3D modelling and monitoring of Indonesian peatlands aiming at global climate change mitigation

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May this work contribute to a more sustainable world!

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ABSTRACT

Tropical peat swamp forests in Indonesia are highly threatened ecosystems. As a result of economic development during the past two decades, they have been subjected to intensive logging, drainage and conversion to plantation estates, especially for oil palm. The Indonesian peatlands are one of the largest near-surface reserves of terrestrial organic carbon. However, ongoing rapid peat decomposition due to drainage and attendant recurrent fires have recently caused the release of huge amounts of this carbon into the atmosphere as carbon dioxide. If these large emissions from degrading peatlands are taken into account, Indonesia is one of the largest emitters of CO_2 worldwide. Within the context of the ongoing discussions concerning climate change, the importance of peatlands as carbon stores is increasingly recognised by the public, accompanied by a demand for conservation and restoration. Therefore, this thesis utilises innovative geospatial 3D modelling and remote sensing techniques to study the Indonesian peatlands with the overall aim of global climate change mitigation. Previous estimates of the total amount of carbon stored in the Indonesian peatlands could be improved by applying 3D modelling based on a combined analysis of satellite imagery and in situ peat thickness measurements. At least 55±10 Gt of carbon are stored in Indonesia's peatlands. With this huge carbon storage and the current rate of degradation, the tropical peatlands of Indonesia have the power to negatively influence the global climate. Large-scale peatland restoration is needed to prevent further greenhouse gas emissions. This thesis shows that successful rewetting of a 590 km² large area of drained peat swamp forest could result in mitigated emissions of 1.4-1.6 Mt CO_2 yearly, and can be achieved with relatively little effort and at low costs. Multitemporal radar satellite imagery proved to be capable of monitoring the effect of hydrological restoration measures on peat soil moisture and groundwater levels in Central Kalimantan, Indonesia. Satellite remote sensing allows continuous large-scale tropical peatland monitoring, compared to only punctual, temporally limited field measurements. This is particularly important for initiatives aiming at carbon trading on the voluntary carbon market or under the REDD (Reducing Emissions from Deforestation and Degradation) mechanism, which both constitute significant financing schemes for conservation and rehabilitation of Indonesia's peatlands.

PUBLICATIONS ORIGINATING FROM THIS THESIS

CHAPTER II

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

CHAPTER III

Jaenicke J, Wösten J H M, Budiman A, Siegert F (2010) Planning hydrological restoration of peatlands in Indonesia aiming at carbon dioxide emission reduction. Mitigation and Adaptation Strategies for Global Change DOI: 10.1007/s11027-010-9214-5

CHAPTER IV

Jaenicke J, Englhart S, Siegert F (2010) Monitoring the effect of restoration measures in Indonesian peatlands by radar satellite imagery. Journal of Environmental Management (submitted)

CONTRIBUTION OF THE AUTHORS

CHAPTER II

Julia Jaenicke developed the methods of peatland delineation and peat volume estimation, analysed the peat dome structure, calculated the carbon storage and evaluated the results. Dr. Claudius Mott helped with the statistics and Paul Kimman provided the peat thickness drilling data of South Sumatra. Prof. Dr. Jack Rieley gave critical comments and thus improved the manuscript.

CHAPTER III

Julia Jaenicke generated the detailed digital elevation model of the study area, detected the drainage canals on satellite imagery, identified the locations for dam construction and discussed the results in view of avoided carbon dioxide emissions. Arif Budiman managed the field work (assessment of canals) in Sebangau peatland and provided the data. Dr. Henk Wösten, a hydrologist from Wageningen University in The Netherlands having many years of experience in the Indonesian peatlands, performed the hydrological modelling.

CHAPTER IV

Julia Jaenicke developed the methodology for image processing and change detection analysis and interpreted the results. Sandra Englhart helped with processing the large amount of remote sensing data.

I hereby confirm the above statements

Julia Jaenicke Prof. Dr. Florian Siegert

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CHAPTER I

Introduction

1 The tropical peatlands of Indonesia

1.1 Extent and characteristics

Peat is dead organic material that has been accumulated over thousands of years in waterlogged environments that lack oxygen. Under natural circumstances peat consists of 90% water and 10% plant remains. Areas with peat soils are called peatlands. Tropical peatlands are found in mainland East Asia, Southeast Asia, the Caribbean, Central and South America and in southern Africa. Of the tropical peatlands worldwide about 70% are located in Southeast Asia (Immirizi and Maltby 1992; Rieley et al. 1996a). In Indonesia, most of the peat deposits are located at low altitudes in coastal and sub-coastal areas on the islands of Sumatra, Borneo (Kalimantan) and New Guinea (West Papua, Papua) (Fig. 1). Estimates of their extent range from 16.8 to 27.0 million ha (Page and Banks 2007), hence peatlands cover at least 9% of the Indonesian land surface. The thickness of the peat layer varies among locations and can be up to 20 m as reported from old peat deposits in the province of Riau, Sumatra (Whitten et al. 1987). Based on radiocarbon dating, the onset and development of the Indonesian peatlands range from the Late Pleistocene to the Holocene (Sieffermann et al. 1988; Neuzil 1997; Page et al. 2004). Most of the extensive peatlands along the coastlines, however, started to accumulate between 6,000 and 2,000 years BP, following stabilisation of global sea levels. During the Holocene, the average accumulation rate for Indonesian peatlands ranged between 0.6 and 2.7 mm/yr.

Naturally, tropical peatlands are covered with peat swamp forest whose biomass is the main contributor to the accumulating peat. Different forest types having different maximum canopy height (15-40 m; low, medium, tall pole) are discriminated and reflect variations in waterlogging and nutrient availability for tree growth (Anderson 1964; Page et al. 1999). Most Indonesian peatlands are ombrogenous, i.e. rainfall is the only source of water and nutrients (Rieley and Page 2005). Ombrogenous peatlands are situated topographically above the highest limit of wet season river flooding. Their formation is highly linked to the capacity to hold water and the peat is therefore dome shaped, like a drop of water. The system depends on the hydrostatic equilibrium that enables the peat to hold rain water above the normal ground water level. The topography of the mineral, water impounded subsoil usually drops gently from riverbanks or the coast to the centre of the peat dome and gives the peat deposits their characteristic biconvex cross-section (Fig. 2). Tropical peat domes can be up to 50 km wide occupying entire catchments between adjacent rivers.

As ombrogenous peatlands are purely rainwater-fed, the water is very acid (pH 3.0-4.5) and nutrient poor. Due to their capacity to store and maintain large quantities of water, peatlands play an important role in flood mitigation during monsoon rains and ensure a continuous water supply during the dry season, which usually lasts from May until October. Despite the lack of nutrients tropical peatlands represent a high biodiversity ecosystem with thousands of species (Andriesse 1988; Page and Rieley 1998). The peat swamp forests are among the last vast tracks of rainforest in Indonesia, and are therefore of particular importance for the survival of endangered species like the Orang Utan and Sumatran Tiger. In tropical peatlands, the vegetation and especially the underlying peat constitute a large and highly concentrated carbon pool (Sorensen 1993). Most studies consider a peat soil carbon content in the order of 58 kg C m^{-3} (Neuzil 1997; Page et al. 2002; Hooijer et al. 2006). Due to their high wood content as well as huge thickness and extent, the Indonesian peatlands are one of the largest near-surface reserves of terrestrial organic carbon. However, the process of peat accumulation is highly sensitive to changes in abiotic circumstances like hydrology and (micro-)climate and small changes can easily lead to a complete shift from accumulation to oxidation.

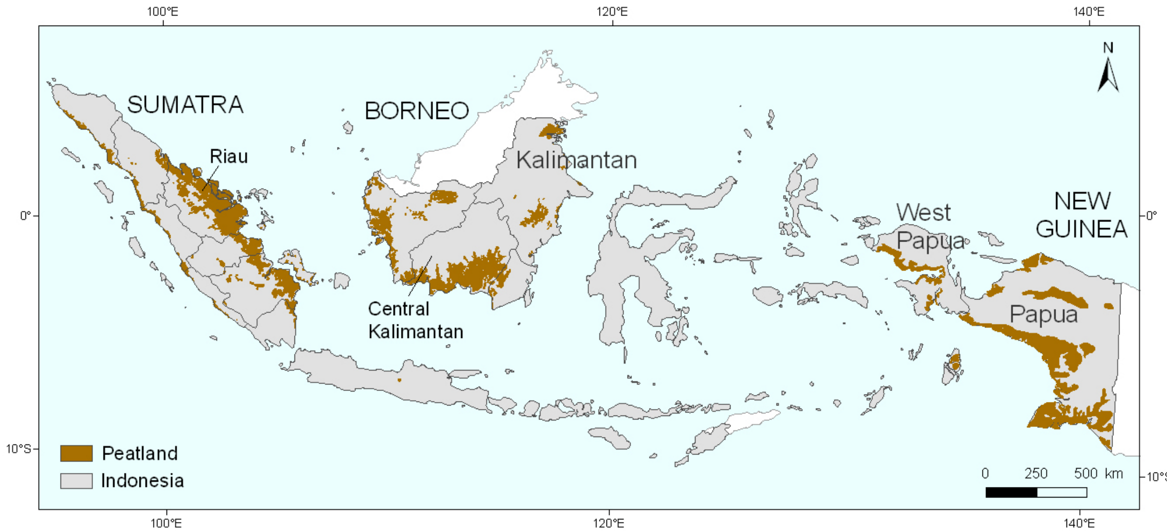

Fig. 1 Map of peatlands in Indonesia (data from Wetlands International 2003; 2004; 2006).

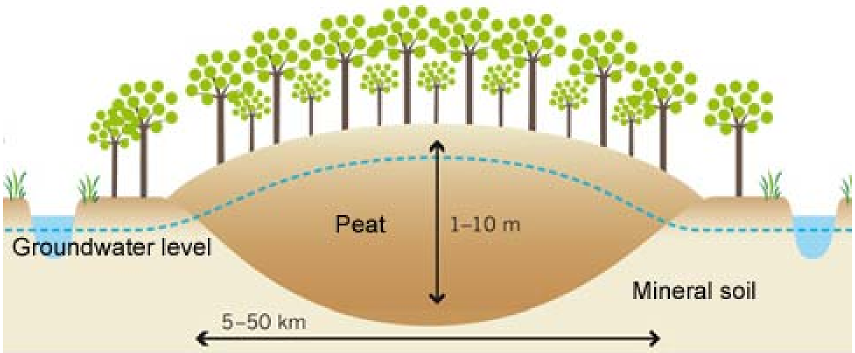

Fig. 2 Schematic cross-section of a typical tropical peat dome (WWF Germany, modified).

1.2 Degradation

As a result of economic development during the past two decades the Indonesian peatlands have been subjected to intensive logging, drainage, human-induced forest fires and conversion to plantation estates, especially of oil palm and pulp wood (Curran et al. 2004; Rieley and Page 2005; Hansen et al. 2009). The forest clearing rate in Indonesia is among the highest reported by the United Nations Food and Agriculture Organisation (FAO 2006), behind only Brazil in terms of forest cover lost. The expansion of oil palm estates in Indonesia grew from 100,000 ha in the late 1960s to 2.5 million ha in 1997 (Casson 2000, FWI/GFW 2002). An areal reduction of lowland forest extent by 41.3% in 15 years (1990-2005) for Sumatra and Kalimantan indicates an unsustainable rate of deforestation (Hansen et al. 2009). Recently, the raised demand for biofuel in Europe and the US increased the pressure on the remaining peatlands, even though the wet, acid and nutrient poor deep peat soils are hardly suitable for agricultural use and difficult to access. Drainage has to be applied to make the land useable for plantations and small-scale agriculture. About 12 million ha of the peatlands in Southeast Asia are currently deforested and drained, and another 45% impacted by selective logging (Hooijer et al. 2006). In the Indonesian province of Central Kalimantan alone over 1.5 million ha of tropical peat swamp forests are severely degraded. The Mega Rice Project (MRP), a resettlement project initiated by the Indonesian government in 1995 in Central Kalimantan, largely contributed to this degradation and is the most disastrous example of the failure of peatland ecosystem management and development that ignored sustainable management principles and rules (Muhamad and Rieley 2002; Page et al. 2002). Despite warnings by scientists, President Suharto planned to convert 1 million ha of peatlands for rice cultivation and ordered a transmigration program. Intensive deforestation took place and a massive network of drainage canals was built, with a combined length of 4,500 km and depth of up to 10 m, but rice production appeared to be impossible. As a consequence many of the transmigrated people started illegally logging the forested peatlands around the MRP area to earn their livelihood (Fig. 3).

There are two reasons for the construction of dense networks of drainage canals and ditches in tropical peatlands: 1) to control and lower the water level for plantation forestry and agricultural development, and 2) to facilitate access to the peat swamp forests and extract timber. Due to persistent high temperatures in the tropics, degradation of tropical peat soils proceeds rapidly once there is a change in the peatland ecosystem and its water regime. Drained peat rapidly oxidises due to aerobic, microbial activity and releases stored carbon to the atmosphere as carbon dioxide. Furthermore, ongoing peat decomposition is leading to peatland subsidence. It has been observed that subsidence of tropical peat soils increases by 0.9 cm per year for each 10 cm of additional drainage depth (Couwenberg et al. 2009). Naturally the groundwater level is close to the peat surface throughout the year and fluctuates with the intensity and frequency of rainfall. However, if the water level falls below a critical threshold of -40 cm, irreversible drying occurs and a layer of dry peat is created on the surface which is very susceptible to fire (Takahashi et al. 2003; Usup et al. 2004; Wösten et al. 2008).

Undisturbed tropical peat swamp forest is normally highly resistant to fire because of low loads of available fuel, low fuel-energy content and high humidity even during the dry season (Goldammer 1990; Cochrane and Schulze 1999; Siegert et al. 2001). Fires have become a threat to the Indonesian peatlands only within the last decade and are most severe during extended El Niño related droughts, as in 1997/98 when about 2.4-6.8 million ha of peatland burnt in Indonesia (Page et al. 2002; Langner and Siegert 2009). The fires severely damage the remaining forests and increase the risk of recurrent fire disasters by leaving huge amounts of dead flammable wood (Siegert et al. 2001; Cochrane 2003; Langner et al. 2007). This feedback cycle between drainage, logging and fire occurrence leads to progressive forest degradation and continuous release of the greenhouse gas CO_2. In Indonesia, severe peat fires occurred during prolonged El Niño induced droughts in 1997/98, 2002, 2004, 2006 and 2009. There is a clear relationship between the occurrence of fire and access to the areas, as most fires start near villages, roads, canals and logging railway tracks. Especially in dry years, fires are started by farmers to clear land and on a much larger scale by private companies as the cheapest tool to clear forests before establishing oil palm and pulp wood plantations (ADB 1999; Bompard and Guizol 1999; Langner et al. 2007). Once ignited, tropical peat fires continue to burn for several days or even weeks and produce huge amounts of noxious haze, causing severe health problems for the local population (Levine 1999) (Fig. 3).

Fig. 3 Illegal logging, drainage canals and smouldering fire in the peatlands of Central Kalimantan (photos © Siegert).

1.3 Impact on global climate change

Extensive degradation of the Indonesian peatlands has regional consequences for indigenous people and the biodiversity as well as global effects by contributing to climate change processes. Oxidation of peat in combination with burning of dry surface peat results in significant carbon outputs to the atmosphere. While peat oxidation causes the continuous release of carbon dioxide, peat fires are the sources of huge amounts of CO_2 emissions in short period of time. Based on various field studies of gas flux emissions from degraded tropical peat soils, it is estimated that an increase of drainage depth by 10 cm results in the emission of about 9 t CO_2 $ha^{-1}a^{-1}$ (Hooijer et al. 2006; Couwenberg et al. 2009). In an average tropical peat fire 33 cm of peat is lost, which corresponds to 702 t CO_2 ha^{-1} (Ballhorn et al. 2009; Couwenberg et al. 2009). This is more than 15 times the annual oxidative loss from 50 cm deep drained peat soil and exceeds average Holocene accumulation rates by 100 to 550 times. As a result of burning peat and vegetation in Indonesia during the severe El Niño event of 1997/98 about 1.8-3.0 Gt of carbon dioxide were released to the atmosphere (Page et al. 2002; Van der Werf et al. 2008b; Couwenberg et al. 2009). The current total peatland CO_2 emission from peat oxidation after drainage and peat fires is estimated to be 1.8 Gt per year (Hooijer et al. 2006), which is equivalent to 24% of mean annual global carbon emissions from fossil fuels (IPCC 2007). Thus, the role of tropical peatlands has changed from being a CO_2 sink to a source and Indonesia became one of the largest producers of greenhouse gases worldwide.

Other greenhouse gases contributing to the global climate warming are methane (CH_4) and nitrous oxide (N_2O). Methane fluxes in peat soils are negligible, whereas N_2O are erratic with very high values upon application of fertilizer to wet peat soils (Hadi et al. 2005; Furukawa et al. 2005; Takakai et al. 2006; Couwenberg et al. 2009). Climate model simulations suggest there will be a rise in mean global surface air temperature by about 0.2 °C per decade for the next two decades due to increasing concentrations of greenhouse gases (mainly CO_2) in the atmosphere (IPCC 2007). After fossil fuel combustion, deforestation is the second largest anthropogenic source of carbon dioxide to the atmosphere, with tropical peatlands emerging as a notable source (Van der Werf et al. 2009). Within the context of the ongoing discussions concerning climate change the role of tropical peatlands in global carbon cycling has now been recognised (Rieley and Page

2005; Hoojer et al. 2006; Uryu et al. 2008). With peat thicknesses ranging mainly from 0.5 to 10 m (Wetlands International 2003; 2004; 2006), undisturbed tropical peatlands store between 400 and 5,900 t C ha^{-1} which is up to 40 times more than in tropical rainforests of the same size without peat soils (Uryu et al. 2008). Therefore, restoration and conservation of tropical peatlands plays a crucial role in global climate change mitigation.

1.4 Restoration and conservation

Studies of restoration ecology are well established for peatlands in the boreal and temperate zones, but at an early stage for tropical peatlands (Page et al. 2008). At present little is known about the techniques and technologies required for the restoration of large areas of degraded tropical peatlands. It is not appropriate to transfer knowledge acquired from the restoration of northern peatlands directly to tropical peatland situations, because they differ in some important respects, especially climate and peat forming vegetation. Owing to an open pore structure that results from the hemic and fibric remains of trees, tropical peat has a very high hydraulic conductivity (Silvius et al. 1984).

There are enormous challenges for the restoration of tropical peatlands, especially of completely deforested areas, because fires not only destroy the above-ground biomass but also penetrate into the underlying peat. As a consequence, huge amounts of carbon dioxide and particulate matter are released; the hydrology is impaired through loss of the water regulation functions of the near-surface peat layer, resulting in floods; subsidence of the peat surface occurs; seed banks and tree bases for vegetation re-establishment are lost; and human health and livelihoods are damaged through loss of natural resources and high levels of air pollution. Therefore, peatland rehabilitation needs to address several tasks: 1) reinstatement of carbon sequestration and storage, 2) restoration of hydrology, 3) restoration of vegetation cover to protect the peat soil from direct sunlight and to reduce water streams at the surface level, and 4) promotion of sustainable livelihoods for local communities.

Restoration of the hydrological functions is a pre-requisite for the establishment of a positive or, at least, neutral peatland carbon balance and for the re-establishment of forest vegetation (Page et al. 2008). Complete rewetting is the only way to prevent the problems of peat decomposition, soil subsidence and annual fires. Their predominant dependence on groundwater level shows that rewetting drained tropical peat soils will lead to large reductions of carbon dioxide emissions (Couwenberg et al. 2009). In practice, this means damming drainage canals and thus raising the water level of the surrounding peatland. The dam construction must be designed to cope with the high hydraulic conductivity (Wösten and Ritzema 2001) and low load bearing capacity (Salmah 1992) of tropical peat. The dams mainly act as barriers to prevent the water flow but cannot store water for long periods because it seeps away through the surrounding peat. Dams built in large drainage canals like in the MRP area in Central Kalimantan (Fig. 4) must withstand enormous pressure while standing in the very soft peat soils (CKPP 2008). For small canals (about 2 m wide), as those used for extracting illegal timber, simple dams made of locally available material can be constructed, which is a low cost but effective method of raising upstream water levels (Page et al. 2008) (Fig. 4). Studies of the effect of peat dams on water flow have demonstrated that a cascade of closely spaced dams is most effective for water control, with the distance between the dams dependent on the gradient of the peat dome (Wösten and Ritzema 2001; Beekman 2006). To increase the resistance of large dams trees are planted on and behind them. Furthermore, reduced water flow in the canals allows sedimentation of organic and mineral material upstream of the dam which in turn facilitates the re-growing of vegetation and eventually the dams should become redundant. Hydrological restoration by dam construction is not only a technical but also a social challenge. As drainage canals are often used for navigation and transportation, dam construction can provoke opposition from local communities. Many communities are hardly aware of the role of drainage in creating the conditions for fires and land subsidence, which would eventually destroy their lives. Therefore, the local communities must be involved in the dam planning, construction and maintenance. In the long term, a sustainable source of income must be provided as an alternative to logging and drainage-dependent agriculture. Within the Central Kalimantan Peatlands Project (CKPP 2008) local people were supported to establish fish ponds behind the dams in drainage canals, set up nurseries and plant commercial crops that do not need drainage, such as rubber and peat swamp hardwood species.

