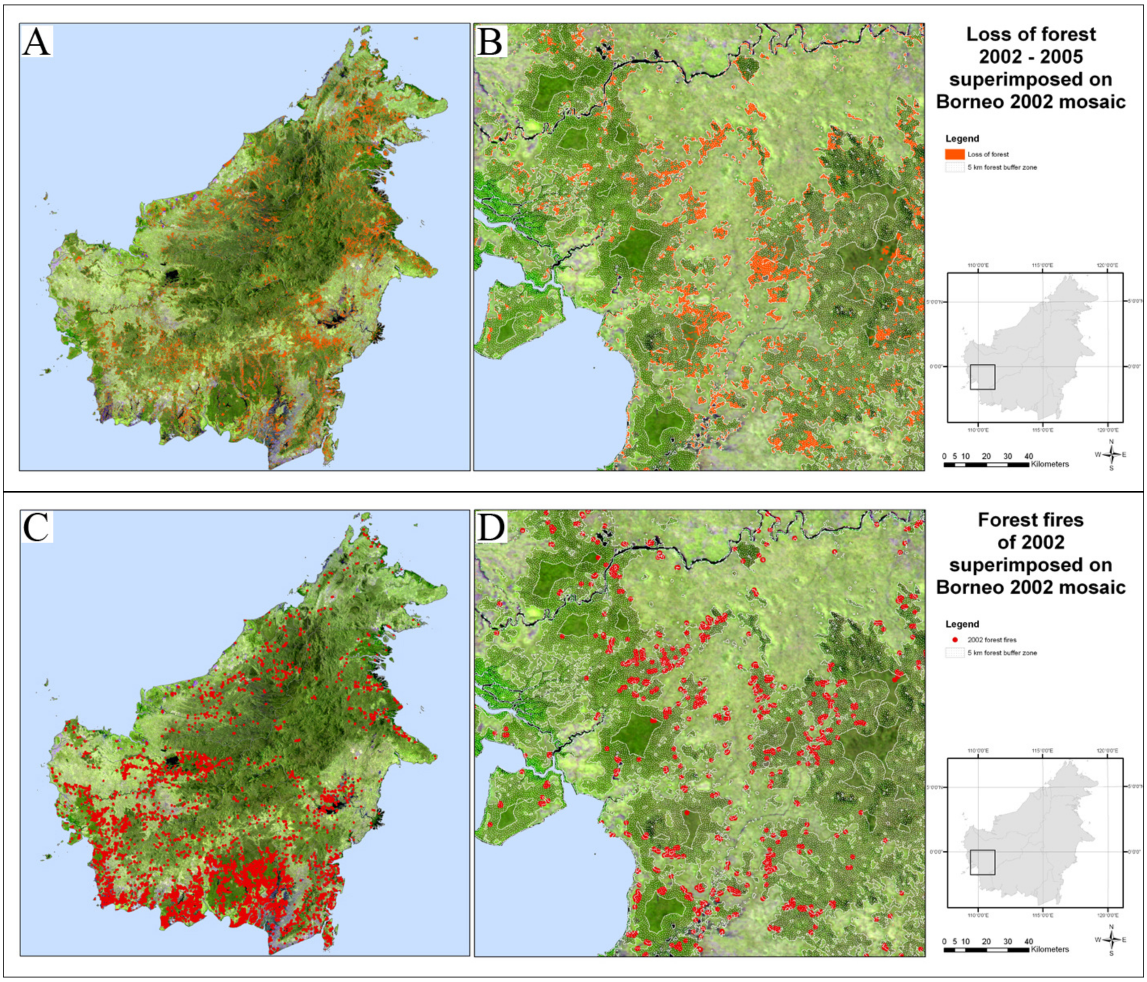

Figure 2:
(A, B) Loss of forest between 2002 and 2005, superimposed on 2002 MODIS multitemporal composite. Forest loss clearly occurs next to forest edges and fragmented forest mosaics (marked with 5km buffer zone to forest edges).
(C, D) Forest fires of 2002, superimposed on 2002 MODIS multitemporal composite. Forest fires clearly occur next to forest edges and fragmented forest mosaics (marked with 5km buffer zone to forest edges).

Discussion and conclusion

The results of this study showed that an average compositing method can be successfully used to create cloud-free MODIS composites for land cover mapping purposes over Borneo. The main advantage of this method is that it reduces the BRDF effects, haze and shadow artifacts. Artificial heterogeneity caused by these effects often complicate the interpretation of composite images produced using methods that select single pixels among the candidates: e.g. the MODIS 8 day composites (Hansen *et al.*,

2003) or the SPOT VGT composite of Southeast Asia (Stibig & Malingreau, 2003). We found that this multitemporal averaging process results in spatially more homogeneous cloud-free composites with great radiometric stability in this humid tropical region, thus enabling more reliable change detection between different years. It must be noted, however, that averaging has the disadvantage of blurring the changes in spectral characteristics over time. Therefore, it is important that the observed area does not show significant seasonal changes during the compositing period. This is typically the case for the tropical vegetation of Borneo. The combination of this compositing algorithm and the 250m spatial resolution of the MODIS sensor made it even possible to identify areas of intense selective logging in the Malaysian part of Borneo.

The overall accuracy of the 2002 base map with 11 classes (84.8%) almost reached the commonly recommended 85% target (Foody, 2001). The forest - non-forest detection accuracy of 89.2% with a k coefficient of 0.7789 is comparable to other published results (Fuller *et al.*, 2003). Fuller and Murphy were able to discriminate six different land cover classes over Southeast Asia with an overall accuracy of 83% using 32-day MODIS composites (Fuller & Murphy, 2005). In this study we were able to discriminate 11 land cover classes, which is a significant improvement demonstrating the potential of the compositing method used in this study. The comparison of our result with the GLC2000 map resulted in an overall agreement of 74%. It must be remembered, however, that the GLC2000 map was derived from satellite images collected between 1998 and 2000 whereas the MODIS images were acquired in 2002. The most significant differences were found in the spatial distribution of peat swamp and mangrove forests whose spatial extents are underestimated in the GLC2000 map. This can be attributed to the fact that the GLC2000 team used ancillary GIS/map data to discriminate the two classes whereas our classification is based on different spectral properties of the two forest types.

The deforestation rate in Borneo between 2002 and 2005 was 1.7% yr^{-1}. This is almost double compared with the annual deforestation rate of the whole Southeast Asian region of 0.91% (Achard *et al.*, 2002), which already is higher than the corresponding figures for Africa or Latin America. Other studies showed that illegal logging has increased tremendously in the past years in Borneo (MacKinnon *et al.*, 1996; Boehm & Siegert, 2001; Casson & Obidzinski, 2002; Page *et al.*, 2002; Dudley, 2004). Our analysis showed that most changes were related to overexploitation of forests and forest conversion. For example, mangrove forests showed a deforestation rate of almost

8%yr^{-1} and further investigation on high-resolution Landsat images revealed that large areas had been converted to crab ponds in the past years. The accurate mapping of peat swamp forests was emphasized because this ecosystem is a carbon sink/source of global importance (Page *et al.*, 2002). These peat swamp forests were cleared or degraded at a rate of 2.2% yr^{-1}. Lowland forests were decreasing at a rate of more than 1.8% yr^{-1} while the more-remote upper dipterocarp forests showed only 0.6% loss per year. Degraded forests and cultivated lands already cover almost half of all the land area.

It has to be noted, however, that reforestation was also observed in some areas. Regrowth would not result in mature forests in only 3 years, but the vegetation can grow considerably in size (up to several meters), which then appears similar in spectral reflectance as more mature forests. This way the increase in mountain forests in Sarawak of almost 3%yr^{-1} could be explained where intense selective logging activities opened the crown cover in 2002, resulting in higher soil signal. In 2005 the crown cover seemed to be less disturbed due to regrowing vegetation. A great proportion of the class regrowing forests were found on peat lands. This also includes fern and shrub regrowth on old burnt scars.

The spatiotemporal analysis of the high deforestation rates provided increased evidence that fire plays an extraordinary and complex role in deforestation. Between November 2002 and December 2004 the MODIS sensors detected 44,869 hotspots in Borneo. Half of all hotspots (22,412) occurred on areas with land cover change, mainly agricultural fires. Almost 20% of the hotspots (8,967) were found in areas of severe deforestation revealing a high level of human impact on the ecology of Borneo. According to MacKinnon, slash and burn techniques have a long history in Southeast Asia (MacKinnon *et al.*, 1996). In general these techniques are considered sustainable if the time period between the burning events is long enough. The problem is not the fire itself but the use of fire [i.e. the fire repeat cycle (Cochrane, 2003)]. There are many sources of ignition such as arson, cooking fires, fires to clear vegetation for better access to commercially valuable timber or to hunt animals (Dennis *et al.*, 2005; Tacconi & Vayda, 2005). However, most fires analyzed in this study occurred in agricultural areas and grasslands and they were most likely related to slash and burn activities. Fire is still the cheapest means of land clearing (Cochrane, 2003; Rieley & Page, 2005).

Although the total area of peat swamp forests is just 40% of the area of the lowland dipterocarp forests, 73% (591,816 ha) of the forest area affected by fire in 2002 occurred in the peat swamp forests and in 2005 it was 55% (120,377 ha). Focusing on the actual number of fires the situation became more evident: in 2002 10,633 of 13,073 forest hotspots occurred on peat swamp forests, which corresponds to 81%, and in 2005 it was 61% of the forest hotspots (1,621 of 2,639) occurring on peat swamp forests. This indicated that peat swamp forests are much more prone to fire than any other forest type. Many fires occurred yearly on the drained and previously burnt peat swamp forests on the former Mega Rice Project area in Central Kalimantan. Peat fires release much larger amounts of CO_2 into the atmosphere than fires on mineral soils because they affect both the surface vegetation and the underlying peat layer, which might be up to 20m thick (Page *et al*., 2002; Rieley & Page, 2005). Between 2002 and 2005 intense selective logging activities occurred in the lowland forests of Sabah. However, fires were less frequently detected in these areas, indicating that fire seemed to be less frequently used for land clearing and deforestation in Sabah.

The susceptibility to fire is strongly related to the level of moisture content in the soil and vegetation but remains low if the crown cover is closed even during extended drought conditions (Cochrane, 2003). If the crown cover is opened the microclimate of the forest floor becomes drier, thus increasing strongly the fire risk. As a consequence, fires do not occur randomly but often appear close to forest edges or in forests disturbed by logging (Siegert *et al*., 2001; Cochrane, 2003). Our results confirmed this observation for the whole of Borneo. We found a strong correlation between fire and forest degradation as 97.7% of forest degradation occurred in a buffer zone of 5 km along the outskirts of the forest in which about 98% of all forest fires occurred. This observation underlines the conclusion that undisturbed forests are most unlikely to burn (Siegert *et al*., 2001) and forest degradation does not normally start in the middle of intact forests but originates from the edges where human activities are most intense. The more remote and undisturbed a forest, the more unlikely it is to burn.

The results of this study suggested that MODIS can be successfully used to monitor deforestation and forest degradation in Borneo and on other tropical forests of Southeast Asia. The high temporal resolution of the images provided enough data necessary to obtain cloud-free composites suitable for land cover classification in this humid tropical region. Eleven land cover classes could be distinguished and forest degradation and larger selective logging activities could be detected. In our mind, a synergistic use of low- and high-resolution satellite data seems to be the most promising technique for environmental monitoring in Southeast Asia: the medium-resolution MODIS data can be used to screen for areas of changes, which can be investigated thereupon with high-resolution sensors.

The uncontrolled forest and peat fires in Southeast Asia are of global importance because they destroy unique ecosystems with an extremely high endemic biodiversity, while peat fires release huge amounts of green house gases, which accelerate climate change. For the 1997 El Niño event Page *et al*. calculated that between 0.81 and 2.57 Gt of carbon were released to the atmosphere, which was equivalent to 13–40% of the mean annual global carbon emissions from fossil fuels (Page *et al*., 2002).

Our results in Borneo also support the positive feedback between forest disturbance and fire, which was first recognized in the Amazon region (Cochrane, 2003). Forest degraded by logging (legal and illegal operation) or previous fire disturbance showed significantly more vulnerability to fire than closed undisturbed forest. It also confirms results by Asner *et al*. (2005) in the Amazon region, who showed that selective logging activities doubled previous estimates of forest degradation by human activities.

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References
Achard F, Estreguil C (1995) Forest classification of Southeast Asia using NOAA AVHRR data. *Remote Sensing of Environment*, **54**, 198–208.

Achard F, Eva HD, Stibig H-J, Mayaux P, Gallego J, Richards T, Malingreau J-P (2002) Determination of deforestation rates of the World's humid tropical forests. *Science*, **297**, 999–1002.

Asner GP, Knapp DE, Broadbent EN, Oliveira PJC, Keller M, Silva JN (2005) Selective logging in the Brazilian Amazon. *Science*, **310**, 480–482.

Boehm H-DV, Siegert F (2001) Ecological impact of the one million hectare rice project in Central Kalimantan, Indonesia, using remote sensing and GIS; Land Use Change and (Il)-legal Logging in Central Kalimantan, Indonesia. In: *22nd Asian Conference on Remote Sensing*, 5–9 November 2001, Singapore. Copyright © 2001 Centre for Remote Imaging, Sensing and Processing (CRISP), National University of

Singapore, Singapore Institute of Surveyors and Valuers (SSIV), Asian Association on Remote Sensing (AARS).

Boehm H-DV, Siegert F, Rieley JO, Page SE, Jauhiainen J, Vasander H, Jaya A (2001) Fire impacts and carbon release on tropical peatlands in Central Kalimantan, Indonesia. In: *22nd Asian Conference on Remote Sensing*, 5–9 November 2001, Singapore. Copyright © 2001 Centre for Remote Imaging, Sensing and Processing (CRISP), National University of Singapore, Singapore Institute of Surveyors and Valuers (SSIV), Asian Association on Remote Sensing (AARS).

Brook BW, Sodhi NS, Ng PKL (2003) Catastrophic extinctions follow deforestation in Singapore. *Nature*, **424**, 420–423.

Casson A (1999) The hesitant boom: Indonesia's oil palm sub-sector in an era of economic crisis and political change. *Program on the Underlying Causes of Deforestation, Bogor Indonesia*, Centre for International Forestry Research.

Casson A, Obidzinski K (2002) From new order to regional autonomy: shifting dynamics of ''Illegal'' logging in Kalimantan, Indonesia. *World Development*, **30**, 2133–2151.

Cihlar J (2000) Land cover mapping of large areas from satellites: status and research priorities. *International Journal of Remote Sensing*, **21**, 1093–1114.

Cochrane MA (2003) Fire science for Rainforests. *Nature*, **421**, 913–919.

Curran LM, Trigg SN, McDonald AK, Astiani D, Hardiono YM, Siregar P, Caniago I, Kasischke E (2004) Lowland forest loss in protected areas of Indonesian Borneo. *Science*, **303**, 1000–1003.

DeFries RS, Hansen MC, Townshend JRG, Janetos AC, Loveland TR (2000) A new global 1 km dataset of percent tree cover derived from remote sensing. *Global Change Biology*, **6**, 247–254.

Dennis RA, Mayer J, Applegate G *et al*. (2005) Fire, people and pixels: linking social science and remote sensing to understand underlying causes and impacts of fires in Indonesia. *Human Ecology*, **33**, 465–504.

Dudley RG (2004) Modeling the effects of a log export ban in Indonesia. *System Dynamics Review*, **20**, 99–116.

Eva HD, Glini A, Janvier P, Blair-Myers C (1999) Vegetation Map of South America at Scale 1/5M. *TREES Publications Series D*, **No. 2**, EUR EN 18658. European Commission, Luxembourg.

FAO (2000) Global Forest Resources Assessment 2000; *Main Report*. Available from URL: ftp://ftp.fao.org/docrep/fao/003/Y1997E/FRA%202000%20Main%20report.pdf.

Foody GM (2001) Status of land cover classification accuracy assessment. *Remote Sensing of Environment*, **80**, 185–201.

Friedl MA, McIver DK, Hodges JCV *et al*. (2002) Global land cover mapping from MODIS: algorithms and early results. *Remote Sensing of Environment*, **83**, 287–302.

Fuller DO (2006) Tropical forest monitoring and remote sensing: a new era of transparency in forest governance? *Singapore Journal of Tropical Geography*, **27**, 15–29.

Fuller DO, Jessup TC, Salim A (2003) Loss of forest cover in Kalimantan, Indonesia, since the 1997–1998 El Niño. *Conservation Biology*, **18**, 249–254.

Fuller DO, Murphy KJ (2005) Rapid assessment of land surface conditions in insular Southeast Asia with MODIS reflectance composites: an example using 2004 imagery. *Asia Oceanic Geoscience Society*, Annual Meeting Abstracts. Available from URL: http://www.asiaoceaniaconference.org/abstract/HS/2nd%20Round/HS07/58-HS-A1284.pdf.

Geist HJ, Lambin EF (2002) Proximate causes and underlying driving forces of tropical deforestation. *BioScience*, **52**, 143–150.

Gomez-Landesa E, Rango A, Bleiweiss M (2004) An algorithm to address the MODIS bowtie effect. *Canadian Journal of Remote Sensing*, **30**, 644–650.

Hansen MC, DeFries RS, Townshend JRG, Carroll M, Dimiceli C, Sohlberg R (2003) Global percent tree cover at a spatial resolution of 500 meters: first results of the MODIS vegetation continuous field algorithm. *Earth Interaction*s, **7**, 1–15.

Hoffmann A, Hinrichs A, Siegert F (1999) Fire damage in East Kalimantan in 1997/98 related to land use and vegetation classes: satellite radar inventory results and proposals for further actions. With contributions from G.Ruecker, L.Christy, and B.Yuliarso. Sustainable Forest Management Project (SFMP) & Integrated Forest Fire Management

(IFFM) Project, *Report* **No. 1**. Indonesian Ministry of Forests and Estate Crops (MoFEC) and German Technical Cooperation Agency (GTZ), Samarinda, Indonesia.

Huang S, Siegert F (2006) Land cover classification optimized to detect areas at risk of desertification in North China based on SPOT VEGETATION imagery. J*ournal of Arid Environments*, **67**, 308–327.

Jensen JR (2000) Remote Sensing of the Environment: An Earth Resource Perspective. Prentice Hall, New Jersey, USA. ISBN 0-13-489733-1.

Jepson P, Jarvie JK, MacKinnon K, Monk KA (2001) The end for Indonesia's Lowland Forests? *Science*, **292**, 859–861.

Justice CO, Giglio L, Korontzi S *et al*. (2002) The MODIS fire products. *Remote Sensing of Environment*, **83**, 244–262.

Loveland TR, Reed BC, Brown JF, Ohlen DO, Zhu Z, Yang L, Merchant JW (2000) Development of a global land cover characteristics database and IGBP DISCover from 1 km AVHRR data. I*nternational Journal of Remote Sensing*, **21**, 1303–1330.

MacKinnon K, Hatta G, Halim H, Mangalik A (1996) The Ecology of Kalimantan. The Ecology of Indonesia series, Vol. III. Periplus Editions (HK) Ltd, I–XXIV, ISBN 0-945971-73-7.

Malingreau J-P, Tucker CJ, Laporte N (1989) AVHRR for global tropical monitoring. *International Journal of Remote Sensing*, **10**, 855–867.

Mayaux P, Achard F, Malingreau J-P (1998) Global tropical forest area measurements derived from coarse resolution maps at a global level: a comparison with other approaches. *Environmental Conservation*, **25**, 37–52.

Mayaux P, Eva H, Gallego J *et al*. (2006) Validation of the global land Cover 2000 Map. *IEEE Transactions on Geoscience and Remote Sensing*, **44**, 1728–1739.

Page SE, Siegert F, Rieley JO, Boehm H-DV, Jaya A, Limin S (2002) The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature*, **420**, 61–65.

Rieley JO, Page SE (2005) Wise use of tropical peatland: focus on Southeast Asia. ALTERRA – Wageningen University and Research Centre and the EU INCO – STRAPEAT and RESTORPEAT Partnership. *Report*. ISBN 90327-0347-1.

Siegert F, Hoffmann A (2000) The 1998 forest fires in East Kalimantan (Indonesia): a quantitative evaluation using high resolution, multitemporal ERS-2 SAR images and NOAAAVHRR hotspot data. *Remote Sensing of Environment*, **72**, 64–77.

Siegert F, Ruecker G, Hinrichs A, Hoffmann AA (2001) Increased damage from fires in logged forests during droughts caused by El Niño. *Nature*, **412**, 437–440.

Sodhi NS, Koh LP, Brook BW, Ng PKL (2004) Southeast Asian biodiversity: an impending disaster. *TRENDS in Ecology and Evolution*, **19**, 654–660.

Stibig H-J, Malingreau J-P (2003) Forest cover of insular Southeast Asia mapped from recent satellite images of coarse spatial resolution. *Royal Swedish Academy of Sciences*, **32**, 469–475.

Sunderlin W (1999) Policy Reviews - Between danger and opportunity: Indonesia's forests in era of economic and political change. *Society & Natural Resources*, **12**, 559–570.

Tacconi L, Vayda AP (2005) Slash and burn and fires in Indonesia: a comment. *Ecological Economics*, **56**, 1–4.

Thompson H (1996) Indonesia's wood resource: trends and policies. *Journal of Mineral Policy*, **12**, 14–23.

Trigg SN, Curran LM, McDonald AK (2006) Utility of Landsat 7 satellite data for continued monitoring of forest cover change in protected areas in Southeast Asia. *Singapore Journal of Tropical Geography*, **27**, 49–66.

Turner W, Sterling EJ, Janetos AC (2001) Contributions of remote sensing to biodiversity conservation: a NASA approach. *Conservation Biology*, **15**, 832–834.

van Nieuwstadt MGL, Sheil D (2005) Drought, fire and tree survival in a Borneo rain forest, East Kalimantan, Indonesia. *Journal of Ecology*, **93**, 191–201.

WRM (2000) The pulp and paper sector's unsustainable growth. *World Rainforest Movement Bulletin* **41**, December 2000. Indonesia.

Zhan X, DeFries R, Townshend JRG, Dimiceli C, Hansen M, Huang C, Sohlberg R (2000) The 250m global land cover change product from the moderate resolution imaging Spectroradiometer of NASA's earth observing system. *International Journal of Remote Sensing*, **21**, 1433–1460.

Zhan X, Sohlberg RA, Townshend JRG *et al*. (2002) Detection of land cover changes using MODIS 250m data. *Remote Sensing of Environment*, **83**, 336–350.

5.3 Chapter III

Using low and medium resolution MODIS data to investigate deforestation in Borneo

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Abstract

In comparison to other tropical regions of the world Southeast Asia is experiencing the highest rates of tropical forest degradation and deforestation. In comparison to 2005, the El Niño fire season 2006 was very strong, especially affecting closed forests. We detected a clear shift from agricultural fires in 2005 to forest fires in 2006. Deforestation normally starts at the outskirts of the forests where humans have easy access, but it can also occur inside closed forests. By monitoring daily low resolution Moderate Resolution Imaging Spectroradiometer (MODIS) hotspot data on a forest map of Borneo it is easily possible to detect current logging activities and analyze the causes for fire events inside closed forests. Investigating the 2005/2006 fire events in a peat swamp forest area in Central Kalimantan we found that 94% of all fire events inside closed canopy forests were located closer than 1 km to existing small-scale logging infrastructures. The situation of all Indonesian National Parks is alarming because of a strong trend towards forest fires, especially affecting peat swamp forests. In comparison to 2005 we experienced an increase of fire events inside closed forests by a factor of 24. During the 2005/2006 fire seasons on Borneo 1,450 new logging activities could be detected inside closed canopy forests. More than 1,100 occurred in 2006 alone, because of the drier conditions of the El Niño year.

Keywords: Indonesia, fire, El Niño, MODIS, hotspot, monitoring, deforestation, forest degradation

Introduction

Tropical deforestation increased tremendously in the past two decades (Fuller, 2006). In addition to 5.8 Mha of tropical rain forest worldwide which get deforested per year, there are another 2.3 Mha which get degraded annually through fragmentation, legal and illegal logging or fires (Mayaux *et al*., 2005). The highest rate of deforestation shows Southeast Asia with 0.8 to 0.9% per year (Achard *et al*., 2002; FAO, 2000; FWI and GFW, 2002). According to studies about global warming the conservation of forests, especially of the large tropical rain forests is regarded to be very important (Brown *et al*., 2002; Niles *et al*., 2002; Houghton, 2002). Therefore a monitoring system has to be developed which is able to monitor vast areas of tropical rainforest and quickly recognize actual deforestation events, thus enabling to take action for fire prevention and suppression.

Forest degradation or deforestation normally starts from the edges of the forests where farmers and loggers do have easy access (Cochrane, 2003). New patches of deforestation can also be detected inside closed canopy forests. In such a case any kind of infrastructure such as selective logging activities, small scale logging roads or the construction of narrow drainage canals must be existent which provide access to the forests enabling people to extract timber (van Schaik *et al*., 2001). To be able to detect such small-scale structures high resolution satellite sensors such as the Landsat Enhanced Thematic Mapper Plus (ETM+), Satellite Pour l'Observation de la Terre – High Resolution Visible Infraed (SPOT HRVIR), Advanced Land Observing Satellite – Advanced Visible and Near Infrared Radiometer type 2 (ALOS AVNIR-2) or Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) are necessary (Asner *et al*., 2005; Fuller, 2006). However, due to their high spatial resolution such sensors have a low temporal coverage, thus becoming virtually useless for monitoring fast land cover changes in humid tropical forests with their persistent cloud coverage (Fuller, 2006). On the other hand low and medium resolution satellite sensors such as National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer (NOAA AVHRR), Along Track Scanning Radiometer (ATSR) and Moderate Resolution Imaging Spectroradiometer (MODIS) are more suitable for monitoring deforestation in the humid tropics because they all have the advantage of a high temporal resolution due to their wide swath of view. These systems are also highly effective in monitoring active fire events (Justice *et al*., 2002). However, low resolution systems are unable to resolve small-scale deforestation and forest degradation activities as well as logging infrastructures.

Many studies showed that fire is strongly correlated to deforestation (Asner *et al*., 2005; Cochrane, 2003; Siegert *et al*., 2001). On the one hand fire is used as a tool in land clearing since thousands of years (Dennis *et al*., 2005; Cochrane, 2003); on the other hand fires accelerate deforestation because of a positive feedback between forest degradation and fire (Cochrane, 2003; Page *et al*., 2002; Siegert *et al*., 2001; Siegert and Hoffmann, 2000). These fire events can be detected using high temperature events recording systems on the NOAA AVHRR, ERS, ENVISAT and TERRA/AQUA satellites, which deliver coordinates of active fire events, so called hotspots. Thus, such fire events might be possibly used as indicator for any kind of logging infrastructure and deforestation activity.

