The role of fire on land cover changes in Borneo

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Abstract
Borneo has experienced heavy deforestation, forest degradation and repeated disastrous forest fires during the past two decades. In this study the Moderate Resolution Imaging Spectroradiometer (MODIS) was used to monitor land cover changes in Borneo between 2002 and 2005 in order to assess the current extent of the forest cover, the deforestation rate and the role of fire in deforestation. Using Landsat and ground observation for validation it was possible to discriminate 11 land cover classes in cloud-free MODIS image mosaics. In 2002 57% of the land surface of Borneo was covered with forest of which 74% was lowland dipterocarp forest and 23% peat swamp forest. The average deforestation rate between 2002 and 2005 was 1.7% per year. The carbon rich ecosystem of peat swamp forests showed a deforestation rate of 2.2%. Almost 98% of all deforestation occurred within a range of 5 km to the forest edge. The role of fire was investigated with special emphasis on the tropical peat land areas, which are store and sink for carbon of global importance (Page et al. 2002). A complete data set of MODIS active fire detections (hotspots) for the years 2002 – 2006 was used to investigate fire occurrence in relation to land cover and the spatial pattern of the distribution of fire. Fire occurrence was highly correlated to previous forest disturbance: Most fires were detected in logged over forests, degraded forests and forest mosaics. 98% of all forest fires were detected within a 5 km zone from the forest edge. Undisturbed and undrained peat swamp forests were hardly affected by fire even under El Niño drought conditions. Our results show the importance of long term time series analysis to better understand conditions leading to recurrent forest fires in tropical rain forests underlining that fire is a major driver for forest degradation and deforestation. Furthermore our results are useful to improve fire management, fire hazard prediction and early warning in order to preserve remaining forests and the peat carbon store.

Introduction
The world’s tropical rain forests are highly threatened by overexploitation and forest conversion. Several studies showed that the global relative rate of deforestation is 0.5% per year. It is highest in Southeast Asia with 0.8 - 0.9% followed by Latin America and Africa both with an annual deforestation rate of 0.4 - 0.5% (FAO 2000, Achard et al. 2002, FWI and GFW 2002, Fuller 2006). Before deforestation takes place, forest degradation by logging and fire occurs as a preliminary stage (Asner et al. 2005). To the annual deforestation of 5.8 million ha of tropical rain forests worldwide adds another 2.3 million ha which get degraded per year through fragmentation, legal and illegal logging or fires (Mayaux et al. 2005). Major drivers in Southeast Asia are logging, agricultural expansion, the establishment of infrastructure and the conversion of forests into oil palm and pulp wood plantations

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To observe these processes satellite remote sensing is the only feasible way to qualitatively assess deforestation on a regional scale. Most regional land cover mapping surveys were done at low and moderate resolution using SPOT VEGETATION (Satellite Pour l’Observation de la Terre), MODIS (Moderate Resolution Imaging Spectroradiometer), MERIS (MEdium Resolution Imaging Spectrometer) and NOAA AVHRR (National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer) (Malingreau et al. 1989, Achard and Estreguil 1995, Mayaux et al. 1998, Eva et al. 1999, DeFries et al. 2000, Loveland et al. 2000, Zhu and Waller 2003, Fuller et al. 2003, Giri et al. 2005). High resolution systems such as Landsat or SPOT allow a detailed analysis (Achard et al. 2002) but to monitor vast tropical areas their use is limited because their swath is narrow and they have only a low temporal resolution, (Fuller 2006).

In our study we focused on Borneo because it has the largest remaining area of tropical rainforest in Southeast Asia and it is representative for the fast deforestation processes in the region (Achard et al. 2002, Fuller 2006, Trigg et al. 2006). We used multitemporal medium resolution MODIS image composites to analyze land cover changes and deforestation between 2002 and 2005 and MODIS hotspot data to investigate the role of fire related to deforestation.

