Biogeosciences Discuss., 10, 12625–12653, 2013
www.biogeosciences-discuss.net/10/12625/2013/
doi:10.5194/bgd-10-12625-2013

Biogeosciences
Discussions
Open Access

Change in tropical forest cover of Southeast Asia from 1990 to 2010

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Received: 4 July 2013 – Accepted: 22 July 2013 – Published: 5 August 2013

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The study assesses the extent and trends of forest cover in Southeast Asia for the period 1990–2000–2010 and provides an overview on the main drivers of forest cover change. A systematic sample of 418 sites (10 km × 10 km size) located at the one-degree geographical confluence points and covered with satellite imagery of 30 m resolution is used for the assessment. Techniques of image segmentation and automated classification are combined with visual satellite image interpretation and quality control, involving forestry experts from Southeast Asian countries. The accuracy of our results is assessed through an independent consistency assessment, performed from a subsample of 1572 mapping units and resulting in an overall agreement of > 85 % for the general differentiation of forest cover vs. non-forest cover. The total forest cover of Southeast Asia is estimated at 268 Mha in 1990, dropping to 236 Mha in 2010, with annual change rates of 1.75 Mha (∼ 0.67 %) and 1.45 Mha (∼ 0.59 %) for the periods 1990–2000 and 2000–2010, respectively. The vast majority of forest cover loss (∼ 2/3 for 2000–2010) occurred in insular Southeast Asia. Combining the change patterns visible from satellite imagery with the output of an expert consultation on the main drivers of forest change highlights the high pressure on the region's remaining forests. The conversion of forest cover to cash crop plantations (e.g. oil palm) is ranked as the dominant driver of forest change in Southeast Asia, followed by selective logging and the establishment of tree plantations.

1 Introduction

About 15 % of the world's tropical forests are located in Southeast Asia (FAO, 1995), including for this study Papua New Guinea (PNG) and the Solomon Islands as part of the Southeast Asia region (Fig. 1). Forests in continental Southeast Asia consist for the most part of mixed deciduous forest types, including for instance the precious Teak forests, whilst the insular sub-region holds for example large extents of highly productive evergreen *Dipterocarpus* forests. Carbon-rich ecosystems of mangrove and peat swamp forests still occupy many coastal zones of the region (Donato et al., 2011; Page et al., 2011). Southeast Asia's tropical forests play an important role for environmental protection and biodiversity, as well as for socio-economy and living conditions of forest depending populations (e.g. Lee, 2009). These forests are also of importance in the context of global carbon balance. Deforestation in the tropics is considered to contribute about 15 % of man-made global emissions (van der Werf et al., 2009), and the deforestation rate in Southeast Asia has been among the highest in the tropics (e.g. Achard et al., 2002). The United Nations Food and Agriculture Organisation (FAO) reported a net annual forest area loss in Southeast Asia of 2.4 Mha in the 1990s, and then of 0.4 Mha and 1.0 Mha for the periods 2000–2005 and 2005–2010, respectively (FAO, 2010).

However, estimates of tropical forest area and change contain still considerable uncertainty, having impact on the estimation of carbon emissions caused by deforestation and forest degradation in the tropics (e.g. Harris et al., 2012). At regional levels, forest cover estimates derived by aggregation of national forest data (e.g. FAO, 2010) often suffer from incompatibilities of inventory methodologies, definitions and inventory dates. But there is also variability of forest change estimates at national levels. For example, for Indonesia annual forest loss for the periods 2000–2005 and 2005–2010 has been reported by FAO (2010) at 0.3 Mha and 0.7 Mha, respectively, whilst recent remote sensing studies presented annual change estimates of 0.71 Mha and 0.88 Mha for the periods 2000–2005 and 2000–2010, respectively (Hansen et al., 2009; Miettinen et al., 2011). There is a need to reduce such uncertainties in estimating forest cover change, also in view of reporting in the context of initiatives related to "Reducing Emissions from Deforestation and Degradation" (REDD+) (Bucki et al., 2012).

The objective of this study is to provide a uniform assessment of forest cover and forest cover changes of Southeast Asia for the periods 1990–2000–2010. We aim at a regional perspective, consistent across country boundaries and through the study period, with linkage to the main causes and drivers of forest change. The results are

expected to serve as a reference at regional scale, for example as input to regional emission scenarios, but they can also be of interest for cross-boundary concepts of forest conservation, protected area networking or watershed management. The study has been implemented in the context of the Global Forest Resources Monitoring activity (TREES-3) of the Joint Research Centre, it is analysing a systematic pan-tropical sample with more than 4000 sites through the use of satellite imagery of medium spatial resolution. This activity also contributes to the Remote Sensing Survey of the FAO Forest Resources Assessment 2010 (FRA-2010) Project (FAO and JRC, 2012).