In our study we focused on the island of Borneo because it still has the largest remaining area of tropical rainforest in Southeast Asia and it is representative for the fast deforestation processes in the region (Achard *et al*., 2002; Trigg *et al*., 2006). Especially in Kalimantan deforestation has been rampant in recent years (Jepson *et al*., 2001) and many protected areas had been designated to timber concessions (Fuller, 2006). We combined active fire event detection using low resolution MODIS hotspot data and medium resolution MODIS land cover data to screen for forest degradation and deforestation. Analyzing the daily active fire detections on a forest and land cover map of Borneo dating from 2005, provided an easy method to detect fire events inside closed forests. Special emphasis was further put on the tropical peat lands in Central Kalimantan which are one of the last and biggest remaining peat swamp forest areas of Southeast Asia. We examined the role of fire in peat land degradation in Borneo and the spatial correlation between fire events inside the formerly logged peat swamp forest of the Sebangau National Park in Central Kalimantan and the existing logging infrastructures.

Material and methods

Satellite data and GIS analysis

MODIS hotspot data is designed to detect active fire events at a spatial resolution of 1 km. However, the sensor is not able to distinguish between one or more individual fires within a hotspot pixel. Therefore we used the terminology of a “fire event” as synonym of a hotspot pixel, which should not be confused with the terminology of “a fire”. A real fire on the ground can consist of several fire spots depending on the duration and the size of the fire. A Geographic Information System (GIS) was used for spatial analysis of all MODIS hotspots. The data was acquired between January 2005 and December 2006 by the MODIS Rapid Response System (Web Fire Mapper, http://maps.geog.umd.edu/). The hotspots were superimposed on a 2005 land cover map of Borneo in order to analyze the spatial distribution of the fire events inside closed canopy forests. The land cover map was based on multitemporal MODIS surface reflectance data acquired before the start of the 2005 fire season with a medium resolution of 250 m (Langner *et al.*, 2007). Only forests with a crown cover ≥40% were considered as closed forests (Langner *et al.*, 2007). Forest fire events were discriminated into fire events occurring close to forest edges and those which started inside closed canopy forests. The 2005 forest map of Borneo was buffered with a 1 km zone from the forest edges to derive 3 different land cover types: non-forest areas, forest-edge areas within this 1 km zone and areas of closed forest. Due to the spatial resolution of 1 km of the MODIS hotspot data (Justice *et al.*, 2002) only fire events detected at least 1 km inside the forests could be regarded as fires inside closed forests. The hotspots for both years were marked according to their spatial occurrence as non-forest-fire events, forest-edge-fire events and fire events inside closed canopy forests. To evaluate the fire affected forest area, the hotspot data was buffered with a 1 km square buffer and intersected with the 2005 land cover. The area of overlapping hotspots was considered to be burnt only once. Another study in Borneo using the same algorithm showed that MODIS hotspot data slightly underestimates the actual burnt area (Miettinen *et al.*, 2006). Besides analyzing the total number of hotspots, all active fire detections inside closed canopy forests forming coherent clusters were combined and counted as single entities to derive the number of impact areas. Fire affected spots bigger than 300 ha were considered as high fire impact areas.

All river and canal structures as well as logging roads, logging railways inside the Sebangau catchment which were established or used during the last decade for the purpose of timber extraction were delineated manually on a scale of 1:50,000 using several high resolution satellite scenes. As not all logging infrastructures are used every year, secondary regrowth and a fast growing shrub layer easily accrue smallest canals or cover tracks which have been abandoned for some time. For this sake several Landsat 5 TM and Landsat 7 ETM+ scenes and one SPOT 5 scene of the same study area in Central Kalimantan, all recorded in between 1997 and 2007, were used to complementary detect all existing infrastructures. These infrastructures were buffered with 1 km to both sides and intersected with all active fire detections in that area to analyze the spatial correlation between fire event and infrastructure.

Validation of MODIS fire detections

For validation purposes a spatial subset of the MODIS 2006 hotspot data was generated according to a cloud-free subset of the Landsat scene from January 9th 2007. Due to its acquisition date, the Landsat scene clearly shows all recent burn scars which occurred in 2006. The scene was recorded in Scan Line Corrector (SLC)-off mode, which shows stripes of missing data. After masking these stripes as well as all cloud and haze contaminated areas the image was classified into four classes: burnt vegetation, non-burnt vegetation, water and remaining cloud/haze. To reduce the impact of atmospheric disturbances as remaining haze we used a spectral subset of the Landsat bands 3, 4, 5, 7 only covering the red to the short wavelength Infra Red (IR) spectrum which contain the most relevant information for detecting vegetation and burnt scars. Using an unsupervised ISODATA algorithm with 10 iterations, 100 clusters were assigned to one of the abovementioned classes by visual inspection. The classification was manually revised according to field observations and in-depth knowledge on local conditions. In a final step all active fire events (hotspot point data) detected in 2006 were superimposed on the high resolution burnt area map to evaluate the accuracy of the MODIS sensor for active fire event detection.

Results

Forest fire events

In 2005 forest fire events were only a minority of all detected hotspots, accounting for 17% of all fire detections while most of the fires events were linked to the seasonal land clearing activities in agricultural areas. In 2006 however, 34% of all fire events were forest fires (Figure1 A, B). In comparison to 2005, the amount of forest fire events in 2006 increased almost 7-fold to 18,152, with 5,248 detections inside closed canopy forests (29%) and 12,904 forest-edge-fire events (71%), the latter ones occurring in a buffer zone of 1 km along the outskirts of the forests. The number of fire detections inside closed forests was strongly biased towards peat swamp forest (4,466), followed by lowland forests (667) and a small number of fire events in the other forest types and is more than 10 times greater than in 2005 where the fire detections inside closed forests were almost equally distributed over peat swamp and lowland forests (Figure 1 C, D). In Central Kalimantan the number of forest fire events increased from 1,282 in 2005 to 12,014 in 2006 with a bias towards inside-forest-fires.

Table 1. Number of inside-forest-fire clusters

Inside-forest-fire clusters	2005			2006		
	Nr	Nr > 300 ha	Percent	Nr	Nr > 300 ha	Percent
Borneo	328	7	2.1 %	1,122	148	13.2 %
Sarawak	79	2	2.5 %	84	4	4.8 %
Brunei Darussalam	2	0	0.0 %	0	0	0.0 %
Sabah	1	0	0.0 %	0	0	0.0 %
West Kalimantan	89	0	0.0 %	316	22	7.0 %
Central Kalimantan	124	4	3.2 %	584	115	19.7 %
South Kalimantan	7	0	0.0 %	48	3	6.3 %
East Kalimantan	27	1	3.7 %	92	4	4.4 %
Sebangau National Park	0	0	0.0%	42	17	40.5%

Fire clusters inside closed canopy forests

Analyzing the clusters of fire events inside forests, 328 areas of deforestation by fire were detected in 2005 with 7 larger than 300 ha and this number increased in 2006 to 1,122 areas with 148 bigger than 300 ha (Table 1). In both years Central Kalimantan was most strongly affected, with 124 areas occurring in 2005 and 4 areas bigger than 300 ha. In 2006 the total number increased to 584 which is more than half of all such patches in Borneo and 115 of them were bigger than 300 ha (Table 1). In 2006 the largest areas of forest fires were situated on Indonesian territory with a maximum patch size of 6 Mha in Central Kalimantan, 5 Mha in West Kalimantan, 1.7 Mha in South Kalimantan and 1.4 Mha in East Kalimantan.

Table 2. Number of fire events inside and outside National Parks in Kalimantan

	Non-forest-fires		Forest-edge-fires		Inside-forest-fires		Total	
	2005	2006	2005	2006	2005	2006	2005	2006
Inside	639	3,046	195	1,585	37	882	871	5,513
Outside	12,044	31,895	1,936	11,319	471	4,366	14,451	47,580
Total	12,683	34,941	2,131	12,904	508	5,248	15,322	53,093

Fires in Indonesian National Parks

In the Indonesian part of Borneo 46 National Parks cover 9.3 Mha. In 2005 a total of 871 fire events were detected inside these National Parks corresponding to 5.7% of all fire detections in that year whilst only 37 were inside-forest-fire events (Table 2).

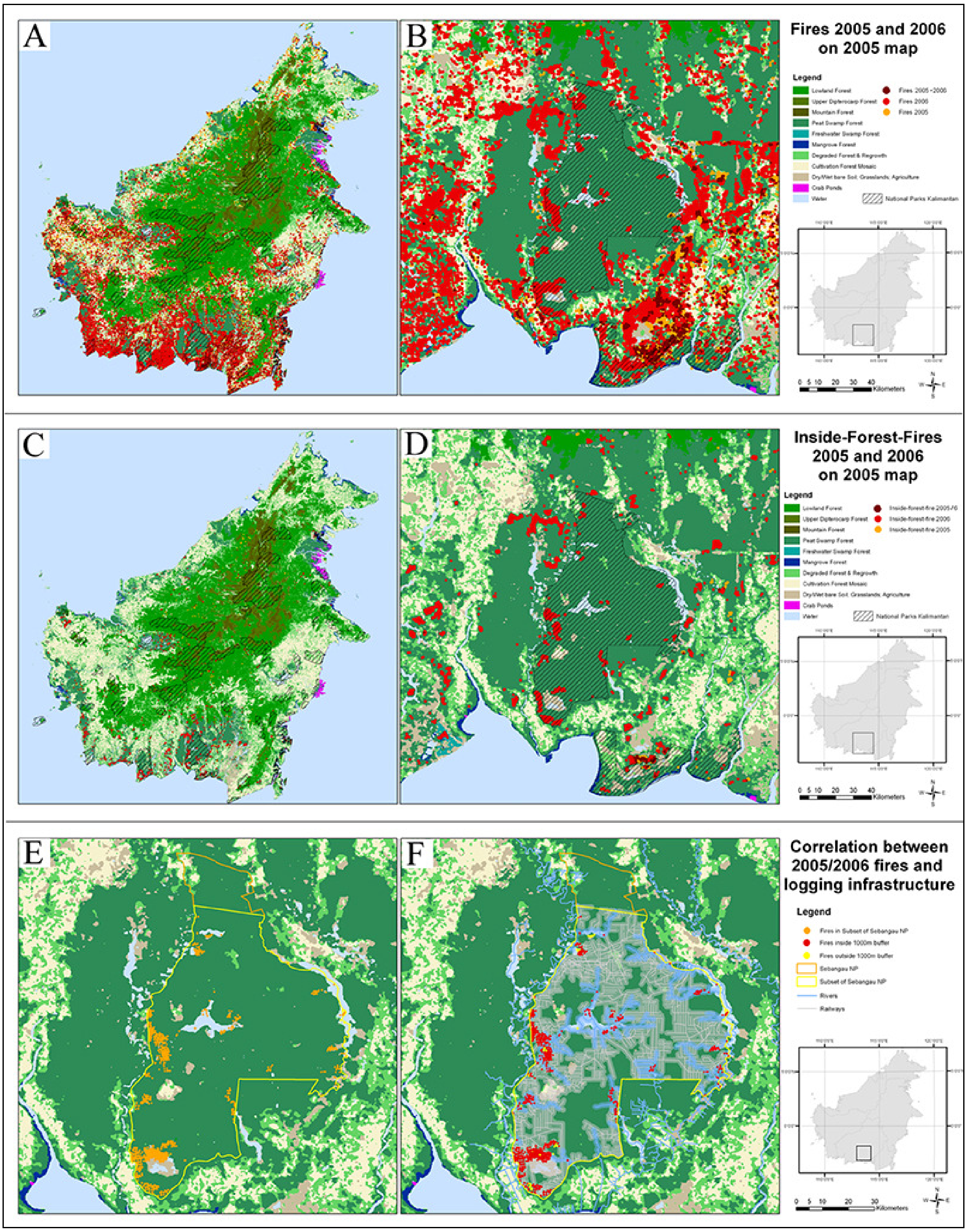

Figure 1:

(A, B) MODIS fire hotspots of 2005/2006 superimposed on land cover map of Borneo based on MODIS data dating from 2005 with a subset of an area in Central Kalimantan. Hatched areas show National Parks of Kalimantan.

(C, D) MODIS fire hotspots of 2005/2006 which occur more than 1 km inside forests

superimposed on land cover map of Borneo based on MODIS data dating from 2005 with a subset of an area in Central Kalimantan. Hatched areas show National Parks of Kalimantan.
(E) MODIS fire hotspots of 2005/2006 superimposed on map of the Sebangau National Park in Central Kalimantan based on MODIS data dating from 2005.
(F) Hotspots in close vicinity to logging infrastructures as rivers and logging railways.

In 2006 the number of fire events increased to 5,513 corresponding to 10.4% of all fire events and 882 of them were detections inside closed canopy forests. The most strongly affected parks in 2006 were the Tanjung Puting (1,332 fire events) and the Sebangau National Park with 1,186 fire events while the Sebangau National Park experienced the highest amount of fire detections inside closed forests of all parks. The number of forest fire events in the Sebangau National Park increased by a factor of over 200 from 4 detections in 2005 to 822 fire events in 2006 whereas in the same period the number of non-forest-fire events increased only by a factor of 17. The amount of fire clusters inside closed canopy forests increased from no single fire in 2005 to 42 in 2006, with 17 bigger than 300 ha (Table 1) and the largest area had a size of 3.2 Mha. The correlation between fire occurrence and any kind of logging infrastructure such as railways, railroads, canals and rivers was analyzed in a 0.53 Mha subset of the Sebangau National Park. Inside this area we detected 3,618 km of logging railways and logging roads as well as 706 km of rivers, smaller rivers and canals (Figure 1 E, F). During the time period between 2005 and 2006, 96% and 94% of all fire events occurred inside the 1 km buffer zone around these infrastructures.

Accuracy assessment of MODIS hotspot data

According to the Landsat reference the overall accuracy of the MODIS sensor to detect the active fire events of the year 2006 was 78.5%. To investigate the spatial characteristics of false detections we analyzed the exact location of the hotspot data. Our results showed that 21.5% of the hotspot point data in the study area were located outside the Landsat derived burnt scars. It has to be kept in mind that the Landsat reference image was acquired in the middle of the wet season, so areas which are susceptible to fire in the dry season were flooded at the time of image acquisition and thus classified as water areas. The observed error decreases to 19.4% if fire events detected in the Landsat water class were considered as correctly classified. The mean nearest distance of fire detections situated outside the burnt areas was only 181 m with a standard deviation of 186 m.

One single MODIS hotspot pixel represents the area of the sensor resolution of 1 km (Giglio *et al*., 2003). This pixel can be affected by a single fire or more than one fire. The actual size of a fire saturating the sensor element can be as small as 10 m^2, as gas flames on oil platforms were also detected, but it has to be noted that the factual size of the actual burnt area is unknown. Due to this inaccuracy we buffered each hotspot with a 1 km square and intersected again with the Landsat derived burnt scars. Our analysis showed that 99.9% of the hotspot data intersected at least in parts with these areas.

Discussion and conclusion

Tropical rainforests in Southeast Asia are extremely threatened by forest degradation and deforestation. In Indonesia forest degradation is often correlated with illegal logging activities (Casson & Obidzinski, 2002) which increased dramatically since the end of 1998 after the fall of the Soeharto regime (Casson & Obidzinski, 2002; Dudley, 2004; Fuller, 2006). Any kind of logging activities make forests extremely susceptible to fire due to their higher ground fuel loads (Siegert *et al.*, 2001; Cochrane, 2003; Goldammer, 2007) and fire is often correlated to forest degradation or deforestation activities because it is the best means for clearing the land (Cochrane, 2003; Dennis *et al*., 2005). To quickly respond to burning events, it is necessary to monitor fires with the help of low-cost, frequently collected satellite data (Cochrane, 2003). This monitoring can be done in real-time by the synergistic use of daily low resolution active fire detection data and a current land cover map of the region of interest.

In their study Langner *et al*. (2007) found a strong correlation between fire and forest degradation, showing that almost 98% of forest degradation occurs in close vicinity to the outskirts of the forest in which also about 98% of all forest fire events occur. This means that most deforestation by fire occurs along the forest edges where humans have easy access. However, deforestation can also be observed inside forests – though to a much lesser extent – suggesting the existence of any kind of small scale infrastructure providing humans access to the forest. These small-scale disturbances inside forests are nevertheless hazardous for the remaining forest ecosystems because they can be used by people to access the forest for timber extraction (van Schaik *et al*., 2001). Normally these structures can only be detected using high resolution satellite systems (Asner *et al*., 2005; Fuller, 2006). However, these high resolution systems cannot be applied operationally area-wide in the humid tropics due to frequent cloud coverage in these areas, a low temporal resolution with orbit repeat cycles of 20 days and less and a narrow swath of view (Fuller, 2006). Therefore low and medium resolution systems have to be used as their wider swath of view allows a much higher temporal resolution. These systems in turn cannot resolve small scale deforestation and forest degradation activities but several such platforms carry high temperature events recording sensors which are the tool of choice for the detection of active fire events (Justice *et al*., 2002). Due to the fact that fire is strongly correlated to forest disturbances (Cochrane, 2003; Dennis *et al*., 2005), we were able to show in our study that fire events inside closed canopy forests can be used as indicator for existing small-scale infrastructures, thus enabling to easily screen for new patches of deforestation which might be cryptic to the observer on the ground because they are located inside closed forests and therefore stay long-time undetected. Therefore the spatial correlation between fire events and existing logging infrastructures is examined.

Though National Aeronautics and Space Administration (NASA) scientists of the earth observatory described the 2006 El Niño as relatively weak (http://earthobservatory.nasa.gov/Newsroom/NewImages/images.php3?img_id=17419) the 2006 fire season on Borneo was very strong resulting in vast burnt areas, especially affecting closed forests. Our study showed a clear shift from fires in agricultural areas in 2005 to forest fires in 2006 which were responsible for further degradation of the remaining forests and deforestation. While the number of all fire events increased by a factor of 3 between 2005 and 2006 the number forest fire events increased by a factor of 7 during the same period. Most of these fire events occurred inside peat swamp forests where the number of fire events per Mha increased by a factor of 16 from 30 in 2005 to 484 in 2006. Fire events inside lowland dipterocarp forests only increased by a factor of 3 from 9 fires per Mha in 2005 to 28 fire detections per Mha in the following year. Apparently there is a higher susceptibility to fire of peat swamp forests during a dry El Niño year. The cause for this is the extensive utilization of peat swamp forests in the last decades when vast areas of peat swamp forests have been impacted by the construction of drainage and irrigation canals (Boehm & Siegert, 2001). The drainage of the peat layer through this dense network of canals lowers the water table exceptionally in El Niño years. Furthermore, disturbances of the forest canopy cover lead to an increased solar radiation at the forest floor and foster the growth of a dense scrub vegetation of fast growing species (Rieley & Page, 2005) which die quickly because of the dry and hot microclimate at the forest floor, thus increasing the fire hazard due to the huge amounts of dry biomass, which easily become ignited (Siegert *et al*., 2001). Besides the fire hazard, the danger of a forest catching fire is also related to the fire risk, which describes the probability that fuel will ignite. Some reason for this high fire occurrence in peat swamp forest might be that this forest type still contains economically valuable tree species which are not yet totally exploited in such extent as in dipterocarp forests. It has to be mentioned that forest fires and notably fires in peat swamp forests contribute in a much higher extent to releasing green house gases thus affecting global climate change than fires in agricultural areas (Page *et al.*, 2002).

Normally fires start at the outskirts of forests. Fire events inside forests can be regarded as an indicator for any kind of infrastructure giving local people access to timber resources. Using the combination of low resolution MODIS hotspot data and medium resolution MODIS land cover data we were able to localize areas of new deforestation starting inside forests. We differentiated the forest fires by their spatial location in forest-edge-fire events occurring in a 1 km buffer along the outskirts of the forests and inside-forest-fire events. The number of forest-edge-fire events increased 6-fold between 2005 and 2006. To detect new patches of forest degradation and deforestation we focused on the inside-forest-fire events. In 2005 508 inside-forest-fire events have been detected and this number increased more than 10-fold to 5,248 in 2006. Fire events in close vicinity most probably belonged to the same fire, which moves forward by burning biomass, were counted as single entities to calculate the amount of fire events representing potential new “grains of deforestation”. While the number of inside-forest-fire clusters increased 3-fold the amount of these patches larger than 300 ha increased by a factor of 21 between 2005 and 2006. Our results indicate that beyond the trend towards more forest fire events in 2006 there is also a trend towards an increase in the number and the size of inside-forest-fire patches.

In his study Mayaux et al. (2005) mentioned that it is especially important to monitor protected areas from being degraded because they represent the keystone of conservation policy in many countries. Analyzing the fire events which occurred inside the 46 National Parks of Kalimantan showed alarming results: There is a strong trend towards forest-fire events – especially in peat swamp forests. While the number of fire events inside these National Parks increased by a factor of 6 which is already double the amount of the increase in the number of all fire detections on Borneo, the number of inside-forest-fire events increased by a factor of 24 in comparison to 2005. This indicates the high pressure on these protected areas with special emphasis on protected forests. In 2006 the most strongly affected parks were the Tanjung Puting and the Sebangau, both dominated by peat swamp forests. In the Sebangau National Park in Central Kalimantan the forest fire events increased by a factor of more than 200. In

2006 504 inside-forest-fire events were detected, forming 42 fires with 17 larger than 300 ha, highlighting again the higher susceptibility of peat swamp forests to fire during dry El Niño conditions. Analyzing this area with different high resolution satellite images it became obvious that the peat swamp forests of the Sebangau catchment, still representing the largest area of this forest type in Kalimantan, have been subject to intensive illegal logging activities for almost 10 years (Rieley & Page, 2005). Illegal loggers need to have access to be able to remove the timber – this can be any kind of infrastructure. In Kalimantan Curran et al. (2004) analyzed all bigger World Conservation Monitoring Centre (WCMC) protected areas and detected high logging activities in combination with the construction of industrial logging roads. In our study we evaluated the length of the formerly built logging railways in the Sebangau National Park. We analyzed 90% of the area of the Sebangau National Park for potential logging infrastructure. Altogether some 3,618 km of logging railways and logging roads could be identified which are highly correlated to the spatial occurrence of the 1,086 fire events in 2005 and 2006. Altogether 94% of all fire events over both years were detected inside a 1 km buffer zone around the logging infrastructures such as railways, railroads, canals and rivers. This supports results of Cochrane (2003) that forest which was degraded by any king of logging operation showed significantly more vulnerability to fire than undisturbed forest with a closed canopy cover. Furthermore, these results underline the conclusion that undisturbed forests are most unlikely to burn (Siegert *et al.*, 2001) and forest fires do normally not start in the middle of intact forests but originate from areas where humans have access to the forest.

The combination of low resolution MODIS hotspot data which can be obtained daily and medium resolution MODIS land cover data clearly offers synergistic effects to detect areas of current deforestation with high accuracy. It is possible to respond in short time on current changes in forest cover. This method can be used to screen for forest fires which can be investigated thereupon with high resolution sensors. Hotspot data can be easily processed every day for observing areas of special concern as National Parks to be able to better coordinate immediate help on the ground and to take actions to fight against the fires and save the remaining forests from further degradation. If no serious action is taken for fire prevention and suppression, the recurrent forest and peat fires in Southeast Asia will destroy these unique ecosystems with their extremely high endemic biodiversity. This is also of global importance as especially the peat swamp forests can act as major carbon store and sequester of CO_2, but will release huge amounts of green house gases when burnt, thus accelerating global warming.

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References

Achard F, Eva HD, Stibig H-J, Mayaux P, Gallego J, Richards T, Malingreau J-P (2002) Determination of Deforestation Rates of the World's Humid Tropical Forests. *Science,* **297,** 999-1002.

Asner GP, Knapp DE, Broadbent EN, Oliveira PJC, Keller M, Silva JN (2005) Selective Logging in the Brazilian Amazon. *Science,* **310,** 480-482.

Boehm H-DV, Siegert F (2001) Ecological Impact of the One Million Hectare Rice Project in Central Kalimantan, Indonesia, using Remote Sensing and GIS, Paper prensented at the *22nd Asian Conference in Remote Sensing*, Singapore, 05-09.11.2001.

Brown S, Swingland IR, Hanbury-Tenison R, Prance GT, Myers N (2002) Changes in the use and management of forests for abating carbon emissions: issues and challenges under the Kyoto Protocol. *Philosophical Transactions of the Royal Society of London, Series A: Mathematical, Physical and Engineering Sciences,* **360,** 1593-1605.

Casson A, Obidzinski K (2002) From New Order to Regional Autonomy: Shifting Dynamics of "Illegal" Logging in Kalimantan, Indonesia. *World Development,* **30,** 2133-2151.

Cochrane MA (2003) Fire Science for Rainforests. *Nature,* **421,** 913-919.

Curran LM, Trigg SN, McDonald AK, *et al.* (2004) Lowland Forest Loss in Protected Areas of Indonesian Borneo. *Science,* **303,** 1000-1003.

Dennis RA, Mayer J, Applegate G, *et al.* (2005) Fire, people and pixels: linking social science and remote sensing to understand underlying causes and impacts of fires in Indonesia. *Human Ecology,* **33,** 465-504.

Dudley RG (2004) Modeling the effects of a log export ban in Indonesia. *System Dynamics Review,* **20,** 99-116.

FAO (2000) Global Forest Resources Assessment 2000; Main Report.

Fuller DO (2006) Tropical forest monitoring and remote sensing: A new era of transparency in forest governance? *Singapore Journal of Tropical Geography,* **27,** 15-29.

FWI/GFW (2002) The State of the Forest: Indonesia. Bogor, Indonesia: Forest Watch Indonesia, and Washington DC: *Global Forest Watch.*

Giglio L, Descloitres J, Justice CO, Kaufman YJ (2003) An Enhanced Contextual Fire Detection Algorithm for MODIS. *Remote Sensing of Environment*, 273-282.

Goldammer JG (2007) History of equatorial vegetation fires and fire research in Southeast Asia before the 1997–98 episode: A reconstruction of creeping environmental changes. *Mitigation and Adaptation Strategies for Global Change*, **12**, 13-32.

Houghton RA (2002) Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000. *Tellus,* 378-390.

Jepson P, Jarvie JK, MacKinnon K, Monk KA (2001) The End for Indonesia's Lowland Forests? *Science,* **292,** 859-861.

Justice CO, Giglio L, Korontzi S, *et al*. (2002) The MODIS fire products. *Remote Sensing of Environment,* **83,** 244-262.