Funding obtained from intact peatlands through REDD (Reducing Emissions from Deforestation and Degradation) mechanisms and carbon crediting could also be used to improve the livelihoods of the local people. Increased awareness of the current large scale degradation of tropical peatlands by drainage and associated fires releasing significant amounts of the greenhouse gas CO_2 promotes interest in these alternative funding systems. Currently, emissions due to peatland loss (and forests) do not fall under the Kyoto emission reduction agreements, however, the 2007 UNFCCC summit agreed to address loss of forests and their associated carbon stocks, like peat soils in developing countries in the decision on REDD. Incentives to reduce emissions from deforestation and degradation of tropical peatlands need to be developed, which requires pilot and demonstration projects. The Australian Department of Climate Change and the Australian Government's overseas aid program (AusAID) have committed AU$30 million over four years to the Kalimantan Forests and Climate Partnership (KFCP). Under the KFCP, Australia and Indonesia are working together to develop and implement a large-scale REDD demonstration activity in Central Kalimantan which is based on the Netherlands-funded CKPP initiated in December 2005. These projects include the cooperation of international Non-Governmental Organisations (NGO) for conservation and poverty relief, like the World Wide Fund for Nature (WWF), Wetlands International, CARE International, the Borneo Orangutan Survival Foundation (BOS) and the University of Palangka Raya (UNPAR). Furthermore, WWF has been working in Riau province, Sumatra, since 1999 and is developing a pilot "Avoided Deforestation" carbon project in association with Jikalahari, a local NGO, to preserve one of the last remaining natural peat swamp forests on the Kampar Peninsula (Uryu 2007). Preserving tropical peatlands as part of a carbon offset business may be more lucrative for landowners than conversion to palm oil, or such business could generate funding to compensate opportunity costs of sustainable plantation development in already degraded areas (Silvius and Diemont 2007). To be tradable under REDD or other mechanisms, including the voluntary carbon market, carbon dioxide emission reductions, e.g. from peatland rewetting and fire prevention, must use result-based and transparent methods for baseline setting and monitoring of the emissions to allow third party verification of the reductions (UNFCCC 2007).

Fig. 4 Left: Large dam constructed in a canal in the Mega Rice Project area (© Wageningen UR). Right: Example of a small dam in an illegal logging canal in the Sebangau peatland, Central Kalimantan, using locally available materials (© WWF Indonesia - Sebangau Project).

2 The use of remote sensing data for monitoring Indonesian peatlands

Peatland restoration and conservation of the remaining peat swamp forests in Indonesia requires exact and detailed knowledge about their status and current extent. Field studies show severe restrictions, as only punctual data can be obtained. In situ data collection is limited because dense vegetation cover and wet soils make peatland access difficult (Page et al. 2002). Therefore, field work in tropical peatlands is laborious, time-consuming and cost-intensive and global positioning system (GPS) recordings are often inaccurate due to dense forest cover hampering the GPS receiver. Remote sensing allows peatland monitoring on a regional to national scale and spaceborne satellite imagery is available in a repetitive and cost-efficient manner.

The principle of remote sensing is to detect electromagnetic energy reflected from objects on the earth's surface by various sensors. Visible light is only one form of electromagnetic energy. Radio waves, microwaves, infrared (IR) and ultraviolet (UV) rays are other forms and only differ in their wavelength. The sensors can be summarised as active and passive systems (Lillesand and Kiefer 1994). While active systems, such as radar and Lidar, supply their own source of energy to illuminate features of interest, passive systems sense naturally available energy. All satellite remote sensing systems are characterised by their spatial, temporal and spectral resolution. The spatial resolution determines the pixel size in the recorded image ranging from about 0.5 m to 1 km, the temporal resolution is the revisit time of a satellite overpass (hours to days), and the spectral resolution refers to the wavelength bandwidth and the associated number of spectral bands recorded (1 to over 200). Widely used for peatland monitoring is imagery from passive satellite systems that operate within the optical spectrum which extends from 0.3 to 14 µm, including UV, visible, near-, mid-, and thermal IR wavelengths. Substantial peatland monitoring from space is also performed using radar systems which operate in the microwave portion of the spectrum (1 mm to 1 m wavelength). Optical and radar imagery both have their strengths and constraints regarding the monitoring and assessment of Indonesian peatlands. Most studies and projects benefit from using several optical and/or radar sensors.

2.1 Optical satellite data

The most known optical satellite program is the Landsat mission, operational since 1972. Landsat ETM+ imagery has a high spatial resolution (30 m), a repetition rate of 16 days, 8 spectral bands and is freely available. A combination of the bands 3, 4 and 5 (visible red, near-IR and mid-IR) has proven to be best for monitoring peat swamp forests and degraded peatlands (Fig. 5a). Page et al. (2002) used a combination of Landsat and ground survey data to estimate the extent of peatlands, pre-fire land cover types and burnt area after the severe 1997 El Niño event in the MRP area in Central Kalimantan. Landsat data analysis of the entire province of Riau showed that between 1982 and 2007 the forest cover declined by 4 million ha, of which 53% were cleared for palm oil and pulpwood plantations (Uryu et al. 2008). There is a severe stricture in monitoring temporal and spatial variability of Indonesia’s forests with passive remote sensing due to persistent cloud cover. By integrating the complementary characteristics of high spatial resolution Landsat data with medium/low resolution data (MODIS/AVHRR), that have a larger observational swath and an imaging rate of 1 to 2 days, Hansen et al. (2009) were able to compare rates of forest clearing in Indonesia for two epochs, 1990-2000 and 2000-2005.

Independent from day-light is the detection of active fires (fire hotspots) by thermal infrared (Fig. 6). Thermal IR bands (3-4 µm) e.g. onboard AVHRR, ATSR and MODIS are able to sense high temperature events (Cochrane 2003; Siegert et al. 2004; FIRMS

2009). Being on-board two satellites (Aqua and Terra), MODIS has a very high temporal resolution of 4 observations daily on the equator. During the El Niño in the year 2006 a total of 53,093 fire hotspots were detected in Borneo, of which 34% occurred in swamp forests (mainly peat swamp) (Langner et al. 2009).

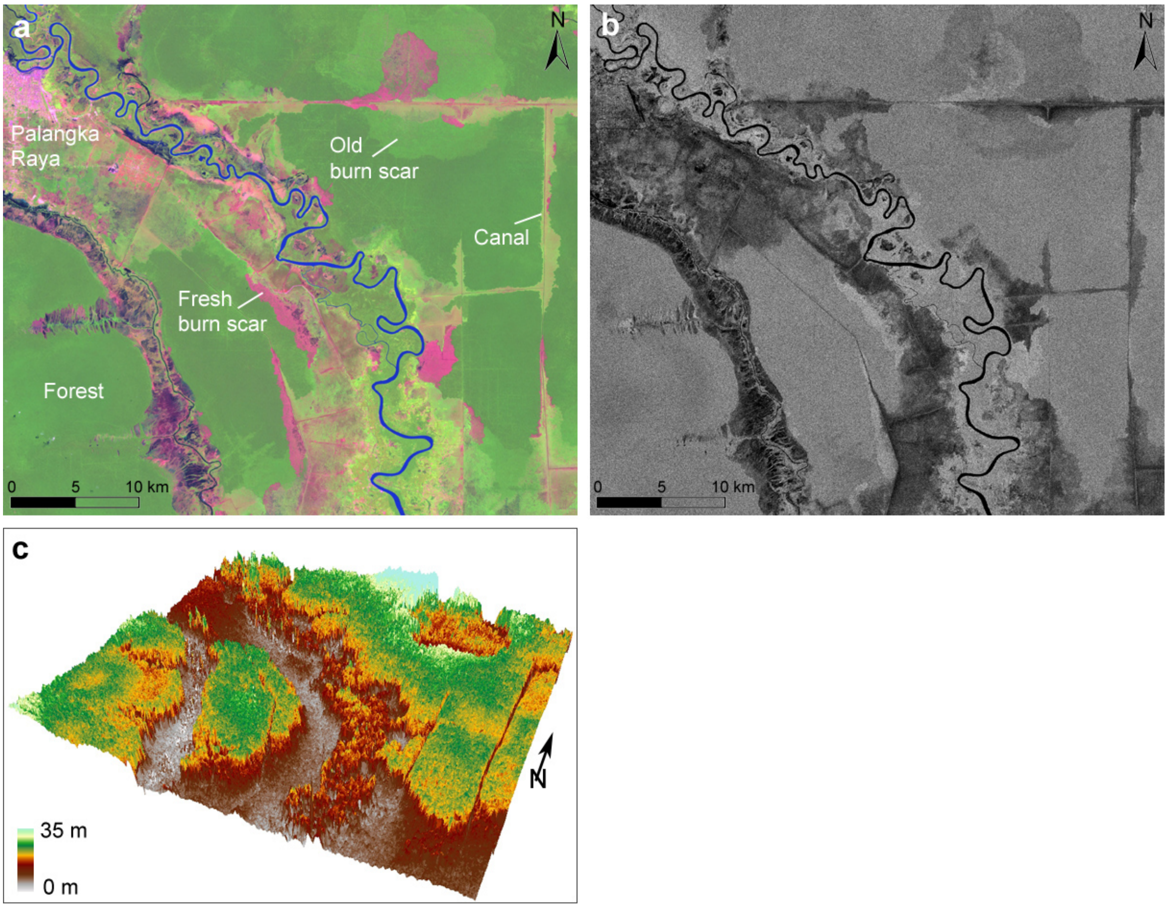

Fig. 5 Comparison of an optical (a) and radar (b) satellite image and SRTM topographic data (c). Shown is part of the MRP area south east of the city of Palangka Raya, Central Kalimantan. (a) is a Landsat image acquired on 5 August 2007, displayed in bands 3, 4 and 5; buildings and fresh burn scars (bare soil) appear in red, old burn scar (re-growth) in light green and peat swamp forest in dark green. (b) shows a PALSAR L-band scene from 24 August 2007 in HV polarisation; as higher the radar backscatter the brighter an object appears. The SRTM image (c), acquired in February 2000, is displayed in 3D with a vertical exaggeration of 200; burn scars, rivers and canals clearly contrast with the peat swamp forest canopy.

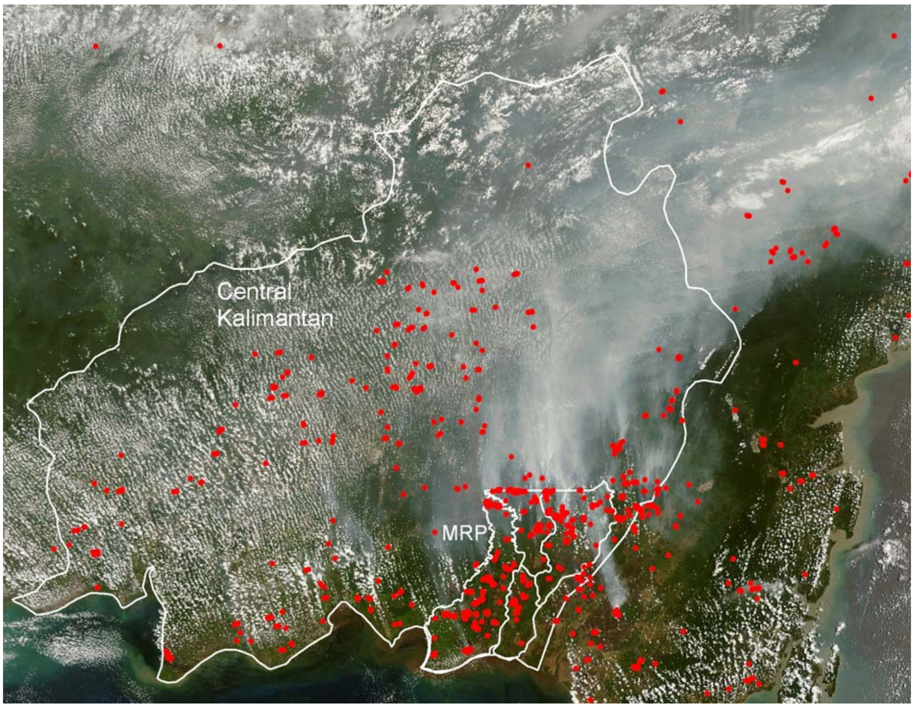

Fig. 6 Fire hotspots detected on 20 September 2009 (2:40 and 5:40 am) by the MODIS thermal IR sensor are superimposed on a MODIS visible image acquired on the same day at 1:30 pm. Fires occur mainly in the severely degraded peatlands of the MRP area in Central Kalimantan and produce dense haze spreading north east.

2.2 Radar satellite data

Operational radar remote sensing from space started in the early 1990s and thus is relatively young. Being an active system, radar sensing is day-light independent and able to penetrate clouds and haze, and therefore of high interest for monitoring the Indonesian peatlands. However, due to limited data availability and because radar imagery is more difficult to interpret than optical data only few studies using radar imagery for tropical peatland monitoring have been published so far (Siegert and Ruecker 2000; Siegert et al. 2001; Hoekman 2007; CKPP 2008). Figure 5b, an image of the MRP area acquired by the Japanese radar sensor PALSAR, shows the typical speckle or “salt and pepper effect” inherent to radar imagery. This seemingly random pattern of brighter and darker pixels is produced by the microwave signals being in or out of phase by varying degrees when received by the sensor, after returning from a given location on the earth’s surface (Lillesand and Kiefer 1994). The two primary factors influencing the characteristics of radar signals are the wavelength and the polarisation of the energy pulse used. Radar systems usually include only one spectral band producing black and white imagery. The most common wavelength bands used for land cover monitoring are the X-band (2.4-3.75 cm), the C-band (3.75-7.5 cm) and the L-band (15-30 cm). The longer the wavelength, the more the radar signal can penetrate a forest canopy or dry soil layer. Irrespective of wavelength, radar signals can be transmitted and/or received in different modes of polarisation, i.e. in either a horizontal (H) or a vertical (V) plane. Since objects modify the polarisation to varying degrees, the polarisation mode influences how the objects look on the resulting imagery. Furthermore, the shape, orientation and roughness of objects must be considered when evaluating radar returns. The side looking radar system receives no energy back from a smooth surface like a lake, which therefore appears black in the image. The intensity of radar returns is also determined by the dielectric properties of terrain features. In the microwave region of the spectrum, water has a dielectric constant that is up to 25 times higher than of most natural materials, therefore the presence of moisture in either soil or vegetation can significantly increase radar reflectivity (Ulaby et al. 1986). These characteristics were used to map areas of burnt forests in Kalimantan and to assess the level of fire damage (Siegert and Ruecker 2000; Siegert et al. 2001). Hoekman (2007) shows that continuous radar observations are very useful for determining and mapping certain degrees of tropical peatland damage following the construction of drainage canals.

2.3 Topographic data

Knowledge of the elevation and topography of peat domes is essential for hydrological restoration (Wösten et al. 2008). Topographic mapping of the earth's land surface is possible with radar systems. Imaging radar interferometry is based on analysis of the phase of the radar signals as received by two antennas located at different positions in space (Lillesand and Kiefer 1994). Knowing the geometry of the line between the two antennas (interferometric baseline) with a high degree of accuracy, the phase difference of the received signals is used to compute the elevation of a specific point. By means of these data, a three dimensional digital elevation model (DEM) of the earth's surface can be generated. Launched in February 2000, the Shuttle Radar Topography Mission (SRTM), a joint project of the National Imagery and Mapping Agency (NIMA) and NASA, collected radar inteferometry data from 60°N to 56°S latitude. A DEM was produced with a spatial resolution of 90 m horizontally and 1 m vertically, and is available without expense. Figure 5c shows a SRTM elevation model of degraded peat swamp forest; drainage canals and burn scars clearly contrast with the forest canopy.

Much higher accuracies can be achieved using light detection and ranging (Lidar) aerial remote sensing. Lidar systems radiate pulses of laser light to the terrain and measure the time delay between pulse transmission and recording of the return signal. Using aircraft and ground based GPS, relative and absolute surface heights can be determined with an accuracy of several centimetres. Lidar data, acquired in August 2007 in Central Kalimantan, allows for burn scar depth determination in peatlands and consequently estimates of the carbon released (Ballhorn et al. 2009). However, Lidar data is very expensive to obtain and limited to some kilometres in length and about 0.4 km in width, depending on the flight stripes of the aircraft and the project budget.

3 Objectives of this thesis

In view of the ongoing discussions on climate warming, conservation and rehabilitation of the tropical peatlands in Indonesia are very important tasks (Hooijer et al. 2006; Uryu et al. 2008; CKPP 2008; Van der Werf et al. 2009). Huge amounts of the greenhouse gas CO_2 have already been released due to peatland degradation, and the remaining peat swamp forests are highly threatened by human activities. Currently, massive pressure on peatland conversion to palm oil plantations is being generated by an increasing demand for biofuel in Europe and the US. Scientists forecast that natural peat swamp forests will disappear from Sumatra soon after 2010 and from Kalimantan around 2020 (World Bank 2001). To show the importance of peatland preservation in controlling global climatic change, it is essential to know how much peat carbon is still stored. Estimating the carbon storage in Indonesian peatlands by using remote sensing data, field measurements and 3D modelling techniques is the objective of chapter II. Major improvements compared to previous estimates are obtained from consideration of the dome shaped appearance of peatlands by using SRTM elevation data and a more accurate assessment of peat dome extent. International action must be taken to help Indonesia to better conserve their peat resources through forest conservation and improved water management. A growing voluntary carbon market and REDD pilot projects yield financial support for tropical peatland restoration and conservation. Carbon trading needs repeatable, transparent and cost-effective methods to mitigate carbon dioxide emissions. Such a method is developed in the study of chapter III by planning hydrological restoration of disturbed tropical peatlands. The target area is the Sebangau peat dome in Central Kalimantan which is suffering from serious drainage due to the construction of hundreds of canals by illegal loggers. Being covered with dense peat swamp forest, an in situ assessment of the entire hydrology of Sebangau peat dome is impossible. Therefore, a combination of field inventory, remote sensing and topographic and hydrological modelling is used to determine the optimal number and location of dams required for a rise of the groundwater level, which eventually leads to a reduction of CO_2 emissions. In chapter IV a time series of radar satellite images is used to monitor the effects of tropical peatland restoration by canal blocking. In contrast to in situ measurements, this approach has the advantage of being cost- and time-efficient, continuous and applicable to large areas. Change detection analysis is applied and based on radar backscatter being sensitive to changes in the moisture content of peat soils and vegetation. The large size dams monitored in this study are located in the MRP area in Central Kalimantan. The overall aim of this thesis is to create a basis for large-scale peatland rehabilitation in Indonesia by using innovative modelling and remote sensing techniques. The driving factor for tropical peatland restoration and conservation measures can be the carbon trading market. However, such projects must be accompanied by poverty relief for local communities and sustainable plantation management in order to persistently mitigate carbon dioxide emissions of global significance.

CHAPTER II

Determination of the amount of carbon stored in Indonesian peatlands

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Abstract

Extensive peatlands in Indonesia are a major store of carbon. Deforestation, conversion to other land uses, especially plantations of oil palm and pulpwood trees, and recurrent fires have recently caused the release of large amounts of this carbon to the atmosphere. If these large emissions from degrading peatlands are taken into account Indonesia is one of the largest emitters of CO_2 worldwide. To improve estimates of the amount of carbon stored in Indonesian peatlands we applied 3D modelling based on the combined analysis of satellite imagery (Landsat ETM+, SRTM) and 750 in situ peat thickness measurements. We demonstrate that SRTM radar data can be used to determine the extent and topography of the dome shaped surface of a selection of peatlands in Central Kalimantan, South Sumatra and West Papua. A strong correlation was obtained between the convex peat dome surface and the underlying mineral ground, which was used to calculate the peat volume and carbon store. Conservatively, we estimate that at least 55±10 Gt of carbon are stored in Indonesia's peatlands. This amount is higher than previous results published because it takes into account the biconvex nature of the tropical peatlands. With this huge carbon storage and the current rate of degradation the tropical peatlands of Indonesia have the power to negatively influence the global climate.

Keywords: Carbon storage; Climate change; Indonesia; Spatial modelling; Tropical peat

1 Introduction

Peat consists of dead, incompletely decomposed plant material that has accumulated over thousands of years in waterlogged environments that lack oxygen. Consequently, peatlands act as sinks and stores of huge amounts of carbon. Within the context of the ongoing discussions concerning climate change there has been an increased interest in tropical peatlands because of their importance as carbon stores and their role in carbon fluxes between the earth's surface and the atmosphere (Uryu et al. 2008; Hooijer et al. 2006; Rieley and Page 2005). All over the world, however, the CO_2 sequestering function of peatland ecosystems is threatened by drainage and land use change that leads to organic matter oxidation and increased emission of greenhouse gases. This problem is particularly acute at the present time on tropical peatland in Southeast Asia where fires on natural and degraded peatlands result in a rapid release of large amounts of CO_2 to the atmosphere contributing to global climate change processes (Page et al. 2002). Recent climate model simulations suggest there will be a rise in mean global surface air temperature by about 0.2 °C per decade over future decades owing to the increasing concentrations of greenhouse gases (mainly CO_2) in the atmosphere, resulting primarily from fossil fuel use and land use changes (IPCC 2007). Therefore, recognition of tropical peatlands, monitoring impacts upon them and restoring degraded peatlands to as near their former natural condition as possible are not only of regional but also of global importance.

In Indonesia tropical peatlands cover almost 10% of the land surface mostly at low altitudes in coastal and sub-coastal areas on the islands of Sumatra, Borneo (Kalimantan) and New Guinea (West Papua, Papua) (Rieley et al. 1996a) with estimates ranging from16.8 to 27.0 million ha (Page & Banks 2007). With peat thickness of up to 20 m (e.g. Whitten et al. 1987; Page et al. 1999), the Indonesian peatlands are one of the largest near-surface reserves of terrestrial organic carbon. Radiocarbon dating suggests that some sub-coastal peatlands on the Indonesian island of Borneo started to accumulate around 26,000 years ago while coastal peatlands commenced their development only between 6000 and 2000 years BP (Page et al. 2004; Sieffermann et al. 1988; Neuzil 1997). Similar age data have been recorded for the island of Sumatra (Neuzil 1997; Giesen 2004). Initially, all these peat deposits were covered with pristine peat swamp forest but, as a result of economic development during the past two decades, they have been subjected to intensive logging, drainage and conversion to plantation estates (e.g. Rieley et al. 1996b; Rieley and Page 2005), especially of oil palm in Sumatra. In Central Kalimantan, Borneo, the failed Mega Rice Project (MRP), a resettlement project initiated in 1995, disrupted the peatland ecosystem over an area of more than 1 million ha. Drainage canals up to 30 m wide were constructed for a combined length of approximately 4500 km.

Under natural circumstances peatland fires are extremely rare but, when damaged by logging and drainage, peatlands become susceptible to fire. Fires are most severe during El Niño periods, as in 1997/98 when about 2.4-6.8 million ha of peatlands burnt in Indonesia (Page et al. 2002). Furthermore, peatlands burnt once are more likely to burn again (Siegert et al. 2001; Cochrane 2003; Langner et al. 2007). This positive feedback cycle leads to progressive forest degradation and continuous release of CO_2. After the severe El Niño event of 1997/98, fires reoccurred in Indonesia in 2002 and 2006. During the prolonged drought in 2006, 40,601 fire hotspots were detected by the MODIS satellite sensor on Indonesian peatlands (FIRMS 2006). Hooijer et al. (2006) estimated the annual CO_2 emissions from peatland fires in Indonesia over the ten year period from 1997 to 2006 to be 1.4-4.3 Gt, which is equivalent to 19-60% of mean annual global carbon emissions from fossil fuels. Thus, the role of Indonesian peatlands has changed from being a CO_2 sink to a source.