2 Materials and methods

2.1 Sampling, image processing, automated classification and visual review

The TREES-3 sample over Southeast Asia comprises 418 sample sites, of which 161 sites are located in continental Southeast Asia (Cambodia, Laos, Myanmar, Thailand and Vietnam) and 257 in insular Southeast Asia (Brunei, East Timor, Indonesia, Malaysia and the Philippines, in addition PNG and the Solomons). The sample units, each covering an area of 10 km × 10 km, are systematically placed at each integer confluence of the geographic grid and cover in total about 1 % of the total land area. The choice for a systematic sampling grid has been made in co-ordination with FAO FRA-2010 (Mayaux et al., 2005), permitting easy linkage to national forest inventories, which are based on systematic sampling in most tropical countries (FAO and JRC, 2012). For all sample units satellite imagery from optical sensors at medium resolution (i.e. circa 30 m) has been selected as close as possible to the reference years 1990, 2000 and 2010. Great effort has been made for establishing an optimal image data base, obtaining acquisitions of the best quality for individual locations, and accounting particularly in continental Southeast Asia for vegetation seasonality (Beuchle et al., 2011). The vast majority of imagery was obtained from the Landsat TM/ETM+ archive of the US Geological Survey (USGS, 2013). For the year 2010 imagery from other optical sensors was included in the database (Table 1). The satellite data was pre-processed including radiometric calibration, de-hazing, spectral normalization and cloud-masking (Bodart et al., 2011). A multi-stage and multi-date image segmentation algorithm was applied, creating spatially and spectrally consistent mapping units (polygons) with a stable minimum mapping unit (5 ha) and a unit size of about 40 ha in average (Raši et al., 2011). A preliminary labelling of the mapping units was performed by automated supervised classification. For the years 1990 and 2000 the classification was based on the spectral signatures of 73 initial land cover types, which were grouped to a few main land cover classes (Raši et al., 2011). For the automated labelling of the 2010 mapping units, the spectral training signatures of the main land cover classes were established for each sample unit from the year 2000 classification results. Then a minimum distance change detection procedure was applied to the spectral signatures of the 2010 polygons. Polygons detected as "changed" between 2000 and 2010 were labelled for the year 2010 according to the training signatures, whilst all other 2010 mapping polygons were labelled identical to those of the year 2000 (Raši et al., 2013). This largely automated phase was followed by an intense phase of visual review and adjustment of the mapping results, with the following objectives: (i) correcting labelling errors of the automated classification procedure, (ii) ensuring a consistent and interdependent mapping for the three dates, and (iii) integrating the forest knowledge from tropical forestry experts through a series of workshops. The importance of the visual-manual component is reflected by the fact that for example for the 1990–2000 classification about 20 % of the automatically pre-labeled polygons were re-coded after visual control (Raši et al., 2011). As reference for the visual review and correction we used mainly high-resolution satellite imagery from Google Earth© and from the TROPFOREST project (ESA, 2013). The latter provided 325 ALOS-AVNIR (10 m resolution) and 104 KOMPSAT images (4 m resolution), most of them from the year 2010, partly also from 2011. ALOS PALSAR mosaics (50 m resolution) from the year 2008 (ALOS, 2010) were used to support the differentiation between forest cover and oil palm plantations (e.g. Miettinen and Liew, 2011).

2.2 Land cover categories and area estimation

Our study focused on the assessment of forest and other woody vegetation cover, particularly on the land cover classes "Tree Cover" (TC), "Tree Cover Mosaic" (TCM) and "Other Wooded Land" (OWL) (Fig. 2). TC and TCM were defined as land cover units containing a tree cover portion of > 70 % and 30–70 %, respectively. We adopted a "tree cover" definition compatible to the FAO "forest" definition, i.e. canopy density and tree heights were expected to be ≥ 10 % and ≥ 5 m, respectively. Our tree cover includes natural forests, forest plantations as well as tree cover outside forest lands. However, aspects of dominant land use or potential tree growth were not taken into account. OWL comprises all other woody vegetation (expected height < 5 m), including shrubs, re-growing and young tree cover, as well as oil palm plantations. All non-woody land cover was grouped into the category "Other Land" (OL), except for inland water bodies (WA).