Langner A, Miettinen J, Siegert F (2007) Land cover change 2002 – 2005 in Borneo and the role of fire derived from MODIS imagery, *Global Change Biology*, (OnlineEarly Articles). doi:10.1111/j.1365-2486.2007.01442.x.

Mayaux P, Holmgren P, Achard F, Eva H, Stibig H-J, Branthomme A (2005) Tropical forest cover change in the 1990s and options for future monitoring. *Philosophical Transactions of the Royal Society,* **360,** 373-384.

Miettinen J, Langner A, Siegert F (2006) Burnt area estimation for the year 2005 in Borneo using multi-resolution satellite imagery. *International Journal of Wildland Fire*.

Niles JO, Brown S, Pretty J, Ball AS, Fay J (2002) Potential carbon mitigation and income in developing countries from changes in use and management of agricultural and forest lands. *Philosophical Transactions of the Royal Society of London, Series A: Mathematical, Physical and Engineering Sciences,* **360,** 1621-1639.

Page SE, Siegert F, Rieley JO, Boehm H-DV, Jaya A, Limin S (2002) The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature,* **420,** 61-65.

Rieley JO, Page SE (2005) *Wise Use of Tropical Peatland: Focus on Southeast Asia*. ALTERRA - Wageningen University and Research Centre and the EU INCO - STRAPEAT and RESTORPEAT Partnership.

Siegert F, Hoffmann A (2000) The 1998 Forest Fires in East Kalimantan (Indonesia): A Quantitative Evaluation Using High Resolution, Multitemporal ERS-2 SAR Images and NOAA-AVHRR Hotspot Data. *Remote Sensing of Environment,* 64-77.

Siegert F, Ruecker G, Hinrichs A, Hoffmann AA (2001) Increased damage from fires in logged forests during droughts caused by El Nino. *Nature,* **412,** 437-440.

Trigg SN, Curran LM, McDonald AK (2006) Utility of Landsat 7 satellite data for continued monitoring of forest cover change in protected areas in Southeast Asia. *Singapore Journal of Tropical Geography,* **27,** 49-66.

van Schaik CP, Monk KA, Robertson JMY (2001) Dramatic decline in orang-utan numbers in the Leuser Ecosystem, Northern Sumatra. *Oryx,* **35,** 14-25.

5.4 Chapter IV

Spatiotemporal fire occurrence in Borneo over a period of 10 years

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Abstract

Southeast Asia's tropical rainforests are experiencing the highest rate of deforestation worldwide and fire is one of the most important drivers of forest loss and subsequent carbon dioxide emissions. In this study we analyzed all fire events in Borneo recorded by satellites over a period of 10 years. About 16.2 Mha, which corresponds to 21% of the land surface, have been affected by fire at least once and 6% more than one time. During El Niño conditions, which cause prolonged droughts in the region, the fire affected area was on average 3 times larger than during normal weather conditions. Similarly, fires in forests affected 0.3 Mha in normal years and 1 Mha during El Niño years. Carbon rich peat swamp forest ecosystems were most severely affected. There is a pronounced difference in fire occurrence between different countries and provinces in Borneo although ecosystem and land use are very similar across the island. Compared to Sarawak, Sabah (Malaysia) and Brunei the relative annual fire affected area in Kalimantan, the Indonesian part of Borneo, was on average 5 times larger. During El Niño conditions the fire affected area increased only in Kalimantan and not in Brunei and the Malaysia. A similar pattern was observed in National Parks. This suggests, that El Niño related droughts are not the only cause of increased fire occurrence and do not necessarily lead to a higher number of fire events. These results improve our understanding of existing fire regimes and drivers of fire in SE Asian tropical ecosystems and may help to better protect the remaining rainforests.

Keywords:
Borneo, Indonesia, Malaysia, fire, hotspot, MODIS, AVHRR, ATSR, deforestation, forest degradation

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Introduction

The conservation of forests, especially of the large tropical rain forests is regarded to be very important in the context of climate change and the conservation of biodiversity (Brown *et al.,* 2002; Houghton, 2002; Niles *et al.,* 2002; IPCC, 2007). Despite that, deforestation in tropical rainforests increased tremendously in the past two decades (Achard *et al.*, 2002; Fuller, 2006). Forest degradation by logging and fire is often a precursor to complete deforestation (Nepstad et al. 1999; Achard *et al.*, 2004). About 5.8 Mha of tropical rain forest are converted into other land covers worldwide and 2.3 Mha become degraded each year (Mayaux *et al.,* 2005). The highest rate of deforestation worldwide shows insular Southeast Asia with 1.3% per year (FAO, 2000; Marcoux, 2000; Achard *et al.,* 2002; FWI & GFW, 2002). A detailed analysis of Borneo revealed an annual deforestation rate of 1.7% between 2002 and 2005 (Langner *et al.*, 2007).

Major drivers of deforestation in insular Southeast Asia are linked to human activities, such as shifting cultivation, governmental resettlement activities (transmigrasi), logging of natural forests and establishment of plantations and industrial timber estates (Christanty, 1986; Sunderlin & Resosudarmo, 1996; Barber & Schweithelm 2000; FWI & GFW, 2002; Schroeder-Wildberg & Carius, 2003; Goldammer, 2007). For all of these activities fire is used for land clearing. In comparison to mechanical or manual methods, burning is by far the cheapest means for land preparation (ASEAN, 2003; Suyanto *et al.,* 2004; Dennis *et al*., 2005). Several devastating fire events have been recorded in Indonesia over the past 10 years which were connected primarily with land speculation, and developmental projects (Siegert *et al*., 2001; Page *et al*., 2002; Goldammer, 2007). According to Fuller and Murphy (2006), fires in Southeast Asia are especially devastating during El Niño weather conditions, which cause prolonged droughts in the region. In Kalimantan on the island of Borneo several Mha of forests were lost during two El Niño episodes in 1997-98 and 2002 (Siegert *et al*., 2001; Fuller *et al.,* 2003).

In tropical closed canopy forests fires are very unusual due to high air humidity and little amounts of fuel (Uhl & Kauffman, 1990; Siegert *et al*., 2001; Rieley & Page, 2005). However, if a forest has been logged and affected by fire once, the probability for recurrent fires increases dramatically (Cochrane *et al.*, 1999; Cochrane, 2003; Asner *et al*., 2006). Especially damaging are fires in intensely logged forests, where large amounts of potential fuel such as buttresses and treetops are left in the forest after the logging process (Goldammer, 2007). Recurrent fires eventually lead to complete deforestation transforming the forest vegetation into fire prone alang-alang (*Imperata cylindrica*) grasslands (Goldammer, 1993 Asner *et al.,* 2005).

To better understand the drivers of fire occurrence we analyzed the spatial pattern of fire occurrence in relation to land cover and land use in Borneo over a period of 10 years, as this island is typical for the fast deforestation processes in that region and showed some of the most severe fire disasters (Page et al., 2002; Tacconi, 2003; Fuller, 2006; Trigg *et al.,* 2006). When investigating retrospectively fire incidence and burnt areas we identified several methodological problems, which cannot be resolved. It is not possible to map burnt areas every year because in the past there were not enough high resolution satellite images such as Landsat, SPOT or IRS recorded to cover the whole island each year. Reasons are high costs, frequent cloud coverage, narrow swath, and long orbit repeat cycles. Also low or medium spatial resolution satellite imagery such as NOAA, SPOT VEGETATION and MODIS are either not available for each year or have too coarse spatial resolution to resolve small fire scars (Miettinen *et al.*, 2007). There is only one type of satellite data available which covers the full area with almost daily coverage. These are high temperature events recording systems on the NOAA AVHRR, ERS, ENVISAT and TERRA/AQUA satellites, which deliver coordinates of active fire events, so called hotspots. Unfortunately there is not a single sensor system which would cover the full period. Each of the satellite has different spectral properties, sensitivities and orbit repeat cycles, which makes it difficult to compare the results of different years (Siegert and Ruecker, 2000; Li *et al*., 2001; Justice *et al*., 2002). Being aware that there are no other options, we tried to consider the potential errors. We did a separate analysis for two investigation periods: from 1997 to 2001 using NOAA AVHRR and ATSR hotspots and from 2002-2006 using MODIS hotspots only. Beside the direct comparison of the number of the fire events over the years using three different sensors we converted active fire pixels into fire affected areas. For this we assumed the corresponding spatial resolution of the sensor element at nadir as to be completely burnt, areas of overlapping hotspots were regarded as burnt once. Deriving burnt areas from active fire detections is also error-prone, as the detected hotspots do not provide information about the actual burnt area (Stolle *et al.*, 2004; Miettinen *et al.*, 2007). According to Miettinen et al. (2007) every land cover type has its distinct fire regime such as grasslands with short but intense fire events and long time burning forest fires. Especially peat lands show extended burning events as fires can affect the standing forest biomass as well as the underlying peat layer (Rieley & Page, 2005). High resolution satellite imagery would be necessary to calibrate each sensor for different years, land covers and land uses but this data was not available to this extent. However, as far as available we tried to incorporate high resolution data sets. To account for this uncertainty, we intentionally did not aim for calculating the burnt area in absolute values and instead use the term 'fire affected area'. Bearing in mind the above described problems as well as a shortage of alternatives, we consider the combination of analyzing the number of detected hotspots as well as the fire affected area as a feasible approach.

Specific questions to be investigated in this study were: 1) which are the major land cover types affected by fire, 2) what are the effects of El Niño, 3) is there a correlation between land use and fire and 4) how well are National Parks protected from fire. Finally we tried to identify the major drivers of fire in order to better understand the processes leading to fire in tropical rainforest ecosystems and to foster improved fire management in the future.

Material and Methods

Sensor systems for active fire detections

Actively burning fire events, so called hotspots, are regularly recorded in Southeast Asia by three specific low resolution satellite sensors: 1) The National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer (NOAA AVHRR), which was kindly provided by the Integrated Forest Fire Management (IFFM) project, 2) The European Remote Sensing Satellite Along Track Scanning Radiometer (ERS-2 ATSR) provided in the framework of the ATSR Fire Atlas Validation study by European Space Research Institute/European Space Agency (ESRIN/ESA) and 3) The Moderate Resolution Imaging Spectroradiometer (MODIS), kindly provided by the University of Maryland, (NASA & University of Maryland, 2002). All three systems are equipped with specific thermal detector elements, which allow measuring the temperature on the earth surface. If the temperature in a specific sensor element is above a certain threshold, this location is defined as an actively burning fire event. Each sensor may produce false detections due to various reasons and elaborated algorithms have been developed to increase the accuracy of hotspot detection (Kaufman & Justice, 1998; Dwyer *et al.*, 2000; Mota *et al.*, 2006). Each of the satellite systems has distinct advantages and disadvantages for the envisaged study: the NOAA AVHRR 14 sensor records data in Borneo twice a day, but the sensor is saturated at low temperatures and sun glint, leading frequently to false alarms (Siegert & Hoffmann, 2000). The probability of fire detection highly depends on fire temperature and satellite viewing zenith angle, causing an error of omission of up to 10% (Giglio *et al.*, 1999; Li *et al.*, 2001). The NOAA 14 orbit is subjected to a drift over the years changing the local overpass time. This could potentially have crucial effects on the number of active fire events detected by the satellites, as described by Giglio (2007). The use of alternative NOAA AVHRR sensors is restricted as only NOAA 9, 10 and 12 recorded data during the sample period of 1997-2006. NOAA 12 and 10 were inapplicable for these studies as their overpass time is in the early morning and early evening (see NOAA KLM User's Guide at http://www2.ncdc.noaa.gov/docs/klm/index.htm) and NOAA 9 even showed an increased drift in the local overpass time (Giglio, 2007). The spatial accuracy of the ATSR sensor is high and there are few false alarms due to night-time acquisition, but there is also a high error of omission because fire activity often peaks in the afternoon and the revisit cycle is only every three days (Siegert *et al.,* 1999; Arino *et al*., 2001). MODIS records hotspots with high accuracy, but this data set is only available since 2002. The MODIS sensor is mounted on-board of two satellites (Terra and Aqua) that pass Borneo four times a day (day passes at 10:30 a.m. for Terra and 1:30 p.m. for Aqua, night passes at 10:30 p.m. and 01:30 a.m., respectively). For fires before 2002 we used all hotspots recorded by NOAA 14 and ATSR by adding their datasets. ATSR was used in addition to NOAA because especially in 1997 and 1998 several large fires were not recorded by NOAA due to operation errors at the receiving station. For fires from 2002 till 2006 we used all hotspots detected in both day and night passes by the MODIS sensor.

Number of detected hotspots

None of the sensor systems is able to distinguish between one or more individual fires within a pixel. Therefore we used the terminology of a "fire event" as synonym of a hotspot pixel, which should not be confused with the terminology of "a fire". A real fire on the ground can consist of several fire spots depending on the duration and the size of the fire. As we used different satellite systems to cover this 10 years period, a direct comparison of the absolute numbers of detected fire events of the two different acquisition periods is problematic. One of the main reasons for this is the completely differing temporal resolution of the distinct sensors to detect the fire events. For the period 1997-2001 fire events were detected with a maximum of 2.3 satellite overpasses per 24 hours. Fire events were recorded by the MODIS sensors at maximal 4 times per 24 hours since 2002. The number of the detected fire events could not be normalized for better comparison between the two acquisition periods, because of several issues: due to technical problems the AVHRR sensor did only record fire events between August and November 1997, January and May 1998, January and September 1999, and February and October 2000. During these times fire events could only be detected by the ATSR sensor. For the first half of 2002 only fire events detected by the Terra satellite could have been used, because the Aqua satellite started broadcasting not until July 2002. As the fire seasons differed decisively between the years, an extrapolation was not feasible. A further problem was that the affected land cover types showed different fire regimes, with quickly spreading fires in grasslands (not recorded by ATSR sensor at all) and long lasting fires in peat swamps (recorded several times a day over several days) (Siegert *et al.*, 2004; Stolle *et al.*, 2004). Nevertheless the order of magnitude of fire occurrence is comparable and therefore we also refer to hotspot numbers in the results section.

From hotspots to fire affected areas

Due to lack of high resolution data to assess burnt areas, we estimated the annual fire affected areas based on hotspot data of the three satellites. We are aware that these calculations can only be estimates, but since there is no continuous time series of any satellite system available for Borneo over 10 years, we considered this estimate as justified. Several studies based on high resolution Landsat imagery proved that there is a reasonable agreement between hotspots and burned areas derived from them and possible sources of error are known (see below). One single hotspot pixel (sensor element) represents the area of the corresponding sensor resolution of 1 km for ATSR and MODIS and 1.1 km for AVHRR (Liew *et al.*, 1998; Justice *et al.*, 2002; Giglio *et al.*, 2003). This pixel can be affected by a single fire or more than one fire. The actual size of a fire saturating the sensor element can be as small as 10 m^2, since gas flames on oil platforms were detected by all three systems. It has to be noted that the actual size of the actual burnt area is unknown. For the hotspot-area conversion it was assumed that the area of each hotspot has been completely affected by fire. However, as a sensor element can also be saturated by a small but very hot fire of only 10 m^2 it is difficult to directly derive the burnt area from the hotspot data. Areas of overlapping hotspots of were regarded to be affected by fire only once, thus solving the problem of same fires detected several times. Thus, a comparison of the two acquisition periods becomes more significant than comparing the number of detected fire events.

From 1997 till 2001 we used both NOAA AVHRR and the ERS-2 ATSR hotspots to cope with sensor specific errors. In terms of burnt area the ATSR sensor seriously underestimates the area but the spatial accuracy is much better than that of the NOAA data processed by IFFM (Siegert *et al.*, 1999). The NOAA AVHRR sensor tends to overestimate (up to 30%) the fire affected area due to a high number of false alarms and low spatial accuracy or underestimate the fire affected area (up to 15%) due to missing acquisitions related to technical problems of the receiving station or haze and cloud cover (Liew *et al.*, 1998; Siegert *et al.*, 1999; Siegert & Hoffmann, 2000; Bechteler & Siegert, 2004). From 2002 onwards only MODIS based active fire detections were used. This system is the most accurate and reliable in terms of detection accuracy and completeness. Studies in Kalimantan and Sumatra showed that the MODIS sensor underestimates the actual burnt area by 12%-42%, depending on the land cover type (Liew *et al.*, 2003; Miettinen *et al.*, 2007). Fires in agricultural areas or grasslands may burn only a short time (1 hour or less) and become extinguished during the night. Therefore many of such fires remained undetected due to missing satellite overpasses. Fires in forested areas, especially in degraded forest, burn more persistent and thus are easier to detect. In closed canopy forests, fires frequently burn as ground fires with little heat production. These fires escape detection by any of the available satellites (Nepstad et al. 1999; own observations).

Validation and accuracy assessment

The results were evaluated with Landsat based burnt area maps by comparing fire affected areas to the actual burnt area. The validation was done for the area of a full Landsat scene (Landsat 7 ETM+ scene (P118 R062), dating from January 9th 2007) by correlating the annually accumulated hotspot map (2006 MODIS hotspots) with the corresponding burnt area of that year. After masking cloud and haze obscured areas as well as stripes of missing data, the image was classified into four classes: burnt, non-burnt, water and remaining cloud/haze. To reduce the impact of atmospheric disturbances such as haze we used a spectral subset (only the Landsat bands 3, 4, 5, 7), covering the red to the short wavelength Infra Red (IR) spectrum, which contains the most relevant information for detecting vegetation and burnt scars. Using an unsupervised ISODATA algorithm with 10 iterations, 100 clusters were assigned to one of the abovementioned classes. The automatic classification results were controlled and revised by visual interpretation. To evaluate the accuracy we analyzed the error of omission and commission, the overall accuracy and the kappa coefficient. The Landsat derived burnt areas (in ha) were intersected and compared with the area (in ha) of the corresponding hotspot data. From linear regression, we obtained the slope of the relationship (scaling factor), the coefficient of determination (R^2) and the corresponding significance level. For statistical analysis we used the DAG_Stat module of Mackinnon (2000) to derive the kappa coefficient and to test the significance of the results on a 95% confidence interval (Cohen 1960).

GIS analysis of hotspots and fire affected areas

To assess the number of fire events per land cover and to analyze the spatial patter of the fire affected areas the hotspot data as well as the fire affected areas was superimposed on a land cover map of Borneo. The nature of (recurrent) forest fires in the humid tropics is to result in land cover changes, forest degradation and finally deforestation. Thus, every single year should be analyzed on basis of its respective land cover map. As such detailed land cover information was not available; we refer to a single map showing the land cover of 2002 – representing the situation right in the middle of the analyzed period. The analysis may be therefore biased towards an underestimation of the fire affected forest area in 1997 to 2001, while for the years 2003 till 2006 the fire affected forest area might be overestimated (because the forest has vanished before). The land cover map was based on multitemporal MODIS surface reflectance data acquired between November 2001 and October 2002 with a medium resolution of 250 m, discriminating between six distinct forest types: ‘lowland dipterocarp forests’, ‘peat swamp forests’, ‘freshwater swamp forests’, ‘mangrove forests’, ‘upper dipterocarp forests’ and ‘mountain forests’ (Langner *et al.,* 2007). For our study ‘peat swamp forests’ and ‘freshwater swamp forests’ were combined into swamp forests and ‘upper dipterocarp forests’ and ‘mountain forests’ were combined to ‘mountain forests’, accounting for all forests above 800 m sea level.

GIS layers with administrative and concession boundaries, National Parks and other protected areas, which were downloaded from Global Forest Watch (http://www.globalforestwatch.org/english/index.htm), were intersected with the annual hotspot data and the annual fire affected areas. All results were evaluated concerning the number of detected active fire events as well as the total areas affected by fire. The former ones were displayed in fire events per 100 ha and the latter ones in ha and in percentages as unit to ensure the subsequent comparison of the fire impacts between areas of different size.

Results

Analysis of hotspots

Both, in the first period from 1997-2001 and in the second period from 2002-2006, El Niño years (1997-98, 2002, 2006) showed a much higher fire occurrence over whole Borneo than in years with normal weather conditions. In comparison to the mean number of fire events in non-El Niño seasons with 10,886 and 19,902 in the first and the second investigation period, the mean number of fire events in El Niño years rose to 65,499 and 48,875 respectively (Table 1). Between 1997 and 2001 the mean number of detected fire events in agricultural areas (29,321) and degraded forests (22,318) during El Niño years was much higher in comparison to normal years with 5,510 and 3,203 fire events respectively (Table 1). The same situation was found when comparing fire events in various forest types. In general, fire events in swamp forests were most frequent. In average 9,584 active fire events were detected in swamp forests, which is more than double the number of fire events occurring in dipterocarp forests (4,030). For the period 2001 till 2006 there is a clear shift towards fire events in swamp forests (14,395) and less fire events in dipterocarp forests (2,915) during El Niño conditions, even though the total area of swamp forests is less than half of the remaining area of lowland dipterocarp forests. Figure 1 C clearly shows the trends of fire occurrence per land cover type. To facilitate comparisons between the categories we did not use the absolute number of the fire events but the normalized unit of number of fire events per 100 ha.

Fire occurrence and land cover

During the last decade almost 16.2 Mha, corresponding to 21.1% of the land area of Borneo has been affected by fire at least once and 6.1% (4.5 Mha) has been affected more than once. Figure 1 A shows the fire affected areas in ha of whole Borneo for every year from 1997 till 2006. This result is visualized in figure 1 B where each detected active fire event is displayed in red color. Areas, which were affected by fire events more than once, are displayed in lighter yellow colors. The largest areas affected more than once are located in Central and in East Kalimantan. In non-El Niño seasons the mean area of Borneo affected by fire was almost 1.3 Mha per year (1.7% of the landmass of Borneo) which increased to an average 3.7 Mha in El Niño years (5.1% of the landmass of Borneo). During the severe 1997 fire season almost 4.6 Mha has been affected by fire, both agricultural lands and forested areas.

By superimposing all fire affected areas on the 2002 land cover map of Borneo, the impact of these fires on the forests was investigated. The pattern is similar as before:

during El Niño 2.4% of forest has been affected by fire and only 0.8% in normal years (Figure 1, D). Further analysis revealed that not all forest types were equally affected. While all other forest types were only marginally affected by fire in non-El Niño years with an average of 0.4% in dipterocarp forests and 0.6% in mangrove forests, swamp forests showed an average of 2.1%. This percentage rose to 6.9% for swamp forests during El Niño conditions, while only 1.2% and 1.0% was recorded for dipterocarp forests and mangrove forests respectively (Table 2).

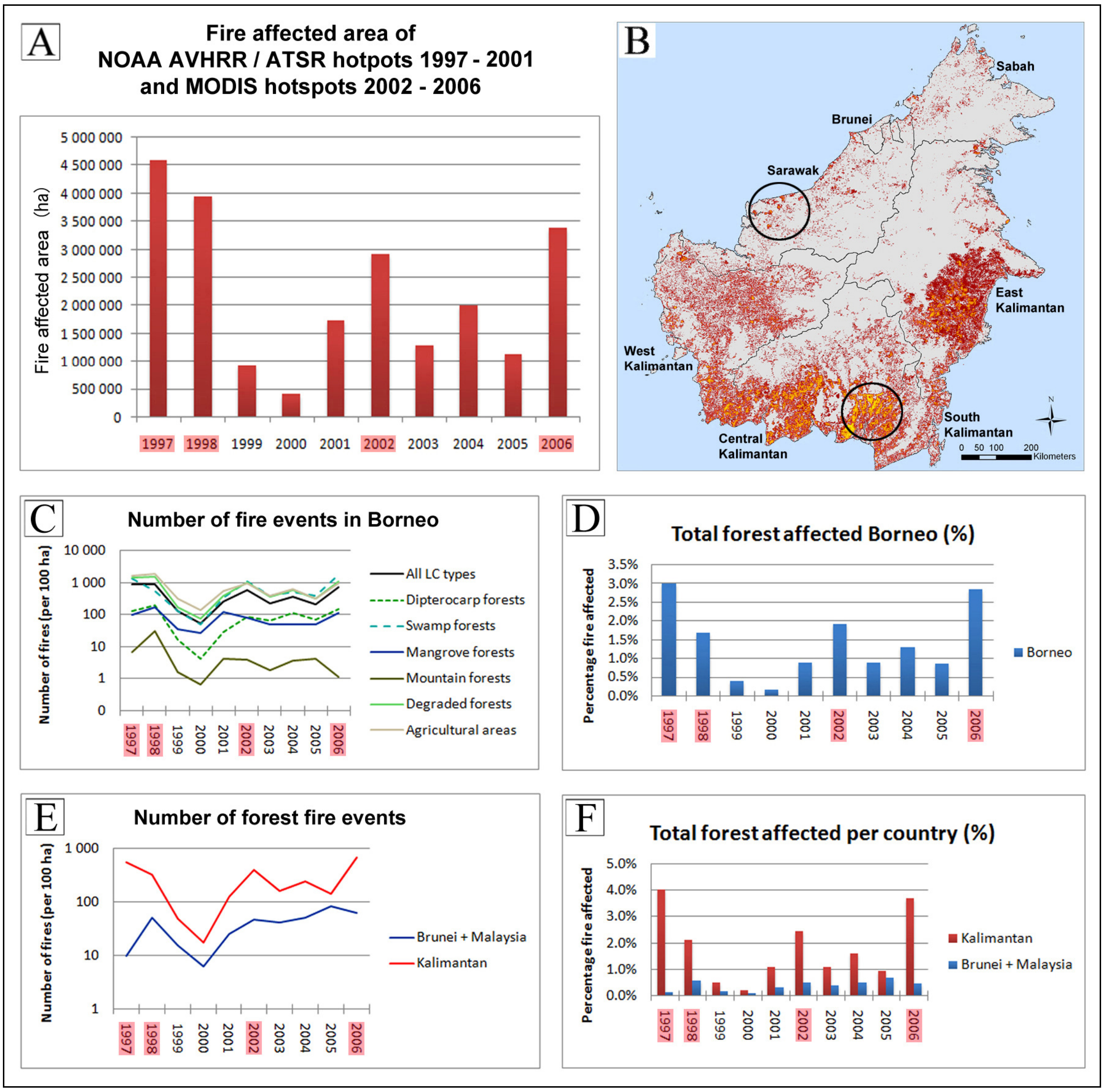

Figure 1:
It has to be noted that NOAA AVHRR / ATSR hotspot data were used from 1997 – 2001 and MODIS hotspot data were used from 2002 – 2006. El Niño years are marked with red color. (A) Absolute fire affected area per year. (B) Fire affected area over the last

decade 1997 – 2006. Areas burnt once in dark red, areas burnt more than once in lighter yellow colors. Circles indicating different hotspot pattern between Malaysia and Kalimantan. (C) Total number of fire events in Borneo and split per land cover type (unit is number of fire events per 100 ha). (D) Diagram of percentage of total forest area on Borneo affected by the fires. (E) Number of forest fire events differentiated on country level (unit is number of fire events per 100 ha). (F) Percentages of total forest areas affected by the fires, differentiated on country level.