Materials and methods

Study area

Borneo is situated between 5° S and 8° N latitude and between 108° E and 120° E longitude and is shared by three nations: Brunei Darussalam, Indonesia and Malaysia. It has a tropical climate with high temperatures and frequent rainfall around the year, but with a drier period between May and October. Typical for the Southeast Asian region is the diverse occurrence of members of the dipterocarp tree family (MacKinnon et al. 1996). The coastal lowlands of Borneo are covered by vast areas of peat swamp forests which contain many commercially important timber species (Rieley and Page 2005). All forest ecosystems are highly threatened by over-exploitation and fire (Page et al. 2002, Brook et al. 2003, Curran et al. 2004, Sodhi et al. 2004, van Nieuwstadt and Sheil 2005, Trigg et al. 2006).

Satellite data

The MODIS L2G daily surface reflectance product (MOD09GHK/ MYD09GHK for the 500 m bands and MOD09GQK/ MYD09GQK for the 250 m bands) was downloaded from the EOS Data Gateway with bands 1 and 2 for red and NIR in 250 m resolution and bands 3-7 in 500 m spatial resolution. Owing to frequent cloud cover in this part of the tropics it was necessary to create a cloud-free image mosaic suitable for land cover classification. For 2002 and 2005 57 and 60 single day images were selected visually as the most fitting to minimize off-nadir
effects and unfavorable cloud conditions as haze and scattered clouds (Langner et al. submitted).

**Land cover classification**

An unsupervised classification was used for the land cover classifications of the 2002 and 2005 composites. Unsupervised approaches give better classification results for large and unknown areas because no prior information about the land cover types and their distribution is required and the algorithm purely relates on spectral characteristics (Cihlar 2000). Elevation data of the Shuttle Radar Topography Mission (SRTM, http://srtm.usgs.gov/, 90 m resolution) was used to discriminate lowland and mountain forests. The land cover map of 2002 served as base map, it was validated using 18 high resolution Landsat 7 ETM+ images covering all ecological zones of Borneo. Two different sampling methods were combined to derive 650 randomly selected points which were visually interpreted, thus taking into account the varying extent of the different land cover types.

**Active fire detection and patterns of deforestation**

MODIS hotspot data detected by the MODIS Rapid Response System (Web Fire Mapper, http://maps.geog.umd.edu/) using the version 4 contextual fire detection algorithm were used to identify active fires at a spatial resolution of 1 km (Justice et al. 2002, Giglio et al. 2003). All hotspots acquired between 2002 and 2006 were analyzed to investigate the role of fire in land cover change and deforestation. To calculate the fire affected area the hotspot data were buffered with a 1 km square buffer and superimposed on the land cover maps of 2002 and 2005. The area of overlapping hotspots was considered to be burnt only once. The occurrence of fire in forests was analyzed regarding its spatial pattern in relation to forest edges. All forest areas were buffered inwards with either a 1 km or a 5 km buffer zone.

**Results**

**Land cover in 2002 and 2005**

Between 2002 and 2005 the forested area of Borneo decreased from 57% to 54% consisting of 59.5% lowland dipterocarp forests (56.2% in 2005), 23.6% peat swamp forests (22.0% in 2005), 10.8% of upper dipterocarp forests (10.6% in 2005), 4.0% of mountain forests (4.4% in 2005), 1.9% of mangrove forests (1.5% in 2005) and a small fraction of freshwater swamp forests(table 1).