In view of the on-going discussions on climate warming it is important to know how much peat carbon is still stored in Indonesia’s peatland. In this study we improve the current estimates of carbon storage in Indonesian peatlands by using satellite derived terrain measurements, in situ peat thickness measurements and GIS modelling techniques. Remote sensing data are combined with ground measurements in order to delineate peat domes, calculate peat volumes and estimate carbon storage. 750 peat thickness measurements were inserted into a 3D model and used for verification. Representative peat domes on the three major Indonesian islands of Sumatra, Borneo and Papua New Guinea were selected for the modelling process and carbon storage was extrapolated to the whole of Indonesia. Major improvements compared to previous estimates are obtained from the integration of a digital elevation model (SRTM), consideration of the dome shaped appearance of peatlands and a more accurate assessment of the area of peat covered landscapes.

2 Study area, materials and methods

2.1. Study area

Several Indonesian lowland peat domes were chosen for 3D modelling (Fig. 1): two in South Sumatra (*Airsugihan* and *Telukpulai*), three in Central Kalimantan (*Sebangau*, *Block B* and *Block C*) and one in West Papua (*Teminabuan*). These peat domes differ in area from 188 to 7347 km². The sites in Central Kalimantan and South Sumatra were selected because of their representative character and availability of peat thickness measurements. *Teminabuan* was chosen in order to extend the geographical range of the study and include another type of Indonesian peat dome in the modelling process. In common with most Indonesian peatlands these peat domes are ombrogenous, i.e. subjected to rainfall only as their source of water and plant nutrients. Their surface towards the centre is elevated above their margins as a result of the accumulation of thick deposits of peat over several thousands of years. Maps of the distribution of peatland in Indonesia indicate that peat thickness ranges mainly from 0.5 to 10 m (Wetlands International 2003; 2004; 2006). According to various peat thickness classifications >3 m is considered to be deep, while 0.5 m is the minimum thickness used in the Indonesian system of peat classification (Radjagukguk 1997; Rieley and Page 2005).

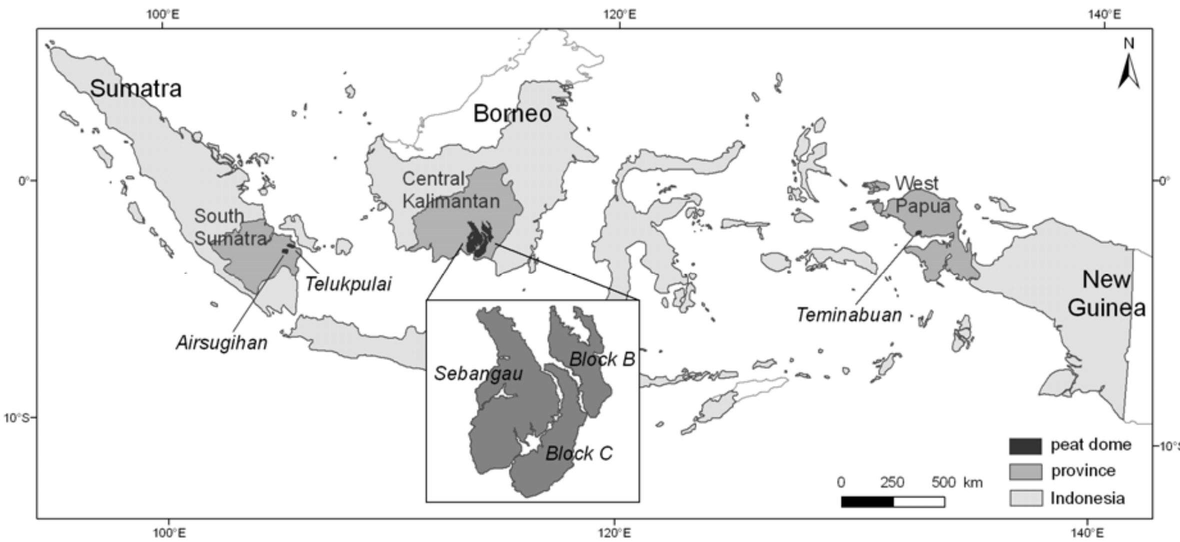

Fig. 1 Map of Indonesia showing the location of the peat domes investigated in the provinces of South Sumatra (Sumatra), Central Kalimantan (Borneo), and West Papua (New Guinea).

2.2 Field and remote sensing data

Ground measurements of peat thickness are essential to estimate the peat carbon store. Peat thickness data for 542 locations in South Sumatra and Central Kalimantan, obtained over the last four years were provided from two EU funded projects (SSFFMP[1] and RESTORPEAT[2]). These data were obtained using manually operated peat corers, at intervals of 500-2000 m. Owing to the difficulty of entering peat swamp forest, drillings were usually made adjacent to drainage channels and logging railways. In addition to these measurements, further 208 drillings from the *Telukpulai* peat dome, published on a map by the Indonesian Department of Mining and Energy (Geology and Peat distribution, sheet no. 1113-14, 2000), were provided by the SSFFMP project but only after the modelling process had been completed. These data, although they could not be included in the modelling process, were valuable for model verification. In addition to peat thickness the peat surface gradient was measured at some locations, both manually and by using an aircraft-borne laser sensor (Lidar).

Because peat drillings and surface measurements are difficult, time-consuming and expensive to obtain it was not possible to acquire field data for all of the vast area of Indonesia's peatland and therefore the use of remote sensing data was essential. Optical satellite images acquired by the Landsat ETM+ sensor and a Digital Elevation Model (DEM) generated from satellite radar data during the Shuttle Radar Topography Mission (SRTM)[3] were used for peat dome delineation and volume calculations. The dates of optical image acquisition were chosen close to the time of the SRTM mission in February 2000 in order to ensure maximum comparability of the land cover information captured by both sensor systems.

[1] SSFFMP: South Sumatra Forest Fire Management Project
[2] RESTORPEAT: Restoration of Tropical Peatland for Sustainable Management of Renewable Natural Resources
[3] Landsat and SRTM data available at: http://glcf.umiacs.umd.edu/data/srtm/

2.3 Peatland delineation

The extent of the peat domes investigated was determined by means of Landsat ETM+ and SRTM imagery, which show clearly the major rivers that form the boundaries of these peatlands (Fig. 2). The spatial resolution of the Landsat data is 30 m while the SRTM DEM has a spatial resolution of 90 m horizontal and 1 m vertical. Peat domes can be identified on the DEM because of their typically convex shaped surface. Due to its higher elevation above sea level the interior part of the peat dome is displayed in lighter shades of grey than the marginal areas. This interior part is referred to subsequently as *main peat dome* because peat thickness, volume and carbon store are all greatest there. Accurate delineation of the peat dome margin may require optical satellite images in addition to SRTM data. For example, the peat margin close to Palangka Raya can only be visually delineated on the optical Landsat ETM+ image (Fig. 2) because this feature cannot be identified in the SRTM image owing to similarity in elevations a.s.l. of the town and the neighbouring peatland that has been cleared of forest. With SRTM data it is possible to detect minimal elevation differences of 1-2 m over distances of 10-20 km in the Indonesian lowlands. However, in shallow peatland or plantations on peat the gradient of the peat dome can be too small to be detected on the SRTM image. In these cases, optical imagery should be employed to obtain a better view of peatland vegetation and other special features such as blackwater lakes and rivers. The SRTM elevation data were valuable for peatland detection at first hand, and thus many peat domes could be identified apart from the sites selected for volume modelling.

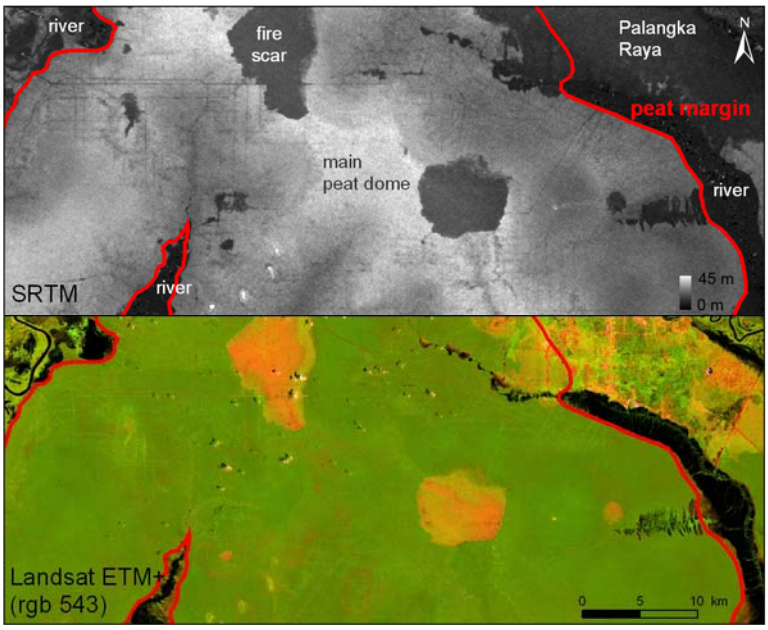

Fig. 2 Delineation of the *Sebangau* peat dome in Central Kalimantan by means of a DEM (SRTM) and a Landsat ETM+ image from 7 February 2000. The Landsat image is required in addition to SRTM data for detection of the peat margin (SRTM © USGS; Landsat © NASA).

2.4 Peat volume estimate

In order to estimate the amount of carbon stored in a peatland the volume of the peat dome must be determined. This is obtained by a combination of 3D modelling of the selected peat domes by means of remote sensing data, field obtained thickness data and spatial interpolation. Modelling is generally based on simplifications of nature and assumptions were made based upon known characteristics of tropical peatlands, namely that they (1) exhibit the typical dome shaped surface of ombrogenous peatlands and (2) have a biconvex cross-section resulting from their formation in more or less basin-shaped depressions in the landscape as well as different rates of peat accumulation in the centre of the dome compared to the margins (e.g. Rieley and Page 2005). In addition, it is assumed that the peat thickness along the peat dome margins is 0.5 m.

The peat volume determination was carried out in two modelling steps: (1) generation of a surface model and (2) modelling of the peat thickness. The surface models for each peat dome were derived from SRTM data and could be directly generated for peat domes without forest cover. Kriging interpolation in ArcGIS was used to generate a dome shaped peat surface model as indicated by the digital elevation data. The interpolation was conducted between surface grid points at intervals of 1000 m, which were extracted from the SRTM image. Whereas the SRTM data represents in deforested peat areas a Digital Terrain Model (DTM), i.e. bare-earth model, in forested areas it displays a so called Digital Surface Model (DSM) because the SRTM C-band sensor does not penetrate dense vegetation cover. Therefore, on forested peat domes the canopy had to be considered and spatial interpolation between deforested patches was applied. Different peat swamp forest types, which are known from field investigations to have different maximum canopy height depending on the local substrate conditions (Page et al. 1999), were also considered by analysing texture variations in the radar imagery and spectral information from Landsat ETM+ data. In order to verify results obtained from the SRTM modelling the peat domes derived were compared with in situ peat surface measurements and high resolution Lidar data.

The surface model, together with peat drilling data, formed the basis for modelling peat thickness. Since thickness data were not evenly distributed over the peat domes and were not available for all of them, correlation was used to provide the missing peat thickness information. Correlation functions between the peat surface and bedrock were derived for each peat dome using thickness data for *Block B*, *Block C*, *Sebangau* and *Airsugihan*. The correlation obtained for *Airsugihan* was applied to *Telukpulai* and *Teminabuan* peat domes because of their similar structure and size and location at the same elevation a.s.l. Strong correlation coefficients of $r>0.8$ were obtained between peat surface and peat thickness. Thus, peat thickness values were derived from SRTM data. Using these data together with a general peat thickness of 0.5 m along the dome’s margins a smooth Kriging interpolation was applied to generate peat thickness models. When generating the peat thickness models of *Block B*, *Block C* and *Sebangau*, however, a correction of the absolute elevations of each surface model was necessary before applying the correlation functions, because these elevations, given in metres above sea level, and peat thickness are correlated only if the peat dome is located on a plain. Whereas most Indonesian peatlands have been formed mainly on flat alluvium, the very northern parts of *Block B*, *Block C* and *Sebangau* are located on sloping sediments rocks. These additional elevations result in incorrect peat thicknesses and were thus subtracted from the surface models prior to thickness modelling. The bedrock of each peat dome was estimated using peat surface and thickness models. By subtracting the peat bedrock from the surface model using ArcGIS 3D Analyst the peat volume was calculated.

3 Results

3.1 Peat dome structure using SRTM data

The dome structure of Indonesian peatlands can be detected clearly using SRTM data. The vertical and horizontal accuracy of the elevation model proved to be adequate for the large tropical peatlands. SRTM elevation profiles were investigated over the whole of Indonesia and they reflect the predominant dome shaped appearance of the tropical peatlands with height differences of between 4 and 10 m from the margin to the top (Fig. 3 shows examples). This technique demonstrates that peat domes can be measured under three different conditions in an SRTM image: (1) deforested, (2) with forest fragments and (3) completely forest covered. Remnants of the forest canopy are visible because a C-Band radar sensor does not completely penetrate dense vegetation cover. A typical SRTM elevation profile of peat dome *Block C* in Central Kalimantan (Fig. 3a) is composed of remnant peat swamp forest 'islands' and large burnt areas (white and dark grey areas, respectively). A curved relationship was applied to the SRTM height data in order to remove small-scale surface roughness, which is inherent to radar images. The remnant forest patch shows a mean tree height of 10 m in the digital elevation model. This is not the real tree height but results from partial penetration of the radar signal into the forest canopy. A closed peat swamp forest canopy commonly has a maximum tree height of 35 m. One also has to keep in mind that the SRTM data is globally referenced, and thus absolute elevations (a.s.l.) differ by about 10 m (airport Palangka Raya) from real elevations in Indonesia. Since the peat swamp forest of *Telukpulai* was completely removed before SRTM acquisition in February 2000 the characteristic dome shaped peat surface is depicted directly by the SRTM data (Fig. 3b). A transect across *Teminabuan* in West Papua shows a third type of peat dome revealed by the SRTM sensor (Fig. 3c), which is covered almost entirely with peat swamp forest. Even so, the SRTM elevation profile reflects the dome shaped surface of the peat. These results show that the model assumption of a convex peat surface is correct, and that the dome-shape of Indonesia's peatlands should be taken into account when calculating peat volumes and hence estimating carbon storage.

Figure 4 shows the comparison of SRTM with in situ and Lidar data. Field surface measurements, derived with a sighting telescope, were available for *Block B* and *Block C* of the Ex Mega Rice Project area in Central Kalimantan (Fig. 4a,b,c). Along the Kalampangan Channel in *Block C* surface data obtained with a high resolution laser scanner (Lidar) was deployed by Kalteng Consultants in 2007 (Figure 4d). This comparison shows that the SRTM derived peat surface, especially the gradient, agrees very well with the field and Lidar measurements and supports the interpolation method applied to correct the SRTM data for forest height.

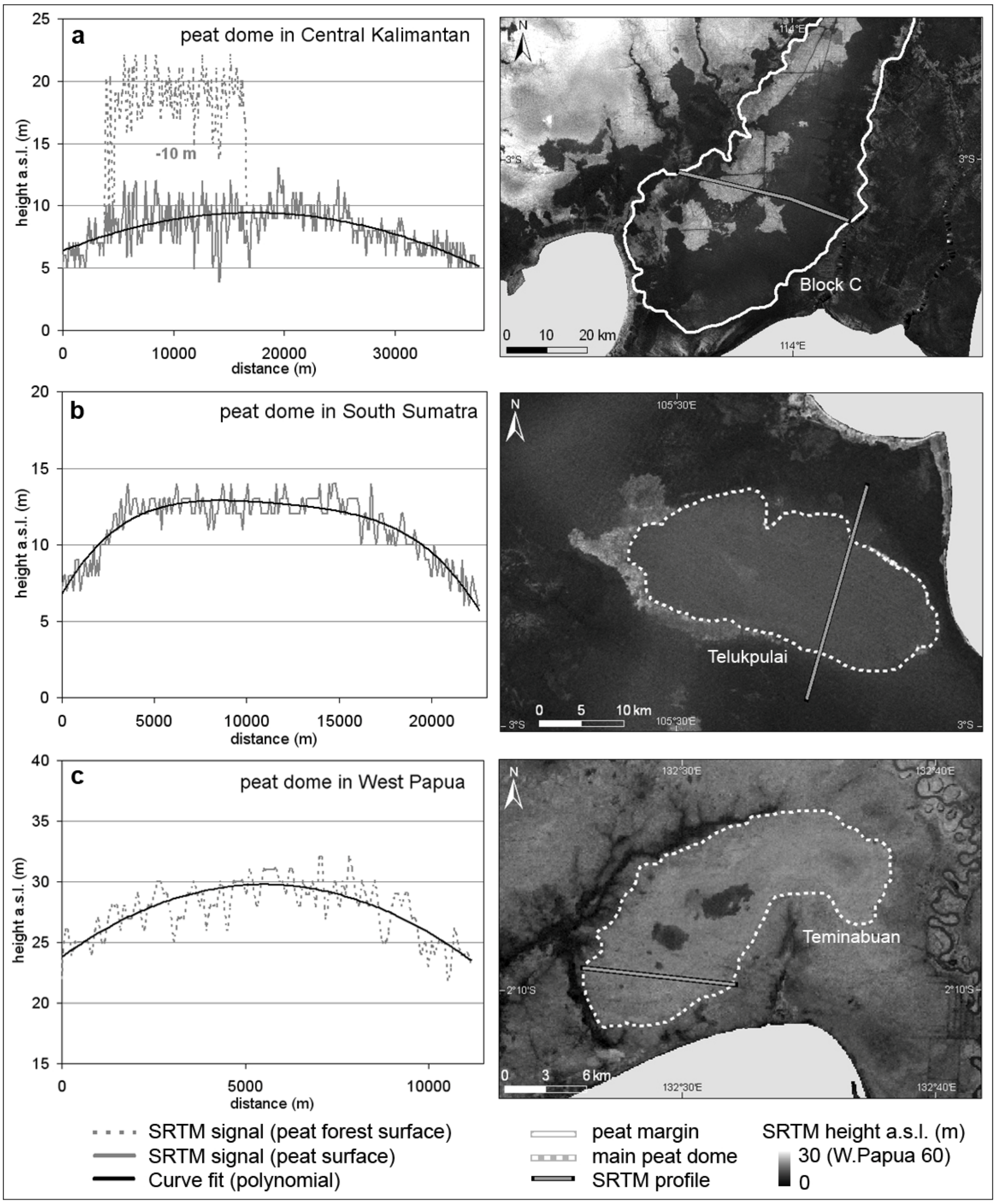

Fig. 3 SRTM elevation profiles of peat domes for the Indonesian provinces Central Kalimantan (a), South Sumatra (b) and West Papua (c). The SRTM data clearly show the characteristic dome shaped surface of ombrogenous peat (SRTM © USGS).

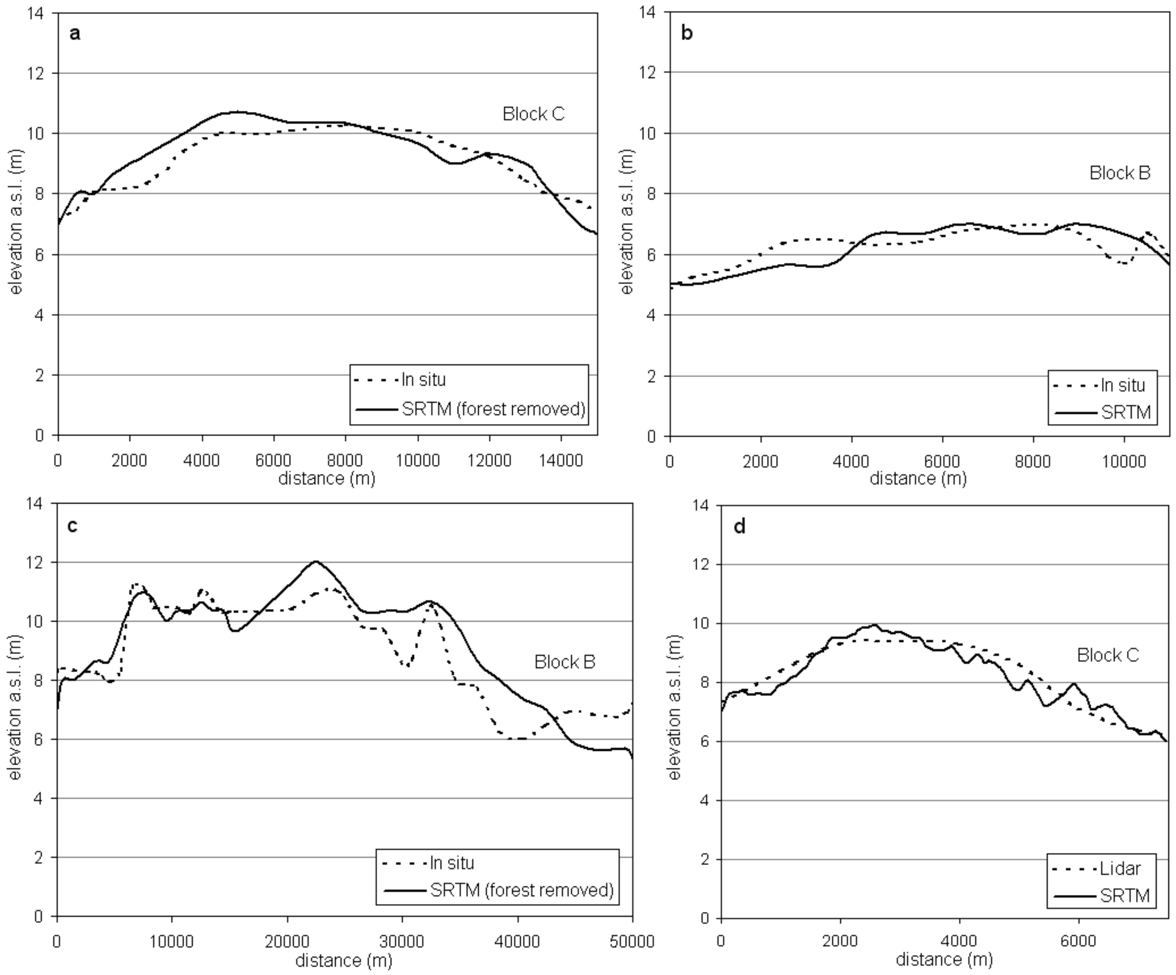

Fig. 4 A comparison of SRTM with in situ (a,b,c) and Lidar (d) peat surface measurements shows very good agreement. In (a) and (c) tree heights were subtracted from the SRTM data in order to reveal the peat surface. All data are referenced to the SRTM elevation a.s.l.