Analysis of hotspots in Malaysia and Indonesia

Forest fire occurrence showed distinctive difference in Malaysia and Brunei in comparison to Kalimantan, the Indonesian part of Borneo. In both investigation periods the number of active fire event detections is much lower in Brunei and Malaysia. Between 1997 and 2001 the impact of El Niño years on fire occurrence was clearly visible in all countries. In Kalimantan this relation was more pronounced with 13,473 (El Niño) to 1,972 fire events (non-El Niño) than in Brunei and Malaysia (388 in comparison to 201). During the second period from 2001 till 2006 only Kalimantan showed this relation, while in Brunei and Malaysia the El Niño condition did not lead to an increase in fire event occurrence (Table 1). Figure 1 E shows the relative number of forest fire events split per country level.

Analysis of fire affected area in Malaysia and Indonesia

Analyzing the fire affected areas revealed similar results. The forests in Kalimantan were much stronger affected by fire with 1.8% on average than Brunei and Malaysia with only 0.4%. Furthermore, only Kalimantan showed the typical pattern with high fire impact during El Niño years (3.1% in average) and low fire impact during the other years (0.9% in average). The provinces with the highest impact were Central and South Kalimantan in 1997 with 15.0% and 17.5% fire affected areas respectively.

Table 1. Analysis of fire occurrence in Borneo during a 10 year period. The table shows the number of all detected active fire events (HS) per year. El Niño years are highlighted with grey color. Between 1997 and 2001 AVHRR and ATSR sensors were used for active fire event detection. From 2002 till 2006 only the MODIS sensor was used. Additionally the MEAN numbers for all El Niño (Mean E N) and non-El Niño years (Mean N Y) for both investigation periods are calculated and displayed in italic.

		Total number of fires (Borneo)	Number of fires in agricultural areas (Borneo)	Number of fires in degraded forests (Borneo)	Number of fires in swamp forests (Borneo)	Number of fires in mangrove forests (Borneo)	Number of fires in dipterocarp forests (Borneo)	Number of fires in mountain forests (Borneo)	Total number of forest fires (Brunei + Malaysia)	Total number of forest fires (Kalimantan)	Number of fires in protected areas (Malaysia)	Number of fires in protected areas (Kalimantan)	Number of fires in conversion forests (Kalimantan)	Number of fires in production forests (Kalimantan)	Number of fires in limited production forests (Kalimantan)
AVHRR + ATSR	1997	65,986	26,979	21,775	13,817	98	3,276	41	126	17,106	4	4,108	21,581	29,561	3,819
	1998	65,011	31,663	22,860	5,350	171	4,783	184	649	9,839	149	8,487	27,107	19,498	7,773
	1999	9,571	5,177	2,678	1,253	37	416	10	194	1,522	18	257	1,668	2,405	1,021
	2000	4,001	2,225	1,155	485	28	104	4	80	541	6	102	518	1,168	284
	2001	19,086	9,127	5,777	3,323	119	715	25	330	3,852	37	1,276	5,288	5,363	1,365
	Mean E N	*65,499*	*29,321*	*22,318*	*9,584*	*135*	*4,030*	*113*	*388*	*13,473*	*77*	*6,298*	*24,344*	*24,530*	*5,796*
	Mean N Y	*10,886*	*5,510*	*3,203*	*1,687*	*61*	*412*	*13*	*201*	*1,972*	*20*	*545*	*2,491*	*2,979*	*890*
MODIS	2002	44,656	16,211	15,372	10,825	84	2,140	24	590	12,483	47	4,430	12,795	17,872	2,756
	2003	17,190	6,182	5,540	3,794	51	1,612	11	522	4,946	160	1,522	5,056	5,538	1,526
	2004	27,195	10,036	8,981	5,314	52	2,790	22	647	7,531	45	1,858	7,601	8,992	2,514
	2005	15,322	5,024	4,765	3,786	50	1,671	26	1,071	4,462	60	871	4,677	3,437	1,001
	2006	53,093	15,545	15,772	17,965	115	3,689	7	787	20,989	10	5,513	15,678	22,194	2,952
	Mean E N	*48,875*	*15,878*	*15,572*	*14,395*	*100*	*2,915*	*16*	*689*	*16,736*	*29*	*4,972*	*14,237*	*20,033*	*2,854*
	Mean N Y	*19,902*	*7,081*	*6,429*	*4,298*	*51*	*2,024*	*20*	*747*	*5,646*	*88*	*1,417*	*5,778*	*5,989*	*1,680*

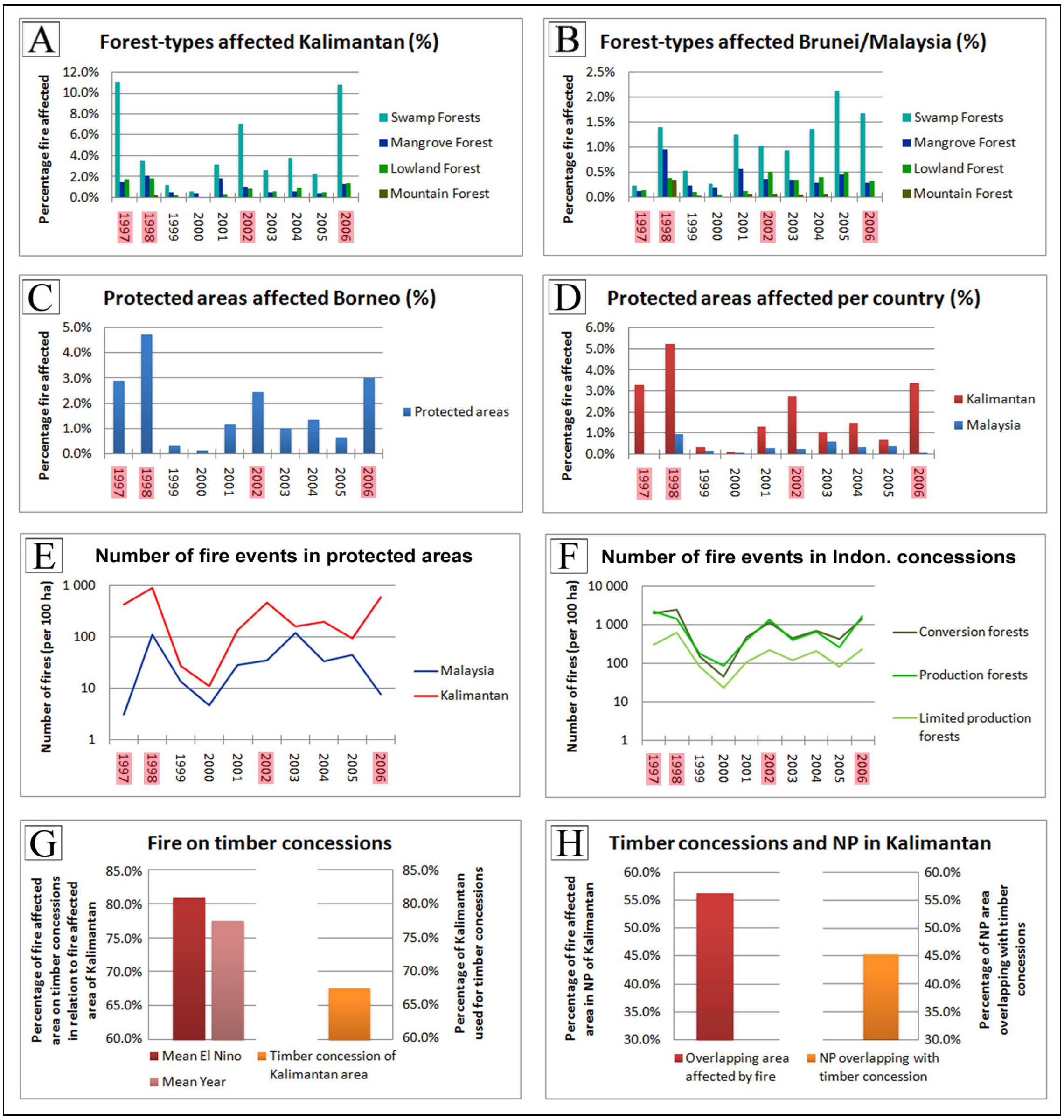

Figure 2:

It has to be noted that NOAA AVHRR / ATSR hotspot data were used from 1997 – 2001 and MODIS hotspot data were used from 2002 – 2006. El Niño years are marked with red color. (A) Percentages of fire affected areas of four different forest types in Kalimantan. (B) Percentages of fire affected areas of four different forest types in Brunei and Malaysia. (C) Percentage of protected areas on Borneo affected by the fires. (D) Percentages of fire affected protected areas, differentiated on country level. (E) Number of fire events in National Parks and protected areas differentiated on country level (unit is number of fire events per 100 ha). (F) Number of fire events in different forest concessions of Kalimantan (unit is number of fire events per 100 ha). (G) Correlation between land use of timber concessions and fire occurrence in Kalimantan.

Even though different ordinates, the percentage values can directly be compared. (H) Fire in National Parks in Kalimantan which overlap with timber concessions. Even though different ordinates, the percentage values can directly be compared.

During the 1998 El Niño season 3.4 Mha of agricultural and forest land of East Kalimantan were affected by fire, which corresponds to 17.2% of the province area. In Sarawak, Sabah and Brunei, El Niño seemed to have no influence on fire occurrence. Between 0.4% and 0.3% of the forest area was affected in average in El Niño and normal years respectively (Figure 1 F). During all years, swamp forests were most affected by fire all over Borneo (Figures 2 A, B), even though Indonesia showed a much higher impact ranging from 2.3% in normal years to 8.1% in El Niño years. Swamp forests in the non-Indonesian part of Borneo were affected by fires at about 1.1% in average – no matter what conditions.

Fire occurrence in protected areas

To investigate the efficiency of forest ecosystems protection in National Parks and other conservation areas, we analyzed the annual fire affected areas. Altogether 10.6 Mha are under of protection in Borneo – either in National Parks or other protected areas, which corresponds to 14.2% of the total landmass of the island. The clear pattern with larger fire affected areas in El Niño years (3.3% in average) and less during normal years (0.8% in average) was also observed in National Parks. Especially the El Niño year 1998 showed highest impact when about 0.5 Mha were affected by fires, which corresponds to 4.7% of the total area of National Parks in Borneo (Figure 2 C).

Table 2. Analysis of the fire affected area in Borneo during a 10 year period. El Niño years are highlighted with grey color. Between 1997 and 2001 AVHRR and ATSR sensors were used for active fire detection. From 2002 till 2006 only the MODIS sensor was used. The fire affected areas of each year are displayed both in hectare (ha) and in percentage (%). Additionally MEAN values and standard deviations (δ) for all El Niño and non-El Niño years are calculated and displayed in italic.

		Fire affected area of swamp forests in Borneo		Fire affected area of mangrove forests in Borneo		Fire affected area of dipterocarp forests in Borneo		Fire affected area of mountain forests in Borneo		Timber concessions in Kalimantan		Protected areas in Kalimantan		Protected areas in Malaysia	
		ha	%	ha	%	ha	%	ha	%	ha	%	ha	%	ha	%
AVHRR + ATSR	1997	919,621	9.2%	8,314	0.9%	320,612	1.3%	4,112	0.1%	3,643,063	9.9%	306,465	3.3%	430	0.0%
	1998	291,684	3.1%	11,829	1.6%	340,160	1.5%	11,922	0.3%	3,210,255	8.7%	489,455	5.3%	12,402	0.9%
	1999	105,682	1.1%	3,175	0.4%	40,831	0.2%	308	0.0%	490,367	1.3%	30,033	0.3%	1,822	0.1%
	2000	48,210	0.5%	2,653	0.3%	9,539	0.1%	319	0.0%	209,632	0.6%	11,859	0.1%	716	0.1%
	2001	264,521	2.9%	10,379	1.3%	65,539	0.3%	1,907	0.1%	1,023,576	2.8%	120,549	1.3%	4,116	0.3%
MODIS	2002	589,997	6.1%	5,893	0.7%	160,236	0.8%	810	0.0%	2,057,465	5.6%	256,522	2.8%	3,005	0.2%
	2003	218,144	2.3%	2,728	0.4%	110,898	0.5%	820	0.0%	869,448	2.4%	98,442	1.1%	7,969	0.6%
	2004	315,422	3.4%	3,715	0.5%	174,210	0.8%	1,043	0.0%	1,345,350	3.7%	139,532	1.5%	4,228	0.3%
	2005	187,867	2.2%	2,437	0.4%	100,901	0.5%	1,278	0.0%	662,218	1.8%	63,377	0.7%	5,020	0.4%
	2006	895,217	9.2%	7,746	0.9%	246,844	1.1%	356	0.0%	2,498,257	6.8%	316,615	3.4%	1,172	0.1%
Average El Niño		*692,383*	*6.9%*	*10,372*	*1.0%*	*290,518*	*1.2%*	*6,482*	*0.1%*	*2,852,260*	*7.8%*	*342,264*	*3.7%*	*4,252*	*0.3%*
Average non-El Niño		*208,135*	*2.1%*	*5,749*	*0.6%*	*101,613*	*0.4%*	*1,816*	*0.0%*	*766,765*	*2.1%*	*77,299*	*0.8%*	*3,979*	*0.3%*
δ *El Niño*			*2.9%*		*0.4%*		*0.3%*		*0.1%*		*1.9%*		*1.1%*		*0.4%*
δ *non-El Niño*			*1.1%*		*0.3%*		*0.3%*		*0.0%*		*1.1%*		*0.5%*		*0.2%*

National Parks in Kalimantan were much more affected by fire. The 46 parks of the Indonesian part of Borneo cover 9.3 Mha. During non-El Niño years about 0.8% of the park area were affected and 3.7% in El Niño years. Malaysia, where 1.3 Mha are under protection, shows no difference between the years (Figure 2 D), with 0.3% of the park area affected by fire (Table 2). Regarding the relative number of fire events figure 2 E shows the increased fire occurrence in the National Parks of Kalimantan in comparison to Malaysia and the nonexistent correlation to El Niño seasons in the protected areas of Malaysia.

Fire occurrence and land use

Timber concession permits are issued for different kinds of usage by the Indonesian Ministry of Forestry such as production forests for conversion, for intense logging, and limited production forests for low-intensity timber harvest (FWI & GFW, 2002). This information was only available for Kalimantan. From 1997 till 2001 fire occurrence in conversion forests and production forests was almost identical with 24,344 and 24,530 hotspots during El Niño years demonstrating that there is no effective fire management in timber concessions designated for continuous production. This is much more than in limited production forests, where only 5,796 fire events have been detected. Normal years in comparison show a much lower fire activity with about $1/10^{th}$ of the fire events in conversion and production forest. The second investigation period is characterized by an increase of fire events in non-El Niño years. During El Niño years 14,237 and 20,033 hotspots were detected in conversion forests and production forests, while in normal years this is about $1/3^{rd}$ (Table 1). Figure 2 F shows the relative number of fire events in the different concession areas of Kalimantan.

To analyze a possible correlation of fire and land use, fire affected areas were intersected with timber concession areas. In the year 2000, about 36.8 Mha of Kalimantan were under timber concession licenses. Production and conversion forests were generally more affected than the limited production forests and also showed much higher impacts during El Niño years with 10.0% and 10.6% respectively in comparison to 2.8% for the limited production forests. While 67.6% of the area of Kalimantan is timber concession, about 77.4% of the total fire affected area over the whole period was located in these concessions. This number rose to 80.9% in El Niño years (Figure 2 G). About 4.2 Mha of timber concessions are overlapping with National Parks and protected areas in Kalimantan. This corresponds to 45.3% of the National Park area in Kalimantan. Over this 10 years period, 0.8 Mha of these 4.2 Mha were affected by fire, representing 56.2% of all fire affected areas in Kalimantan's National Parks (Figure 2 H).

Accuracy assessment

The overall accuracy of the 2006 fire affected area derived from MODIS hotspots was 90.6% with a kappa coefficient of 0.579 in comparison with the Landsat burnt area result. The error of omission of 38.1% (undetected burnt areas) was slightly higher than the error of commission with 35.2% (false alarms). According to this subset area the MODIS hotspot data slightly underestimated the burnt area by 5%. To investigate the spatial characteristics of false detections the exact location of the hotspots was analyzed. 21.5% of the hotspots were located outside the burnt scars detected in the Landsat image. It has to be kept in mind that the Landsat reference image was acquired in the middle of the wet season, so wetland areas which are susceptible to fire in the dry season were flooded at the time of image acquisition and thus classified as water areas. The observed error decreases from 21.5% to 19.4% if fire events detected in water areas were considered as correctly classified. The mean nearest distance of false detected fire events was 181 m to the Landsat burnt scars with a standard deviation of 186 m clearly showing the geolocation error of the MODIS sensor. If the burnt scars were expanded by a 1 km buffer, 99.9% of all hotspots occurred within this area. Similar accuracies were observed in Sumatra and Kalimantan (Liew *et al.,* 2003). Regarding a subset area focusing on peat swamp forests only the overall accuracy was 93.4% with a kappa coefficient of 0.636. Compared to the values of the total reference area the error of omission decreased to 28.9% the error of commission slightly increased to 36.2%. Regarding the fire events in the peat swamp forests the MODIS hotspot data slightly overestimated the burnt area by 10%.

Discussion and conclusion

To be able to analyse fire impact on Borneo, with an area of 74 Mha, we had to rely on measurements of hotspots by low resolution satellite instruments. High resolution optical imagery has never been successfully acquired for this large area on an annual basis by any of all operational satellite sensors due to high costs, frequent cloud cover and technical constraints. Similar is true for cloud penetrating SAR imagery, in addition major methodological problems impede reliable burnt scar detection in tropical environments with complex land covers (Siegert & Ruecker, 2000). As medium and low resolution optical satellite imagery was not available for each of the years or too coarse to resolve smaller burnt scars, the only other option was to collect and analyse all available active fire event detections by all three operational fire detection satellites.

The drift in the overpass orbits of the NOAA AVHRR sensors was analyzed in detail as it could have crucially affected the number of detected active fire events (Giglio, 2007). We used NOAA-14 data between 1997 and 2001. Therefore we expect a shift of the local overpass time from 2 p.m. to 4 p.m. This slight shift will not significantly influence the number of detected fire events, because in this tropical region most fires occur in the afternoon between 1 p.m. and 5 p.m. (unpublished filed data collected by the IFFM Integrated Fire Management project, in charge of fire management in East Kalimantan from 1994 – 2002). To show that the utilization of the NOAA data is legitimate, we compared the number of detected active fire events of both NOAA-14 and the ATSR sensors. Considering the fact that NOAA generally detects a much higher number of active fire events than ATSR, which is mainly related to the 3 days revisit cycle, we obtained the same trend in hotspot numbers over the years. Additionally the NOAA AVHRR hotspots were evaluated in previous studies using more than 10 hours of aerial survey data and 2000 km of field transects on burn scars (Siegert & Hoffmann, 2000; Siegert *et al.*, 2001). Dismissing NOAA data would not allow elaborating the impact of fires. ATSR alone would miss more than 70% of all fire events. Alternative use of active-fire event time series from the Tropical Rainfall Measuring Mission (TRMM) Visible and Infrared Scanner (VIRS) sensor would significantly blur the result as the data is recorded with 4.4 km spatial resolution (Giglio & Kendall, 2004). Additionally the TRMM orbit causes the local overpass time to drift over the entire 24 hours of a day approximately once each month, which has much worse impact than a shift of 2 hours over a period of 4 years as with NOAA (http://earthobservatory.nasa.gov/Observatory/Datasets/fires.trmm.html).

To analyse the spatiotemporal pattern and impact of fire we applied two approaches: 1) analysis of the spatial distribution and number of hotspots and 2) estimation of the fire affected area and intersection with land use and land cover maps. Both approaches have constraints: first, fires might have been detected two times in the first investigation period, when two sensors had to be used. Second, the estimation of the burnt areas is delicate as hotspots provide only restricted information about the actual burnt area (Miettinen *et al.*, 2007). Due to that reason we did not refer to absolute values for burnt areas, but fire affected areas. By using fire affected areas the problem of multiple detection of a fire event became irrelevant and the comparison of successive years became feasible.

In our study we did not aim to calibrate the hotspot derived fire affected areas with the area of fire scars, based on high resolution satellite data because of insufficient availability of high resolution reference satellite data. However, several studies in Indonesia (Fuller & Fulk, 2001) and other regions of the world (e.g. Giglio *et al*., 2006, Sukhinin *et al*., 2004, George *et al*., 2006, Kasischke *et al*., 2003) demonstrated that such calibration generally leads to reasonable results. Giglio *et al*. (2006) on the other hand, caution against scaling active fire event counts to a constant burned area since the slope (i.e. effective area burned per fire pixel) may vary dependent on the year, season and vegetation type (Miettinen *et al*., 2007). Beyond the above described effects, active fire event count data sets derived from different sensor types also inherit their own calibration factors. Therefore, the fire affected areas derived from ATSR, AVHRR and MODIS would have to be evaluated separately. However, due to missing cloud-free high resolution reference data sets acquired at appropriate times in the year to provide information about the burnt area of the corresponding fire season, we were only able to exemplarily conduct a validation of the 2006 MODIS derived hotspots using a Landsat scene. The total burnt area was slightly underestimated (5%) by MODIS. This is most likely related to the fact that fires in agricultural areas or grasslands burn for short periods of time and the orbit repeat cycle is inadequate to cover such fast spreading fires. The correlation was an overestimation of the burnt area by 10% in peat swamp forest. In contrast to the short-term fire events in the open fields, fires in forested areas are more persistent and can last from several hours to several days, thus leading to overestimation of the burnt area.

The tropical rainforests in Borneo are extremely threatened by fire, which is used as the cheapest means for land clearing. Slash and burn techniques have a long history in Southeast Asia and are practiced with experience by the indigenous people of Borneo (Marten, 1986). In general these techniques are regarded sustainable if the time period between the burning events is long enough, i.e. more than 20 or 30 years. Today, the problem is not the fire itself but the large scale and number of fires and the short fire repeat cycle (Cochrane, 2003). This was clearly confirmed by the present study. During 10 years satellites recorded more than 320,000 active fire events on the island of Borneo affecting 21% of the land surface once and 6% two times or more.

One of the consequences of the El Niño phenomenon in Southeast Asia is the late onset of the rainy season, which usually ends the annual cycle of anthropogenic fire activity linked to land clearing. Fires affected an area 3 times larger during the El Niño years 1997-1998, 2002 and 2006. Since fires on agricultural land are unavoidable and have little impact on the deterioration of biodiversity and carbon dioxide emissions, we focused the analysis on fires in forested land. With the exception of mountain forests, which are less accessible, all lowland forest formations have been affected seriously by fires each year, with more impact in El Niño years. Swamp forests were most severely affected in Kalimantan with 4.6% per year on average. The analysis of hotspot numbers per years revealed a shift from high numbers in dipterocarp forests towards swamp forests – especially during the second observation period from 2002 till 2006. This is most likely linked to the trend that in recent years large oil palm plantations have been established in peat swamp forests in West and Central Kalimantan (Rieley & Page, 2005; Hooijer *et al.*, 2006). The close vicinity of the last huge peat swamp forest areas in Central Kalimantan to the deforested and devastated areas of the former Mega Rice Project certainly also affects fire occurrence in these swamp forests, but these effects might have stayed the same in the first and second part of the observation period.

As the impact of El Niño on precipitation is comparable all over Borneo and ecosystems and land use are similar in Kalimantan and the Malaysian part of the island, the impacts of fires should also be comparable. Surprisingly, we found a pronounced difference in fire occurrence between Indonesia and Malaysia, which means that El Niño related droughts may not necessarily lead to an increase of the fire affected area. While the number of active fire event observations showed a high correlation to El Niño conditions in the forests of Kalimantan, this was clearly not the case in Brunei and the Malaysian provinces Sarawak and Sabah. This was even more pronounced in peat swamp forests highlighting the unsustainable land use policy in Indonesia and the lack of an appropriate fire management during dry conditions. The hotspot pattern showed that fires spread over much larger areas in Kalimantan, while in Malaysia and Brunei most fire events showed a punctiform distribution associated with land clearing for plantations (see two encircled regions in Figure 1B). These results are significant and suggest the existence of efficient fire prevention and fire suppression in Malaysia and no such measures in Indonesia.

Since it has been shown that protected areas are under strong pressure by illegal logging we investigated the occurrence of fire in Indonesian and Malaysian sanctuaries and National Parks (Fuller *et al.,* 2003; Curran *et al*., 2004). Fire affected 0.8% of the protected land in Indonesia in normal years while in Malaysia on the average only 0.3%. El Niño conditions caused an almost 5 times increase in fire activity in Kalimantan's protected areas, while there was no increase in Malaysia. In comparison to the percentage of limited production forest affected by fire, the values for the National Parks of Kalimantan were more than 30% higher, showing that Kalimantan's designated protected areas are under considerable high pressure.

Intensive illegal logging activities were made responsible for the rapid deterioration of the National Parks in Kalimantan (Fuller *et al.,* 2003; Curran *et al.,* 2004). Our analysis supports these findings, as more than 45% of all National Parks of Kalimantan overlap with timber concessions. Over a period of 10 years fires affected 0.8 Mha (19 %) of these overlapping areas. Related to almost 1.4 Mha, which became affected by fire on the National Parks of Kalimantan, these 0.8 Mha correspond to more than 56% - clearly showing the increased pressure on the protected areas. Especially parks with large swamp forest ecosystems in the coastal areas of Kalimantan such as the Sebangau National Park are exposed to the rising pressures from the timber and plantation business.

There is a clear link between land use and fire. In 2000, about 36.8 Mha of forest concessions were issued in Kalimantan, which corresponds to 67.6% of its land area. Timber concessions accounted for a higher proportion on the annual fire affected areas than shifting cultivators and plantation holders. In average more than 77% of the total fire affected area of Kalimantan occurred in timber concessions and this percentage rose to almost 81% during El Niño years. Conversion and production forests showed much higher fire occurrence than limited production forests, in which logging impact is comparatively low. This suggests that fire is used to clear the land after timber extraction in conversion and production forests for further development into plantations. On the other hand it also shows that conversion and production forests, in which logging impact is usually high, are much more susceptible to fire. Reason for this greater probability of fire reoccurrence in tropical forests that have previously been degraded by logging is that such forests have higher ground fuel loads, which substantially increase the fire hazard (Siegert *et al.*, 2001; Cochrane, 2003; Goldammer, 2007). Further detailed analysis was not possible as the proportion of legal and illegal activities inside timber concessions is unknown. However, it is well-known that the Indonesian government is not very authoritative against illegal logging activities because the officially designated amount of timber to be cut legally is by far not able to meet the demand of all the sawmill, plywood, pulp and paper companies in the country (Barber & Schweithelm 2000; FWI & GFW, 2002).