**Table 1 — Area of land cover classes 2002 and 2005**

<table>
<thead>
<tr>
<th></th>
<th>2002 (ha)</th>
<th>2005 (ha)</th>
<th>Annual change (%)</th>
</tr>
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<tbody>
<tr>
<td>Mangrove Forest</td>
<td>804,463</td>
<td>613,269</td>
<td>-7.92%</td>
</tr>
<tr>
<td>Freshwater Swamp Forest</td>
<td>85,088</td>
<td>90,813</td>
<td>2.24%</td>
</tr>
<tr>
<td>Peat Swamp Forest</td>
<td>9,893,231</td>
<td>9,228,638</td>
<td>-2.24%</td>
</tr>
<tr>
<td>Lowland Forest (&gt;40% crown cover)</td>
<td>24,925,694</td>
<td>23,553,588</td>
<td>-1.83%</td>
</tr>
<tr>
<td>Upper Dipterocarp Forest (forest &gt; 800 m)</td>
<td>4,512,075</td>
<td>4,435,425</td>
<td>-0.57%</td>
</tr>
<tr>
<td>Mountain Forest (forest &gt; 1,200 m)</td>
<td>1,676,356</td>
<td>1,825,344</td>
<td>2.96%</td>
</tr>
<tr>
<td>Degr. Forest (≤40% crown cover), Regrowth</td>
<td>15,228,238</td>
<td>14,343,831</td>
<td>-1.94%</td>
</tr>
</tbody>
</table>
The validation of the 2002 land cover map with its 11 classes showed an overall accuracy of 84.8% with a kappa coefficient of 0.829. Regarding the detection of forest versus non-forest the overall accuracy was 89.2% with a kappa coefficient of 0.779.

Land cover change 2002 - 2005

The total land mass of Borneo is 75 Mha. Without taking into account areas of reforestation, 18 Mha showed changes in land cover and more than 7 Mha were degraded or deforested. Highest deforestation rates occurred in mangrove forests with almost 8% owing mainly to conversions into crab ponds. Peat swamp forests were deforested with 2.2% per year, while lowland forests had a deforestation rate of 1.8% per year. The overall rate of forest loss was 1.7% per year.

To examine the causes of deforestation we analyzed the spatial pattern of change. We investigated whether there is increased deforestation in a 5 km zone from the forest edge and analyzed the proportion of deforestation which occurred in this zone since this area is most easily accessible by farmers and illegal loggers compared to the more inaccessible forests further than 5 km from the forest edge. Not surprisingly 97.7% of all forest conversion/degradation between 2002 and 2005 occurred within the 5 km zone (Figure 1).

Figure 1 — Loss of forest between 2002 and 2005, superimposed on 2002 MODIS multitemporal composite. Most forest loss clearly occurs next to forest edges and fragmented forest mosaics (marked with 5 km buffer zone to forest edges).

Deforestation and fire

It is important to highlight that there are different fire regimes on Borneo which strongly correlate to the forest and land cover type (Miettinen et al. 2006). Small-scale clearings are a typical feature of slash and burn agricultural activities while large-scale fire scars occur in peat lands in Kalimantan. Our results indicate that small-scale fires are not be reliably detected by MODIS while large fires, which burn...
for several hours of days such as peat fires are easily detected by the MODIS sensor (Siegert et al. 2004) (Figure 2).

**Figure 2** — Different fire regimes in Borneo. Left panel: 2005 MODIS hotspots superimposed on burn scars in West Kalimantan. Right panel: large-scale fire scars in Central Kalimantan.

The role of fire in land cover change and deforestation was investigated by analyzing the spatio-temporal pattern of all hotspots recorded both in 2002, 2005 and 2006 (Table 2). Both years, 2002 and 2006, have been affected by the El Niño Southern Oscillation (ENSO) and showed much higher fire activities. In 2002 44,656 hotspots were detected potentially affecting 2.9 Mha of which 0.8 Mha was forest. In 2005 this number was much lower with 15,322 hotspots potentially burning an area of 1.1 Mha of which 0.2 Mha was forest. The year 2006 was much stronger with more than 3 times the amount of the 2005 fires (53,093) potentially affecting an area of almost 3.4 Mha of which 1 Mha was forest. There is a small bias towards the 2006 forest fires because the 2006 fires were superimposed on the 2005 land cover which does not show the areas of degraded forests due to the 2005 fires. In figure 3 the El Niño years 1997/97, 2002 and 2006 are clearly visible with an increased number of fire detections.
Fire affected cultivation forest mosaics and degraded forests most in all years. However, there is a clear trend towards forest fires and especially the carbon rich peat swamp forest are increasingly affected by fire in El Niño years. In 2002 and 2006 0.59 Mha and 0.76 Mha of peat swamp forests were affected by fire even though the total area of peat swamp forests is less than half of the area of lowland dipterocarp forests.