3.2 Carbon storage estimation

The result of the peat dome modelling in Central Kalimantan is shown in Figure 5. The modelled peat thicknesses for *Block B*, *Block C* and *Sebangau* peat domes range from 0.5 m at the margins to a maximum of 10.6 m in the centre of *Sebangau*. The maximum in situ thickness, determined by coring at approximately the same location, is 12.2 m. This ground-truthed value is only a single point measurement while the model result of 10.6 m represents the mean maximum value. For the *Sebangau* peat dome only a relatively small amount of 188 drilling measurements were available for a peatland area of 7347 km² although these show a good distribution over different peat thicknesses making them valuable for model confirmation. According to the model the greatest peat thickness occurs at the centre of each dome, which is characteristic of ombrotrophic peat deposits. The peat volumes for all peat domes modelled range from about 0.84 km^3 for the smallest *Teminabuan* (188 km^2 area) up to ca. 39.64 km^3 for *Sebangau* (Table 1). The volume mainly depends on the size and location of the peatland. Near the coast the peat layer is generally shallower. *Telukpulai* has a relatively large peat volume of ca. 2.25 km^3 compared to its area because only the central part of the dome was considered. Using the model, mean peat thicknesses of 3.65 m and 5.40 m were derived for *Block C* and *Sebangau*, respectively. The mean peat thickness of the *Telukpulai* dome calculated from the field data is 4.94 m, which compares favourably with the model value of 4.83 m.

After calculating peat dome volumes, the carbon storage can be estimated. The amount of carbon sequestered in peat depends on the carbon content, measured in %, and bulk density. Both values vary for different peat types. A dry bulk density of 0.1 g/cm^3 together with a carbon content of 58% can be regarded as an average for the tropical peat in Indonesia (e.g. Neuzil 1997; Shimada et al. 2001; Supardi et al. 1993). Assuming an average carbon content in tropical peat of 58 kg/m^3, it is estimated that there is total storage of 4.15 ± 0.89 Gt carbon in the selected Indonesian peat domes which cover a total area of 14,960 km^2 (Table 1). The margin of error results from comparison of the peat thickness models with in situ measurements. A mean deviation of the peat thickness was determined for each peat dome investigated and converted into a volume and carbon storage error, respectively. Maximum carbon storage error estimates range from 13% for *Telukpulai* to 25% for *Block C*. The large deviations result probably from bedrock unconformity, which is not taken into account in the model. About half of the in situ thickness values are larger than the model results, while the other half are smaller. This suggests that discontinuities in the mineral ground topography are balanced by spatial Kriging interpolation and thus the modelled volume results are close to reality.

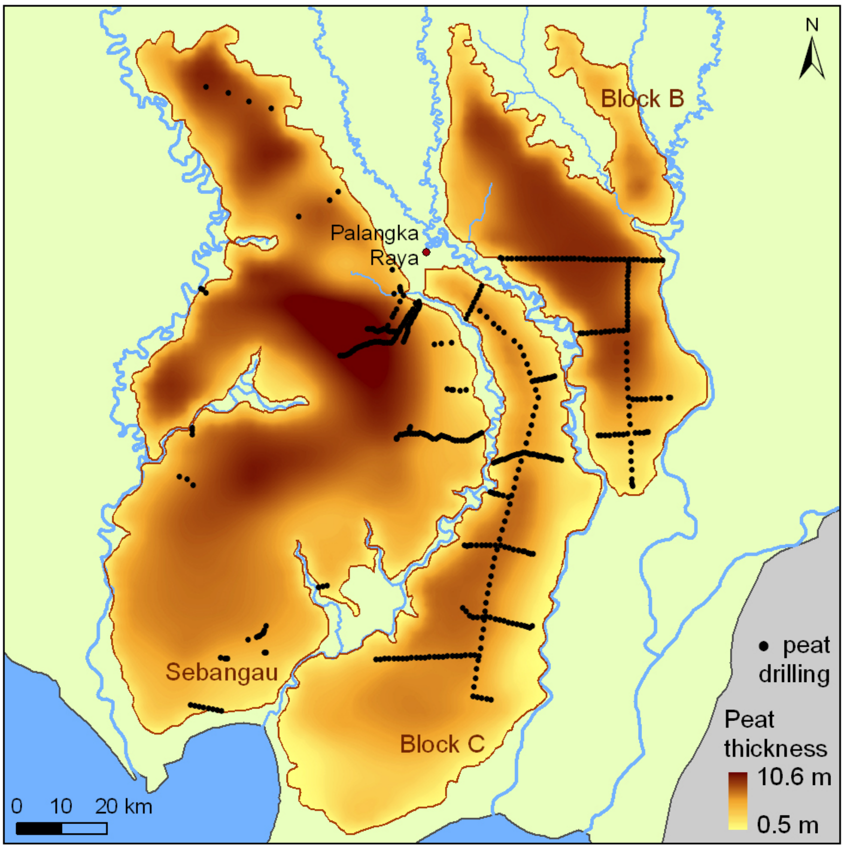

Fig. 5 Peat thickness model of selected peat domes in Central Kalimantan. Kriging interpolation was applied using 542 peat drilling values and a correlation function between the peat dome surface and peat thickness.

Table 1 Estimated volumes and carbon storage of selected peat domes in Indonesia

Peat dome	Area (km^2)	Drillings	Mean thickness (m)	Volume (km^3)	Carbon storage (Gt)
Airsugihan	503	77	3.68 ± 0.64	1.82 ± 0.32	0.11 ± 0.02
Telukpulai	470	-	4.83 ± 0.64	2.25 ± 0.30	0.13 ± 0.02
Teminabuan	188	-	4.52 ± 0.64	0.84 ± 0.12	0.05 ± 0.01
Block C	3614	172	3.65 ± 0.92	13.17 ± 3.32	0.76 ± 0.19
Block B	2838	105	4.90 ± 1.15	13.86 ± 3.26	0.80 ± 0.19
Sebangau	7347	188	5.40 ± 1.08	39.64 ± 7.93	2.30 ± 0.46
Total	14,960	542		71.58 ± 15.25	4.15 ± 0.89

3.3 Uncertainties in the modelling process and the predictions derived from it

There are uncertainties in the model volume calculation and hence carbon storage estimation that cannot be quantified directly. Systematic errors may result from the spatial resolution of the satellite data. There is a maximum displacement error of ±30 m for Landsat ETM+ data and ±90 m in horizontal and ±1 m in vertical direction for SRTM data. These uncertainties are very small, however, compared to the large area of the peatlands in Indonesia. Furthermore, random errors might be introduced by the analyst during mapping of the peat boundaries and generation of the surface model. Mistakes in the peat outline only cause small volume uncertainties because of relatively shallow peat thickness along the margins, and the SRTM forest correction should be verified by means of forest cleared areas as well as ground-truthing and high resolution Lidar data. Further uncertainties are introduced in the surface model and hence peat volume if the peatlands are located on sloping bedrock, which cannot be measured directly but derived from the regional geology and from SRTM elevation data.

The real shape of the bedrock remains to be the largest unknown in the modelling process. However, due to verification of each assumption and modelling step, error propagation could be minimised: (1) the surface model was verified with field and Lidar data, (2) the correlation function between peat surface and bedrock is based on 542 drilling measurements and (3) the peat thickness model was validated with additional field data from Sumatra.

4 Discussion

Even though a large number of 750 peat drilling measurements were available for this study, these data alone are insufficient to accurately estimate the amount of carbon stored in Indonesia’s peatlands. Additional analysis of remote sensing imagery, especially SRTM radar, was necessary to supplement the field data. Using SRTM elevation data it was possible to detect and characterize the dome shaped surface of the peatlands and then use this information to undertake 3D modelling of peat volumes. 3D modelling has the advantage of being more accurate than previous peat carbon storage estimations based on information provided by RePPProT (1990) and Wetlands International (2003; 2004; 2006) because it considers the dome shaped appearance of peatlands. Other improvements of this assessment are the collection of hundreds of peat thickness drillings in Sumatra and Central Kalimantan and an accurate delineation of the peatland area.

A direct comparison of the model calculations with the latest Wetlands International (WI) peat maps resulted in significant higher carbon storage estimations in this study (Table 2). On average, considering the 3D shape of the peat domes results in a peat volume that is 112% higher than the WI estimates. Reasons for this difference are a lower mean peat thickness by WI and a slight area underestimation of 10%. The WI maps are of different quality: Whereas in Central Kalimantan the volume estimates agree well with our measurements, in Sumatra they are underestimated by up to 3 times.

This first detailed remote sensing investigation, supported by a large number of ground measurements of representative peat domes of Central Kalimantan, South Sumatra and West Papua provides an estimate of the total carbon storage of Indonesian peatlands in the region of 55±10 Gt. The estimation is based on an average peat thickness of 4.5±0.85 m determined in the three study sites and the total peatland area of 21.1 million ha, given by Wetlands International. If considering the 10% area underestimation as suggested by the direct comparison with WI data even larger carbon storage is possible.

According to the latest IPCC[4] report (2007), during the last decade the global CO_2 concentration growth rate was 1.9 ppm per year on average resulting mainly from the emission of 7.2 Gt carbon per year due to fossil fuel use and approximately 1.6 Gt carbon per year due to land use change, to which the release of peat carbon contributes. A carbon store of 55 Gt has an enormous potential to negatively influence the global climate if the Indonesian peatlands are burnt and drained at rates currently observed. CO_2 is released by two processes, peat oxidation after drainage as it happens when plantations are established and peat combustion. Hooijer et al. (2006) estimate that in the order of 1.4-4.3 Gt is released by peat fires which occur every year during the dry season and result from land reclamation. Peat swamp forest becomes susceptible to fire because of illegal logging which occurs almost completely uncontrolled. Recently, the raised demand for biofuel in Europe and the US increased the pressure on the remaining peatlands in order to establish up to 500,000 ha of new palm oil plantations. Thus, tropical peatland devastation will

[4] IPCC: Intergovernmental Panel on Climate Change

continue to accelerate. A recent study published by WWF showed that while deforestation is decreasing in dryland forest of Riau, Sumatra due to depletion, it is accelerating in peat swamp forest (Uryu et al. 2008). Most studies dealing with climate change by land conversion only consider the above ground biomass, i.e. forest cover, deforestation and afforestation. However, the carbon content of the below ground biomass of tropical peatlands is 18.6 times higher than that of pristine peat swamp forest if considering a forest carbon content of 140.5 t/ha (Uryu et al. 2008) and an average peat thickness of 4.5 m. Therefore, there is an urgent demand for protection of remaining peatlands and restoration of disturbed peat ecosystems requiring substantial investments. Undisturbed tropical peatlands must be considered as a huge sink for carbon and potential source of CO_2 if not protected. CDM[5] and REDD[6] activities under the Kyoto Protocol might be appropriate measures to support these actions.

4.1 Transferability

The approach presented can also be used to estimate the amount of carbon stored in the tropical peatlands of the whole of Southeast Asia, which accounts to about 68% of the global peat area (Page and Banks 2007). Since three different types of tropical peat domes were investigated and field measurements of Sumatra and Kalimantan showed similar results, it is justified to transfer this approach. A preliminary assessment of peat domes in Malaysia and Brunei by means of SRTM data and peat thickness values taken from the literature (e.g. Anderson 1964) has shown that these peatlands are comparable in their structure to the Indonesian ones. Peatlands in Thailand, Vietnam and the Philippines have a different ecology and thus cannot be estimated with this modelling technique. In addition, they account only to 0.3-1.5% of the whole of the Southeast Asian peatland (Page and Banks 2007).

The study shows that SRTM data, which is available without costs and with little processing effort, is very suitable for large-scale investigations of tropical peatlands. In contrast, high resolution Lidar data is expensive and needs special processing, but is

[5] CDM: Clean Development Mechanism
[6] REDD: Reducing Emissions from Deforestation and Degradation

required when analysing small peat areas in mountainous regions like in Europe or when investigating single tropical peat domes in the framework of CDM projects. First results showed that with Lidar data it is possible to determine peat decomposition and subsidence of farmed and degraded peatlands in Central Kalimantan.

Table 2 Comparison of peat area and volume estimations of this study with data by Wetlands International (WI)

Peat dome	Area WI (km^2)	Difference (%)	Volume WI (km^3)	Difference (%)
Airsugihan	417	+21	0.61	+198
Telukpulai	470	0	0.71	+217
Teminabuan	188	0	0.47	+179
Block C	3,031	+19	13.77	-4
Block B	2,793	+2	8.26	+68
Sebangau	6,221	+18	35.55	+12
Average		+10		+112

Differences are based on WI values.

Acknowledgments

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CHAPTER III

Planning hydrological restoration of peatlands in Indonesia to mitigate carbon dioxide emissions

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Abstract

Extensive degradation of Indonesian peatlands by deforestation, drainage and recurrent fires causes release of huge amounts of peat soil carbon to the atmosphere. Construction of drainage canals is associated with conversion to other land uses, especially plantations of oil palm and pulpwood trees, and with widespread illegal logging to facilitate timber transport. A lowering of the groundwater level leads to an increase in oxidation and subsidence of peat. Therefore, the groundwater level is the main control on carbon dioxide emissions from peatlands. Restoring the peatland hydrology is the only way to prevent peat oxidation and mitigate CO_2 emissions. In this study we present a strategy for improved planning of rewetting measures by dam constructions. The study area is a vast peatland with limited accessibility in Central Kalimantan, Indonesia. Field inventory and remote sensing data are used to generate a detailed 3D model of the peat dome and a hydrological model predicts the rise in groundwater levels once dams have been constructed. Successful rewetting of a 590 km² large area of drained peat swamp forest could result in mitigated emissions of 1.4-1.6 Mt CO_2 yearly. This equates to 6% of the carbon dioxide emissions by civil aviation in the European Union in 2006 and can be achieved with relatively small

efforts and at low costs. The proposed methodology allows a detailed planning of hydrological restoration of peatlands with interesting impacts on carbon trading for the voluntary carbon market.

Keywords: Dam construction; drainage canal; groundwater level rise; hydrological modelling; illegal logging

1 Introduction

Of the tropical peatlands worldwide 70% are located in Southeast Asia, 22 million ha of these in coastal and sub-coastal regions on the islands of Sumatra, Borneo and West Papua in Indonesia (Page and Banks 2007). Tropical peat is an accumulation of partially decayed organic matter which has been formed over thousands of years in waterlogged environments that lack oxygen. In Indonesia peat deposits with up to 20 m in thickness store huge amounts of carbon (Whitten et al. 1987; Sorensen 1993; Jaenicke et al. 2008). Under undisturbed conditions, tropical peatlands are covered with peat swamp forests which comprise ecosystems with many endemic species and high biodiversity. Since the 1980s the Indonesian peatlands have been extensively logged, drained and converted to plantation estates as a result of economic development (Curran et al. 2004; Rieley and Page 2005; Hansen et al. 2009). In Southeast Asia 12 million ha of peatlands are currently deforested and drained, including over 1.5 million ha of tropical peat swamp forests in the Indonesian province of Central Kalimantan (Hooijer et al. 2006). Canals and ditches are not only built to control and lower the groundwater level for plantation operations and small-scale agriculture but also to facilitate access to peat swamp forests and to extract timber logs. The extent of these diverse canals and thus the impact on drainage depth varies. For example, the drainage depth of oil palm plantations in Sarawak, Malaysia, is -60 cm (Melling et al. 2005) whereas it is about -30 cm in farm fields in Central Kalimantan, Indonesia (Jauhiainen et al. 2004).

Once peat is drained, it oxidises due to microbial activity and releases stored carbon to the atmosphere as carbon dioxide. This ongoing rapid peat decomposition leads to the irreversible process of peatland subsidence. In developed peat, drainage depth is related to peat organic matter oxidation rates and peat subsidence (Wösten et al. 1997; Furukawa et al. 2005). On average 60% of peat subsidence is caused by oxidation and 40% by irreversible drying or shrinkage of the peat (Wösten et al. 1997). Lowering the groundwater level which naturally is close to the peat surface throughout the year while fluctuating with the intensity and frequency of rainfall, results in an increase in CO_2 emissions. In a recent review it is estimated that an increase of drainage depth by 10 cm results in the emission of about 9 t CO_2 $ha^{-1}a^{-1}$ (Couwenberg et al. 2009).

Another severe consequence of drainage is the occurrence of peat fires. Under natural circumstances peat consists of 90% water and 10% plant matter and hardly ever burns. However, if the groundwater level falls below a critical threshold of -40 cm, the dry peat surface becomes susceptible to fire (Takahashi et al. 2003; Usup et al. 2004; Wösten et al. 2008). Fires are most severe during El Niño events, as in 1997/98 when about 2.4-6.8 million ha of peatlands burnt in Indonesia releasing huge amounts of the greenhouse gas CO_2 (Page et al. 2002; Van der Werf et al. 2008). With a groundwater level at about -100 cm the burn depth was estimated to be 51 cm on average releasing up to 9.4 Gt of carbon dioxide in Indonesia (Page et al. 2002). The failed Mega Rice Project, a resettlement project initiated in 1995 in Central Kalimantan, contributed largely to this ecological devastation. Drainage canals, up to 30 m wide and 10 m deep, with a combined length of 4,500 km disrupted the peatland ecosystem over an area of more than 1 million ha. There exists a positive feedback of recurrent fires which leads to progressive forest degradation and continuous release of CO_2 with regional and global consequences for the environment and climate (Siegert et al. 2001; Cochrane 2003; Langner et al. 2007).

Complete rewetting is the only way to prevent fires and peat oxidation by microbial decomposition. Due to its high permeability peat acts as a sponge, i.e. it shrinks when dried and swells when rewetted, unless water contents fall below a threshold value at which irreversible drying occurs (Wösten et al. 2008). Therefore, one of the most important peatland restoration measures is blocking of drainage canals by dams and thus raising the groundwater level of the surrounding peatland. Damming activities performed in the former Mega Rice Project area, in Sebangau National Park and in Merang peatland of South Sumatra have shown that the water retention upstream of dams could be increased thereby decreasing peat desiccation during the dry season (Suryadiputra et al. 2005; CKPP 2008; Jauhiainen et al. 2008). Few rehabilitation attempts have been undertaken in the past

(Page et al. 2008), however, within the context of ongoing discussions concerning climate change tropical peatlands have now been recognised as major sources of greenhouse gas emissions (Rieley and Page 2005; Hooijer et al. 2006; Uryu et al. 2008). The carbon content of the peat soils in Indonesia is about 18 times higher than that of pristine peat swamp forest (Jaenicke et al. 2008). Therefore, peatland rehabilitation projects are of high interest for carbon trading on the voluntary carbon market. While peat oxidation causes continuous release of carbon dioxide, peat fires are the source of huge amounts of CO_2 emissions in short time. These emissions can be mitigated if peatland rewetting measures are implemented.

The objective of this study was the development of an efficient and cost-effective methodology to plan hydrological restoration of disturbed tropical peatlands. The study was conducted in the Sebangau catchment in Central Kalimantan under supervision of the World Wildlife Fund (WWF) aiming at mitigation of carbon dioxide emissions. The surface of tropical peat shows little slope; with gradients of only 0.2-1 m per kilometre in the centre they appear virtually flat (Page et al. 1999; Rieley and Page 2005). In addition, the Sebangau peat dome is covered with dense vegetation which makes an in situ assessment of the entire hydrology impossible. The proposed restoration programme comprises several steps: 1) planning: selection of locations best suited for effective restoration measures and dam construction, 2) hydrological modelling: predicting the effect of dams, 3) implementation: dam construction, 4) monitoring: monitoring the performance of dams in time. The methodology presented here for steps 1) and 2) builds on a combined approach of field inventory, remote sensing, geospatial analysis and 3D peat dome topography assessment as well as sophisticated hydrological modelling. Steps 3) and 4) are briefly discussed in section 4 and will remain as a future research topic.

2 Study area, materials and methods

2.1 Study area

The hydrological restoration project will be carried out in a 1,480 km² area of the Sebangau catchment which is located in the Indonesian province of Central Kalimantan on the island of Borneo (Fig. 1). The catchment is part of a 7,347 km² large peat dome which contains the largest remaining continuous area of dense peat swamp forest in Borneo and stores about 2.3 Gt of peat soil carbon (Jaenicke et al. 2008). The extent of the study area is defined by natural, hydrological borders, i.e. the Sebangau River to the east, tributary streams to the southwest and north and the highest elevation of the peat dome to the northwest. As most Indonesian peatlands the Sebangau peat dome is ombrogenous, i.e. rainfall is the only source of water and nutrients. Organic matter accumulation started around 26,000 years ago (Page et al. 2004). The climate of Central Kalimantan is determined by a dry season which usually begins in May and lasts until October and a wet season from November until April. Annual rainfall varies between 2000-4000 mm and is influenced by periodic El Niño events which cause a prolonged dry season. During the dry season the groundwater level in the peat drops as precipitation decreases. The Sebangau ecosystem is renowned for its high conservation value and important natural resource functions. Consequently, the Sebangau catchment was designated as National Park in 2004, also to protect the largest population in the world of the endangered Bornean orang-utan. Nevertheless, the Sebangau peat dome is suffering from serious drainage in recent years due to the construction of hundreds of canals by illegal loggers. Until 1997 timber concessions constructed thousands of kilometres of simple railway tracks to transport felled timber to the Sebangau River (Boehm and Siegert 2004). The concession companies removed their infrastructure equipment but illegal loggers excavated canals along the former railway tracks to enable timber transport (Fig. 2). Difficult access restricts the knowledge of the total number of canals in Sebangau peat dome to estimations by local fisherman and environmental organisations. In this study, field surveys were conducted to map all canals within two specific areas located in the eastern part of the peatland. Burn scars occurring on Landsat satellite imagery since 1997 as well as fire hotspots yearly detected by the MODIS satellite sensors (FIRMS 2009) demonstrate the negative impacts of canal drainage on the Sebangau peatland.