The analysis of hotspot data over the last decade in Borneo clearly showed that the remaining tropical forests are severely threatened by recurrent fires and El Niño conditions generally aggravate this situation. The analysis for whole Borneo showed that huge areas of forest burn each year, likely leading to significant carbon dioxide emissions. We did not attempt to estimate CO_2 emissions from forest fires, because the estimation of emissions is beyond the scope of the present paper. However, fires in peat swamp forests release huge amounts of carbon dioxide and other greenhouse gases and thus contribute largely to global warming (Page *et al.,* 2002). Due to emissions from peat fires, Indonesia became one of the world's largest producers to CO_2 emissions (Hooijer *et al.,* 2006).

This study reveals that El Niño cannot be made responsible alone for the recurrent fire disasters as there is a pronounced difference in fire occurrence between the Indonesian and Malaysian part of Borneo. Detailed future research on selected study sites both in Kalimantan and Malaysia in combination with the analysis of social and political aspects will help to better understand the underlying factors. Improved fire prevention is required not only to preserve the biodiversity in the last remaining tropical forests in Southeast Asia but also to mitigate the consequences of global climate change and to avoid further emissions of CO_2.

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References

Achard F, Eva HD, Stibig H-J, Mayaux P, Gallego J, Richards T, Malingreau J-P (2002) Determination of Deforestation Rates of the World's Humid Tropical Forests. *Science*, **297**, 999-1002.

Achard F, Eva HD, Mayaux P, Stibig H-J, Belward A (2004) Improved estimates of net carbon emissions from land cover change in the tropics for the 1990s. *Global Biogeochemical Cycles*, **18**, 1-11, GB2008, doi:10.1029/2003GB002142.

Arino O, Simon M, Piccolini I, Rosaz JM (2001) The ERS-2 ATSR-2 World Fire Atlas and the ERS-2 ATSR-2 World Burnt Surface Atlas projects. *Proceedings of the*

8th ISPRS conference on Physical Measurement and Signatures in Remote Sensing, Aussois, 8-12 January 2001.

ASEAN (2003) Guidelines for the implementation of the ASEAN policy on zero burning. Jakarta, Indonesia, ASEAN Secretariat, ISBN 979-8080-98-X

Asner GP, Knapp DE, Broadbent EN, Oliveira PJC, Keller M, Silva JN (2005) Selective Logging in the Brazilian Amazon. *Science,* **310,** 480-482.

Asner GP, Broadbent EN, Oliveira PJC, Keller M, Knapp DE, Silva JNM (2006) Condition and fate of logged forests in the Brazilian Amazon. *Proceedings of the National Academy of Sciences*, **103**, 34, 12947-12950

Barber CV, Schweithelm J (2000). Trial by fire. Forest fires and forestry policy in Indonesia's era of crisis and reform. *World Resources Institute (WRI), Forest Frontiers Initiative, in collaboration with WWF-Indonesia and Telapak Indonesia Foundation*, Washington DC.

Bechteler A, Siegert F (2004) Recurrent fires in the tropical Peatland of Central Kalimantan, Indonesia. In '*Wise Use of Peatlands. Proceedings of the 12th International Peat Congress*'. (Ed. J Päivänen) 607–613. (International Peat Society: Jyväskylä).

Brown S, Swingland IR, Hanbury-Tenison R, Prance GT, Myers N (2002) Changes in the use and management of forests for abating carbon emissions: issues and challenges under the Kyoto Protocol. *Philosophical Transactions of the Royal Society of London, Series A: Mathematical, Physical and Engineering Sciences,* **360,** 1593-1605.

Christanty L (1986) Shifting Cultivation and Tropical Soils: Patterns, Problems, and Possible Improvements. In Marten GG (1986) *Traditional agriculture in Southeast Asia: A human ecology perspective*, Westview Press, Boulder, Colorado, 226-240.

Cochrane MA, Alencar A, Schulze MD, Souza Jr. CM, Nepstad DC, Lefebvre P, Davidson EA (1999) Positive Feedbacks in the Fire Dynamic of Closed Canopy Tropical Forests. *Science* **284**, 1832-1834

Cochrane MA (2003) Fire Science for Rainforests. *Nature,* **421,** 913-919.

Cohen J (1960) A coefficient of agreement for nominal scales. *Educational and Psychological Measurement,* **20**, 37–46.

Curran LM, Trigg SN, McDonald AK, *et al.* (2004) Lowland Forest Loss in Protected Areas of Indonesian Borneo. *Science,* **303,** 1000-1003.

Dennis RA, Mayer J, Applegate G, *et al.* (2005) Fire, people and pixels: linking social science and remote sensing to understand underlying causes and impacts of fires in Indonesia. *Human Ecology,* **33,** 465-504.

Dwyer E, Pinnock S, Grégoire J-M, Pereira JMC (2000) Global spatial and temporal distribution of vegetation fire as determined from satellite observations. *International Journal of Remote Sensing*, **21**, 6&7, 1289-1302

FAO (2000) Global Forest Resources Assessment 2000; Main Report.

Fuller DO, Fulk M (2001) Burned area in Kalimantan, Indonesia mapped with NOAA-AVHRR and Landsat TM imagery. *International Journal of Remote Sensing*, **22**, 691–698.

Fuller DO, Jessup TC, Salim A (2003) Loss of Forest Cover in Kalimantan, Indonesia, Since the 1997-1998 El Nino. *Conservation Biology,* **18,** 249-254.

Fuller DO (2006) Tropical forest monitoring and remote sensing: A new era of transparency in forest governance? *Singapore Journal of Tropical Geography,* **27,** 15-29.

Fuller DO, Murphy K (2006) The ENSO-Fire Dynamic in insular Southeast Asia. *Climatic Change,* **74,** 435-455.

FWI/GFW (2002) The State of the Forest: Indonesia. Bogor, Indonesia: Forest Watch Indonesia, and Washington DC: Global Forest Watch.

George C, Rowland C, Gerard F, Balzter H (2006) Retrospective mapping of burnt areas in Central Siberia using a modification of the normalised difference water index. *Remote Sensing of Environment*, **104**, 346–359.

Giglio L, Kendall JD, Justice CO (1999) Evaluation of global fire detection using simulated AVHRR infrared data, *International Journal of Remote Sensing*, **20,** 1947-1985

Giglio L, Descloitres J, Justice CO, Kaufman YJ (2003) An Enhanced Contextual Fire Detection Algorithm for MODIS. *Remote Sensing of Environment*, **87**, 273-282.

Giglio L, Kendall JD (2004) Commentary on "Improving the seasonal cycle and interannual variations of biomass burning aerosol sources" by Generoso *et al.* *Atmospheric Chemistry and Physic*s, **4**, 585-587.

Giglio L, van der Werf GR, Randerson JT, Collatz GJ, Kasibhatla P (2006) Global estimation of burned area using MODIS active fire observations. *Atmospheric Chemistry and Physics,* **6**, 957-974.

Giglio L (2007) Characterization of the tropical diurnal fire cycle using VIRS and MODIS observations. *Remote Sensing of Environment*, **108,** 407-421.

Goldammer JG (1993) Feuer in Waldoekosystemen der Tropen und Subtropen. *Birkhäuser Verlag AG*, Basel-Boston, ISBN-10: 3764328134, ISBN-13: 978-3764328139.

Goldammer JG (2007) History of equatorial vegetation fires and fire research in Southeast Asia before the 1997–98 episode: A reconstruction of creeping environmental changes. *Mitigation and Adaptation Strategies for Global Change*, **12**, 13-32.

Hooijer A, Silvius M, Wösten H, Page S (2006) PEAT-CO2, Assessment of CO2 emissions from drained peatlands in SE Asia, Delft Hydraulics report Q3943

Houghton RA (2002) Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000. *Tellus,* **55B**, 378-390.

IPCC (2007) Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1-18.

Justice CO, Giglio L, Korontzi S, *et al.* (2002) The MODIS fire products. *Remote Sensing of Environment,* **83,** 244-262.

Kasischke ES, Hewson JH, Stocks B, van der Werf G, Randerson J (2003) The use of ATSR active fire counts for estimating relative patterns of biomass burning – a study from the boreal forest region. *Geophysical Research Letters*, **30**, 18, 1969, doi:10.1029/2003GL017859.

Kaufman Y, Justice C (1998) Algorithm Technical Background Document MODIS FIRE PRODUCTS (Version 2.2 Nov. 10 1998) (EOS ID# 2741)

Langner A, Miettinen J, Siegert F, Land cover change 2002 – 2005 in Borneo and the role of fire derived from MODIS imagery, *Global Change Biology*, **13**, 11, 2329-2340(12).

Li Z, Kaufman YJ, Ichoku C *et al.* (2001) A review of AVHRR-based active fire algorithms: principles, limitations, and recommendations. In *Global and Regional Vegetation Fire Monitoring from Space*, edited by Ahern FJ, Goldammer JG and Justice CO (*The Hague: SPB Academic Publishers BV*), pp. 199–225.

Liew SC, Lim OK, Kwoh, LK, Lim H (1998) A Study of the 1997 Forest Fires in South East Asia using SPOT Quicklook Mosaics. *1998 International Geoscience and Remote Sensing Symposium*, 6 - 10 July 1998, Seattle, Centre for Remote Imaging, Sensing and Processing, National University of Singapore

Liew SC, Shen C, Low J, Lim A, Kwoh LK (2003) Validation of MODIS fire product over Sumatra and Borneo using high resolution SPOT imagery. *Proceedings of 24th Asian Conference on Remote Sensing & 2003 International Symposium on Remote Sensing,* **Vol I**, 671-673.

Mackinnon A. (2000) A spreadsheet for the calculation of comprehensive statistics for the assessment of diagnostic tests and inter-rater agreement. *Computers in Biology and Medicine*, **30**, 3, 127-134.

Marcoux A (2000) *Population and deforestation*. From Population and the environment: a review and concepts for population programmes. Part III: Population and deforestation, FAO

Marten, GG (1986). Traditional Agriculture in Southeast Asia: A Human Ecology Perspective. *Westview Press,* Boulder, Cololorado and London

Mayaux P, Holmgren P, Achard F, Eva H, Stibig H-J, Branthomme A (2005) Tropical forest cover change in the 1990s and options for future monitoring. *Philosophical Transactions of the Royal Society,* **360,** 373-384.

Miettinen J, Langner A, Siegert F (2007) Burnt area estimation for the year 2005 in Borneo using multi-resolution satellite imagery. *International Journal of Wildland Fire, 16, pp 45-53, 2007.*

Mota BW, Pereira JMC, Oom D, Vasconcelos MJP, Schultz M (2006) Screening the ESA ATSR-2 world fire atlas 1997-2002. *Atmospheric Chemistry and Physics*, **6**, 1409-1424.

NASA/University of Maryland (2002) MODIS Hotspot / Active Fire Detections. Data set. MODIS Rapid Response Project, NASA/GSFC [producer], University of Maryland, Fire Information for Resource Management System [distributors]. Available on-line [http://maps.geog.umd.edu]

Nepstad DC, Verissimo A, Alencar A *et al.* (1999) Large-scale impoverishment of Amazonian forests by logging and fire. *Nature* **398**, 505-508.

Niles JO, Brown S, Pretty J, Ball AS, Fay J (2002) Potential carbon mitigation and income in developing countries from changes in use and management of agricultural and forest lands. *Philosophical Transactions of the Royal Society of London, Series A: Mathematical, Physical and Engineering Sciences,* **360,** 1621-1639.

Page SE, Siegert F, Rieley JO, Boehm H-DV, Jaya A, Limin S (2002) The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature,* **420,** 61-65.

Rieley JO, Page SE (2005) Wise Use of Tropical Peatland: Focus on Southeast Asia. ALTERRA - Wageningen University and Research Centre and the EU INCO - STRAPEAT and RESTORPEAT Partnership. ISBN 90327-0347-1. Report.

Schroeder-Wildberg E, Carius A (2003) Illegal Logging, Conflict and the Business Sector in Indonesia. *InWEnt - Capacity Building International, Germany*, Berlin, ISBN: 3-937235-33-7

Siegert F, Hoffmann A, Kuntz S (1999) Comparison of ATSR and NOAA AVHRR hotspot data acquired during an exceptional fire event in Kalimantan (Indonesia).

International Workshop on Applications of the ERS Along Track Scanning Radiometer. 23.-25.06.1999 Frascati, ESRIN Italy.

Siegert F, Hoffmann A (2000) The 1998 Forest Fires in East-Kalimantan (Indonesia): A quantitative evaluation using high resolution, multitemporal ERS-2 SAR Images and NOAA-AVHRR hotspot data. *Remote Sensing of Environment*, **72**, 64-77

Siegert F, Ruecker G (2000) Use of multitemporal ERS-2 SAR images for identification of burned scars in south-east Asian tropical rainforest. *International Journal of Remote Sensing,* **21,** 4, 831-837.

Siegert F, Ruecker G, Hinrichs A, Hoffmann AA (2001) Increased damage from fires in logged forests during droughts caused by El Nino. *Nature,* **412,** 437-440.

Siegert F, Zhukov B, Oertel D, Limin S, Page SEl, Rieley JO (2004) Peat fires Detected by the bird satellite. *International Journal of Remote Sensing,* **25**, 16, 3221–3230.

Stolle F, Dennis RA, Kurniwan I, Lambin EF (2004) Evaluation of remote sensing-based active fire datasets in Indonesia. *International Journal of Remote Sensing*, **25**, 2, 471-479.

Sukhinin AI, French NHF, Kasischke ES *et al*. (2004) AVHRR-based mapping of fires in Russia: New products for fire management and carbon cycle studies. *Remote Sensing of Environment*, **93**, 546-564.

Sunderlin WD, Resosudarmo IAP (1996) Rates and Causes of Deforestation in Indonesia - Towards a resolution of the ambiguities. *CIFOR Occasional Paper* No. 9, ISSN 0854-9818.

Suyanto S, Applegate G, Permana RP, Khususiyah N, Kurniawan I (2004) The role of fire in changing land use and livelihoods in Riau-Sumatra. *Ecology and Society* 9(1): 15. [online] URL: http://www.ecologyandsociety.org/vol9/iss1/art15/, 1-11.

Tacconi L (2003) Fires in Indonesia: Causes, Costs and Policy Implications. *CIFOR Occasional Paper* No. 38, ISSN 0854-9818.

Trigg SN, Curran LM, McDonald AK (2006) Utility of Landsat 7 satellite data for continued monitoring of forest cover change in protected areas in Southeast Asia. *Singapore Journal of Tropical Geography,* **27,** 49-66.

Uhl C, Kauffman JB (1990) Deforestation, Fire Susceptibility, and Potential Tree Response to Fire in the Eastern Amazon. *Ecology*, 71, 2, 437-449

6 GENERAL DISCUSSION

6.1 Applicability of Different Monitoring Systems

Due to the fast deforestation processes in the tropical forests of Southeast Asia a quick detection of land cover changes such as forest degradation or deforestation is a crucial step to derive information about the status of the forest ecosystems. Therefore two different approaches to monitor land cover and land cover changes in the humid tropics were analyzed:

1) Radiometric change detection analysis directly examines the spectral properties of optical satellite imageries derived from two different acquisition dates without classifying the images themselves.

2) Delta classification analysis is the comparison of classification results which were derived based on spectral categorization of optical satellite imageries.

While the most important advantage of the radiometric change detection technique is the omission of a classification step, thus providing much faster results, the disadvantage is that no information about the affected land cover type is provided. In contrast to most other change detection methodologies which only make use of a subset of their spectral bandwidth (Coppin *et al.,* 2004), the information of all available bands of the sensor devices were analyzed – thus performing a multispectral change detection analysis. However, the weather and atmospheric conditions in the humid tropics proofed to be very problematic, as optical sensor systems interfere with clouds and atmospheric disturbances (Lillesand *et al*., 2004). Therefore clouds, cloud shadows, and haze were masked by defining adequate thresholds. Change maps derived without atmospheric correction show results from a mixture of different factors, such as artifacts due to different atmospheric conditions of the two images, possible composition artifacts and real land cover changes. To separate the actual land cover changes from the artifacts it was necessary to correct as far as possible for atmospheric influences to ensure the direct comparability of the corresponding pixel locations. Most of absolute and relative atmospheric correction methodologies require additional information other than that provided by the imagery itself (Chavez, 1989; Coppin & Bauer, 1994; Ekstrand, 1994; Liang *et al.,* 1997; Michener & Houhoulis, 1997; Schott *et al*., 1988; Spanner *et al.,* 1990). As this study aimed to evaluate the capabilities of a multispectral change detection methodology to quickly detect land cover changes in humid tropical areas, where less or no information about the actual conditions on the ground are available, no algorithms depending on any kind of ground truth information were applied. Though high resolution sensors are able to resolve even small-scale changes with high overall accuracy of 96% for the study area in Borneo, such sensor systems are not applicable for monitoring larger tropical forest areas such as the whole island of Borneo to quickly resolve land cover changes due to several reasons: high costs, narrow swath, and most crucial long orbit repeat cycles. Additionally the humid tropics are characterized by frequent cloud coverage, further lowering the frequency to obtain cloud-free image pairs. Coppin *et al*. (2004) identified the low temporal frequency of observations of high spatial-resolution sensors as a serious disadvantage for change detection. Sensor systems with low or medium spatial resolution, which are therefore able to secure images with higher temporal resolution, show better potential for change detection analysis in tropical areas. Furthermore, the larger the area to be monitored the more difficult to secure cloud-free imageries of the study area. Some drawback of systems with coarser spatial resolution is that small-scale changes such as new established logging roads or areas of selective logging are impossible to be detected. Using low or medium resolution satellite sensors with their short orbit repeat cycles enables mosaiking the cloud-masked single images to derive cloud-free composites for operational monitoring. For that sake different composition algorithms can be used. Single pixel selection algorithms such as maximum value NDVI composites (Mayaux *et al.*, 2004) have the advantage that only one single scene is necessary per pixel location, keeping the time period of composition as short as possible. Based on single pixel selections, the resulting composites show artifacts due to different atmospheric conditions of the acquisition days and BRDF effects. As the multispectral change detection analysis applied in this study is solely based on differences in the observed reflectance values, it is very sensitive concerning any kind of compositing artifacts. Due to that reason cloud-free images derived by compositing methods based on the selection of single pixels are of very limited use as input data for multispectral change detection analysis. The analysis of 8-day MODIS surface reflectance data, which were derived using such algorithm (Hansen *et al.*, 2003), showed no correlation to the Landsat reference data. Another method to obtain cloud-free composites, which show less compositing artifacts, is the average compositing algorithm. This algorithm was described in parallel by Vancutsem *et al*. (2007a; 2007b) using SPOT VEGETATION and MERIS data as well as Langner *et al*. (2007) using MODIS surface reflectance data. Instead of selecting and mosaiking the reflectance values of single pixels several cloud-free observations for a single pixel with different viewing and illumination angles were combined by calculating the arithmetic mean of these observations to average the reflectance values. The main advantage of this compositing method is that it reduces the

BRDF effects, as well as remaining haze and shadow artifacts. The higher the amount of single images to derive the cloud-free composite, the better is the quality of the resulting composite, as can be seen for the SPOT VEGETATION data (Langner *et. al.*, manuscript; 81.4% overall accuracy). However, the higher amount of images also prolongates the period of image acquisition, thus losing the advantage of the multispectral change detection method in comparison to post classification approaches to quickly derive land cover changes in the tropics.

Advantage of the delta classification approach with post classification comparison of two corresponding images is that it also provides crucial information about the affected land cover type beside the information about the change itself. However, this monitoring approach is more time consuming as it requires two classification steps, which have to be compared. Sensors with high spatial resolution allow detailed forest cover assessments (Achard *et al.*, 2002), but due to their narrow swath and orbit repeat cycles of 20 days and less they are of limited use in humid tropical regions as a result of high cloud cover. On the other hand, low-resolution systems provide daily coverage, which is required to manage the cloud problem, but their low spatial resolution limits the ability to resolve land cover details. A good compromise is offered by medium resolution sensor systems which represent a good combination between both extremes (Cihlar, 2000; Fuller, 2006; Huang & Siegert, 2006). After preliminary tests with the MODIS 8-day composites, the MODIS single-day reflectance product was used because these images contained less artificial heterogeneity of reflectance values related to BRDF and haze than the MODIS 8-day composites in which cloud-free pixels from different viewing angles are combined using the minimum-value rule (Cihlar, 2000; Fuller *et al*., 2003). Cloud-free composites were derived for 2002 and 2005 from about 60 single MODIS scenes for each composite, which were masked for clouds, cloud shadows and haze and combined by calculating the arithmetic mean of each pixel-location. In comparison to single pixel selection algorithms (Hansen *et al.*, 2003; Stibig & Malingreau, 2003), resulting in artificial heterogeneity, which often complicate the interpretation of composite images, the multitemporal averaging process resulted in spatially more homogeneous cloud-free composites with great radiometric stability in humid tropical regions, thus enabling more reliable change detection between different years (Figure 8).

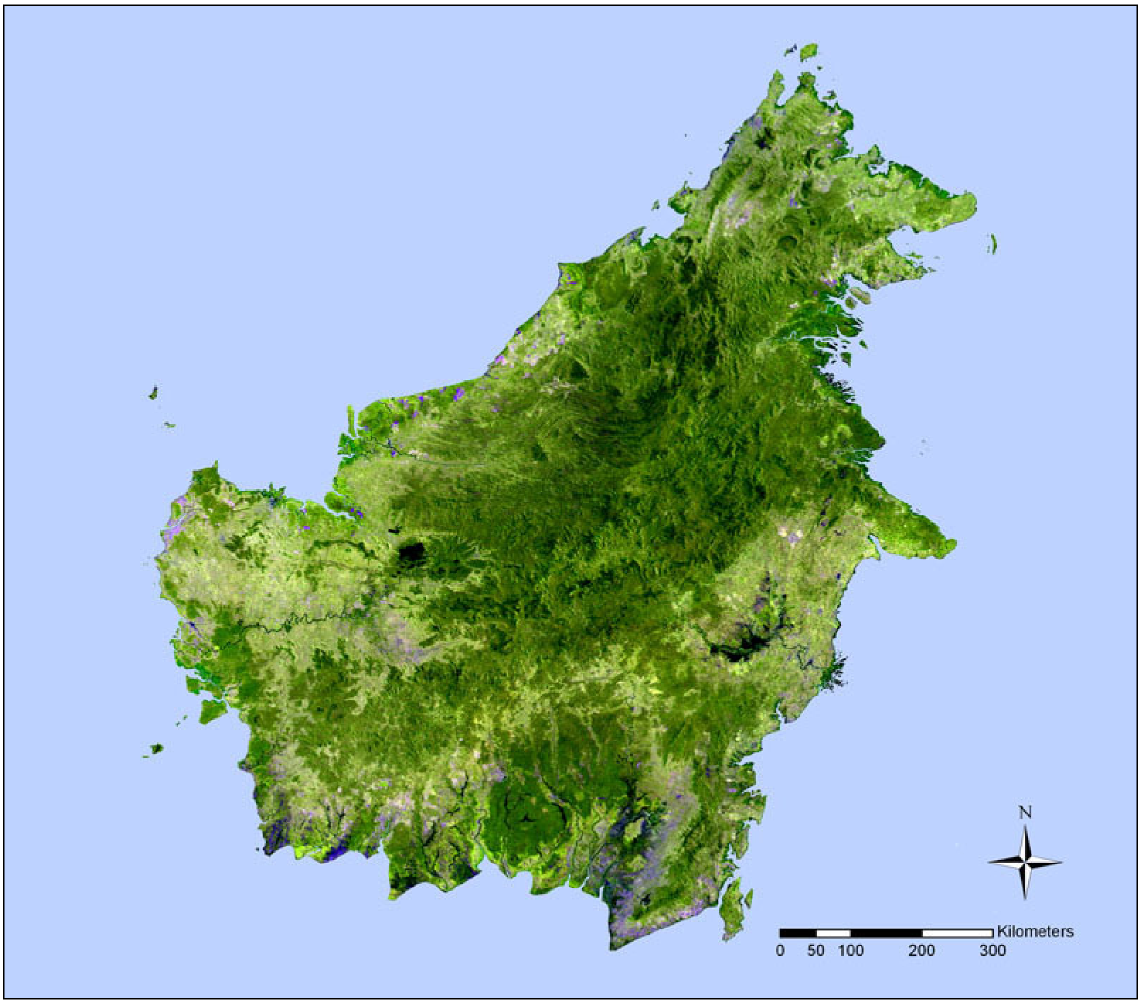

Figure 8: Cloud-free composite Borneo based on 57 single day MODIS surface reflectance imageries of 2002.

Based on these composites of medium resolution MODIS surface reflectance data, the classification process was able to distinguish between 11 land cover classes including 6 different types of forest classes (Figure 9) – a significant improvement compared to other land cover maps (Fuller & Murphy, 2005). The overall accuracy of the 2002 base map almost reached the commonly recommended 85% target (Foody, 2001). The forest - non-forest detection accuracy of 89.2% with a kappa coefficient of 0.7789 is comparable to other published results (Fuller *et al*., 2003). It must be noted, however, that averaging has the disadvantage of blurring the changes in spectral characteristics over time. Therefore, it is important that the observed area does not show significant seasonal changes during the compositing period, which is not the case for the evergreen tropical vegetation of Borneo.