**Table 2 — Distribution of fire-affected area into land cover types**

<table>
<thead>
<tr>
<th>Land cover class</th>
<th>2002 (%)</th>
<th>2005 (%)</th>
<th>2006 (%)</th>
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<tbody>
<tr>
<td>Mangrove Forest</td>
<td>0.3</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Peat Swamp Forest</td>
<td>20.2</td>
<td>10.7</td>
<td>22.4</td>
</tr>
<tr>
<td>Degraded Forest ≤ 40% crown cover and Regrowth</td>
<td>33.4</td>
<td>27.1</td>
<td>29.4</td>
</tr>
<tr>
<td>Cultivation Forest Mosaic</td>
<td>25.3</td>
<td>37.1</td>
<td>29.6</td>
</tr>
<tr>
<td>Dry/Wet bare Soil; Grasslands; Agriculture</td>
<td>13.5</td>
<td>16.4</td>
<td>11.3</td>
</tr>
<tr>
<td>Lowland Forest (&gt; 40% crown cover)</td>
<td>6.7</td>
<td>8.1</td>
<td>6.3</td>
</tr>
<tr>
<td>Upper Dipterocarp Forest</td>
<td>0.1</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>Freshwater Swamp Forest</td>
<td>0.5</td>
<td>0.2</td>
<td>0.9</td>
</tr>
<tr>
<td>Mountain Forest</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
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The study of the spatial distribution of forest fires showed that there is a strong correlation between distance from the forest edge and number of forest fires. The closer to the forest edges the higher the number of forest fires (Figure 4). In 2002 75% and 98% of all fires which were detected in undisturbed forests were within 1 km or 5 km distance of the forest edge and in 2005 it was 81% and 99% respectively.

We studied the impact of fire on land cover change by analyzing the spatial distribution of all hotspots which were recorded between November 2002 and December 2004 (analyzing only the hotspots which might be responsible for land cover change). During this period 44,869 hotspots have been detected which affected an area of 3.1 Mha. According to the change map 50% of these fires occurred on
areas showing land cover change, mainly on agricultural areas and 20% of the hotspots were detected in areas where deforestation occurred.

**Figure 4** — Forest fires of 2006, superimposed on 2005 MODIS multitemporal composite. Forest fires clearly occur next to forest edges and fragmented forest mosaics (marked with 5km buffer zone to forest edges).

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**Discussion and Conclusion**

Between 2002 and 2005 we recorded a deforestation rate of 1.7% per year in Borneo which is almost double in comparison to the whole Southeast Asian region with 0.9% (Achard et al. 2002). According to other studies in Borneo, illegal logging increased tremendously in the past years (MacKinnon et al. 1996, Boehm and Siegert 2001, Casson and Obidzinski 2002, Page et al. 2002, Dudley 2004, Fuller 2006). Our results show that most changes are related to the overexploitation of forests or forest conversion. To investigate possible causes for the high annual deforestation rate of 8% in mangrove forests we used high resolution Landsat data. The images clearly show that most of the forests have been clear felled for the establishment of shrimp ponds. The second largest deforestation rate was observed on peat swamp forests. Because these forests grow on a layer of peat up to 20 m deep, they are a carbon source of global importance if fires ignite the peat layer (Page et al. 2002, Rieley and Page, 2005). Peat swamp forests decreased with an annual rate of 2.2% while lowland dipterocarp forests were degraded at a rate of 1.8% per year and the more remote upper dipterocarp forests showed only 0.6% loss per year. Almost half of the land area of Borneo is covered by plantations, degraded forests, fallow land and cultivated land.