The eastern part of the Sebangau catchment was selected for hydrological restoration due to its vicinity to the city of Palangka Raya and its relative easy access via the Sebangau River and tributary streams. Two water sub-catchments, named after their main outlet rivers Bakung and Bangah, were identified for the project (Fig. 1). Outlet rivers give loggers access to the forest and thus most drainage canals start there. On the basis of a

Digital Terrain Model (DTM) the two catchments were delineated comprising a total area of 590 km². It is assumed that if all canals actually draining the peat within a specific catchment are blocked, it will be possible to permanently raise groundwater levels to the original situation in which groundwater levels are normally at or close to land surface.

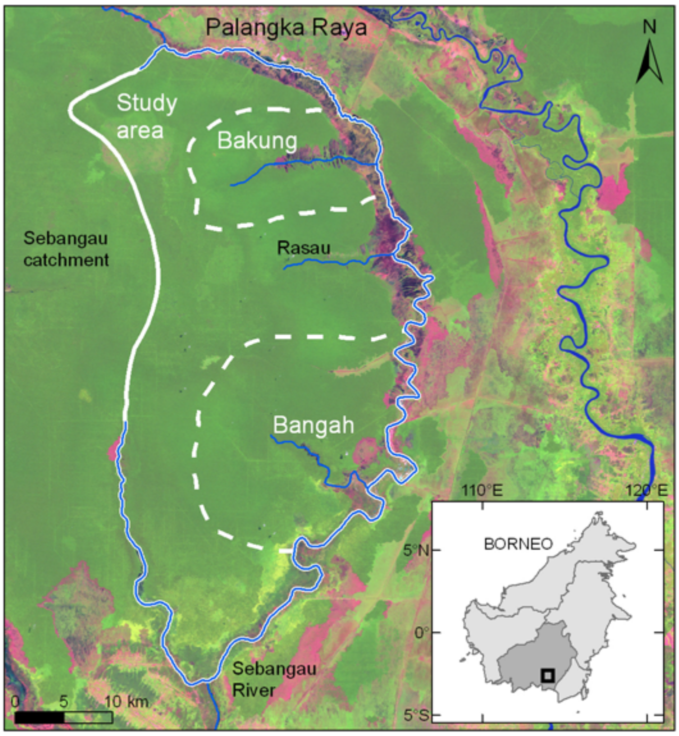

Fig. 1 Landsat ETM+ satellite image from August 2007 showing the study area located in Central Kalimantan on the island of Borneo, Indonesia. Dark green: peat swamp forest, red: fire scars in the year 2006.

Fig. 2 Typical drainage canal in the Sebangau catchment used to transport timber.

2.2 Remote sensing

Difficult access of tropical peat swamp forests and limited project funds, require the use of remote sensing data and modelling techniques in combination with field surveys of canal attributes. Optical satellite imagery from Landsat ETM+, SPOT HRVIR and ALOS AVNIR sensors, radar satellite data from the Shuttle Radar Topography Mission (SRTM) and high resolution airborne laser scanning data (Lidar) were used to: 1) generate a Digital Terrain Model (DTM) of the peat surface and determine peat thickness, and 2) localise drainage canals for hydrological modelling of groundwater levels. Hydrological modelling allows identification of areas with good restoration potential and helps to optimise the number and location of dams required for rewetting a specific area. Canal location, length, width, depth and slope as well as peat bulk density, hydraulic conductivity and the stratification by peat thickness are required parameters for the modelling.

Lidar (LIght Detection And Ranging) measurements were acquired in August 2007 for the northern part of the study area along a 34 km long and 0.4 km wide flight stripe running from west to east. Lidar systems are active, airborne remote sensing systems which radiate pulses of laser light to the terrain and measure the time delay between transmission of the pulse and measurement of the reflected signal by the sensor. The three dimensional clouds of points were differentiated into ground points and non-ground points reflected from vegetation. To extract ground points from vegetation points the terrain-adaptive bare earth filtering algorithm from Cloud Peak software was applied (Ballhorn et al. 2009). Lidar measurements allow assessing the terrain height beneath forests with unrivalled accuracy. The ground surface generated by airborne Laser data has a spatial resolution of 1 m. Lidar data were used to assess the peat dome topography across the Sebangau catchment and to validate the DTM generated for the study area.

The elevation of the DTM was calculated from SRTM imagery acquired in February 2000. Kriging interpolation in ArcGIS was used to generate a dome shaped peat surface model as indicated by the Lidar and SRTM data. For this surface grid points at 500-1000 m intervals extracted from the SRTM data, were interpolated. SRTM data represent in deforested peat areas a Digital Terrain Model (DTM), i.e. bare-earth model. However, in forested areas they display a so called Digital Surface Model (DSM) because the SRTM C-band radar sensor does not penetrate the dense peat swamp forest cover. The tree canopy height was estimated by means of deforested patches, like burn scars, rivers and canals. Different peat swamp forest types were identified by analysing their texture variations in the radar imagery in combination with spectral information from a Landsat ETM+ image also acquired in February 2000. The terrain model, together with peat drilling data, formed the basis for modelling peat thickness. Peat thickness drillings using manually operated peat corers are laborious and expensive. The limited terrain accessibility restricts these drillings usually to sites adjacent to drainage canals and along logging railway tracks. A total of 129 drilling measurements were available for the study area but not evenly distributed to directly apply spatial interpolation. Therefore, correlation was used to provide missing peat thickness information (Jaenicke et al. 2008). The correlation function makes use of a biconvex shape model typically for ombrogenous, tropical peatlands (Rieley and Page 2005; Jaenicke et al. 2008). A strong correlation coefficient of $r = 0.87$ was obtained between peat surface and peat thickness.

2.3 Hydrological modelling

For hydrological modelling, the physically-based SIMGRO (SIMulation of GROundwater flow and surface water levels) model was used to simulate water flow in the saturated zone, unsaturated zone, river channels and over the peat surface (Querner et al. 2008; Querner and Povilaitis 2009). Using the DTM and the watercourses map, delineations of the project area were determined with the hydrology extension in the GIS package ArcView. Saturated groundwater flow was modelled using the finite element method for which the model area was subdivided into triangular segments. The top of the mineral layer was set as aquifer bottom. Hydraulic conductivity of the peat is an essential element of hydrological modelling. In turn, the hydraulic conductivity and also the moisture retention relationship of the peat is strongly influenced by the degree of humification of the peat. Based on hydraulic conductivity measurements using the pumping test method as reported by Ong and Yogeswaran (1992) and by Takahashi and Yonetani (1997) the peat profile in this study is schematised in a two layer system consisting of a fibric to hemic peat top layer (0-1 m) with an average hydraulic transmissivity (cumulative thickness multiplied by conductivity) of 30 m^2 d^{-1} and a deeper, sapric peat layer with an average hydraulic transmissivity of 2.2 m^2 d^{-1}. While using these average values it should be realised that the relatively few measurements available for tropical peatlands show a considerable range. In addition, a peat water storage coefficient is required as a model input parameter. This coefficient was not measured directly but obtained in the model calibration process and set to 0.5 (Wösten et al. 2006). Groundwater levels calculated using both the original and calibrated model for the test site directly south of Palangka Raya (Fig. 1) are shown in Figure 3a. The correlation coefficient (R^2), the root mean square error (RMSE) and the mean square error (MSE) for the calibrated model are 0.74, 5.22 and 7.79 respectively. After calibration the model was validated and the results are shown in Figure 3b. The calibrated and validated model represents groundwater levels measured in a dip well at the test site with acceptable accuracy (within 0.10 m).

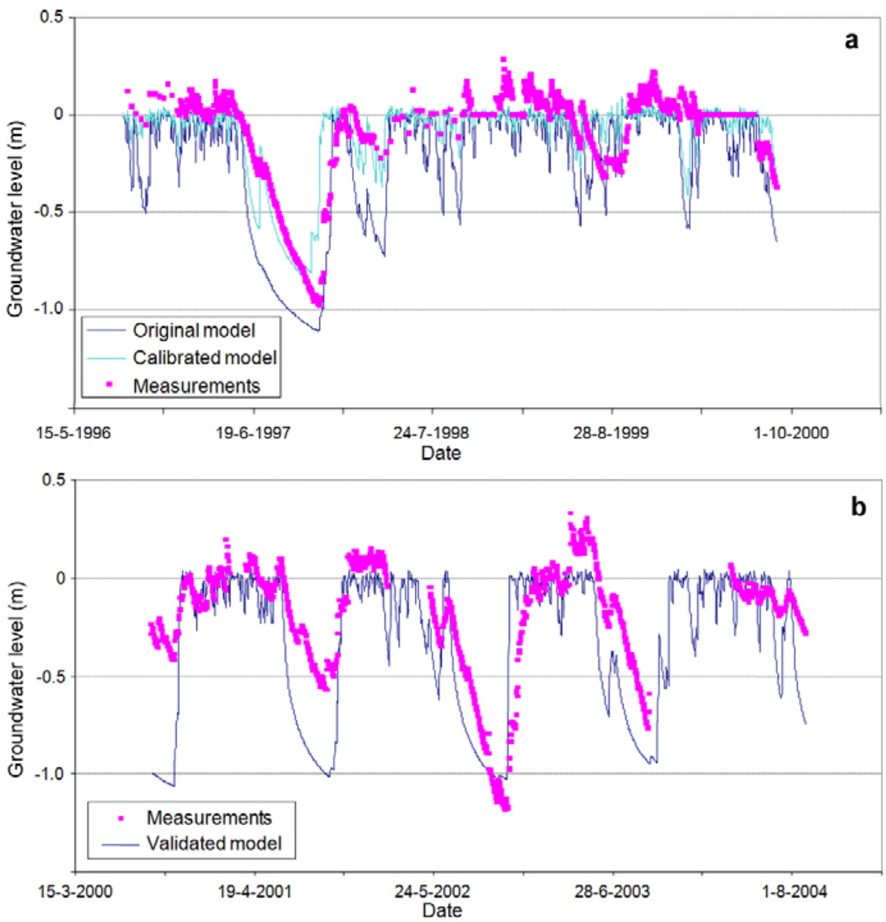

Fig. 3 Measured and calculated groundwater levels relative to land surface at the test site (Lat = 2.323 S, Lon = 113.903 E) versus time. (a) Model calibration, (b) Model validation.

3 Results

3.1 Peat dome 3D topography

The 3D topography of the peat layer is an essential input for hydrological modelling of groundwater levels. The DTM of the peat dome surface was used for slope calculations to identify water sub-catchments and to determine the number and location of dams for hydrological restoration. Lidar data analysis showed that the surface of the Sebangau peat dome towards the centre is elevated by a maximum of 13 m above its margins with an average gradient of 0.7 m per kilometre which appears flat when in the field (Fig. 4). The SRTM derived peat dome surface correlates very well with the Lidar measurements; the average discrepancy is only 0.35 m (Fig. 4). The Lidar as well as SRTM DSM reveal different peat swamp forest types (low, medium, tall pole), which in accordance with field investigations have different maximum canopy heights depending on local substrate conditions (Page et al. 1999). Biomass data, i.e. breast height diameter, tree height and tree species, were collected in October 2007 and 2008 along the transect shown in Figure 4 and these data confirm the results. Even across large distances with little relief it is possible to derive the DTM from the SRTM DSM using spatial interpolation between deforested patches. The result was a detailed DTM of the Sebangau peat dome and its sub-catchments with 30 m spatial resolution. Figure 5 shows the fine topography along cross sections in the middle of Bakung and Bangah catchments. The slope of the southern part of Bakung catchment appears relatively steep but the gradient is only 1 m per kilometre at maximum. Besides detailed peat dome topography, hydrological modelling requires peat thickness and bedrock data. The result of the thickness modelling reveals an average peat thickness of 5.4±0.95 m within the study area and a maximum depth of approximately 10.7 m in the centre of the Sebangau peat dome. The margin of error results from comparison of the peat thickness model with in situ measurements. The large deviations result probably from bedrock unconformity, which is not taken into account in the model. About half of the in situ thickness values are larger than the model result, while the other half are smaller. This suggests that discontinuities in the mineral ground topography are balanced by spatial Kriging interpolation and thus the modelled volume results are close to reality (Jaenicke et al. 2008).

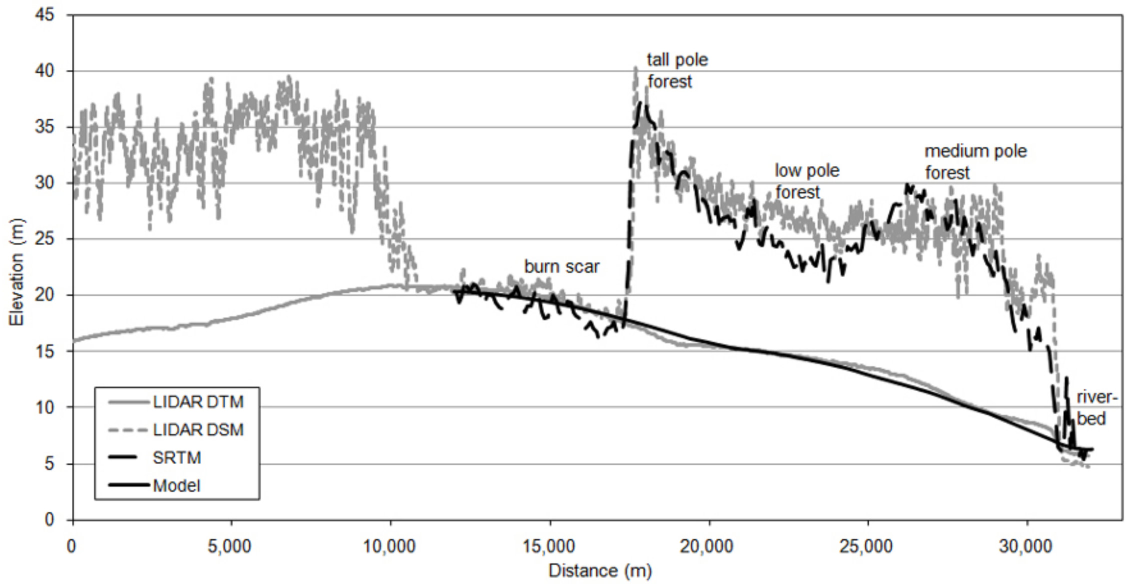

Fig. 4 The Lidar DTM and the peat surface derived from SRTM data (Model) agree very well. The SRTM DSM data reveal relative canopy heights of various peat swamp forest types.

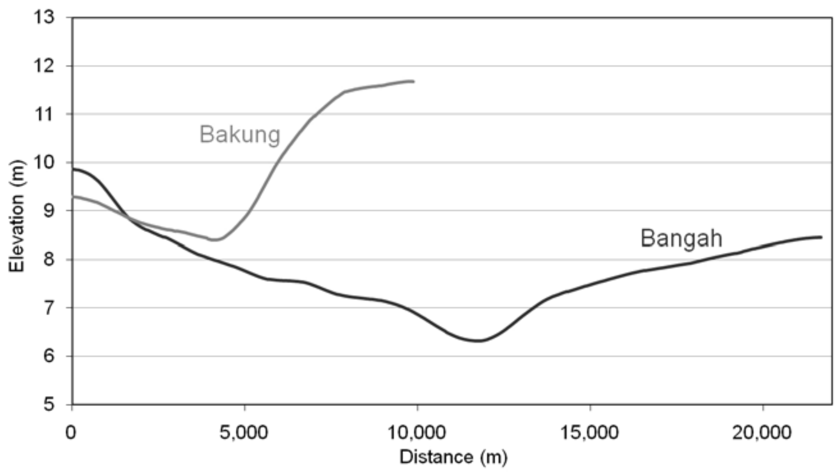

Fig. 5 DTM cross sections in the middle of the Bakung and Bangah catchment (from north to south).

3.2 Canal delineation

During field surveys in the Bakung and Bangah catchments the origin of 65 drainage canals was recorded. Eventually all these canals need to be blocked to rewet the surrounding peatland. The field team also recorded direction, length, width and depth of all canals as well as water depth, water flow, mud sedimentation or weed growth. With an average depth of 0.7 m and an average width of 2.4 m the canals are relatively small in terms of their cross-sectional dimensions, but they are closely spaced with an average distance of about 200 m in the Bakung and of about 800 m in Bangah catchment and they extent for distances up to 13 km. All information was stored in a geodatabase and a ranking was assigned indicating the priority of a canal to be closed. Long, wide and deep canals with a high water level and flow were assigned a high priority, whereas canals filled with mud and weeds were categorised as low priority. Twenty-two canals showed a high or medium need for closure. Canal lengths were estimated by consulting local people since access to the canals is very laborious and because GPS recordings are inaccurate due to dense forest cover hampering the GPS receiver. Narrow canals were invisible even from high resolution satellite images (SPOT and ALOS AVNIR, both at 10 m spatial resolution) because the tree canopy covers the streams (Fig. 6). However, knowing the outlet of the canal, the direction and approximate length it was possible to delineate most canals.

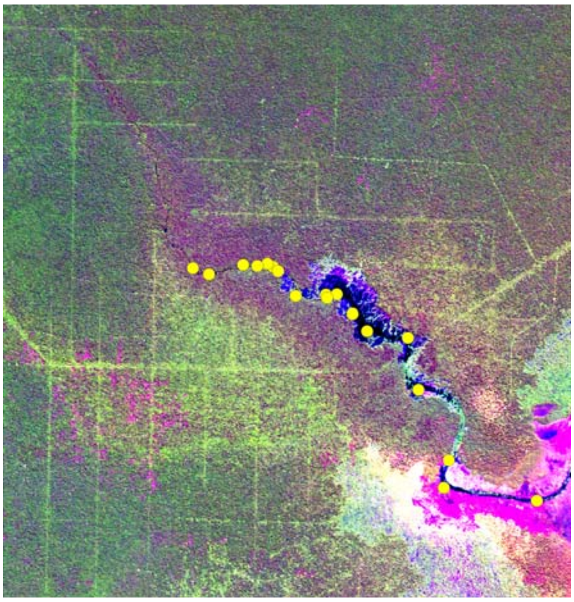

Fig. 6 SPOT satellite image from May 2004 showing the course of canals and railway tracks in the Bangah catchment as bright green lines as well as sites of illegal logging (pink and bright green "dots"). The origin of drainage canals recorded during field work is superimposed as yellow dots.

3.3 Identification of locations for dam construction

Dams act as flow barriers but they cannot store water for long periods as water will eventually seep through the surrounding peat. As dams restrict water flow rather than stop all water movement, they do not have to be watertight and thus construction can be relatively simple. To determine the optimal number and location of dams required for efficient drainage reduction, the surface slope was determined along each canal selected to be closed. Hydrological model simulations revealed that a cascade of closely spaced dams is most effective for water control (Wösten and Ritzema 2001). The steeper the slope, the more dams are needed to reduce drainage. Figure 7 shows the slope of a medium priority canal in the Bangah catchment (length 10 km, width 3 m, depth 1 m). The absolute elevation difference of the canal from its origin at the top of the peat dome to its outlet into Bangah river is 3.1 m. Because the slope of the canal is not constant over its total length it was subdivided into two sections: an upper, relatively flat section (Fig. 7, Slope1) and a lower, steep section (Fig. 7, Slope2). The distance between dams required to reduce drainage is determined by the hydraulic head difference, i.e. difference between upstream and downstream canal water level across a dam. Field experiments showed that for small canals the water level over each dam should be limited to about 25 cm to reduce seepage and to prevent erosion. Thus, the canal in figure 7 requires a series of 13 dams to overcome the 3.1 m elevation difference[1]. In the upper section of the canal a spacing of 975 m between dams is sufficient to keep water level differences low, while in the steeper section the spacing needs to be reduced to 320 m. The Bakung catchment requires the construction of 141 dams to efficiently reduce drainage. For the Bangah catchment 84 dams are needed in addition to 30 dams previously constructed. Figure 8 shows the location of dams planned and already built, as well as the priority status of the canals superimposed on the DTM. The Bakung catchment is smaller than Bangah catchment but requires more dams because of the steeper topography and higher density of canals to be closed. Figure 9

[1] $H(slope1)/0.25 + H(slope2)/0.25 + \ldots + H(slope_n)/0.25 = N(dams)$

$D(slope_n)/N(dams) = S(dams)$

H = maximum elevation difference of the canal within each “slope section”
N = optimum number of dams (rounded up to be on the save side)
D = distance of each “slope section”
S = spacing between dams

shows an example of a relatively simple dam in the Bangah catchment mainly made of locally available material.

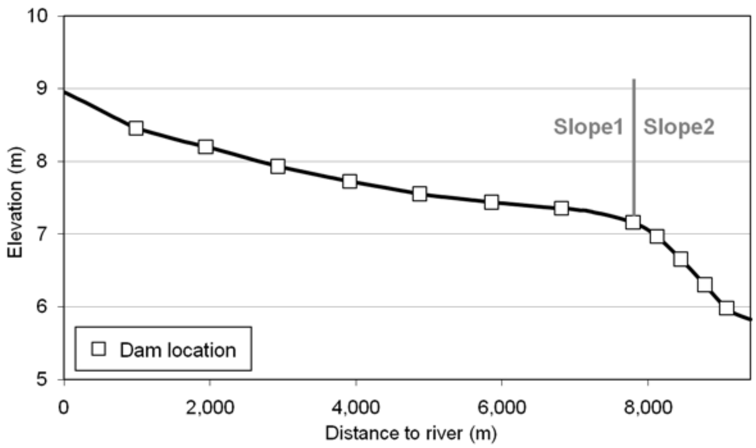

Fig. 7 Slope of the peat surface next to a canal in Bangah catchment as measured in the modelled DTM (0 marks the most upstream part of the canal). 13 dams are required to reduce large scale drainage.