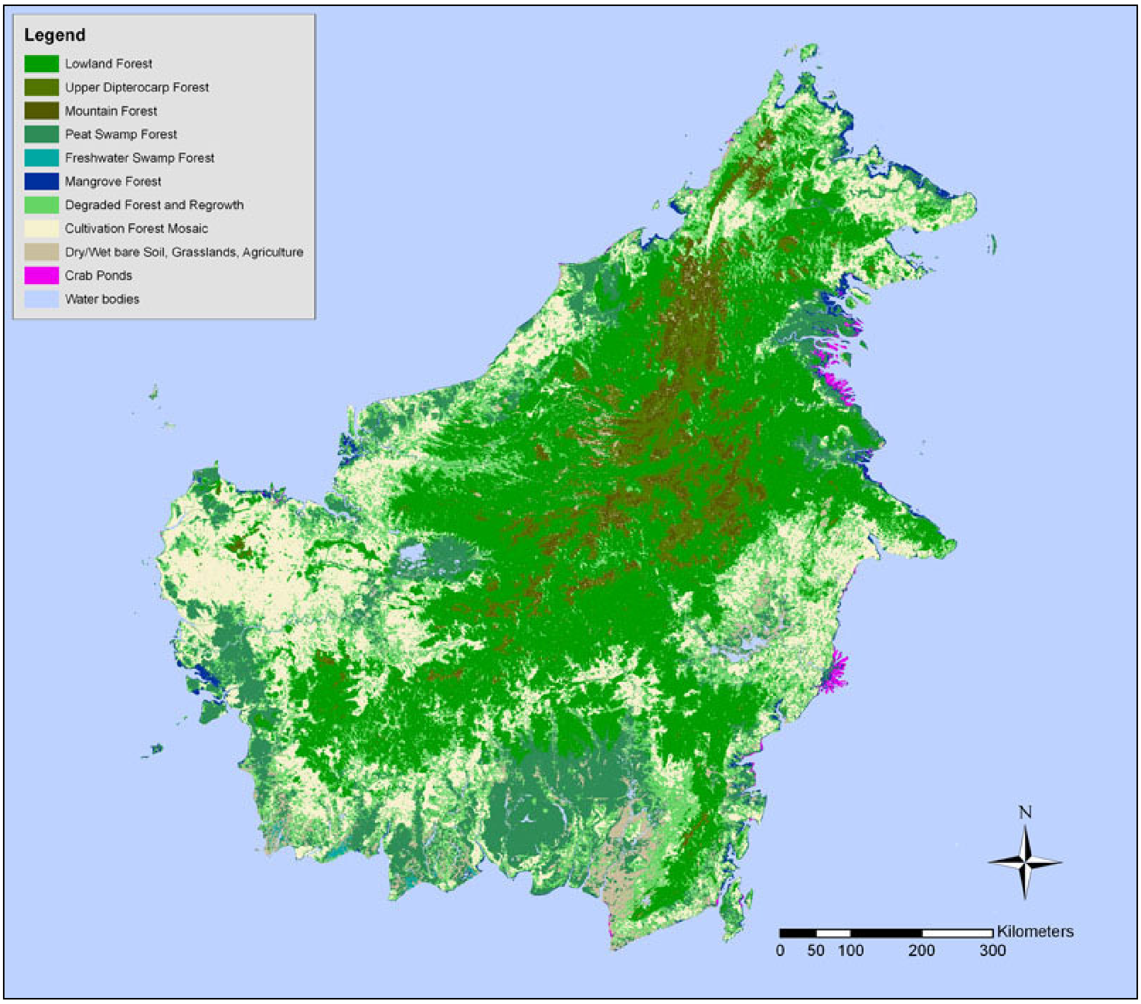

Figure 9: Land cover map of Borneo based on a cloud-free composite derived from MODIS surface reflectance data of 2002.

The results of this study showed that an average compositing method can be successfully used to create cloud-free composites for land cover and land cover change monitoring in the humid tropics – some problematic area when working with optical satellite data. Concerning the best monitoring technique it became clear that according to the above described constraints of the multispectral change detection analysis an operational application in the humid tropics is not advisable. Under ideal conditions such as no frequent cloud coverage or other atmospheric disturbances the use of multispectral change detection analysis of optical data is a very good approach to quickly monitor changes in the land cover. However, due to the frequent cloud coverage and the atmospheric conditions in the tropics the concept of detecting such changes by applying multispectral change detection technique is not feasible in an operational way. All further studies of this PhD thesis were therefore based on results of the delta classification analysis of cloud-free composites of medium resolution MODIS surface reflectance imageries, which were derived using an average composition method.

6.2 Analysis of Land Cover and Land Cover Change on Borneo

Before the spread of human influence in the post-Pleistocene about 8,000 years ago, most of Borneo was covered by forest (Billington *et al.*, 1996). Mainly due to low soil fertility (Rautner *et al.*, 2005) the population densities of the first humans on Borneo stayed very low. Thus, the pressure on the forests and other natural resources was almost nonexistent. Starting with colonialism the situation began to change. Mainly the agricultural expansion, to meet the local and global demand for rice (*Oryza sativa*), rubber (*Hevea brasiliensis*), oil palm (*Elaeis guineensis*) and coconut (*Cocos nucifera*), was responsible for the first large-scale deforestation activities in that region starting from the 19th century. In the second half of the 20th century the increasing demand for timber triggered the proliferation of commercial logging activities (Flint, 1994; Holmes, 2002; Sodhi *et al.*, 2004). Deforestation is a complex phenomenon and many factors are responsible for the high deforestation rate of that region – some of them even show positive feedback reactions with the ongoing loss of tropical forest.

The analysis of the land cover and land cover changes on Borneo revealed a significant change from natural ecosystems to degraded and managed land cover types, showing that most changes were related to overexploitation of forests and forest conversion. Almost half of the land area of Borneo is covered by degraded forests and cultivated lands. The deforestation rate in Borneo between 2002 and 2005 was 1.7% yr^{-1}, which is almost double compared with the annual deforestation rate of the whole Southeast Asian region of 0.9% (Achard *et al.*, 2002). Different forest types were not equally affected. Mangrove forests, for example, showed a deforestation rate of almost 8% per year and investigation on high-resolution Landsat images revealed that large areas had been converted to shrimp ponds in the past years. Besides mangrove forests, peat swamp forests also showed an increased deforestation rate with 2.2% yr^{-1}.

This high pressure on the forest ecosystems of Borneo can be largely attributed to timber shortages, which occurred in the 1990s due to over-logging. In order to meet the high wood demand large-scale timber estates were promoted such as hardwood plantations, estates for fuel wood and charcoal production and timber estates to support the pulp, paper and rayon industries (Sunderlin, 1999b; Barber & Schweithelm, 2000; Barr, 2000; Barr, 2001; Rautner *et al.*, 2005). Though large areas of degraded lands are available, natural forests are often converted to industrial timber plantations, mainly due to two reasons. On the one hand, planting on totaly degraded lands is more expensive because it often requires considerable investment in land preparation to rehabilitate soil fertility. On the other hand, industrial timber plantations in Indonesia also include the right to obtain a license to clear-cut and use the remaining standing timber, thus considerably increasing the profit (Barber & Schweithelm, 2000; FWI & GFW, 2002).

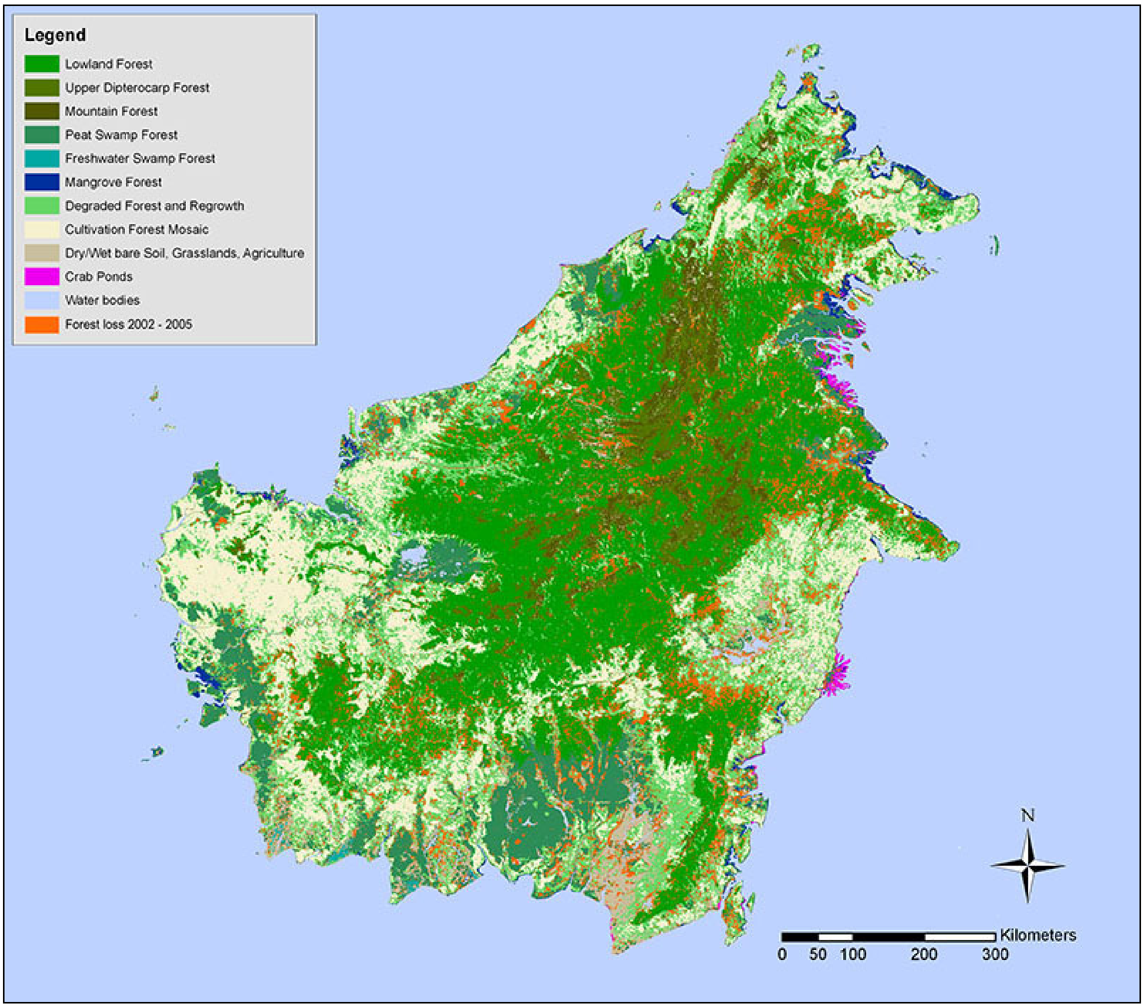

Figure 10: Forest loss between 2002 and 2005 superimposed on the land cover map of Borneo based on a cloud-free composite derived from MODIS surface reflectance data of 2002. Clearly visible is that most deforestation occurred in close vicinity to the forest edges.

Besides the pure statistical data of the deforestation rates per forest type, further data could be extracted using a GIS system. The spatial analysis of the deforestation patterns on Borneo revealed that deforestation does not occur in the middle of intact forests, but starts from the edges of the forests where farmers and loggers do have easy access (Cochrane, 2003). The analysis of the deforestation pattern on Borneo showed that 98% of all forest degradation and deforestation occurred in a buffer zone of 5 km along the outskirts of the forest (Figure 10).

The spatiotemporal analysis of the high deforestation rates provided increased evidence that fire plays an extraordinary and complex role in deforestation (Uhl & Kauffman, 1990; Taylor *et al*., 1999). Land speculation, and poorly planned developmental projects have led to devastating fire events in Borneo during the last decade (Page *et al*., 2002; Siegert *et al*., 2001; Goldammer, 2007). About 80% of all fires analyzed over a period of two years between 2003 and 2004 occurred in agricultural areas and grasslands as fire is still the cheapest means of clearing the land (Cochrane, 2003; Suyanto *et al*., 2004; Rieley & Page, 2005). About 20% of the fires were found in areas of severe deforestation revealing a high level of human impact on the ecology of Borneo.

The spatial analysis of these forest fires revealed that also about 98% of all forest fires occurred in the 5 km buffer zone along the outskirts of the forest. A detailed analysis of the remaining 2% of fires detected inside closed canopy forests showed that about 94% of these forest fires were strongly correlated to existing small-scale infrastructures such as logging roads, rivers and canals as they were detected within 1 km around these structures. Such infrastructures allow loggers and farmers unprecedented access into otherwise highly inaccessible forests (Barber & Schweithelm, 2000). These small-scale infrastructures were impossible to be detected using medium resolution satellite imagery, but could only be identified based on high resolution data (Asner *et al*., 2005; Fuller, 2006). However, the combination of low resolution active fire detections, which are detected inside a forest map, based on medium resolution data, can be regarded as indicator for existing small-scale infrastructures.

The spatial pattern of deforestation as well as forest fire occurrence revealed the strong correlation between both factors, as 98% of forest degradation occurred in the same buffer zone of 5 km along the outskirts of the forest in which also about 98% of all forest fires occurred. This observation underlines the conclusion that undisturbed forests are most unlikely to burn (Siegert *et al*., 2001) and forest degradation does not normally start in the middle of intact forests but originates from the edges where human activities are most intense. The more remote and undisturbed a forest, the more unlikely it is to burn.

A reason for this is that pristine tropical rainforests usually have a moist and humid climate and are therefore unlikely to burn because the susceptibility of vegetation to fire is correlated to the level of fire hazard (Uhl & Kauffman, 1990; Siegert *et al.,* 2001). The fire hazard describes the amount, type and dryness of potential fuel in the forest and remains low in undisturbed forests. Any kind of biomass can be regarded as combustible fuel such as leaf litter, logging waste and dead trees. The dryness of this biomass is correlated to local weather conditions, such as air temperature, wind and sunshine. As undisturbed rainforests have a closed forest canopy cover, the conditions at the forest floor are dominated by lack of sunshine and high humidity (Uhl & Kauffman, 1990; Siegert *et al.*, 2001; Rieley & Page 2005). El Niño events are responsible for extended droughts in Borneo and coincided with all major fire events of the island during the last decades (Browen *et al.,* 2001). However, even during El Niño related extended droughts, pristine forests do not burn due to a low level of fire hazard (Siegert *et al.,* 2001). In contrast to undisturbed forests, logged-over forests are more prone to fires, as large amounts of potential fuel are left by the logging process (Asner *et al*., 2006; Goldammer, 2007). Examples are natural forest concessions, which are managed using selective logging techniques (FWI & GFW, 2002; Schroeder-Wildberg & Carius, 2003). Selective logging results in the removal of a certain number of economically valuable trees per hectare, leaving behind a number of commercial species with a prescribed minimum size for regeneration (Priyadi *et al.,* 2006). Even though only few trees are removed, the process can destroy up to 50% of the forest canopy because additional damage to surrounding vegetation is caused by felling of large trees and due to the use of heavy machinery (Cannon *et al.,* 1998; Priyadi *et al.,* 2006). Thus, selective logging leaves behind large quantities of woody debris because tree crowns and roots are removed on the spot and left there to dry out, increasing thus the fire hazard enormously (Cochrane, 2003; Tacconi *et al.*, 2007). Disturbances of the closed forest canopy such as logging activities or low impact ground fires lead to an increased solar radiation at the forest floor and which in turn fosters the growth of a dense scrub vegetation of fast growing species (Rieley and Page 2005). In case of an extended drought these light demanding species quickly die because of the dry and hot microclimate at the forest floor. Owing to the opened canopy cover wind further dries out the vegetation. The drier microclimate in combination with the higher fuel loads increase the fire hazard substantially resulting in a positive feedback between forest degradation and fire (Siegert *et al.*, 2001). Besides the fire hazard, the danger of a forest catching fire is also related to the fire risk, which describes the probability that the fuel will ignite. Thus, fires do not occur randomly and forests which are in close vicinity to human settlements or which have been made available by infrastructural developments such as roads or rivers have a much higher fire risk (Barber & Schweithelm 2000; Siegert *et al.,* 2001; Cochrane, 2003). It is also important to note that in general fires in tropical forests burn only a small fraction of the biomass depending on the availability of fuel, moisture content of the vegetation and other factors. Frequently, trees are killed by the fire, but the biomass remains largely unburnt, because the flames damage only the thin bark of the trees. Thereby fire causes a further thinning of the forest canopy. If fire has affected a forest once, large amounts of partly burned biomass remain, thus increasing the future fire hazard (Cochrane, 2003). Forests degraded in such a way by fire are very likely to burn again and thus to become more deforested in the future (Cochrane, 2003; Siegert *et al.,* 2001). If the fire repeat cycle is short enough such recurrent fire event are even able to transform forest into fire prone alang-alang grassland (Goldammer, 1993; Asner *et al.,* 2005).

Fire on Borneo is generally used for two different kinds of purposes. On the one hand it is an essential part of both traditional shifting cultivation as well as all other modern ways of land use – especially in Indonesia. In comparison to mechanical or manual methods, burning is a much cheaper means in land preparation for industrial oil palm and cash crop plantations, as well as for smallholder communities (Suyanto *et al.,* 2004; Dennis *et al*., 2005; ASEAN, 2003). Beside its use to clear the land, fires can also be lit due to political reasons, such as expressing a complaint or settling old scores for perceived injustices, especially among poor rural people who cannot afford to officially file a complaint. Main reasons can be land property conflicts between local communities and large plantations. When allocating land for plantations or forest concessions the companies often violate the customary land rights of the indigenous people, such as subsistence farmers, causing conflicts between the locals and the big companies (Byron & Shepherd, 1998; Barber & Schweithelm, 2000; Wakker, 2000; FWI & GFW, 2002; Brown & Jacobson, 2005; Suyanto, 2007). As even government agencies use fire to acquire land for different large-scale development programmes in the agricultural or forestry domain, local people feel forced to also use fire to claim their rights to their traditional lands (Byron & Shepherd, 1998).

6.3 Fires, Fire Management and the Impact of El Niño Droughts

For better understanding the drivers of fire occurrence, the spatiotemporal pattern of fire in relation to land cover and land use in Borneo were analyzed over a period of 10 years using active fire detecting sensor systems as this island is typical for the fast deforestation processes and it has been afflicted by some of the most severe fire disasters of the last decade in that region (Page *et al.*, 2002; Tacconi, 2003; Fuller, 2006; Trigg *et al.*, 2006). The tropical rainforests in Borneo are extremely threatened by fire, which is used as the cheapest means for land clearing. Slash and burn techniques have a long history in Southeast Asia and are practiced with experience by the indigenous people of Borneo (Marten, 1986). In general these techniques are regarded sustainable if the time period between the burning events is long enough, but today the problem is not the fire itself but the large scale and number of fires and the short fire repeat cycle (Cochrane, 2003). This was clearly confirmed by the present study. During 10 years satellites recorded more than 320,000 active fires on the island of Borneo affecting 21% of the land surface once and 6% two times or more (Figure 11).

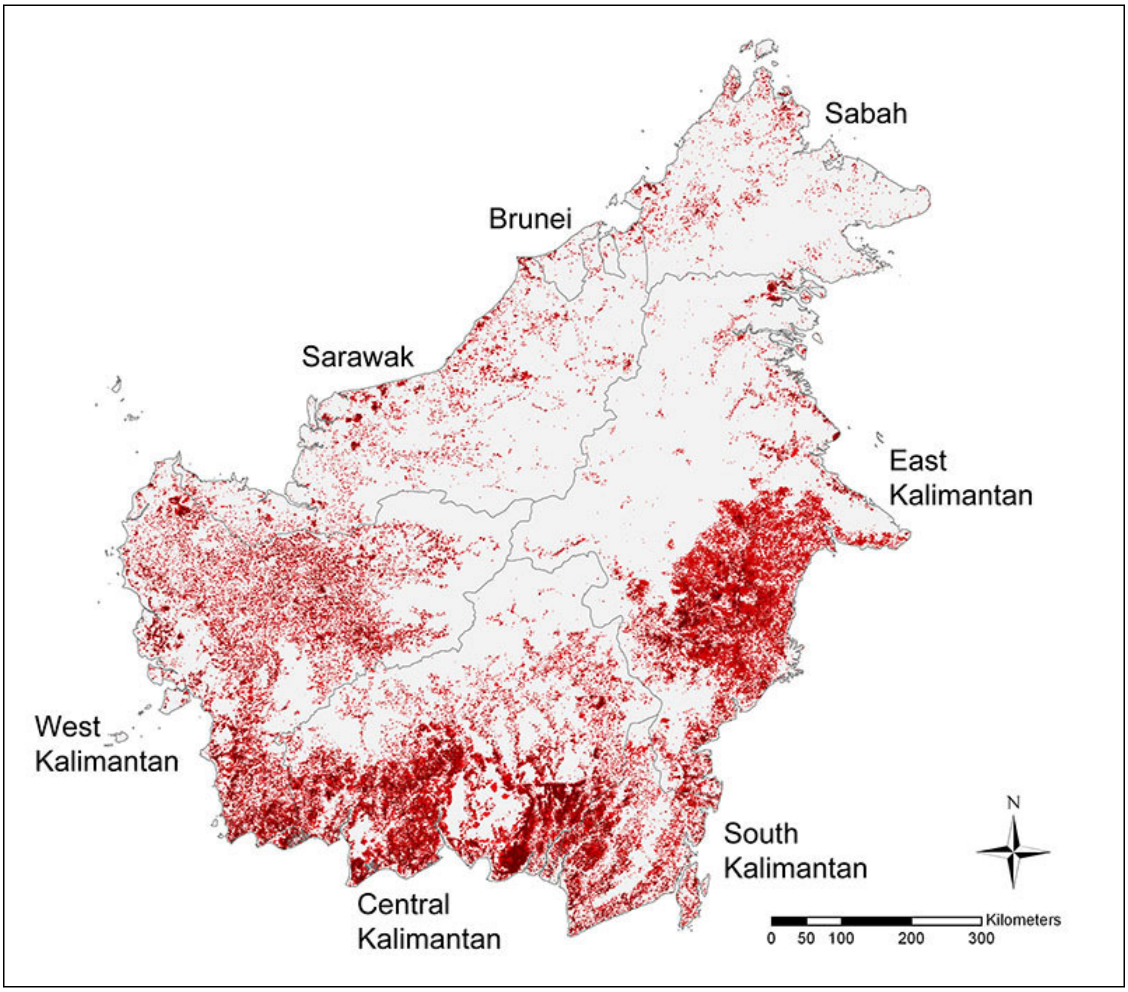

Figure 11: Fire affected area on Borneo (1997-2006). The data was derived from different active fire detecting sensors. While a combination of NOAA AVHRR and ATSR was used for the period 1997-2001, only MODIS data was used for 2002-2006.

As already mentioned above, the El Niño phenomenon in Southeast Asia is responsible for the late onset of the rainy season, which usually ends the annual cycle of anthropogenic fire activity linked to land clearing. Therefore an analysis of all fires between 1997 and 2006, which also covered the major El Niño events in 1997/98, 2002 and 2006, would expect to clearly show an unavoidable higher number of fire events in years of extended droughts. This also proofed true when analyzing the whole island of Borneo, where the fire affected area of forest was 3 times larger during these El Niño seasons.

As the impact of El Niño on precipitation is comparable all over Borneo and ecosystems and land use are similar in Kalimantan and the Malaysian part of the island, the impacts of fires should also be comparable. However, figure 11 shows some different pattern of fire occurrence between the Indonesian part of Borneo in the South and the Malaysian part in the North of the island. In comparison to the large and ample fire affected areas in Indonesia, much smaller areas were affected in Malaysia and the spatial pattern of the latter also totally differed with a punctiform distribution associated with land clearings for plantations. The temporal analysis of the fires further revealed some pronounced difference between Indonesia and Malaysia: while the number of active fire observations showed a high correlation to El Niño conditions in the forests of Kalimantan, this was clearly not the case in Brunei and the Malaysian provinces Sarawak and Sabah.

As a consequence this means that El Niño related droughts may not necessarily lead to an increase of the fire affected area. More precisely these results clearly suggest the existence of efficient fire prevention and fire suppression in Malaysia and no such measures in Indonesia. The research showed that there is a clear link between land use and fire. A detailed analysis of the fire impact on timber concessions in Kalimantan revealed a higher proportion of annual fire affected areas than on shifting cultivations and plantation areas – especially during El Niño seasons. Conversion and production forests showed much higher fire occurrence than limited production forests, in which logging impact is comparatively low. This suggests that fire is used to clear the land in conversion and production forests after timber extraction for further development into plantations. Indonesia is the major tropical timber exporting country of the world with a greater export volume of tropical hardwoods than all of Africa and Latin America combined (Barber & Schweithelm, 2000; FWI & GFW, 2002). Below a certain productivity threshold, degraded natural logging concessions are vulnerable to reclassification to a category that allows concession holders to apply for a conversion license. If granted, these forests may then be cleared completely and converted to timber or estate crop plantations (FWI & GFW, 2002). Since the 1990s, commercial developments such as land clearance for timber estates and plantation farming, especially for oil palm plantations, have become the main agent of deforestation in Borneo (Sunderlin, 1999b; Hai, 2000; Aden *et al.*, 2001; Glastra et al., 2002; Holmes, 2002, Casson, 2003; Brown & Jacobson, 2005; Rieley & Page, 2005; Hooijer *et al.,* 2006). In Indonesia oil palm plantations have been singled out to be one of the major causes of fire because estate companies use fire after removing all valuable timber and leaving behind only fire-prone debris (Barber & Schweithelm, 2000; Glastra *et al.*, 2002; Holmes, 2002; Casson, 2003). In comparison to clearing land for oil palm plantations with the help of fire, zero burning practices are more expensive (FWI & GFW, 2002) increasing the costs by US$50 to US$150 per ha (Guyon & Simorangkir, 2002). Furthermore, it is well-known that the Indonesian government is not very authoritative against illegal logging activities (Sargeant, 2001; FWI & GFW, 2002; Tacconi, 2003) because the officially designated amount of timber to be cut legally is by far not able to meet the demand of all sawmill, plywood, pulp and paper companies in the country (Barber & Schweithelm 2000; FWI & GFW, 2002). Illegal logging occurs all over in Borneo, with a strong increase of 44% since the onset of the Asian economic crisis in the mid-1997 (Sunderlin, 1999b; Sunderlin *et al.*, 2000; Rautner *et al.*, 2005). Currently, an estimated 73-88% of all timber logged in Indonesia is illegal (Schroeder-Wildberg & Carius, 2003). Based on analysis of satellite images of the devastating 1997 fires the Indonesian government had to acknowledge, that large plantation companies, forest concessionaires and transmigration contractors were primarily responsible for setting the fires to clear the land (Barber & Schweithelm, 2000; Holmes, 2002). Detailed future research on selected study sites both in Kalimantan and Malaysia in combination with the analysis of social and political aspects will help to better understand the underlying factors. Improved fire prevention is required not only to preserve the biodiversity in the last remaining tropical forests in Southeast Asia but also to mitigate the consequences of global climate change and to avoid further emissions of CO_2.

6.4 Deforestation, Forest Fires, CO_2 Emission and Future Perspectives

The analysis for whole Borneo showed that huge areas of forest are clear-cut or burnt each year leading to significant carbon dioxide emissions. Atmospheric CO_2 is beside other greenhouse gases such as water vapour, methane, nitrous oxide, ozone and chlorofluorocarbons responsible to reduce the loss of heat into space and therefore contributes to global temperatures through the greenhouse effect (Petty, 2006). During the process of photosynthesis in growing forests atmospheric CO_2 is fixed to build up plant biomass. When these forests are removed, the fixed carbon gets released into the atmosphere again. Regarding the CO_2 balance it does not make much difference if the biomass is burnt immediately or gets decomposed over a longer period of time. Without following reforestation of the logged areas, this carbon increases the net amount of atmospheric greenhouse gases. Therefore, unsustainable management of forest resources, as taking place on Borneo, contributes to a large extent to global climate change (Achard *et al.,* 2004).