The area of each land cover category is calculated for each sample site from the resulting maps. Then land cover areas are linearly adjusted by site to the baseline dates of 30th June of each reference year and then expressed as percentages of the total unit land area, excluding "sea", "clouds" and "no-data" (i.e. proportions over total). For three missing sites (i.e. no imagery available) area estimates are inferred from the weighted average obtained from their eight closest neighbouring sample sites. In the estimation phase, the sample units are weighted with the co-sinus of the corresponding latitude to compensate for increasing sampling probability at higher latitudes (convergence of meridians). The land cover area estimates at sub-regional and regional levels are then calculated by multiplying the average weighted proportions for all sample sites with the appropriate land area of a given region. Regional land areas are obtained from the spatial data set "Country Boundaries of the World" (FAO, 2007). The areas of the categories "TC" and "TCM" are counted as 100 % and 50 % forest cover, respectively. Change rates in forest cover are calculated in relation to the averaged forest areas between the beginning and end of each assessment period, e.g. average of forest areas in 2000 and 2010 for the change rates 2000–2010. For each area estimate the corresponding standard error (SE) is calculated from a local estimation of the variance (Eva et al., 2012).

2.3 Change patterns and drivers of change

To complement the quantitative assessment we established a regional overview of the dominant pattern of forest cover change, as visible from the satellite imagery of 2000 and 2010 within each sample site. We indicate for each sample site the change pattern type most dominant, neglecting patterns of secondary importance. The identified change pattern types include (i) conversion patterns from forest to other land cover, (ii) canopy disturbance by logging, (iii) change of natural forest canopies to tree plantations, (iv) patterns of afforestation or re-forestation, (v) patterns of shifting cultivation and (vi) burned areas or new infrastructure (roads, dams). Logging roads and canopies still in the process of recovering from earlier logging were considered as logging patterns, re-planting or cutting in existing forest plantations were not considered a change, and small and spatially scattered change was neglected. Where no major change was visible during the period 2000–2010, we verified whether major change patterns existed in the imagery of the 1990–2000 period. We further compare to the output of two expert consultations on the main areas and drivers of forest change in Southeast Asia, held for continental and insular Southeast Asia in 2007 (Stibig et al., 2007b). During these consultations we identified and approximately located at regional scale major on-going processes of forest change based on the knowledge of national and regional forestry experts. This information complements our assessment by adding a forward looking dimension on change processes and by including aspects not obtainable from remote sensing.

2.4 Accuracy assessment

To produce an estimate of the accuracy of our change assessment we implemented a consistency assessment by comparing our results to a proxy reference dataset, which was obtained through a careful labelling of a subset of mapping units (polygons) by an independent interpreter with good regional expertise. A strict accuracy assessment based on field data or reference imagery of very high resolution was not feasible in view of the extensive coverage of historical data from 1990 and 2000 to be evaluated. As demonstrated over dry and humid ecosystems in Africa and for South America (Eva et al., 2012; Bodart et al., 2013; Ernst et al., 2013) this approach provides a measure of the overall consistency of the methodology, indicating the variability inherent in the remote sensing interpretation and mapping approach. For this consistency assessment a randomly selected subsample of sites (101 from the total sample of 418 sites) is taken as primary sampling units (PSU). A systematic dot grid of 81 (9×9) dots with a 1 km distance between the dots is positioned over each PSU. All polygons coinciding with the central point or the four corners points of the dot grid are selected as secondary sampling units (SSU). As additional SSU selection, from the remaining 76 points of the dot grid all polygons that display a change in tree cover in either of the two periods 1990–2000 or 2000–2010 are selected. In total 1572 polygons (SSUs) were selected and labelled by an independent interpreter into the main land cover categories ("Tree Cover", "Tree Cover Mosaic", "Other Wooded land" and "Other Land Cover"). The results of this independent interpretation were then compared to the original mapping results.

3 Results

3.1 Status and change of forest cover in Southeast Asia

In total, the forest-covered area of Southeast Asia (incl. PNG and the Solomon Islands) is estimated at 268.0 Mha, 250.6 Mha and 236.3 Mha for the years 1990, 2000 and 2010, respectively (Table 2). This indicates a total net loss of tree cover in the 1990s of 17.5 Mha, and another 14.5 Mha in the 2000s, which corresponds to annual change rates of 0.67 % (SE 0.1) and 0.59 % (SE 0.1), respectively (Table 3). At the same time, the land area covered by other wooded land (OWL = shrubs, young tree plantations, tree regrowth, oil-palm) increased during these two periods by about 10.6 Mha and 7.1 Mha, respectively.