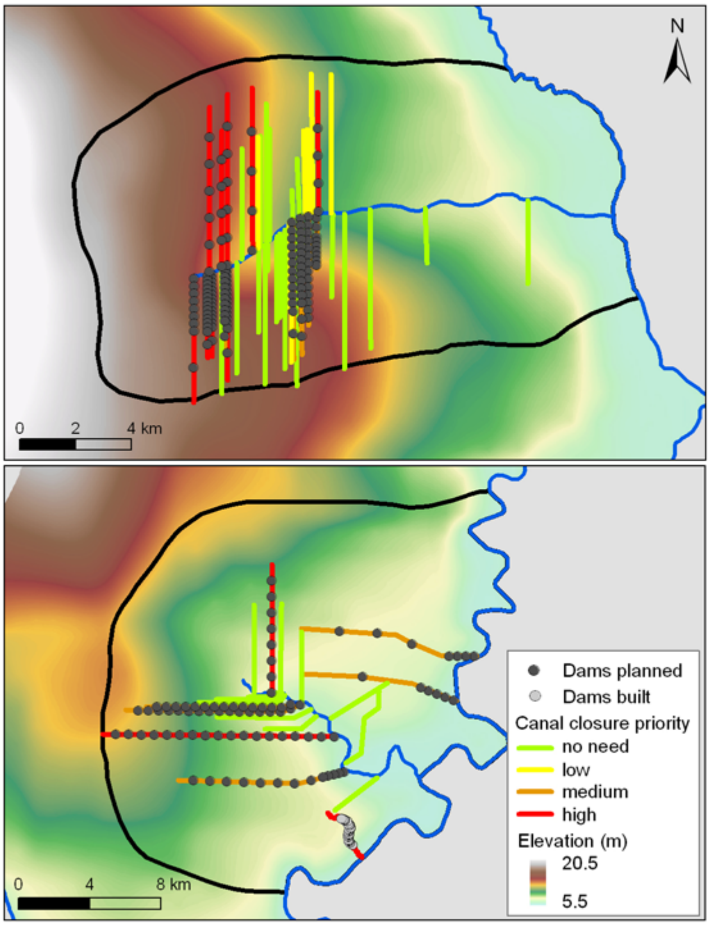

Fig. 8 Location of dams to be constructed for an efficient reduction of drainage in the Bakung and Bangah catchments. Only canals ranked as medium and high priority should be closed. Data are superimposed on the peat surface DTM.

Fig. 9 Simple dam in the Bangah catchment made of locally available material (3 m long, 1 m wide and 2.5 m deep).

3.4 Prediction of groundwater level rise

The effect of dams on groundwater levels is predicted by hydrological modelling comparing the situation before and after dam construction. Figure 3 shows that in wet years calculated groundwater levels are at or close to land surface whereas in dry years they drop to about 1 m below land surface. On average the groundwater level at the undisturbed test site is -16 cm. This value provides an indication of the intended long-term average groundwater level after successful blocking of drainage canals in the Bakung catchment. The calibrated and validated hydrological model was applied to the whole of the Bakung and Bangah catchment for the 25 November 1997, an extremely dry period. Figure 10a shows that dams can raise groundwater levels up to 50-70 cm under these very dry weather and peat conditions. For larger areas the rise is approximately 10-30 cm. Rise in groundwater levels is presented in classes rather than as absolute values to reflect the uncertainty in the calculated results. The areas affected by rewetting are strongly influenced by the slope of the peatland area surrounding the canal as this determines the catchment area draining to the canal. Figure 10b shows surface water levels in a 12 km long canal. Compared to the situation without dams, the result is a rise of the canal water level of up to 35 cm in the upstream part of the canal. The resulting rewetting of the peatland area surrounding this canal is up to 50 cm. Hydrological modelling of the rise of groundwater levels on a daily base for the years 2006, 2007 and 2008 shows that on average this rise is 20 cm during the dry season. As a consequence, construction of dams considerably increases the water retention capacity of the blocked areas thereby creating favourable wet conditions for vegetation re-growth and eventually peatland restoration.

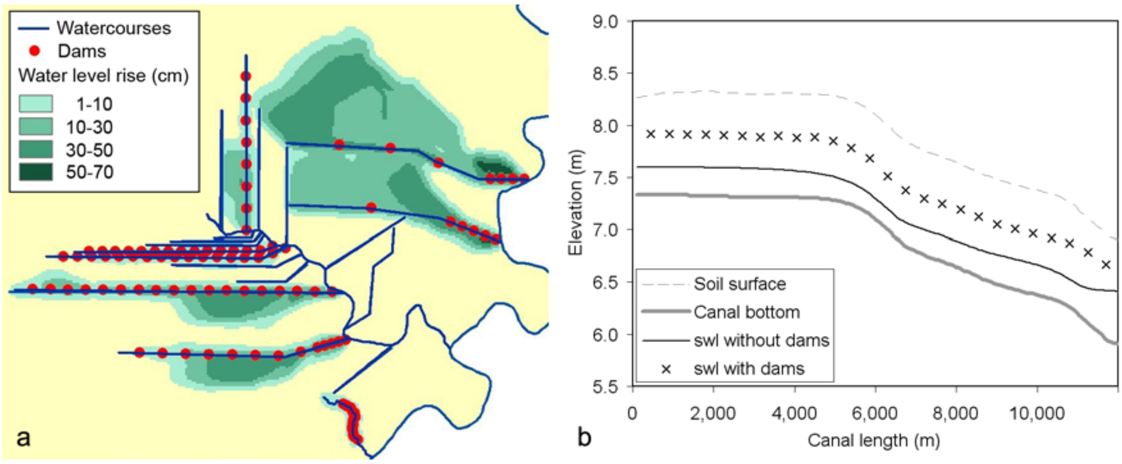

Fig. 10 Hydrological modelling applied to the Bangah catchment for very dry conditions on 25 November 1997. (a) Groundwater level rise in the whole area after construction of 114 small dams (b) Rise of the surface water level (swl) in a single canal after dam construction.

3.5 Mitigation of carbon dioxide emissions

Rewetting of drained tropical peatlands will potentially lead to large mitigations of carbon dioxide emissions (Couwenberg et al. 2009). Quantifying the rise in groundwater levels of hydrological restoration projects in peatlands together with an estimation of the mitigation in CO_2 emissions caused by this rise, is important information to make greenhouse gas emission mitigations tradable under the voluntary carbon market or REDD (Reducing Emissions from Deforestation and Degradation) mechanism. Continuous, long-term groundwater level measurements in tropical peat swamp forests are rare. The only available 12 year average groundwater level recorded at the relatively intact test site is -16 cm, whereas this level in an adjacent, drainage affected, selectively logged forest is -47 cm for the years 2004 and 2005 with normal precipitation (Jauhiainen et al. 2008). Preliminary groundwater level measurements in the drainage affected Bangah catchment indicate an average level of -49 cm. Consequently, an average annual groundwater level of -50 cm was assumed to be a baseline level for the project area before hydrological restoration started. After construction of all dams, hydrological modelling indicates a rise of annual average groundwater levels of 20 cm. With a reported emission mitigation of approximately 0.8-0.9 t CO_2 $ha^{-1}a^{-1}$ per centimetre groundwater level rise (Couwenberg et al. 2009; Hooijer et al. 2006), rewetting of the 590 km^2 area of the combined Bakung and Bangah catchments results in an estimated mitigated emission of 1.4-1.6 Million tons CO_2

annually. This estimated emission mitigation will not be achieved in the first year after all dams have been constructed because only with time sedimentation of organic and mineral material upstream of the dams makes them fully effective. Higher emissions are expected during El Niño years, such as in 1997, 2002, 2006 and 2009 due to very low groundwater levels in addition to drainage. In the project area, long-term measurements of groundwater levels (before and after dam construction) as well as subsidence and gas flux emissions are needed to confirm these preliminary results. In this study, conservative estimates were used of both the reduced CO_2 emission rate per centimetre groundwater level rise (Couwenberg et al. 2009; Hooijer et al. 2006) as well as of the magnitude of the groundwater level rise itself. Results are reported as a class to reflect the uncertainty in the calculations. Other greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O) are not taken into account because they are relatively unimportant in tropical peatlands (Furukawa 2005; Strack 2008).

4 Discussion

Canals constructed for drainage and illegal logging have destroyed the hydrological integrity of many tropical peatland ecosystems (e.g. Giesen 2004; Wösten et al. 2006; Hoekman 2007; CKPP 2008). The only way to prevent soil subsidence, peat decomposition, peat fires and associated carbon dioxide emissions is the restoration of the hydrological integrity by raising groundwater levels and thus rewetting the peat to its original situation. Many studies have shown that groundwater levels control greenhouse gas emissions from tropical peatlands (e.g. Furukawa et al. 2005; Hooijer et al. 2006; Hirano et al. 2008; Jauhiainen et al. 2008; Couwenberg et al. 2009). However, very few practical hydrological restoration measures of degraded tropical peatlands have been reported (Jauhiainen et al. 2008; Page et al. 2008). The aim of this study was to develop a detailed plan to rewet a 590 km² large area of highly inaccessible peat swamp forest drained by a dense network of small canals that are used by illegal loggers. The case as such is typical for many tropical peatlands in Indonesia and the proposed methodology is transferable to other drained tropical peatlands thereby increasing the knowledge base for future hydrological restoration activities. A detailed 3D peat dome model generated using remote sensing data, together with identified dam construction sites, provided input for hydrological modelling to quantify the effects of dams on raising groundwater levels. To verify the calculated groundwater levels a monitoring programme is under construction aiming at measurement of these levels in wells installed at a dam along two transects left and right, and perpendicular to the canal at 5, 25, 50, 150 and 300 metres distances from the canal. Also water discharges will be measured in both blocked and unblocked canals. In this study wider canals were clearly visible in high resolution satellite imagery, while hardly visible, smaller canals were determined as follows: 1) canals do not run parallel to the river or cross each other because they are constructed to facilitate extraction of timber logs from the forest, 2) while in reality the course of the canals might be not completely straight, small meanders do not have any impact on the number of dams required for rewetting. Dams need to be adapted to the characteristic high hydraulic conductivity (Wösten and Ritzema 2001) and low load bearing capacity (Salmah 1992) of tropical peat. Reduced water flow in the canals allows sedimentation of organic and mineral material upstream of the dam which in turn facilitates the re-growing of vegetation. Eventually, original peat forming vegetation will fill in the canal thereby restoring the resistance to water flow in the peat swamp forest to its original value of approximately 30 m/day. To keep subsidence of the area surrounding the dam low, dam construction should not be too heavy. Materials like gelam timber poles and peat are suitable for dam construction and they are locally available. Blocking of a canal can be regarded successful if the blocked canal sections continue to hold water during the dry season. Since some drainage canals are used for navigation and transportation by local people, ownership of each canal should be considered and consensus should be reached before dam construction starts. Failure to do so can result in damage to the dam structures as has happened frequently in the past. After construction, monitoring and maintenance of the dams is very important, especially in the first years (CKPP 2008). Previous work in the Bangah catchment demonstrated that a field team can build 30 dams in 7 days, i.e. 53 days are required to construct all 225 dams required for the Bakung and Bangah catchments together. Labour costs for one dam (transport and material costs excluded) are approximately 150,000 IDR which is equivalent to about 10 Euro. An annual emission mitigation of 1.5 Mt CO_2 from restored tropical peatlands is a significant amount corresponding to 6% of the carbon dioxide emissions by civil aviation in the European Union in 2006 (UNFCCC 2009), and therefore of interest for carbon crediting on the voluntary carbon market. This mitigation can be achieved with relatively small efforts and at low costs by focusing on construction and maintenance of simple dams made of locally available material. In case oxidation by drainage is limited to the top 50 cm of an active peat layer the total carbon at stake is 2.1 times higher than that of the aboveground biomass[2]. This total amount of carbon at stake increases to 22 times the aboveground biomass if no hydrological restoration measures were implemented and continuous oxidation of the whole 5.4 m thick peat layer was allowed to take place. Increased awareness of the large amounts of carbon at risk due to tropical peatland drainage and fires promotes interest in alternative funding mechanisms such as REDD and carbon credits to safeguard these carbon stocks. Canal blocking in tropical peatlands is not only a technical but also a social challenge. Illegal logging was, besides gold mining, a main source of income for people in Central Kalimantan. Now that funding through REDD and carbon credits becomes a realistic alternative it should also be used to improve livelihoods of local people. Restoration can only be successful if local communities are actively involved in planning and implementation of restoration measures as demonstrated in this study by WWF.

Acknowledgments

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[2] A carbon content of 140.5 t/ha for peat swamp forest (Uryu et al. 2008) and of 58 kg/m³ for peat soils (Neuzil 1997, Shimada et al. 2001, Supardi et al. 1993) is assumed.

CHAPTER IV

Monitoring the effect of restoration measures in Indonesian peatlands by radar satellite imagery

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Abstract

In the context of the ongoing climate change discussions the importance of peatlands as carbon stores is increasingly recognised in the public. Drainage, deforestation and peat fires are the main reasons for the release of huge amounts of carbon. Successful restoration of degraded tropical peatlands is of high interest due to their huge carbon store and sequestration potential. The blocking of drainage canals by dam building has become one of the most important measures to restore the hydrology and the ecological function of the peat domes. This study investigates the capability of using multitemporal radar remote sensing imagery for monitoring the hydrological effects of these measures. The study site is the former Mega Rice Project area in Central Kalimantan, Indonesia, where peat drainage and forest degradation is especially intense. Change detection analysis with more than 80 ENVISAT ASAR and ALOS PALSAR images, acquired between 2004 and 2009, shows that high frequency multitemporal radar satellite imagery can be used to detect an increase in peat soil moisture after dam construction. Furthermore, a high correlation between cross-polarised radar backscatter coefficients and groundwater levels above -50 cm was found. Monitoring peatland rewetting and quantifying groundwater level variations is important information for vegetation re-establishment, fire hazard warning and making carbon emission mitigation tradable under the voluntary carbon market or REDD (Reducing Emissions from Deforestation and Degradation) mechanism.

Keywords: ALOS PALSAR; Canal blocking; Carbon dioxide mitigation; ENVISAT ASAR; Hydrology; Restoration; Soil moisture; Tropical peat

1 Introduction

Natural lowland tropical peatlands are covered with trees (peat swamp forests) and are important reservoirs of biodiversity, carbon and water. However, in the past decade, large areas of the Indonesian peatlands have experienced serious damage as a result of human activities such as logging and drainage. Peatland site development is often associated with the construction of drainage canals in order to make the land useable for agriculture or more often for oil palm and pulp wood plantations. The forest clearing rate in Indonesia is the second highest worldwide (FAO 2006); an areal reduction of lowland forest extent by 41.3% in 15 years (1990-2005) for the Indonesian islands of Sumatra and Borneo (Kalimantan) indicates a highly unsustainable rate of deforestation (Hansen et al. 2009). A recent study of the province of Riau, Sumatra, showed that deforestation is decreasing in dryland forest due to depletion but is accelerating in peat swamp forests (Uryu et al. 2008). Increased pressure on the wet, acid and nutrient poor peatlands is caused by the currently raised demand for biofuel in Europe and the US. Of the 22 million ha of peatlands in Indonesia, about 60% are forested but mainly logged (illegally) and drained, 5% are cultivated and managed, and 35% are a mixture of small-scale agriculture and severely degraded "wasteland" (Hooijer et al. 2006).

Canals and ditches are not only built to control and lower the groundwater level for agriculture but also to facilitate access to the peat swamp forest and to extract timber. Naturally, the groundwater level is close to the peat surface throughout the year and fluctuates with the intensity and frequency of rainfall. Once peat is drained, it oxidises due to microbial activity and releases stored carbon to the atmosphere as carbon dioxide. This ongoing rapid peat decomposition leads to the irreversible process of peatland subsidence (Wösten et al. 1997; Furukawa et al. 2005). Another severe consequence of drainage is that the peat surface becomes dry and thus susceptible to fire during the dry season, which usually lasts from May until October. During prolonged El Niño related droughts fires are most severe, as in 1997/98 when about 2.4-6.8 million ha of peatlands burnt in Indonesia, releasing huge amounts of the greenhouse gas CO_2 (Page et al. 2002; Van der Werf et al. 2008b). The water absorption and retention properties of these degraded peatlands are impaired, and hence cause vast flooding during the rainy season with impacts on downstream habitations (Wösten et al. 2008). Mainly due to peat fires, Indonesia became one of the largest producer of greenhouse gases worldwide (Hooijer et al. 2006). With an estimated amount of 55 Gt carbon stored, the Indonesian peatlands are one of the largest near-surface reserves of terrestrial organic carbon (Jaenicke et al. 2008). Therefore, restoration and conservation of tropical peatlands play a crucial role in global climate change mitigation.

Restoration of the hydrological functions is a pre-requisite for the establishment of a positive or, at least, neutral peatland carbon balance and for the re-establishment of forest vegetation (Page et al. 2008). Complete rewetting is the only way to prevent fires and peat oxidation. One of the most important restoration measures of tropical peatlands is blocking of drainage canals with dams and thus raising the groundwater level of the surrounding peatland (Suryadiputra et al. 2005; CKPP 2008; Jauhiainen et al. 2008; Jaenicke et al. 2010). The dam construction must be designed to cope with the high hydraulic conductivity and low load bearing capacity of tropical peat (Wösten and Ritzema 2001; Salmah 1992). The dams mainly act as barriers to prevent water flow but cannot store water for long periods because it seeps away through the surrounding peat. The blocking of a canal can be regarded as successful if the blocked canal sections continue to hold water during the dry season. Damming activities in Central Kalimantan have led to an increase in canal surface water levels between 50 cm to over 1 m (CKPP 2008). Jauhiainen et al. (2008) reported a raise of groundwater levels in a deforested and forested site near the city of Palangka Raya, Central Kalimantan, after dam construction. In the field, peat groundwater levels are measured by using tube wells; for monitoring the effect of dam constructions it is recommended to install these in transects perpendicular to the blocked canals (Jaenicke et al. 2010). Studies of tropical peatland restoration are at an early stage (Page et al. 2008). Therefore, monitoring the effects of hydrological restoration measures is essential in order to optimise the techniques applied. Within the context of the ongoing discussions on global climate change, tropical peatlands have been recognised as major sources of carbon dioxide emissions and peatland rehabilitation projects are now of high interest for carbon trading, especially on the growing voluntary carbon market

(Couwenberg et al. 2009; Van der Werf et al. 2009; Jaenicke et al. 2010). Quantifying the rise in groundwater level, which is the main control on carbon dioxide emissions from peatlands, is important information to make greenhouse gas emission mitigation tradable under the voluntary carbon market or REDD (Reducing Emissions from Deforestation and Degradation) mechanism.

In situ groundwater level measurements are laborious and very time-consuming since access to the wet and densely vegetated tropical peatlands is difficult. Therefore, this paper aims to investigate the capabilities of radar remote sensing for monitoring the effects of tropical peatland restoration by canal blocking. The study area is the Mega Rice Project area in Central Kalimantan, Indonesia, a severely drained and degraded peatland where dam constructions started in July 2004. The principal advantage of remote sensing over field measurements is the possibility of continuously monitoring vast areas. Compared to optical satellite data, radar imagery is available at high temporal frequency due to cloud penetration and daylight independency and is sensitive to changes in soil moisture. In general, vegetation or soil with high moisture content returns more energy to the radar sensor than if it is dry (Lillesand and Kiefer 1994). Several studies have demonstrated the relationship between radar backscatter and surface soil moisture content under varying terrain conditions (e.g. Ulaby et al. 1982; Dubois et al. 1995; Paloscia et al. 2005). Hashim et al. (2002) found a strong correlation between radar backscatter (L-band) and soil moisture as well as groundwater level in drained tropical peatland in Malaysia. The intensity of radar returns is determined by several surface parameters such as dielectric constant and roughness. The dielectric constant is highly dependent on soil moisture because there is a large difference between dry soil (typically 2-3) and water (app. 80). This forms the basis for measuring changes in peat moisture. We applied change detection analysis with a time series of ENVISAT ASAR and ALOS PALSAR radar imagery, acquired before and after rewetting measures (2004-2009). Radar backscatter values of deforested and forested test sites near the dams were compared with in situ groundwater level measurements and with rainfall data. The C-Band ASAR sensor is able to penetrate regenerating tropical forest and to detect soil moisture variations underneath (Grover et al. 1999), while the longer wavelength L-Band ALOS sensor is even capable of observing soil moisture fluctuations and seasonal flooding dynamics under a closed peat swamp forest canopy (Aziz 2003; Stahlhut and Rieley 2005; Romshoo 2006; Hoekman 2007).

2 Study area and materials

2.1 The Mega Rice Project area

The study area is located within the so called Mega Rice Project area, which extends south east of the city of Palangka Raya in the southern lowlands of the Indonesian province of Central Kalimantan on Borneo (Fig. 1). The landscape comprises flat alluvial plains with dome-shaped peat deposits that have accumulated to a thickness of more than 10 m (Rieley and Page 2005; Jaenicke et al. 2008). In 1995, the Mega Rice Project (MRP) was initiated by the Indonesian government under President Suharto. Despite warnings by scientists, it was planned to convert 1 million ha of peatlands for rice cultivation, accompanied by a transmigration program. A massive network of drainage canals was built, with a combined length of 4,500 km and depth of up to 10 m, but rice production appeared to be impossible. Intensive deforestation took place during the El Niño induced drought in 1997/98. Fifteen years of drainage and recurrent fires in 2002, 2004, 2006 and 2009 have severely degraded the MRP area (Langner and Siegert 2009). The MRP is the most disastrous example of unsustainable peatland management (Muhamad and Rieley 2002).

In July 2004, hydrological restoration measures started in the MRP area under the CCFPI (Climate Change Forests and Peatlands in Indonesia) project by building 5 large dams in Block A (Fig. 1). Financed by the Central Kalimantan Peatland Project (CKPP), 19 additional dams were constructed in this area in 2007 and 2008. Within the framework of the Academy of Finland funded project “Keys for Securing Tropical Peat Carbon” (KEYTROP) and the EU funded RESTORPEAT (Restoration of Tropical Peatland for Sustainable Management of Renewable Natural Resources) project, 6 dams were built in 2005 in the drainage canals of Block C, which is located in the most western part of the MRP area. Adjacent to two of these dams automatic groundwater level loggers were placed. The dams in Block C are up to 25 m long, 4 m wide and 3 m high, and were made of a timber frame which was sealed with plastic sheeting and filled with peat (Fig. 2). Trees were planted on top and behind the dams to increase resistance. The water flow reduction capability increases with time because organic sediments accumulate upstream of the dams.