Especially peat swamp forest ecosystems are carbon sinks/sources of global importance (Page *et al*., 2002) as huge amounts of carbon are fixed in the peat domes due to incomplete decomposition (Hai, 2000; Rieley & Page, 2005; Hooijer *et al.,* 2006). Due to the fact that fires on peat lands often affect both the surface vegetation and the underlying peat layer, they release much larger amounts of CO_2 and other greenhouse gases into the atmosphere than fires in forests on mineral soils and thus contribute largely to global warming. On Borneo peat layers can have a thickness of up to 20 meters (Page et al., 2002) and according to Jaenicke et al. (2008) at least 55 ± 10 Gt of carbon are stored in Indonesia's peat lands. Swamp forests were also most severely affected in the Indonesian part of the island. The analysis of fires per year revealed a shift from high numbers in dipterocarp forests towards swamp forests – especially during the second observation period from 2002 till 2006. This is most likely linked to the trend that in recent years large oil palm plantations have been established in peat swamp forests and peat lands in Indonesia and Malaysia (Hai, 2000; FWI & GFW, 2002; Rieley & Page, 2005; Hooijer *et al.,* 2006). Up to now Malaysia is the world's biggest producer of palm oil but it is expected that around 2012 Indonesia will take the lead, providing together 84% of the world's palm oil production. Average annual growth rates between 1998 and 2003 were 7.9% and 11.5% for the Malaysian part of Borneo and Kalimantan respectively (Rautner *et al*., 2005). Due to the high and still increasing global demand for palm oil mainly as cooking oil this industrial sector is expected to grow considerably in the future (Wakker, 2000; FWI & GFW, 2002; Brown & Jacobson, 2005). Despite the existence of degraded land, oil palm plantations are primarily established on forest land, because companies often offset the costs for establishing plantations with profits obtained from timber extraction (Barber &

Schweithelm, 2000; FWI & GFW, 2002; Holmes, 2002; Casson, 2003; Brown & Jacobson, 2005; Rautner *et al.*, 2005; Rieley & Page, 2005). The rising interest in renewable energy resources (BCSE, 2005), which should replace fossil fuels to reduce carbon emissions, is also responsible for the boost of oil palm plantations. As stated above, pristine forests often have to be cleared for the establishment of such plantations which ironically contributes in a much higher extent to CO_2 emissions than are saved by using this kind of renewable energy. Highest negative impact on CO_2 emissions have plantations established on peat swamp forest areas because of the special characteristics of this forest type. In 1997 peat fires in Indonesia released between 0.81 and 2.57 Gt of carbon into the atmosphere, equivalent to 13-40% of the mean annual global carbon emissions from fossil fuels (Page *et al.*, 2002). This notorious fire event in 1997 mainly affected a peat swamp area in Central Kalimantan which had been chosen for the establishment of a large-scale transmigration project. The MRP project initiated by President Suharto in 1995 had the aim of developing one million ha of peat land for rice cultivation (Barber & Schweithelm, 2000; Rautner *et al.*, 2005; Rieley & Page, 2005). Between 1996 and 1998 more than 4,600 km of irrigation channels have been built (Rieley & Page, 2005). The project was finally stopped in early 1999, because it was not possible to establish sustainable agriculture on the chosen nutrient poor and acidic peat lands (Rieley & Page, 2005). Instead of irrigating the planned agricultural areas, the channels served as drainage system because 80% of the land is higher than river level (Barber & Schweithelm, 2000; Rieley & Page, 2005). The peat swamp vegetation, well adapted to waterlogged conditions, suffered from water shortage and dried out. Owing to the fact that the drained peat was unable to retain rainwater and due to the large amount of dried biomass which served as fuel for potential fires, the area became very fire-prone during the dry season. The use of fire to clear the project land (Barber & Schweithelm, 2000) in combination with the El Niño related drought in the degraded and dried out peat lands led to the large-scale fires in 1997, where about 80% of the MRP area burnt (Rieley & Page, 2005). According to Hooijer *et al.* (2006) CO_2 emissions by fires on peat swamp forests and emissions by peat oxidation in drained peat lands make Southeast Asia and especially Indonesia which is responsible for more than 90% of these emissions, one of the major contributors to global CO_2 emissions.

The use of fire to clear the land also has further negative implications beside the negative impact on global climate change. Even though fires on agricultural areas are considered as CO_2 neutral, except for special cases such as fires on peat soil, and only fires responsible for deforestation affect global warming, both types of fires release various kinds of airborne solid and liquid particulates and gases, mainly composed of organic and elemental carbon, which have various negative impacts on the environment and human health, such as causing respiratory infections. Depending on the type of fuel and the intensity of the fire, the resulting smoke has different composition (Byron & Shepherd, 1998). Especially the "dirty" smoke from smouldering peat fires contains high levels of noxious particles, such as sulphur oxides responsible for long-term health damage and an increased risk of cancer (Barber & Schweithelm, 2000). Furthermore, the danger of using fire as means to clear the land is that these fires can get out of control and destroy much larger areas, as originally intended. As shown in these studies, especially during El Niño related droughts the risk of fires spreading into adjacent forests is extremely high.

According to the 2007 IPCC report, the increase in global CO_2 concentration is primarily related to the use of fossil fuels and land use changes (Alley *et al.,* 2007). Dutschke and Wolf (2007) showed that land use change accounts for approximately 20% of the total human-induced greenhouse gas emissions. Due to this high percentage of global emissions, policies and measures such as REDD (Reducing Emissions from Deforestation and Degradation) in developing countries must be developed and implemented to reduce these emissions and prevent further forest degradation. One example of such positive developments, which already exists since several years, should be shortly explained here. The majority of forests on Borneo are covered with forest concessions (FWI & GFW, 2002), that were commercially selectively logged for more than twice (Kitayama *et al.*, manuscript). Even though selective logging results in the removal of only a certain number of economically valuable trees per hectare (Schroeder-Wildberg & Carius, 2003; FWI & GFW, 2002), the process can destroy up to 50% of the forest canopy because additional damage to surrounding vegetation is caused by felling of large trees and due to the use of heavy machinery (Cannon *et al.*, 1998; Priyadi *et al.*, 2006). As many species rely on the selectively logged production forests, production forests are de facto functioning in retaining biodiversity of the degraded landscapes of Borneo (Kitayama *et al.*, manuscript; Leslie *et al.*, 2002). As the commercial use of timber products derived from these logging concessions cannot simply be stopped, it is necessary to promote more sustainably logging techniques. Such harvesting methods already exist – Reduced Impact Logging (RIL) was proposed as an alternative to heavy-impact conventional logging (Putz & Pinard, 1993; Pinard et al., 1995; Dykstra & Heinrich, 1996; Sabah Forestry Department, 1998; Sist *et al.*, 2003). RIL is a harvest method that reduces the physical impacts on the ground, to the remaining standing trees, streams, and ecosystem as a whole by using a combination of a pre-harvest census, carefully controlled felling and skidding, lowered allowable cut, and regulated machinery use (Pinard & Putz, 1996; Chappell & Thang, 2007). RIL reduces the injury to standing trees by 18% in an Indonesian forest when compared with conventional logging (Bertault & Sist, 1997). Such kind of improved forest management is currently practiced in less than 5% of tropical forests (ITTO, 2006). However, using RIL, timber producers have reduced revenue due to a lowered harvest volume and higher costs for preparation and harvesting (Applegate *et al*., 2004). A study of RIL's effects in Sabah, Malaysia, found 44% reduction of area logged within a tract, 22% reduction in timber yield per logged hectare, and 18% increase in cost per m^3 logged compared with conventional logging (Healey *et al.*, 2000).

Therefore, forest protection has to include positive financial incentives, so that protection actively contributes to sustainable and equitable development through consultation with indigenous people and local forest communities. This can be achieved by a forest certification system, which adds economic values to forest products (Leslie *et al.*, 2002; Gullison, 2003) and is therefore able to compensate for the higher costs of a sustainable management. Due to this reason detailed forest ecosystem monitoring has to be undertaken to analyze the status and changes of the forests to account for the amount of emission reduction. International accessibility and sharing of dated mapping and satellite data is key to an effective global response. The research of this PhD thesis regarding the application of monitoring techniques as well as the concrete results of the status of the forests on Borneo could make an essential contribution. Furthermore, capacity building and formal knowledge banks are particularly important for increasing the awareness of ecosystem loss – especially in under-resourced developing countries (Myers, 2007; Anger & Sathaye, 2008).

7 GENERAL CONCLUSIONS

In the scope of an EU funded project this study has investigated the applicability of two different monitoring approaches for land cover and land cover change detection in humid tropical rainforests. In two further projects the status of the different forest ecosystems of the Southeast Asian island of Borneo was analyzed, keeping in mind the special characteristics of land cover, climate and fire regimes of that area. The results of these projects thereby crucially improved our understanding of the drivers of deforestation in that region - information decisive to better protect the remaining rainforests. The actual deforestation rates of especially insular Southeast Asia are extremely high and urge to act. If no serious action is taken, all lowland forest ecosystems on Borneo will be gone in a couple of years. It is therefore important to create knowledge about deforestation and forest degradation and how to best use satellite remote sensing for environmental monitoring within the framework of such projects but it is also very crucial to reinvest this information again into other projects which directly help to preserve the remaining rainforests. The next step should be to apply the findings of this study into practice. As an example it is very important to analyze different selective logging techniques in tropical forest ecosystems regarding their ability to conserve biodiversity and their impact on forest degradation and subsequent CO_2 emissions. Therefore a combination of different monitoring techniques, such as presented in this study, as well as a synergistic use of optical and radar data could be applied to monitor and analyze these impacts. A lot of people on Borneo are dependent on timber or other forest products as their main source of income. Thus some way has to be found to use the existing forest resources in the most sustainable way according to REDD methodologies while providing enough incentives not to get back to less sustainable cultivation methods which destroy the forest resources for the sake of a maximized profit in the short-term. For this sake also social and political aspects have to be involved. However, the sole focus of REDD activities to conserve the area of the forest ecosystems could risk a degradation of the remaining forest ecosystems. As long as an area is still considered as forest, the actual status of the forest can be severely degraded owing to high impact of conventional logging. To prevent from such development, countries should get awarded for applying more sustainable ways of using their natural forest resources. Therefore it is necessary to also focus on the actual quality of the forest ecosystem, monitoring its biomass, degradation status and inherent biodiversity, besides protecting only the area under forest cover. These factors should also be included, together with the protection of the forest areas themselves to form the basis of reducing emissions from deforestation to secure the environmental integrity.

Monitoring techniques which are capable to distinguish between different forest ecosystems in combination with sufficient field work can provide a valuable database for further national and international studies on activities preserving the remaining forest ecosystems with their inherent biodiversity while at the same time mitigating global climate change.

REFERENCES

Achard F, Estreguil C (1995) Forest classification of Southeast Asia using NOAA AVHRR data. *Remote Sensing of Environment*, **54**, 198–208.

Achard F, Eva HD, Stibig H-J, Mayaux P, Gallego J, Richards T, Malingreau J-P (2002) Determination of Deforestation Rates of the World's Humid Tropical Forests. *Science*, **297**, 999-1002.

Achard F, Eva HD, Mayaux P, Stibig H-J, Belward A (2004) Improved estimates of net carbon emissions from land cover change in the tropics for the 1990s. *Global Biogeochemical Cycles*, **18**, GB2008, doi:10.1029/2003GB002142.

Achard F, DeFries R, Eva H, Hansen M, Mayaux P, Stibig H-J (2007) Pan-tropical monitoring of deforestation. *Environmental Research Letters*, **2**, doi:10.1088/1748-9326/2/4/045022.

Aden J, Dore G, Vincent J, *et al*. (2001) Indonesia - Environment and Natural Resource Management in a Time of Transition. *World Bank*.

Alley R, Berntsen T, Bindoff NL, *et al.* (2007) Climate Change 2007: The Physical Science Basis; Summary for Policymakers; *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. pp. 1-21. 10th Session of Working Group I of the IPCC, Paris.

Anger N, Sathaye J (2008) Reducing Deforestation and Trading Emissions: Economic Implications for the post-Kyoto Carbon Market. Zentrum für Europäische Wirtschaftsforschung GmbH (ZEW), Discussion Paper, ftp://ftp.zew.de/pub/zew-docs/dp/dp08016.pdf.

Appanah S, Turnbull JM (1998) A review of Dipterocarps: Taxonomy, ecology and silviculture. *Center for International Forestry Research (CIFOR)*, ISBN 979-8764-20-X.

Applegate G, Putz FE, Snook LK (2004) Who Pays for and Who Benefits from Improved Timber Harvesting Practices in the Tropics? Lessons Learned and Information Gaps. *Center for International Forestry Research*, ISBN 979-3361-42-5.

ASEAN (2003) Guidelines for the implementation of the ASEAN policy on zero burning. Jakarta, Indonesia, *ASEAN Secretariat*, ISBN 979-8080-98-X.

Ashton PS (1988) Dipterocarp Biology as a Window to the Understanding of Tropical Forest Structure. *Annual Review of Ecology and Systematics*,. 19, 347-370, URL: http://links.jstor.org/sici?sici=0066-4162%281988%2919%3C347%3ADBAAWT%3E2.0.CO%3B2-3.

Asner GP, Knapp DE, Broadbent EN, Oliveira PJC, Keller M, Silva JN (2005) Selective logging in the Brazilian Amazon. *Science*, **310**, 480–482.

Asner GP, Broadbent EN, Oliveira PJC, Keller M, Knapp DE, Silva JNM (2006) Condition and fate of logged forests in the Brazilian Amazon. *Proceedings of the National Academy of Sciences*, **103**, 34, 12947-12950.

Barber CV, Schweithelm J (2000). Trial by fire. Forest fires and forestry policy in Indonesia's era of crisis and reform. *World Resources Institute (WRI)*, Forest Frontiers Initiative, in collaboration with WWF-Indonesia and Telapak Indonesia Foundation, Washington DC.

Bartholomé E, Belward AS (2005) GLC2000: a new approach to global land cover mapping from Earth observation data. *International Journal of Remote Sensing*, **26**, 9, 1959-1977.

Barr (2000) Profits on Paper: The Political Economy of Fiber, Finance and Dept in Indonesia's Pulp and Paper Industries. *Center for International Forestry Research (CIFOR), WWF Macroeconomics Program Office.*

Barr C (2001) Banking on Sustainability: Structural Adjustment and Forestry Reform in Post-Suharto Indonesia. *Center for International Forestry Research (CIFOR), WWF Macroeconomics Program Office.*

BCSE (2005) Renewable Energy in Asia: The Malaysia Report. *Australian Business Council for Sustainable Energy*, Carlton Victoria, Australia.

Bertault J-G, Sist P (1997) An experimental comparison of different harvesting intensities with reduced-impact and conventional logging in East Kalimantan, Indonesia. *Forest Ecology and Management*, **94**, 209-218.

Bicheron P, Leroy M, Brockmann C, Krämer U, Miras B, Huc M, Ninõ F, *et al*. (2006) GLOBCOVER: a 300 m global land cover product for 2005 using ENVISAT MERIS time series. *ESA-GLOBCOVER initiative.*

Billington C, Kapos V, Edwards M, Blyth S, Iremonger S (1996) Estimated Original Forest Cover Map - A First Attempt. *World Conservation Monitoring Centre (WCMC)*, Cambridge.

Boehm H-DV, Siegert F (2001) Ecological impact of the one million hectare rice project in Central Kalimantan, Indonesia, using remote sensing and GIS; Land Use Change and (Il)-legal Logging in Central Kalimantan, Indonesia. In: *22nd Asian Conference on Remote Sensing*, 5–9 November 2001, Singapore. Copyright © 2001 Centre for Remote Imaging, Sensing and Processing (CRISP), National University of Singapore, Singapore Institute of Surveyors and Valuers (SSIV), Asian Association on Remote Sensing (AARS).

Brookfield H, Byron Y (1990) Deforestation and timber extraction in Borneo and the Malay Peninsula – The record since 1965. *Global Environmental Change*, 0959-3780/90/010042-15, 42-56.

Browen M, Bompard JM, Anderson IP, Guizol P, Gouyon A (2001) Anthropogenic Fires in Indonesia: A View from Sumatra. Reprinted from: *Forest Fires and Regional Haze in South East Asia,* by Radojevic M, Eaton P, *Nova Science*, New York, *European Union, Ministry of Forestry and Estate Crops, Forest Fire Prevention and Control Project Kanwil Kehutanan Dan Perkebunan*, Palembang.

Brown E, Jacobson MF (2005) Cruel Oil - How Palm Oil Harms Health, Rainforest & Wildlife. *Center for Science in the Public Interest*.

Brown S, Swingland IR, Hanbury-Tenison R, Prance GT, Myers N (2002) Changes in the use and management of forests for abating carbon emissions: issues and challenges under the Kyoto Protocol. *Philosophical Transactions of the Royal Society of London, Series A: Mathematical, Physical and Engineering Sciences*, **360**, 1593-1605.

Byron N, Shepherd G (1998) Indonesia and the 1997-98 El Niño: fire problems and long-term solutions. *ODI Overseas Development Institute*, ISSN: 1356-9228.

Cannon CH, Peart DR, Leighton M (1998) Tree Species Diversity in Commercially Logged Bornean Rainforest. *Science*, **28**, 1366-1368.

Casson A (1999) The hesitant boom: Indonesia's oil palm sub-sector in an era of economic crisis and political change. Program on the Underlying Causes of Deforestation, Bogor Indonesia, *Centre for International Forestry Research*.

Casson A, Obidzinski K (2002) From new order to regional autonomy: shifting dynamics of ‘‘Illegal’’ logging in Kalimantan, Indonesia. *World Development*, **30**, 2133–2151.

Casson A (2003) Oil Palm, Soybeans & Critical Habitat Loss. *WWF Forest Conversion Initiative*, Report.

Chambers JQ, Asner G, Morton D, Anderson LO, Saatchi S, Espirito-Santo FDB, Palace M, Souza Jr C (2007) Regional ecosystem structure and function: ecological insights from remote sensing of tropical forests. *Trends in Ecology and Evolution*, **22**, 414–423.

Chappell NA, Thang HC (2007) Practical hydrological protection for tropical natural forests: the Malaysian experience. *Unasylva*, **229**, 58, 17–21.

Chavez PS, (1989) Radiometric calibration of Landsat Thematic Mapper multispectral images. *Photogrammetric Engineering and Remote Sensing*, **55**, 1285–1294.

Christanty L (1986) Shifting Cultivation and Tropical Soils: Patterns, Problems, and Possible Improvements. In Marten GG (1986) Traditional agriculture in Southeast Asia: A human ecology perspective, *Westview Press*, Boulder, Colorado, 226-240.

Cihlar J (2000) Land cover mapping of large areas from satellites: status and research priorities. *International Journal of Remote Sensing*, **21**, 1093–1114.

Cochrane MA (2003) Fire science for Rainforests. *Nature*, **421**, 913–919.

Conghe S, Woodcock CE, Seto KC, Lenney MP, Macomber SA (2001) Classification and Change Detection Using Landsat TM Data: When and How to Correct Atmospheric Effects? *Remote Sensing of Environment*, **75**, 230-244.

Coppin PR, Bauer ME (1994) Processing of multi-temporal Landsat TM imagery to optimize extraction of forest cover change features. *IEEE Transactions on Geoscience and Remote Sensing*, **32**, 918–927.

Coppin P, Jonckheere I, Nackaerts K, Muys B (2004) Digital change detection methods in ecosystem monitoring: a review. I*nternational Journal of Remote Sensing*, **25**, 9, 1565-1596.

Curran LM, Trigg SN (2006) Sustainability science from space: quantifying forest disturbance and land-use dynamics in the Amazon. *PNAS*, **103**, 12663–12664.

Curran LM, Trigg SN, McDonald AK, Astiani D, Hardiono YM, Siregar P, Caniago I, Kasischke E (2004) Lowland forest loss in protected areas of Indonesian Borneo. *Science*, **303**, 1000–1003.

DeFries RS, Hansen MC, Townshend JRG, Janetos AC, Loveland TR (2000) A new global 1 km dataset of percent tree cover derived from remote sensing. *Global Change Biology*, **6**, 247–254.

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

Dennis R (1999) A review of fire projects in Indonesia (1982-1998). *Center for International Forestry Research (CIFOR)*, ISBN 979-8764-30-7.

Dennis RA, Mayer J, Applegate G, *et al*. (2005) Fire, people and pixels: linking social science and remote sensing to understand underlying causes and impacts of fires in Indonesia. *Human Ecology*, **33**, 465-504.

Dudley RG (2004) Modeling the effects of a log export ban in Indonesia. *System Dynamics Review*, **20**, 99–116.

Dutschke M, Wolf R (2007) Reducing Emissions from Deforestation in Developing Countries. The way forward. *W.B. Druckerei GmbH*, Hochheim am Mein, Eschborn, 32 pp.

Dykstra D, Heinrich R (1996) FAO Model Code of Forest Harvesting Practice. *FAO*, Rome, 85 pp.

Ekstrand S (1994) Assessment of forest damage with Landsat TM: correction for varying forest stand characteristics. *Remote Sensing of Environment*, **47**, 291-302.

Eva HD, Glini A, Janvier P, Blair-Myers C (1999) Vegetation Map of South America at Scale 1/5M. *TREES Publications Series D*, **2**, EUR EN 18658. European Commission, Luxembourg.

FAO (2000) Global Forest Resources Assessment 2000; *Main Report*. Available from URL: ftp://ftp.fao.org/docrep/fao/003/Y1997E/FRA%202000%20Main%20report.pdf.

FAO (2006) Global Forest Resources Assessment 2005, Progress towards sustainable forest management, *FAO Forestry Paper 147*, ISBN 92-5-105481-9.

Field RD, Shen SSP (2008) Predictability of carbon emissions from biomass burning in Indonesia from 1997 to 2006. *Journal of Geophysical Research*, **113**, 1-17, G04024, doi:10.1029/2008JG000694.

Flint EP (1994) Changes in land use in South and Southeast Asia from 1880 to 1980: A data base prepared as part of a coordinated research program on carbon fluxes in the tropics. *Chemosphere*, **29**, 5. 1015-1062.

Foody GM (2001) Status of land cover classification accuracy assessment. *Remote Sensing of Environment*, **80**, 185–201.

Friedl MA, McIver DK, Hodges JCV *et al*. (2002) Global land cover mapping from MODIS: algorithms and early results. *Remote Sensing of Environment*, **83**, 287–302.

Fuller DO, Jessup TC, Salim A (2003) Loss of forest cover in Kalimantan, Indonesia, since the 1997–1998 El Niño. *Conservation Biology*, **18**, 249–254.

Fuller DO, Murphy KJ (2005) Rapid assessment of land surface conditions in insular Southeast Asia with MODIS reflectance composites: an example using 2004 imagery. *Asia Oceanic Geoscience Society*, Annual Meeting Abstracts. Available from URL: http://www.asiaoceaniaconference.org/abstract/HS/2nd%20Round/HS07/58-HS-A1284.pdf.

Fuller DO (2006) Tropical forest monitoring and remote sensing: A new era of transparency in forest governance? *Singapore Journal of Tropical Geography*, **27**, 15-29.

Fuller DO, Murphy K (2006) The ENSO-Fire Dynamic in insular Southeast Asia. *Climatic Change*, **74**, 435-455.

FWI/GFW (2002) The State of the Forest: Indonesia. Bogor, Indonesia: Forest Watch Indonesia, and Washington DC: *Global Forest Watch.*

Geist HJ, Lambin EF (2002) Proximate causes and underlying driving forces of tropical deforestation. *BioScience*, **52**, 143–150.

Glastra R, Wakker E, Richert W (2002) Oil Palm Plantations and Deforestation in Indonesia. What Role Do Europe and Germany Play? *WWF Germany in collaboration with WWF Indonesia and WWF Switzerland*, Update of the 1998 “Lipsticks from the Rainforest” Report.

Glover D, Jessup T (1999) Indonesia's Fires and Haze: The Cost of Catastrophe. *Institute of Southeast Asian Studies*, Singapore, ISBN 981-230-006-6, *International Development Research Centre*, ISBN 0-88936-901-1.

Goldammer JG (1993) Feuer in Waldoekosystemen der Tropen und Subtropen. *Birkhaeuser*, Basel-Boston, ISBN-10: 3764328134, ISBN-13: 978-3764328139.

Goldammer JG (2007) History of equatorial vegetation fires and fire research in Southeast Asia before the 1997–98 episode: A reconstruction of creeping environmental changes. *Mitigation and Adaptation Strategies for Global Change*, **12**, 13-32.

Gullison RE (2003) Does forest certification conserve biodiversity? *Oryx*, **37**, 2, 153-165.

Guyon A, Simorangkir D (2002) The Economics of Fire Use in Agriculture and Forestry - A preliminary Review for Indonesia. *Project FireFight South East Asia*, ISBN no. 979-3260-00-9.

Hai TC (2000) Land use and the oil palm industry in Malaysia. *Abridged report produced for the WWF Forest Information System Database*.

Hansen MC, DeFries RS, Townshend JRG, Carroll M, Dimiceli C, Sohlberg R (2003) Global percent tree cover at a spatial resolution of 500 meters: first results of the MODIS vegetation continuous field algorithm. *Earth Interactions*, **7**, 1–15.

Healey JR, Price C, Tay J (2000) The cost of carbon retention by reduced impact logging. *Forest Ecology and Management*, **139**, 237-255.

Hirschberger P (2008) Illegaler Holzeinschlag und Deutschland – Eine Analyse der Aussenhandelsdaten April 2008. WWF Report.

Hoffmann A, Hinrichs A, Siegert F (1999) Fire damage in East Kalimantan in 1997/98 related to land use and vegetation classes: satellite radar inventory results and proposals for further actions. With contributions from G.Ruecker, L.Christy, and B.Yuliarso. Sustainable Forest Management Project (SFMP) & Integrated Forest Fire Management (IFFM) Project, *Report No. 1. Indonesian Ministry of Forests and Estate Crops (MoFEC) and German Technical Cooperation Agency (GTZ)*, Samarinda, Indonesia.

Holmes DA (2002) Where have all the forests gone. *Environmental and Social Development Uniy (EASES) East Asia and Pacific Region of the World Bank*, Discussion Paper.

Hooijer A, Silvius M, Wösten H, Page S (2006) PEAT-CO2, Assessment of CO2 emissions from drained peatlands in SE Asia, *Delft Hydraulics report* Q3943.

Houghton RA (2002) Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000. *Tellus*, 378-390.