Regrowth was observed in Sarawak where in 2002 intense selective logging activities resulted in a higher soil signal due to opened crown cover whereas the crown cover was closed by regrowth in 2005. Regrowth also occurred on peat lands, where old burnt scars showed dense tree thicket regrowth.

Our results clearly showed that deforestation is strongly correlated to fire. The MODIS sensor detected 44,869 fires between November 2002 and December 2004; 50% occurred on agricultural areas and grasslands, which means that they were related to slash and burn activities. Slash and burn techniques have a long history in Southeast Asia (MacKinnon et al. 1996). In general these techniques are regarded sustainable if the time period between the burning events is long enough. The problem is not the fire itself but the fire repeat cycle (Cochrane 2003). Almost 20%
of these fires were detected on areas with strong deforestation revealing high human impact on the ecology of Borneo.

The investigation of the fire affected area over the period 1997-2006 revealed that there is a strong bias towards forest fires and especially to peat fires in the El Niño years 2002 and 2006. In 2002 0.8 Mha of forest were affected by fire of which almost 0.6 Mha were peat swamp forests, in 2006 it was even 1 Mha of forest – with almost 0.8 Mha of peat land, while in the non-El Niño years such as 2005 only 0.2 Mha of forest were affected by fire of which 0.1 Mha were on peat swamp. It has to be noted that the total area of peat swamp forests is just 23% of the total forest area. This clearly shows that peat swamp forests are much higher susceptible to fire than any other forest type. This may be related to land clearing activities and for the establishment of plantations, especially oil palm and pulp wood. Due to the fact that fires on peat lands often affect both the surface vegetation and the underlying peat layer, they release much larger amounts of CO₂ into the atmosphere than fires in forests on mineral soils.

The susceptibility of vegetation to fire is correlated to the level of moisture content and remains low in undisturbed forests even during extended droughts. As a consequence occurrence of fire more frequents close to forest edges or in disturbed forest with opened canopy (Siegert et al. 2001, Cochrane 2003). Our results confirm these observations for the whole island of Borneo, showing a strong correlation between fire and forest degradation. In a buffer zone of 5 km along the forest edges 97.7% of all forest degradation and 98% of all forest-fires occurred, showing clearly that forest degradation originates from the outskirts of the forests due to human activities and undisturbed forests are very unlikely to burn (Siegert et al. 2001).

Recurrent forest and peat fires in Borneo threaten the unique forest ecosystems with their highly endemic biodiversity. Owing to the high carbon content of peat swamp forests the uncontrolled fires in Borneo and Sumatra are of global importance. Page et al. calculated for the 1997 El Niño event that between 0.81 and 2.57 Gt of carbon were released to the atmosphere, equivalent to 13-40% of the mean annual global carbon emissions from fossil fuels (Page et al. 2002). Assuming the same conditions for the 2002 and 2006 El Niño fire season as in the study of Page et al. with a peat bulk density of 0.1 g cm⁻³, 50% of the above-ground biomass (250 t Cha⁻¹) burned and an average depth of peat burned of 0.5 m (Page et al. 2002), we estimate the amount of carbon released to atmosphere from fires on peat soil (according to FAO and Wetlands International peatland maps and the number of fires detected on peatland) for the EQUAS region (Indonesia, Malaysia, Brunei). During the comparatively weak El Niño years 2002 and 2006 an amount of approximately 0.51 – 0.60 Gt and 0.66 – 0.77 Gt of carbon were released into the atmosphere. If CO₂ emissions from drained peatland are included, this makes the EQUAS region and especially Indonesia, which is responsible for more than 90% these emissions, one of the major contributors to global CO₂ emission.

Our study in Borneo clearly shows that forests which were previously degraded by logging or fire have a higher susceptibility to fire than closed and undisturbed forests confirming a positive feedback between fire and forest disturbance. Referring to the high rate of deforestation and forest degradation in Borneo almost all lowland forest types will be destroyed by recurrent fires within the next few years if no serious action is taken for fire prevention and suppression.
Acknowledgements

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References


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