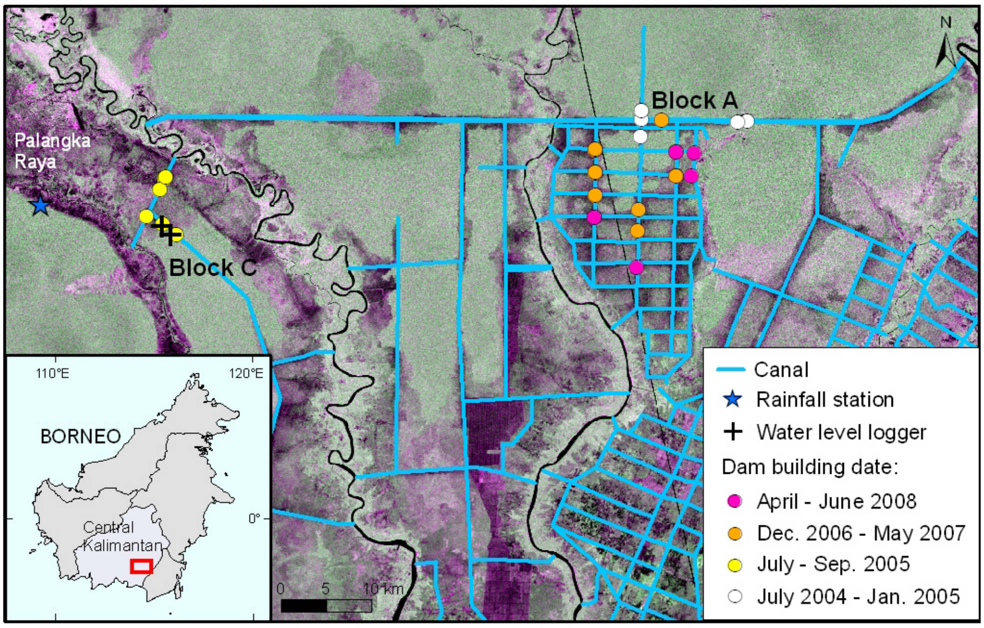

Fig. 1 ALOS PALSAR satellite image (HH, HV) from June 2009 showing the study area located in Central Kalimantan on the island of Borneo, Indonesia. Peat swamp forests appear in green, fire scars in purple. Not all of the 30 dams are shown due to very small distances between some of them.

Fig. 2 Large dam constructed across a drainage canal in degraded peatland in Block C, Mega Rice Project area. A timber frame was sealed with plastic sheeting and then filled with peat (© Kusin).

2.2 Radar imagery

The Indonesian peatlands are covered by clouds 70-80% of the year; in addition haze from smouldering fires during the dry period often impedes the visibility (Langner et al. 2007). Therefore, continuous and cost-efficient monitoring is only possible with radar satellite remote sensing. The Advanced Synthetic Aperture Radar (ASAR) instrument onboard ENVISAT satellite, which was launched by the European Space Agency in March 2002, provides radar data in different modes with varying spatial and temporal resolution and alternating polarisation at C-Band wavelength (5.6 cm). Twenty-eight ASAR scenes, acquired between July 2004 and March 2009 in dual polarisation mode (VV, VH) and with an incidence angle of 23°, were available for monitoring the dams in Block C (Table 1). The pixel spacing is 12.5 m and the temporal resolution 35 days. The Phased Array type L-band (23.6 cm wavelength) Synthetic Aperture Radar (PALSAR) was launched onboard the Japanese ALOS satellite in January 2006. Four scenes are required to cover the whole study area and were available at an incidence angle of 38.8° since the beginning of 2007 (Table 1). The polarisation mode is switched periodically between single mode (HH) during the wet season and dual mode (HH, HV) during the dry season, with a temporal resolution of 46 days. The pixel spacing is 6.25 m for single and 12.5 m for dual polarisation. Altogether 58 PALSAR scenes acquired between January 2007 and October 2009 were analysed in this study.

Table 1 Description of radar imagery available for this study

Sensor	Period	Path/Frame	Incidence Angle	Wavelength (cm)	Polari-sation	Pixel spacing (m)
ASAR AP*	2004-2009	-2.29; 114.13 (scene centre)	23°	5.6	VV, VH	12.5
PALSAR FBS**	2007-2009 (wet season)	421-422/ 7130-7140	38.8°	23.6	HH	6.25
PALSAR FBD***	2007-2009 (dry season)	421-422/ 7130-7140	38.8°	23.6	HH, HV	12.5

* AP = Alternating Polarisation, ** FBS = Fine Beam Single, *** FBD = Fine Beam Dual

2.3 Auxiliary data

When analysing radar imagery it is essential to consider the weather conditions because rain occurring at the time of data acquisition can change the physical and dielectric properties of the surface soil and vegetation, thus affecting backscatter. Daily precipitation data collected by a weather station near Palangka Raya (Fig. 1) between 1997 and February 2008 as well as data from the Global Precipitation Climatology Project (GPCP) were analysed for this purpose. GPCP data incorporates infrared and microwave satellite retrievals and rain gauge observations. It is freely available since 1997 with a spatial resolution of 1 degree latitude and longitude. Daily mean groundwater level data were recorded at a forested and deforested site next to dams in Block C between April 2004 and November 2007, and were used for comparison with radar backscatter. Another important parameter for monitoring the effect of damming is the flow direction of the canal water. This information was derived from a digital elevation model of the study area and from punctual in situ measurements. Since changes in surface roughness, e.g. by burning or vegetation regrowth, can alter the radar backscatter, fire events in the study area were analysed with Landsat optical satellite imagery, acquired between June 1991 and October 2009 (seventeen 80% cloud-free scenes). Active fires were analysed using the thermal infrared MODIS sensor onboard TERRA satellite (FIRMS 2009).

3 Methods

3.1 Image processing

The radar imagery was calibrated using ERDAS Imagine 9.3 software by Leica Geosystems and a digital elevation model (DEM) from the Shuttle Radar Topography Mission (SRTM) with 90 m pixel spacing. This DEM resolution is sufficient because tropical peatlands are very flat, with elevation gradients of only 0.2-1 m per kilometre in the centre (Rieley and Page 2005). ASAR data was calibrated to radar backscatter coefficients (σ^0) using an algorithm implemented in the Imagine software. The PALSAR digital numbers (DN) first had to be transformed into radar brightness (β^0) values applying the following equation (Shimada et al. 2009):

$$\beta^0 \text{ (dB)} = 10*\log_{10}(DN^2) + CF$$

where CF is the calibration factor which varies between -80.2 and -83.4, depending on the processing date, incidence angle and polarisation mode. Absolute calibration into σ^0 values was then performed by calculating local incidence angles from SRTM data in ERDAS Imagine (radiometric terrain correction). The multitemporal radar imagery were co-registered with an accuracy of less than one pixel, using a Landsat ETM+ image from August 2007 as master. The Landsat dataset used for validation of the radar backscatter analysis and acquired after May 2003 had to be “de-striped”, i.e. scan gaps due to Scan Line Corrector (SLC) malfunction were filled. This was done by 1) image registration of the *primary* scene and *fill* scenes and 2) histogram-matching (USGS 2009).

3.2 Change detection analysis

Mean backscatter values of test sites located close to the dams and of reference sites in undrained regions were analysed before and after dam construction. Random interference of microwaves produces a characteristic backscatter fluctuation known as speckle noise on Synthetic Aperture Radar (SAR) data. To reduce radiometric resolution errors due to speckle, backscatter values of a certain amount of pixels were averaged (Laur et al. 1998). Baup et al. (2007) demonstrate that the backscattering coefficient σ^0 and the associated radiometric resolution vary as a function of the size of the sampling window. Therefore, by calculating the radiometric resolution, the optimal sampling window size can be determined. The radiometric resolution R_{rad} of the measured intensity is defined as (Laur et al. 1998)

$$R_{rad} = 10*\log_{10}(1 + 1/\text{sqrt}(ENL))$$

with $ENL = N_{pixel\_az} * N_{pixel\_ra} * NL_{az} * NL_{ra} / R$

where ENL is the equivalent number of looks, N_{pixel_az} and N_{pixel_ra} are the number of azimuth and range pixels of the sampling window, NL_{az} and NL_{ra} are the number of azimuth and range looks, and R is the number of pixels per independent pixel in the data product (Table 2). R is calculated as follows:

$$R = (\rho_{az}/\Delta_{az}) * (\rho_{ra}/\Delta_{ra})$$

where ρ_{az}, ρ_{ra} and Δ_{az}, Δ_{ra} denote the azimuth and ground range spatial resolution, and the azimuth and range pixel spacing, respectively (Table 2). Prerequisite for the calculation of image radiometric resolution is homogeneity within the test site. It was found that test area sizes of 550 x 550 m for ASAR AP data, 220 x 220 m for PALSAR FBS and 300 x 300 m for PALSAR FBD data are large enough to obtain a good accuracy and to ensure homogeneity. With such windows, the radiometric resolution is ±0.14 dB (Table 2). Forty-two test sites next to dams were investigated, and ten reference sites in undrained regions of the MRP area in order to check the stability of the radar backscatter over the whole time period analysed. Some test sites were set with increasing distance to the dam in order to examine the extent of a possible rewetting effect by damming. Furthermore, the influence of the flow direction of the canal water was analysed by placing test sites on both sides of a dam.

In addition to the evaluation of mean backscatter values of test sites, a multitemporal image stack was produced to visualise and investigate peat moisture changes in Block A on a more spatial scale. For this, three images acquired during the dry season of 2007, 2008 and 2009, respectively, were chosen. During dry conditions it can be assumed that there is no temporal variation in dielectric properties of the imaged surface due to rainfall. To reduce speckle in the radar scenes, a Lee-Sigma filter with a 5x5 and 9x9 moving-window was applied.

Table 2 Radar image parameters to calculate the image radiometric resolution

Sensor	Number of looks (azimuth x range)	Spatial resolution (azimuth x range)	R	Test site size	R_{rad} (dB)
ASAR AP	4 x 1	22 x 25	3.52	550 x 550	±0.14
PALSAR FBS	2 x 1	10 x 10	2.56	220 x 220	±0.14
PALSAR FBD	4 x 1	20 x 20	2.56	300 x 300	±0.14

4 Results

4.1 Rainfall and fire occurrence

The annual rainfall in Central Kalimantan varies between 2000-4000 mm and is influenced by periodic El Niño induced drought events. Figure 3 shows daily precipitation measurements during times of radar image acquisition (2004-2009). The prolonged drought in 2006 is clearly visible and resulted in extremely low groundwater levels of up to -2 m in drained peat swamp forest. Due to problems with the data logger, in situ rainfall measurements were available only until February 2008 and thus complemented with GPCP data. A comparison of the two datasets showed that GPCP does not record precipitation events higher than 60 mm per day; however, the trend of monthly and yearly averages is the same. To date, GPCP data is processed and made available only until April 2009, but it is known from global weather observations (CPC 2009), local observations and from remotely sensed fire and burn scar detection that 2009 was an extremely dry year with many fire events occurring in the study area between mid-August and the end of September. With an annual average rainfall of about 3000 mm, 2004 and 2005 were normal precipitation years, whereas 2007 was an unusually wet La Niña influenced year (nearly 4000 mm) and 2008 slightly above average (ca. 3400 mm).

Landsat and MODIS fire hotspot analysis of the study area showed that in 2007 only one small fire event (400x400 m) occurred in Block A, and no fires at all were recorded in 2008. Landsat imagery further revealed that the burn scars in the test site in Block C result from severe fires in 1997/98 and 2002, thereafter no fires occurred until September 2009. The burn scars in Block A originate mainly the extremely dry years 1997/98 and 2006, with recurrent fires in between (Langner et al. 2007; Langner and Siegert 2009). The first vegetation after a severe fire event consists of ferns and sedges, which quickly cover the soil after the first rainfalls (Page et al. 2008).

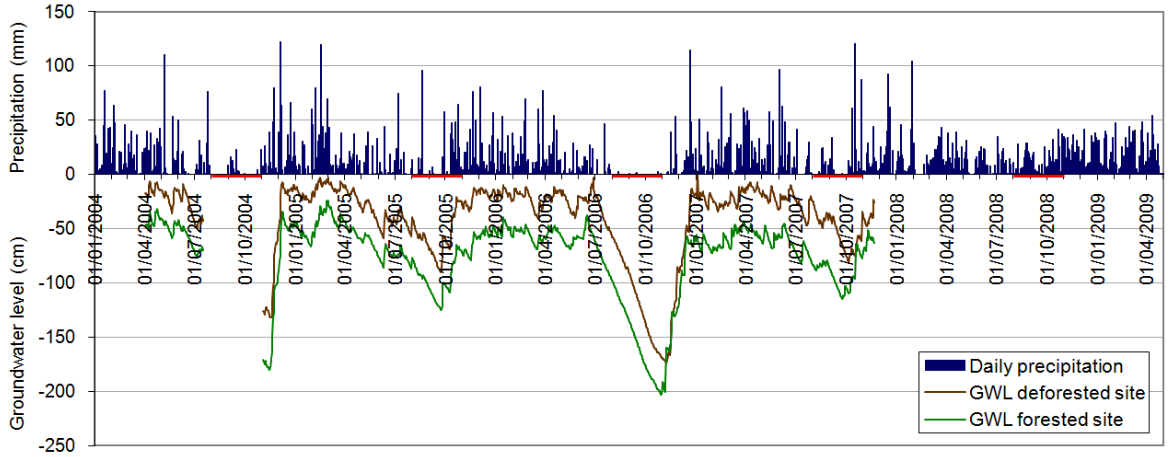

Fig. 3 Daily precipitation (in situ until February 2008, more recent satellite GPCP) and groundwater level data measured in the study area between 2004 and 2009. The dry months August – October are marked in red.

4.2 Correlation of groundwater level and radar backscatter

The groundwater level (GWL) at the drained, deforested site in Block C varies between 0 cm, i.e. the peat surface, recorded after high rainfall events during the wet season and a minimum value of -174 cm in November 2006 (Fig. 3). At the forested site, generally lower GWLs were registered but show the same course over the years. A long-term comparison of in situ GWL measurements and radar backscatter was only possible with ASAR C-band data due to failure of the loggers at the end of 2007. A first, visual comparison of the GWL data at the degraded site with σ^0 backscatter coefficients averaged over a 550x550 m test site at the logger station showed a positive relationship, i.e. higher σ^0 values occurred with higher GWLs, but linear regression revealed bad correlation coefficients. After excluding all GWL values <-50 cm, correlation coefficients of r=0.44 for VH polarisation and 0.35 for VV polarisation were reached and further improved to 0.72 (VH) and 0.46 (VV), respectively, if a delay in groundwater level reaction of nine weeks was assumed (Fig. 4a). This high value of r=0.72 suggests that a relationship exists between VH C-band backscatter of degraded peatland and GWL values (up to -50 cm) recorded nine weeks after image acquisition. The same time delay was found between rainfall and GWL (Fig. 4b). While a comparison of daily values was not significant (r=0.32), mean values of both variables were calculated and very high correlation (r=0.94) reached by averaging rainfall values over a period of nine weeks. There is a time delay between rainfall and changes of the groundwater level because the peat layer with its high permeability acts like a sponge, slowly "filling" and "emptying". The GWL threshold of -50 cm suggests that the sensitivity of the radar signal is not sufficient to detect changes in lower GWLs. Probably the roughness of the peat soil, in terms of L-band wavelength, prevents further decrease of the radar backscatter coefficients. At the forested test site, no relationship between GWL and radar backscatter was found.

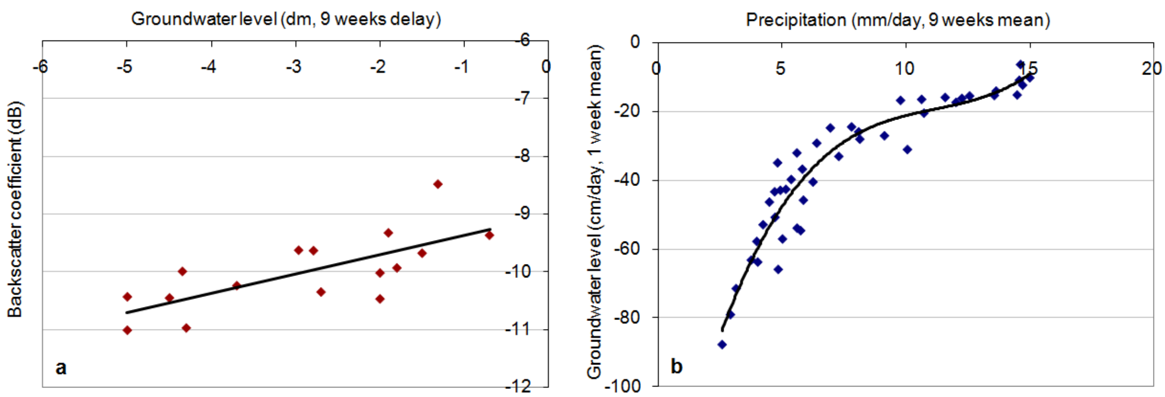

Fig. 4 (a) Linear relationship with r=0.72 exists between radar backscatter coefficients σ^0 (C-Band, VH) determined between July 2004 and October 2009 over deforested peatland and groundwater levels measured nine weeks later at the same site. (b) A similar time delay exists between rainfall and groundwater level (r=0.94).

4.3 Test site evaluation

Before evaluation of the test sites near dams, the temporal variability of the radar backscatter in undisturbed peat swamp forests was investigated. Romshoo (2006) has shown that the L-Band (JERS-1 SAR) backscattering coefficient of dense, high biomass peat swamp forests is very constant. This was confirmed here by investigating 40 multitemporal PALSAR scenes and ten test sites in undrained forests (Fig. 5). Especially the cross-polarised HV backscatter is very stable; with a standard deviation (STD) of only 0.16 during the three year observation period, compared to 0.22 for like-polarised HH backscatter. The backscatter coefficient of primary forest in the study area does not vary more than 0.3 dB for HV polarisation and 0.57 dB for HH, respectively. Thus, an increase or decrease of more than 0.3 dB in the HV backscattering coefficient could be reasonably attributed to anthropogenic or natural changes in the forest. The C-Band ASAR return from undisturbed peat swamp forest shows no stability during the six year observation period (STD_{VH}=0.54, STD_{VV}=0.6). Siegert and Ruecker (2000) report stable backscattering responses from peat swamp forests on C-Band ERS SAR data, but only during dry conditions and over a relatively short period in 1997/98. Due to signal instability, the ASAR data were not used to analyse forested test sites. This discrepancy between L-band PALSAR and C-band ASAR very likely result from the different forest penetration capabilities of the sensors.

Figure 6a shows the result of the evaluation of seven forested test sites next to dams completed in January 2005 in Block A, in comparison to reference sites of undrained forest. Up to a distance of 1 km from the dams, a backscatter increase of 0.41 dB (PALSAR HV) was observed between May 2008 and August 2009. This increase, even though 2008 was a wet and 2009 a very dry year, suggests that the dams have a locally limited rewetting effect. A more distinct increase in L-band backscatter is observed at the dammed, forested test site in Block C (Fig. 6b). A comparison of a test site upstream and downstream of the dam clearly shows the influence of the water flow direction in canals. While there is a σ^0_{HH} backscatter increase of 0.86 dB between 9 July 2007 and 14 October 2009 upstream of the dam, the backscatter downstream the dam is very constant, except on 14 October 2009. At this date a very strong increase of 3.7 dB is observed, caused by a double bounce mechanism of the HH polarised radar signal due to fire impact in September 2009. Fire occurrence only downstream of the dam further suggests a (small-scale) rewetting effect of the dam.

Test sites on degraded peatland in Block C were investigated with multitemporal ASAR images, which allowed a comparison of the radar backscatter before and after dam constructions. Evaluation of the results shows a backscatter increase after completion of the dam construction in September 2005 and a small decrease before (Fig. 7). The increase of 0.9 dB observed between October 2005 and March 2009 is only visible in the cross-polarised VH imagery. During the wet seasons the radar backscatter is generally higher. The continuous backscatter increase after dam construction, even though 2006 had a very prolonged dry period, suggests successful peatland rewetting. Only two of the six dams in Block C show a rewetting effect, namely the most southern ones which have the highest water retention capability being at the end of a "cascade" of dams in terms of water flow direction.

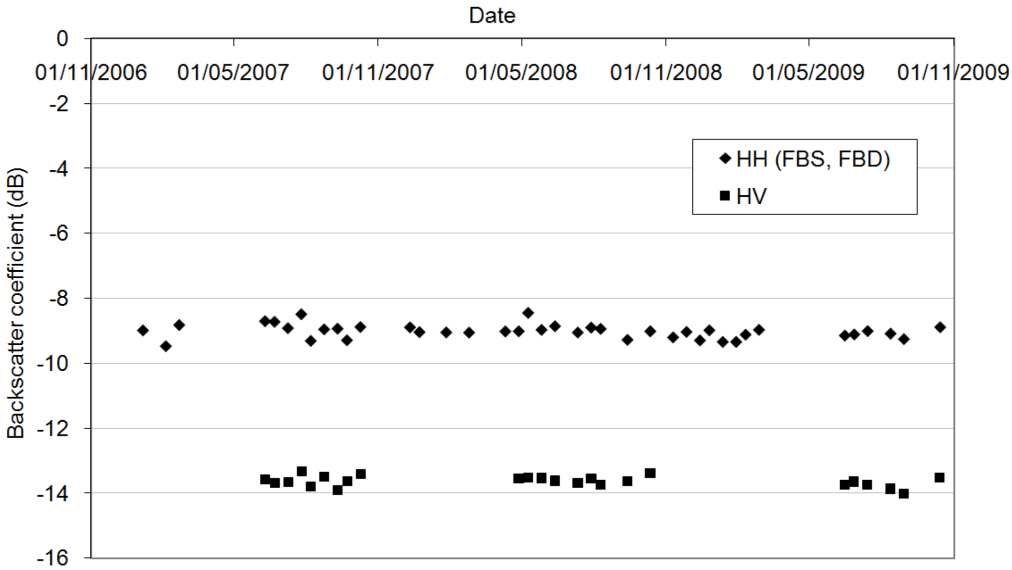

Fig. 5 PALSAR L-Band backscatter coefficients from undisturbed peat swamp forest were constant during the observation period from January 2007 until October 2009, especially in HV polarisation. Shown are mean values over ten test sites.