Huang S, Siegert F (2006) Land cover classification optimized to detect areas at risk of desertification in North China based on SPOT VEGETATION imagery. *Journal of Arid Environments*, **67**, 308–327.

IPCC (2007) Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. *Cambridge University Press*, Cambridge, United Kingdom and New York, NY, USA.

ITTO (2006) Status of Tropical Forest Management 2005. *ITTO Technical Series No 24*, International Tropical Timber Organization, Pacifico-Yokohama, 1–1–1, Minato-mirai, Nishi-ku Yokohama, 220-0012, Japan.

Jaenicke J, Rieley JO, Mott C, Kimman P, Siegert F (2008) Determination of the amount of carbon stored in Indonesian peatlands. *Geoderma*, **147**, 151–158.

Jepson P, Jarvie JK, MacKinnon K, Monk KA (2001) The end for Indonesia's Lowland Forests? *Science*, **292**, 859–861.

Justice CO, Giglio L, Korontzi S, *et al*. (2002) The MODIS fire products. *Remote Sensing of Environment*, **83**, 244-262.

Karjalainen T, Richards G, Hernandez T *et al*. (2003) IPCC Report on Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types. *IPCC National Greenhouse Gas Inventories Programme (IPCC-NGGIP).*

Kitayama K, Nakazono E, Seino T, Aiba SI, Hasegawa M, Onoguchi G, Ito M, Chung AYC, Ong R, Lee YF (2008) Averting biodiversity crisis in Borneo: the role of well-managed production forests in biodiversity conservation. *Manuscript.*

Langner A, Miettinen J, Siegert F (2007) Land cover change 2002 – 2005 in Borneo and the role of fire derived from MODIS imagery, *Global Change Biology*, **13**, 11, 2329-2340 (12).

Langner A, Bartholomé E, Siegert F Monitoring (2008) Deforestation in the Humid Tropics using a Multispectral Change Analysis Technique. *Manuscript.*

Langner A, Siegert F (2009) Spatiotemporal fire occurrence in Borneo over a period of 10 years. *Global Change Biology*, **15**, 48–62, doi: 10.1111/j.1365-2486.2008.01828.x.

Leslie A, Sarre A, Filho MS, bin Buang A (2002) Forest certification and biodiversity, *ITTO Tropical Forest Update*, **12**, 3, 13-15.

Li Z, Kaufman YJ, Ichoku C *et al*. (2001) A review of AVHRR-based active fire algorithms: principles, limitations, and recommendations. *In Global and Regional Vegetation Fire Monitoring from Space*, edited by Ahern FJ, Goldammer JG and Justice CO (The Hague: *SPB Academic Publishers BV*), pp. 199–225.

Liang S, Fallah-Adl H, Kalluri S, JaJa J, Kaufman YJ, Townshend JRG (1997) An operational atmospheric correction algorithm for Landsat Thermatic Mapper imagery over the land. *Journal of Geophysical Research*, **102**, 173–186.

Lillesand TM, Kiefer RW, Chipman JW (2004) Remote sensing and image interpretation, 5th Edition, *John Wiley & Sons Ltd*, ISBN 0-471-15227-7.

Loveland TR, Reed BC, Brown JF, Ohlen DO, Zhu Z, Yang L, Merchant JW (2000) Development of a global land cover characteristics database and IGBP DISCover from 1 km AVHRR data. *International Journal of Remote Sensing*, **21**, 1303–1330.

MacKinnon K, Hatta G, Halim H, Mangalik A (1996) The Ecology of Kalimantan. The Ecology of Indonesia series, Vol. III. *Periplus Editions* (HK) Ltd, I–XXIV, ISBN 0-945971-73-7.

Malingreau J-P, Tucker CJ, Laporte N (1989) AVHRR for global tropical monitoring. *International Journal of Remote Sensing*, **10**, 855–867.

Marcoux A (2000) Population and deforestation. From Population and the environment: a review and concepts for population programmes. Part III: Population and deforestation, *FAO.*

Marten, GG (1986). Traditional Agriculture in Southeast Asia: A Human Ecology Perspective. *Westview Press*, Boulder, Cololorado and London.

Matthews E, Payne R, Rohweder M, Murray S (2000) Pilot Analysis of Global Ecosystems – Forest Ecosystems. World Resources Institute, ISBN: 1-56793-459-3, Library of Congress Catalog No. 00-109787.

Mayaux P, Achard F, Malingreau J-P (1998) Global tropical forest area measurements derived from coarse resolution maps at a global level: a comparison with other approaches. *Environmental Conservation*, **25**, 37–52.

Mayaux P, Bartholomé E, Fritz S, Belward A (2004) A new land-cover map of Africa for the year 2000. *Journal of Biogeography*, **31**, 861–877.

Mayaux P, Holmgren P, Achard F, Eva H, Stibig H-J, Branthomme A (2005) Tropical forest cover change in the 1990s and options for future monitoring. *Philosophical Transactions of the Royal Society,* **360,** 373-384.

McMorrow JM, Talip, Mustapa Abd (2001) Decline of forest area in Sabah, Malaysia: relationship to state policies, land code and land capability. *Global Environmental Change: Human and Policy Dimensions*, **11**, 217–230.

Michener WK, Houhoulis PF (1997) Detection of vegetation changes associated with extensive flooding in a forested ecosystem. *Photogrammetric Engineering and Remote Sensing*, **63**, 1363–1374.

Miettinen J, Langner A, Siegert F (2007) Burnt area estimation for the year 2005 in Borneo using multi-resolution satellite imagery. *International Journal of Wildland Fire*, **16**, 45-53.

Myers EC (2007) Policies to Reduce Emissions from Deforestation and Degradation (REDD) in Tropical Forests, *Resources for the Future (RFF)*, DP 07-50, Discussion Paper.

Nepstad DC, Verissimo A, Alencar A *et al*. (1999) Large-scale impoverishment of Amazonian forests by logging and fire. *Nature* **398**, 505-508.

Niles JO, Brown S, Pretty J, Ball AS, Fay J (2002) Potential carbon mitigation and income in developing countries from changes in use and management of agricultural and forest lands. *Philosophical Transactions of the Royal Society of London, Series A: Mathematical, Physical and Engineering Sciences*, **360**, 1621-1639.

Page SE, Siegert F, Rieley JO, Boehm H-DV, Jaya A, Limin S (2002) The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature*, **420**, 61-65.

Petty GW (2006) A First Course in Atmospheric Radiation. *Sundog Publishing*, Madison, Wisconsin, ISBN-10: 0-9729033-1-3, ISBN-13: 978-0-9729033-1-8, 460 pp.

Pinard MA, Putz FE (1996) Retaining forest biomass by reducing logging damage. *Biotropica*, **28**, 278–295.

Pinard MA, Putz FE, Tay J, Sullivan TE (1995) Creating timber harvest guidelines for a reduced-impact logging project in Malaysia. *Journal of Forestry*, **93**, 41–45.

Putz FE, Pinard MA (1993) Reduced impact logging as a carbon offset method. *Conservation Biology*, **7**, 755–757.

Podest E, Saatchi S (2002) Application of multiscale texture in classifying JERS-1 radar data over tropical vegetation. *International Journal of Remote Sensing*, **23**, 7, 1487–1506.

Priyadi H, Gunarso P, Sist P, Dwiprabowo H (2006) Reduced impact logging (RIL) Research and Development in Malinau Research Forest, East Kalimatan: A challenge of RIL adoption. *Center for International Forestry Research (CIFOR), Regional Workshop "RIL Implementation in Indonesia with reference to Asia-Pacific Region: Review and Experiences, Bogor.*

Rautner M, Hardiono M, Alfred RJ (2005) Borneo: Treasure Island at Risk – Status of Forest, Wildlife and related Threats on the Island of Borneo. *WWF Germany*, Frankfurt am Main.

Rhee S, Kitchener D, Brown T, Merrill R, Dilts R, Tighe S (2004) Report on Biodiversity and tropical forests in Indonesia. *USAID/Indonesia*.

Rieley JO, Page SE (2005) Wise Use of Tropical Peatland: Focus on Southeast Asia. ALTERRA - Wageningen University and Research Centre and the EU INCO - STRAPEAT and RESTORPEAT Partnership. ISBN 90327-0347-1. *Report*.

Rodriguez E, Morris CS, Belz JE, Chapin EC, Martin JM, Daffer W, Hensley S (2005) An assessment of the SRTM topographic products. *Jet Propulsion Laboratory D-31639.*

Sabah Forestry Department (1998) RIL operation guide book: specifically for tracked skidder use. Sandakan, Malaysia, Sabah Forestry Department.

Sargeant HJ (2001) Vegetation Fires in Sumatra Indonesia. Oil Palm Agriculture in the Wetlands of Sumatra: Destruction or Development? *Government of Indonesia, Ministry of Forestry, European Union, European Commission*, IDN/B7-5041/92/644-01.

Schott JR, Salvaggio C, Volchok WJ (1988) Radiometric scene normalization using pseudoinvariant features. *Remote Sensing of Environment*, **26**, 1–16.

Schroeder-Wildberg E, Carius A (2003) Illegal Logging, Conflict and the Business Sector in Indonesia. *InWEnt - Capacity Building International*, Germany, Berlin, ISBN: 3-937235-33-7.

Siegert F, Hoffmann A (2000) The 1998 forest fires in East Kalimantan (Indonesia): a quantitative evaluation using high resolution, multitemporal ERS-2 SAR images and NOAAAVHRR hotspot data. *Remote Sensing of Environment*, **72**, 64–77.

Siegert F, Ruecker G (2000) Use of multitemporal ERS-2 SAR images for identification of burned scars in south-east Asian tropical rainforest. *International Journal of Remote Sensing*, **21**, 4, 831-837.

Siegert F, Ruecker G, Hinrichs A, Hoffmann AA (2001) Increased damage from fires in logged forests during droughts caused by El Niño. *Nature*, **412**, 437-440.

Sist P, Sheil D, Kartawinata K, Priyadi H (2003) Reduced-impact logging in Indonesian Borneo: some results confirming the need for new silvicultural prescriptions. *Forest Ecology and Management*, **179**, 415-427.

Sodhi NS, Koh LP, Brook BW, Ng PKL (2004) Southeast Asian biodiversity: an impending disaster. *TRENDS in Ecology and Evolution*, **19**, 654–660.

Spanner MA, Pierce LL, Peterson DL, Running SW (1990) Remote sensing of temperate coniferous forest leaf area index: the influence of canopy closure, understory vegetation and background reflectance. *International Journal of Remote Sensing*, **11**, 95–111.

Stibig H-J, Beuchle R, Achard F (2002) Mapping of the tropical forest cover of insular Southeast Asia from SPOT4-Vegetation images. International Journal of Remote Sensing, DOI: 10.1080/01431160210000024113, 1–12.

Stibig H-J, Malingreau J-P (2003) Forest cover of insular southeast Asia mapped from recent satellite images of coarse spatial resolution. Royal Swedish Academy of Sciences, 32, 469–475.

Stibig H-J, Belward AS, Roy PS, Rosalina-Wasrin U, Agrawal S, Joshi PK, Hildanus *et al*. (2007) A land-cover map for South and Southeast Asia derived from SPOT-VEGETATION data. *Journal of Biogeography*, **34**, 625–637.

Stolle F, Dennis RA, Kurniwan I, Lambin EF (2004) Evaluation of remote sensing-based active fire datasets in Indonesia. *International Journal of Remote Sensing*, **25**, 2, 471-479.

Sunderlin WD, Resosudarmo IAP (1996) Rates and Causes of Deforestation in Indonesia - Towards a resolution of the ambiguities. *CIFOR Occasional Paper*, **9**, ISSN 0854-9818.

Sunderlin WD (1997) Rural Development Forestry Network – Shifting Cultivation and Deforestation in Indonesia: Steps Toward Overcoming Confusing in the Debate. *RDFN Paper 21b*, ISSN 0968-2627.

Sunderlin WD (1999a) Policy Reviews - Between danger and opportunity: Indonesia's forests in era of economic and political change. *Society & Natural Resources*, **12**, 559–570.

Sunderlin WD (1999b) The Effects of Economic Crisis and Political Change on Indonesia's Forest Sector, 1997-99. *Center for International Forestry Research (CIFOR).*

Sunderlin WD, Resosudarmo IAP, Rianto E, Angelsen A (2000) The Effect of Indonesia's Economic Crisis on Small Farmers and Natural Forest Cover in the Outer Islands. *Center for International Forestry Research (CIFOR)*, Occasional Paper **28**(E), ISSN 0854-9818.

Suyanto S, Applegate G, Permana RP, Khususiyah N, Kurniawan I (2004) The role of fire in changing land use and livelihoods in Riau-Sumatra. *Ecology and Society* **9(1)**: 15. [online] URL: http://www.ecologyandsociety.org/vol9/iss1/art15/.

Suyanto S (2007) Underlying cause of fire: Different form of land tenure conflicts in Sumatra. *Mitigation and Adaptation Strategies for Global Change*, **12**, 67–74, DOI 10.1007/s11027-006-9039-4.

Tacconi L (2003) Fires in Indonesia: Causes, Costs and Policy Implications. *CIFOR Occasional Paper* **No. 38**, ISSN 0854-9818.

Tacconi L, Boscolo M, Brack D (2003) National and International Policies to Control Illegal Forest Activities. *Center for International Forestry Research (CIFOR).*

Tacconi L, Moore PF, Kaimowitz D (2007) Fires in tropical forests – what is really the problem? Lessons from Indonesia. *Mitigation and Adaptation Strategies for Global Change*, **12**, 55–66, DOI 10.1007/s11027-006-9040-y.

Taylor D, Saksena P, Sanderson PG, Kucera K (1999) Environmental change and rain forests on the Sunda shelf of Southeast Asia: drought, fire and the biological cooling of biodiversity hotspots. *Biodiversity and Conservation*, **8**, 1159–1177.

Thompson H (1996) Indonesia's wood resource: trends and policies. *Journal of Mineral Policy*, **12**, 14–23.

Trigg SN, Curran LM, McDonald AK (2006) Utility of Landsat 7 satellite data for continued monitoring of forest cover change in protected areas in Southeast Asia. *Singapore Journal of Tropical Geography*, **27**, 49-66.

Tucker CJ, Townshend JRG (2000) Strategies for monitoring tropical deforestation using satellite data. *International Journal of Remote Sensing*, **21**, 6 & 7, 1461–1471.

Uhl C, Kauffman JB (1990) Deforestation, Fire Susceptibility, and Potential Tree Response to Fire in the Eastern Amazon. *Ecology*, **71**, 2, 437-449

Vancutsem C, Bicheron P, Cayrol P, Defourney P (2007a) An assessment of three candidate compositing methods for global MERIS time series. *Canadian Journal of Remote Sensing*, **33**, 6, 492-502.

Vancutsem C, Pekel J, Bogaert P, Defourney P (2007b) Mean compositing, an alternative strategy for producing temporal synthesis. Concepts and performance assessment for SPOT VEGETATION time series. *International Journal of Remote Sensing*, **28**, 22, 5123-5141.

Van der Werf GR, Dempewolf J, Trigg SN, Randerson JT, Kasibhatla PS, Giglio L, Murdiyarso D, Peters W, Morton DC, Collatz GJ, Dolman AJ, DeFries RS (2008) Climate regulation of fire emissions and deforestation in equatorial Asia. PNAS, 105, 51, 20350-20355.

Vellinga P, van Verseveld WJ (2000) Climate Change and Extreme Weather Events. *WWF-World Wide Fund For Nature*, Gland, Switzerland.

Whitmore TC (1984) Tropical Rain Forests of the Far East. *Clarendon Press*, Oxford, Second Edition.

Wakker E (2000) Funding Forest Destruction - The Involvement of Dutch Banks in the Financing of Oil Palm Plantations in Indonesia. *Report for Greenpeace Netherlands*.

WRM (2000) The pulp and paper sector's unsustainable growth. *World Rainforest Movement Bulletin,* **41**, December 2000. Indonesia.

Zhan X, DeFries R, Townshend JRG, Dimiceli C, Hansen M, Huang C, Sohlberg R (2000) The 250m global land cover change product from the moderate resolution imaging spectroradiometer of NASA's earth observing system. *International Journal of Remote Sensing*, **21**, 1433–1460.

Zhan X, Sohlberg RA, Townshend JRG *et al*. (2002) Detection of land cover changes using MODIS 250m data. *Remote Sensing of Environment*, **83**, 336–350.

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Employment history

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2007 – 2008	**University of Tokyo**, Tokyo, Japan
2004 – 2007	**RSS- Remote Sensing Solutions GmbH**, Munich, Germany
1997 – 1998	**WSB Bayern GmbH & Co. OHG**, Munich, Germany

Education

1998 – 2004

Munich University (Ludwig-Maximilians-University), Munich, Germany, Study in Biology, Graduation: Diploma in Biology (equivalent to MSc)

Field of studies:
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Master thesis title:
Analysis of high and middle resolution satellite imageries for regional mapping of rainforest ecosystems in Borneo

1994 – 1997	Apprenticeship at the **WSB Bayern GmbH & Co. OHG**, Munich, Germany
1994	High school diploma (Abitur) at the **Humboldt-Gymnasium Vaterstetten**, Vaterstetten, Germany

Language skills

German	First language
English	Very good language skills
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IT skills

General	Windows NT, Windows 3.1-2000/XP/VISTA, MS Office (Word, Excel, PowerPoint, Outlook)
Database	MS Access, SPSS
RS / Image processing	ERDAS Imagine 8.x / 9.x, RSI ENVI 3.x, 4.x, Adobe Photoshop CS2
GIS	ArcView 3.x, ArcGIS 8.x / 9.x, ArcInfo, TNTmips
Computer language	JAVA

Work experience

2008 – 2009	**Researcher, Forestry and Forest Products Research Institute (FFPRI), Kansai Research Center,** Kyoto, Japan, Project title: *Tropical Biomass Estimation in well-managed Production Forests in Sabah, Borneo*
2008 – 2008	**Researcher, University of Tokyo**, Tokyo, Japan, Project title 1: *Costs and Benefits of Political Decisions in Large-Scale Regional Development Projects* Project title 2: *Land cover classification in the tropics using ALOS PALSAR data*
2007 – 2008	**JSPS funding, University of Tokyo**, Tokyo, Japan Project title: *Costs and Benefits of Political Decisions in Large-Scale Regional Development Projects*

2004 – 2007	**PhD Student** at the GeoBio Center of the Munich University (Ludwig- Maximilians-University), Munich and the RSS GmbH, Munich/Germany PhD thesis title: *Monitoring Tropical Forest Degradation and Deforestation in Borneo, Southeast Asia*
2004 – 2007	**Supervisor for GIS and Remote Sensing courses** at the GeoBio Center of the Munich University (Ludwig-Maximilians-University), Munich/Germany

Project experience

2008 – 2009	South East Asia – *Environmental monitoring*: Estimation of Biomass Conservation in well-managed Production Forests in Sabah using ALOS PALSAR Data under Prof. Kanehiro Kitayama **(APN Asia-Pacific Network for Global Change Research)**
2007 – 2008	South East Asia – *Environmental monitoring*: Integrated use of multi-mode, multi-angle and multi-band SAR data for land cover identification in tropics under Prof. Mikiyasu Nakayama as **ALOS PI (ALOS Science Program)**
2007 – 2008	Middle East – *Development project*: Costs and Benefits of Political Decisions in Large-Scale Regional Development Projects under Prof. Mikiyasu Nakayama. Project funded by **JSPS short-term program (in cooperation with HEAR-MET Program)**
2006	South East Asia – *Environmental monitoring*: Accuracy assessment of maps in Southeast Asia within the **GMES (GSE Forest Monitoring)** project funded by the EU 6th Framework Program
2006	South East Asia – *Course supervisor*: GIS and Remote Sensing course about Tropical forest landscape restoration in Southeast Asia under the framework of EU/AsiaLink project Forest Restoration and Rehabilitation in Southeast Asia (**FORRSA**)

2006	South East Asia – *Course participation*: Tropical forest landscape restoration in Southeast Asia within the framework of EU/AsiaLink project Forest Restoration and Rehabilitation in Southeast Asia (**FORRSA**)
2005 - 2008	South East Asia – *Environmental monitoring*: Analysis of deforestation between 2002 – 2005 of rainforest ecosystems, deforestation patterns and the correlation between fires and land cover changes and their spatial patterns in Borneo using high-resolution Landsat data and medium-resolution MODIS data within the **RESTORPEAT** project funded by the EU 6^{th} Framework Program
2005	South East Asia – *Environmental monitoring*: Field work for land cover change detection between 2002 – 2005 of rainforest ecosystems in Borneo using high-resolution Landsat data and medium-resolution MODIS data within the **RESTORPEAT** project funded by the EU 6^{th} Framework Program
2005	Africa – *Environmental monitoring*: Land cover classification in tropical and arid regions of Africa within the **EPIDEMIO** project using ENVISAT MERIS imagery data (ESA - European Space Agency)
2004 – 2005	Africa – *Environmental monitoring*: Multispectral change detection analysis in tropical and arid regions of Africa within the **GEOLAND** project funded by the EU 6^{th} Framework Program
2004	Automatic classification of ENVISAT MERIS imagery data for fire scar detection in Siberia within the **SIBERIA II** project
2002 – 2003	South East Asia – *Environmental monitoring*: Land cover classification of rainforest ecosystems in Borneo using high-resolution Landsat data and medium-resolution MODIS data. Comparison of classification results using supervised and unsupervised algorithms. **STRAPEAT** project funded by the EU 5^{th} Framework Program

Conferences

2008 **Andreas Langner, Mikiyasu Nakayama**, **Jukka Miettinen, Soo Chin Liew,**
Integrated use of multi-mode, multi-angle and multi-band SAR data for land cover identification in tropics, Rhodes, Greece – The First ALOS Data Nodes Symposium – ALOS 2008, November 03-07, 2008

2008 **Andreas Langner, Mikiyasu Nakayama**,
Societal Implications upon Implementation of Large-scale Economic Development Projects – A Research Proposal –, Adiyaman, Turkey – Effects of Land Management on Natural Resources and Socio-economy in GAP Region, July 07-12, 2008

2008 **Andreas Langner, Mikiyasu Nakayama**,
Societal Implications upon Implementation of Large-scale Economic Development Projects, Kyoto, Japan – HEAR-MET Research Meeting at RIHN in Kyoto, February 27, 2008

2007 **Andreas Langner, Soo Chin Liew, Mikiyasu Nakayama**,
Integrated use of multi-mode, multi-angle and multi-band SAR data for land cover identification in tropics, Kyoto, Japan – The First Joint PI symposium of ALOS Data Nodes for ALOS Science Program in Kyoto, November 19-23, 2007

2006 **Andreas Langner, Jukka Miettinen, Florian Siegert**,
Remote sensing as a tool for land use change, fire and illegal logging monitoring and peatland restoration planning in Southeast Asia, Greifswald, Germany – 5th European Conference on Ecological Restoration, August 21-25, 2006

2006 **Andreas Langner, Florian Siegert**,
Multi-criteria environmental status and land cover change assessment: methodological considerations, Vienna, Austria – 3rd GEOLAND Forum, February 7-9, 2006

2004 **Andreas Langner, Florian Siegert**, *Multispectral change detection*, Toulouse, France – 2nd GEOLAND OpenDay, Observatory for Land Cover and Forest Change, December 8-10, 2004

Publications (peer reviewed journals)

Andreas Langner, Florian Siegert, *Spatiotemporal fire occurrence in Borneo over a period of 10 years*, Global Change Biology, 15, 48–62, doi: 10.1111/j.1365-2486.2008.01828.x, 2009 (Chapter IV)

Andreas Langner, Jukka Miettinen, Florian Siegert, *Land cover change 2002 – 2005 in Borneo and the role of fire derived from MODIS imagery*, Global Change Biology, Volume 13, Number 11, November 2007, pp. 2329-2340(12) (Chapter II)

Jukka Miettinen, Andreas Langner, Florian Siegert, *Burnt area estimation for the year 2005 in Borneo using multi-resolution satellite imagery*, International Journal of Wildland Fire, 16, pp 45-53, 2007

Publications (submitted at peer reviewed journals)

Allan Spessa, Angelika Heil, Andreas Langner, Uli Weber, Florian Siegert, *Fire in the Vegetation and Peatlands of Equatorial SE Asian: Patterns, Drivers and Emissions*, submitted at Biogeosciences

Publications (in preparation for peer reviewed journals)

Andreas Langner, Kanehiro Kitayama, *Estimation of Biomass Conservation in well-managed Production Forests in Sabah using Satellite Remote Sensing*, Manuscript

Kanehiro Kitayama, Etsuko Nakazono, Tatsuyuki Seino, Shin-Ichiro Aiba, Motohiro Hasegawa, Go Onoguchi, Nobuo Imai, A.Y.C. Chung, R. Ong, Y.F Lee, A. Langner, *Averting biodiversity crisis in Borneo: the role of well-managed production forests in biodiversity conservation*, Manuscript

Andreas Langner, Etienne Bartholomé, Florian Siegert, *Monitoring Deforestation in Tropical Africa using a Multispectral Change Analysis Technique*, Manuscript (Chapter I)

Andreas Langner, Florian Siegert, *Using low and medium resolution MODIS data to investigate deforestation in Borneo*, Manuscript (Chapter III)

Angelika Heil, Andreas Langner, Florian Siegert, *An Estimate of Indonesian Fire Emissions from 1997 - 2006 and their Uncertainties*, Manuscript

Publications (proceeding papers)

Andreas Langner, Mikiyasu Nakayama, Jukka Miettinen, Soo Chin Liew *Integrated use of multi-mode and multi-angle SAR data for land cover identification in tropics*, Proceedings of The First ALOS Data Nodes Symposium – ALOS 2008, Rhodes Greece, November 03-07, 2008

Andreas Langner, Mikiyasu Nakayama, Soo Chin Liew *Integrated use of multi-mode and multi-angle SAR data for land cover identification in tropics*, Proceedings of the First Joint PI symposium of ALOS Data Nodes for ALOS Science Program in Kyoto, Kyoto Japan, November 19-23, 2007

Andreas Langner, Florian Siegert, *The role of fire on land cover changes in Borneo,* Proceedings of 4th International Wildland Fire Conference, Wildfire2007, Seville Spain, May 13-17, 2007

Contributions to books

Susan Page, Agata Hoscilo, Andreas Langner, Kevin Tansey, Florian Siegert, Suwido Limin, Jack Rieley, *Tropical Peatland Fires in Southeast Asia*, in **M.A. Cochrane, ed.** *Tropical Fire Ecology: Climate Change, Land Use and Ecosystem Dynamics.* Springer-Praxis, Heidelberg, Germany, in press

Peatlands and Climate Change. Editor Jack Rieley, in preparation

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