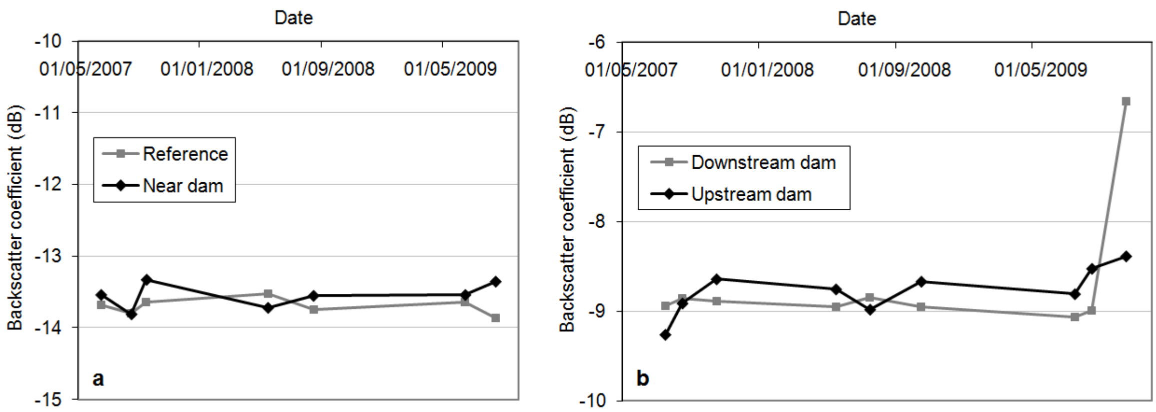

Fig. 6 Comparison of PALSAR radar backscatter from forested, rewetted test sites with reference sites. (a) In Block A, only a slight HV backscatter increase is observed between May 2008 and August 2009. (b) In Block C, there is a HH backscatter increase of 0.86 dB upstream of the dam, compared to a very stable signal downstream of the dam (except of 14 October 2009, due to forest fire).

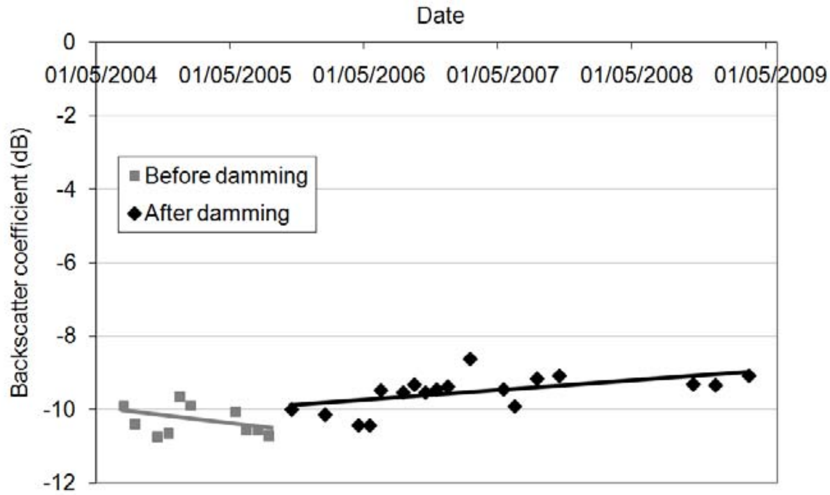

Fig. 7 ASAR C-Band backscatter analysis of a deforested test site in Block C over a six year period shows an increase of about 0.9 dB after completion of dam construction in September 2005.

4.4 Measuring peatland rewetting on a large scale

In order to investigate the spatial pattern of rewetting in Block A, a multitemporal image stack, i.e. red-green-blue (RGB) colour composite of three images acquired during dry conditions in 2007, 2008 and 2009, respectively, was produced. HH polarised data was chosen because of a better discrimination between peat swamp forest and fresh burn scars. An optical Landsat ETM+ image from 5 August 2007 shows the condition of the peatland surface at the beginning of the change detection analysis; the landscape is determined by burn scars from 2006 (Fig. 8a). Figure 8b illustrates the resulting RGB composite, in which the image from 7 August 2007 represents the red channel, the image from 9 August 2008 the green channel and the image from 12 August 2009 the blue channel. Areas that appear in grey (forests, burn scars) and white (riverine vegetation and some fresh burn scars in the southeast) show no significant changes among the three dates. Yellow areas indicate a backscatter decrease between 2007 and 2009; while blue areas reveal an increase in σ^0 values, even though 2009 was an extremely dry El Niño year. This suggests that peatland rewetting was successful in a ca. 6 km² large area after the construction of dams in 2007 and 2008. However, no increase in peat soil moisture is observed in other dammed parts of Block A.

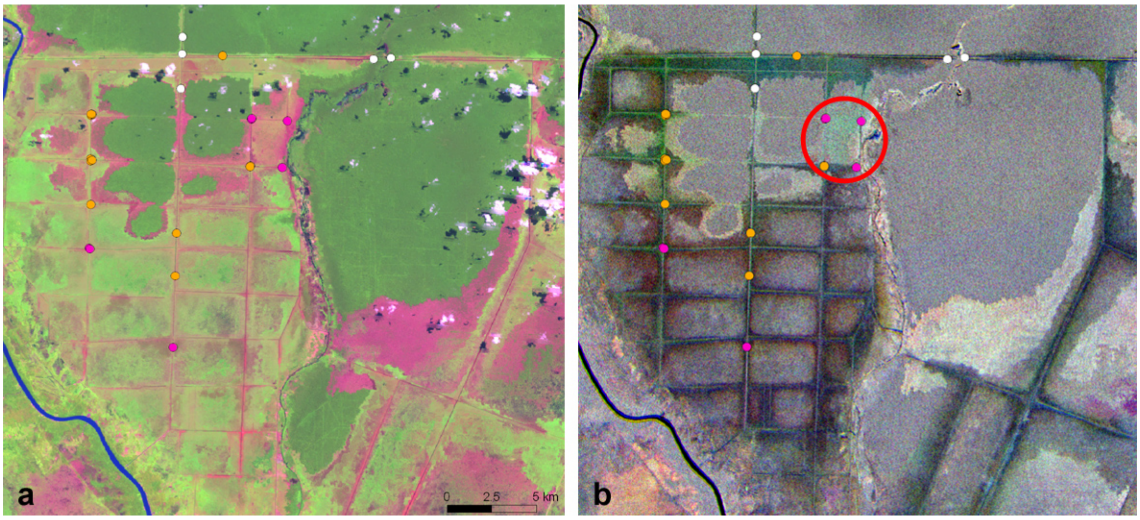

Fig. 8 (a) An optical Landsat ETM+ image shows the condition of the peatland surface in Block A at 5 August 2007; dark green: forested areas, red: burn scars from 2006; light green: vegetation regrowth. (b) RGB composite of three HH polarised PALSAR images (red: 7 August 2007, green: 9 August 2008, blue: 12 August 2009) showing relative changes over three years; marked with a red circle is the area where a significant backscatter increase occurred in 2009.

5 Discussion

This study shows that ASAR Alternating Polarisation and PALSAR Fine Beam mode data are capable of monitoring peatland rewetting in Indonesia. Rewetting, which is achieved by damming drainage canals, is the most important restoration measure of tropical peatlands and a prerequisite for replanting trees and preventing carbon dioxide emissions. Relative changes in peat soil moisture before and after dam construction were observed with radar time series of up to six years. By calculating the radiometric resolution of the measured backscatter intensity, the optimal size of sites for change detection analysis was determined. A multitemporal stack of PALSAR images, acquired during dry weather conditions, proved to be successful in monitoring large-scale temporal and spatial patterns of soil moisture. Variations in backscatter coefficients due to changes in surface roughness were observed with optical Landsat imagery and MODIS fire hotspot data. Both radar wavelength bands investigated (C- and L-band) were able to penetrate post-fire regrowing vegetation, while only L-Band PALSAR data could detect soil moisture changes under a forest canopy. Generally, cross polarisation provided better results; probably because it is less sensitive to surface roughness and object orientation (Envisat 2007). A high correlation was found between VH polarised σ^0 backscatter and in situ groundwater level data above -50 cm, measured two months after image acquisition. This time delay also exists between rainfall and reaction of groundwater levels.

The rewetting of drained, forested and deforested peatland in Block C of the Mega Rice Project area in Central Kalimantan, as detected by ASAR and PALSAR imagery, is confirmed by in situ groundwater level measurements. After restoration, higher annual minimum GWLs prevailed on both sites and the GWL remained considerably longer near the peat surface (Jauhiainen et al. 2008). However, radar image analysis showed that an increase in soil moisture occurred only close to the dams and is strongly influenced by the water flow direction in the drainage canal. In the whole Block A, a relatively small area of ca. 6 km^2 showed a distinct increase in radar backscatter between 2007 and 2009 which can be reasonably associated with soil moisture variations. The occurrence of fires in the study area during the 2009 El Niño also suggests that the dams do not (yet) achieve large scale peatland rewetting. In contrast to its surroundings, the rewetted area in Block A was not affected by the severe 2009 fires. Usually, fires are ignited where the peat is dry and where there is access (mainly via drainage canals). The rewetted area is the only one in Block A which is bordered by dams at each canal junction. This, together with the observations in Block C, support the theory by Wösten and Ritzema (2007) that a cascade of dams is most effective in canal water retention and hence rewetting of the surrounding peatland. The dense network and large size of canals in Block A make this a long-term and cost-intensive task. Furthermore, rising groundwater levels in Block A are restricted by severe peatland subsidence along the canals which has created a “mini-dome” topography (CKPP 2008). The 2009 El Niño fires make clear that peatland restoration must be accompanied by fire prevention, control and education, especially at the early stage.

Even though these first results of monitoring the effect of peatland restoration with radar imagery are very promising, in situ groundwater level measurements distributed over the whole study area should be investigated along with the acquisition of additional images. A longer time series of dual polarised PALSAR imagery, which proved to have best monitoring capabilities, is important to reduce uncertainties introduced by frequent short and long term changes of weather conditions in Central Kalimantan. This study clearly shows the advantage of remote sensing data over in situ measurements which are laborious and cost-intensive due to difficult peatland accessibility and a high need for maintenance; destruction of measuring instruments by animals, humans and fires have been frequently reported from the study area. The identification of areas that have been successfully rewetted is essential for specifically planning the re-establishment of vegetation. In addition, groundwater level prediction is a key element for fire hazard warning systems. It is known that -40 cm is a critical threshold below which irreversible drying occurs; a layer of dry peat is created on the surface being very susceptible to fire (Takahashi et al. 2003; Usup et al. 2004; Wösten et al. 2008). Knowing the effect of peatland restoration measures as well as large scale groundwater levels is necessary to estimate carbon dioxide mitigation in view of carbon trading projects on the voluntary carbon market or under the REDD mechanism. Jaenicke et al. (2010) estimated that successful rewetting of a 590 km² large area of drained peat swamp forest could result in mitigated emissions of 1.4-1.6 Mt CO_2 yearly and Ballhorn et al. (2010) calculate that within a 27,900 km² large region in Central Kalimantan, including this study area, approximately 184 Mt CO_2 were released during the 2006 El Niño event, which equates to 20% of all carbon dioxide emissions from transport in the European Union in 2007. Carbon dioxide emissions of these orders can be avoided if large-scale hydrological restoration measures are accompanied by an efficient monitoring program.

Acknowledgements

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CHAPTER V

Discussion

1 Summary

This thesis shows that remote sensing is a highly beneficial tool for monitoring the vast Indonesian peatlands in view of conservation and restoration. Peatland rehabilitation is not only of regional importance but also of global significance for climate change mitigation. Optical, radar, and Lidar remote sensing data were utilised to overcome some shortcomings of field measurements in tropical peatlands. These are 1) limited in situ data collection due to difficult accessibility and the huge extent of peat domes, and 2) high need for maintenance of measurement instruments. However, field measurements are essential for well-founded analyses of remotely sensed data. The areas of investigation were the Indonesian peatlands, with a focus on the Mega Rice Project area in Central Kalimantan where degradation is especially intense, but the methods proposed are transferable to other tropical peatlands as in Malaysia. A combination of remote sensing and 3D modelling within a GIS environment was successfully applied to estimate the total carbon storage of the Indonesian peatlands. This detailed remote sensing investigation is the first of its kind and is supported by a large number of in situ peat thickness measurements in representative peat domes of Central Kalimantan, South Sumatra and West Papua. The estimation of 55±10 Gt is based on an average peat thickness of 4.5±0.85 m determined in the three study sites and the total peatland area of 21.1 million ha, given by Wetlands International. 3D modelling by means of radar satellite elevation data has the advantage of being more accurate than previous carbon storage estimations, since the dome shaped appearance of peatlands is considered. This technique was also used to generate a detailed peat dome model of a 590 km² large drained area within the Sebangau catchment in Central Kalimantan, intended for hydrological restoration by damming drainage canals. The 3D model together with identified dam construction sites provided essential input for hydrological modelling which allows quantifying the effect of dams on rising groundwater levels. Dam construction sites were determined by analysing optical satellite imagery, field inventory data and peat dome slope. Successful rewetting of the investigated area could result in mitigated carbon dioxide emissions of 1.4-1.6 Mt annually. The effect of restoration measures on increasing peat soil moisture can be monitored from space with radar sensing which is able to penetrate clouds and vegetation cover and is sensitive to changes in soil moisture. Change detection analysis of more than 80 ASAR and PALSAR images, acquired between 2004 and 2009, suggests that regions of up to 6 km² within the Mega Rice Project area have been successfully rewetted by dam constructions. Rewetting occurred only where there was a high density of dams. Furthermore, a strong positive correlation of r=0.72 was found between radar backscatter coefficients and in situ groundwater level measurements. The results of this thesis all yield important information for conservation and restoration of tropical peatlands and for making carbon emission mitigation tradable under the voluntary carbon market and REDD mechanism.

2 Tropical peatland protection − Global importance and solutions

The storage of approximately 55 Gt carbon in the Indonesian peatlands constitute a huge potential for global climate warming, if deforested and drained for palm oil and pulpwood. With an average peat thickness of 4.5 m, the Indonesian peat swamp forests store about 2800 tons carbon per hectare which is 20 times as much as tropical rainforest of the same size without peat soil. For comparison, the European peatlands, which mainly developed from loose mosses and grasses, have an average thickness of 1.75 m (Byrne et al. 2004), and the carbon storage of German peat is ca. 1.6 Gt with an extent of 0.18 million ha (Höper 2007). Whereas in Germany peat soils were formerly used as fuel and for body care, in Indonesia the forests growing on the peat and the land itself are of interest and constitute a source of economic development. The Indonesian peatlands are highly threatened by logging, drainage and land conversion. Poorly regulated forest clearing has lead to the destruction of many peatland ecosystems and attendant disruption of rural livelihoods. Prolonged El Niño related droughts, which occurred every 3-4 years in the past two decades, are seen as a benefit for the local people as they can accomplish fire land clearing in a shorter period of time. In 1997/98, fires burnt out of control across Indonesia for months; haze extended as far as Singapore and resulted in a deficit of more than

US$4.5 billion in tourism and business (Glover and Jessup 1999), in addition to huge amounts of greenhouse gas emissions (Page et al. 2002). The haze is a hazardous cocktail of trace gases, toxic aerosols and smoke particles, most of which derive from peat combustion. In Indonesia, approximately 1.8 Gt of carbon dioxide are annually emitted due to peatland degradation and fires (Hooijer et al. 2006). Raised awareness of global climate warming is increasingly reaching large numbers of people and the Indonesian peatlands recently became a "burning issue" in the media worldwide. It is now recognized that they no longer act as a carbon sink but as a huge source, with global consequences.

The drivers of Indonesian forest clearing are economic, political, social and environmental factors; as these strengthen and weaken so do the temporal rate and spatial extent of forest cover clearing (Hansen et al. 2009). At present, the increased demand for biofuel in Europe and the US causes enormous pressure on the remaining peat swamp forests. Satellite image analysis showed that in 2008 in Block B of the Mega Rice Project area 106 km² of peatland were converted to plantations, the first ones in this area; at least developed on already degraded peatland. Rather than developing palm oil and timber estates on deforested peatland, most schemes have focused on the remaining forested areas. Currently, 35% of the Indonesian peatlands are under concession for logging, timber and oil palms (Hooijer et al. 2006). Of the Indonesian palm oil, 25% is produced on the fragile peat soils, and plans of an additional 6 million ha of development over the next 20 years will focus over 50% of the new plantations on peatland (Page et al. 2008). Palm oil produced on peat soils leads to large amounts of carbon dioxide emissions, as drainage is necessary. The annual emissions are in the order of 55 t/ha (Melling et al. 2005; Murayama and Bakar 1996), compared to oil palm yields of only 3-6 t/ha (CKPP 2008). Palm oil cannot be produced sustainably on peatlands for several reasons: 1) it has a very negative CO_2 balance, 2) it threatens globally important biodiversity, including the Borneo Orang Utan and Sumatran Tiger, and 3) in the long-term creates high flood risks in the plantation area and downstream, caused by subsidence and impaired hydrological peat function. NGOs advocate that palm oil should preferably be produced on mineral soils and not on peat. In addition to the palm oil dispute, clear-felled peat swamp forests often remain as wastelands and restoration is difficult without the cooperation of concession holders (Uryu et al. 2008; CKPP 2008). As long as deforestation is cheaper than conservation, peatland degradation will continue, with severe consequences for the global climate, biodiversity and local communities. International support is needed to help Indonesia to better protect their peat resources through forest conservation, peatland restoration and improved water management in plantations.

The groundwater level is the main control on carbon dioxide emissions from peat soils. Therefore, large-scale peatland restoration by rewetting has very high potential to mitigate global climate change. This thesis shows that the successful rewetting of a 590 km² large area of drained peat swamp forest could result in mitigated emissions of about 1.5 Mt CO_2 annually, and can be achieved by the construction of 225 small dams made of locally available material at low cost. After improving the hydrology of deforested peatlands, regreening is important to protect the peat soils from direct sunlight, to reduce surface water streams and to restore carbon sequestration. Radar sensors should be utilised for monitoring large-scale rewetting from space in order to specifically plan vegetation re-establishment and to optimise restoration techniques, as tropical peatland rehabilitation is at an early stage (Page et al. 2008). Peat soil moisture and groundwater levels are crucial parameters for fire hazard warning systems and to estimate carbon dioxide mitigation. Fire brigades have been established in Central Kalimantan to reduce fire incidence and damage, but are restricted due to difficult peatland access and a lack of financing. Furthermore, peatland rehabilitation must be complemented by a range of efforts to reduce poverty (Page et al. 2008, CKPP 2008). In Indonesia, poverty rates in peatlands are two to four times higher than in other areas (Silvius and Diemont 2007). In the absence of economic alternatives for local people it is impossible to ensure sustainable peatland conservation and management, and to make credible investments in peatland restoration. Integrated conservation and development projects are required to break the vicious circle of poverty and environmental destruction.

Innovative approaches such as carbon financing and biodiversity off-sets can support peatland conservation as well as poverty reduction. Currently, carbon trading with peatlands is only possible on the voluntary carbon market because emissions due to peatland loss do not fall under the Kyoto emission reduction agreements. However, the payment for Reduced Emissions from Deforestation and Degradation (REDD) is a new possibility which has been developed by the World Bank in 2007. Peat swamp forests are candidates for “avoided deforestation”, while deforested peatlands are candidates to prevent further degradation and emissions by drainage and resultant fires. In Indonesia, many REDD pilot schemes and projects are already under development. Whereas during the 2007 UNFCCC summit the REDD mechanism was officially started and included in the Bali Roadmap, which sets the agenda for a new UN climate treaty, at the 2009 summit in Copenhagen (COP-15) negotiations were made on financing models and incentive schemes for REDD-plus. Since several problems emerged from the REDD mechanism, REDD-plus was developed which includes an extra consideration for sustainable forest management and afforestation/reforestation in developing countries. According to estimates by the World Bank, REDD-plus could cost the industrial nations about US$ 50 billion yearly until 2020, which will be given to developing countries. REDD activities are undertaken by national or local governments, NGOs and the private sector. The World Bank's Forest Carbon Partnership Facility (FCPF) and the UN-REDD Programme are examples of organisations that support developing countries interested in REDD. Another finance mechanism for peatland protection in Indonesia is the Bio-rights approach which involves the establishment of a business contract that provides micro-credit for sustainable development in exchange for the conservation or rehabilitation of globally important biodiversity or environmental values such as carbon stocks; business partners are e.g. a NGO or bank and a local partner (Silvius and Diemont 2007). To mitigate global climate change, tropical peatlands need to be protected as fast and as widely as possible. There is a high and urgent demand for peat swamp forest conservation in the Indonesian provinces of Papua and West Papua, where about 70% of the peatlands are still forested (Hooijer et al. 2006). Peatland restoration and sustainable management are necessary in the first place in the provinces of Central Kalimantan and Riau, where degradation and concession holding is especially intense.

3 Ongoing and future work

Part of the work of this thesis has already been implemented and conducted in research projects. Within the South Sumatra Forest Fire Management Project (SSFFMP) (2006-2008), funded by the European Commission and the Indonesian Ministry of Forestry, the peat dome volume and carbon storage of several peat domes in South Sumatra were estimated using the proposed method that combines remote sensing and geospatial 3D modelling techniques. Furthermore, peat dome modelling was successfully applied to the Ketapang peatland in West Kalimantan, with in situ peat thickness measurements provided by Fauna and Flora International (FFI) in 2009. Next, the carbon storage of a 1,400 km^2 large peatland in the Kapuas Hulu district, West Kalimantan, will be estimated in the course of a REDD pilot study by FFI. Within the WWF Sebangau study in Central Kalimantan, which aims at mitigation of carbon dioxide emissions by peatland rewetting, 56 dams have already been constructed and a Project Design Document (PDD) has been under development since January 2010. A PDD is the official application for project approval under the UN Clean Development Mechanism (CDM) or a verification standard in the voluntary carbon market. If validated by an independent third party, approved and registered by the CDM Executive Board or voluntary standard provider, the rewetting project qualifies as a CER (Certified Emission Reduction) or VER (Verified Emission Reduction), respectively, carbon credit earner. If successful, this can be a start for numerous tropical peatland restoration projects to come in Indonesia.

Based on the results of this thesis, future research work is recommended. For carbon storage estimation of the Indonesian peatlands a conservative value of 58% carbon content on average was used. However, this is based on limited field measurements provided in the literature and therefore, should be validated by further data. Moreover, the calculation is based on a peatland area that probably is underestimated by 10%, but no detailed information on peatland extent in Indonesia exists to date. In view of carbon crediting and monitoring of peatland restoration measures, large-scale groundwater level measurements are required, as intended in the WWF Sebangau project.

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