For continental Southeast Asia the forest-covered area in 1990, 2000 and 2010 is estimated at 78.7 Mha, 76.5 Mha and 71.7 Mha, respectively. The annual net losses amount to 0.21 Mha and 0.48 Mha, or change rates of 0.27 % (SE 0.1) and 0.65 % (SE 0.18) for the 1990s and 2000s, respectively (Table 3). For the insular sub-region the forest-covered area in 1990, 2000 and 2010 is estimated at 187.9 Mha, 173.0 Mha and 163.5 Mha, respectively. Annual net losses amount to 1.51 Mha and 0.96 Mha for the 1990s and the 2000s, respectively, corresponding to change rates of 0.84 % (SE 0.14) and 0.57 % (SE 0.13) (Table 3). In the 1990s the vast majority of forest was lost in insular Southeast Asia, in the following 10 yr about one third of the total forest loss took place in continental Southeast Asia. Although the sampling strategy used in this study was designed for regional and sub-regional scales, a national estimate may be given for Indonesia (incl. East Timor). The country holds about 2/3 of the sample units of insular Southeast Asia and makes large contribution to the sub-regional estimates. Based on 156 sample units the total forest-covered area of Indonesia in 1990, 2000 and 2010 is estimated at 123.8 Mha, 112.4 Mha and 104.4 Mha, respectively. The annual forest loss of about 1.15 Mha in the 1990s and about 0.82 Mha in the period 2000–2010 makes up more than 75 % of forest loss of the sub-region. The corresponding annual change rates are 0.98 % (SE 0.21 %) and 0.76 % (SE 0.19 %), respectively (Table 3).

The spatial distribution of forest cover losses across the region shows the concentration on the islands of Sumatra and Borneo, and in the lower Mekong basin (Fig. 3). In continental Southeast Asia there is indication of increased forest cover loss along the Annamite mountain range (Laos, Cambodia and Vietnam), and in the border zones of Cambodia (with Thailand and Vietnam) and of northern Myanmar. Gains in forest cover are found for instance in parts of Vietnam. In insular Southeast Asia the spatial change pattern remains quite similar for both decades. The high pressure on the lowland and peat swamp forests of Sumatra has remained, on Borneo there are signs of expansion of forest cover loss towards the centre and the north. Forest cover gain in central Sarawak in 2010 is rather related to the management cycle of forest plantations. In general there is less forest cover loss on the islands of Sulawesi and New Guinea, however, keeping in mind that there might be change in forest canopies and structure caused by selective logging which is not reflected as change in forest area. In both sub-regions there are change locations close to or coinciding with protected areas.

Including the dominant type of change pattern, as visible from satellite imagery within the individual sample sites, shows the following (Fig. 4): (i) The conversion of forest to non-forest land is the most frequent type of change observed across the region, to a large extent linked to the locations of high forest cover loss (Fig. 3), particularly on Sumatra and Borneo, and in the eastern Mekong basin (Laos, Cambodia, Vietnam border zone). The conversion patterns in the lowlands of Sumatra and Borneo could be related in a number of cases to the presence of oil palm plantations. (ii) Canopy disturbances by (selective) logging are identified as dominant change indications in sites in eastern Sumatra, in the east of Sarawak and in Sabah, as well as in central and north-eastern Borneo. In Papua (Indonesia) and in PNG most logging locations are still related to coastal zones. Whilst the logging patterns (Fig. 4) can be an indicator for potential forest degradation, they are not necessarily linked to a quantitative loss of forest area (i.e. change of the mapping category “Tree Cover” to “Tree Cover Mosaic”). (iii) The replacement of natural forest cover by tree plantations could be observed for sites in Cambodia, on Peninsular Malaysia, on Sumatra and in Sarawak. (iv) Shifting cultivation mosaics stretch particularly across the north of continental Southeast Asia (northern Laos and Thailand, Myanmar), but were not perceived as a major factor of forest loss in the regional context. Typical examples of change patterns in Southeast Asia are displayed in Figs. 5 and 6, including (i) the massive expansion of agricultural areas, (ii) the conversion of lowland forests to oil palm plantations, (iii) the establishment of fast growing tree plantations for pulp and paper production, (iv) burned areas, (v) logging, (vi) agricultural expansion and establishment of rubber plantations, (vii) shifting cultivation, and (viii) the conversion of mangrove forests to aquaculture.

3.2 Accuracy assessment

Based on the pure systematically selected set of the mapping units (five polygons located at corners and centre of the dot grid) the overall agreement between our mapping results and the results from independent interpretation is 85 %, 85 % and 91 % for the years 1990, 2000 and 2010, respectively (overall average agreement for the three classes: "Tree Cover", "Tree Cover Mosaic" and "Other Land Cover"). For the single class "Tree Cover Mosaic" there is a lower degree of agreement, ranging between 50 % and 71 %, which reflects the difficulty to map exact tree cover proportions from the remote sensing data used. Considering the classes "Tree Cover" and "Tree Cover Mosaic" as one unique forest cover category the differentiation to "Other Land Cover" achieved an overall agreement (in area) of more than 95 % through the three reference years. Focusing only at "change" polygons the overall agreement in terms of class area was 74 %, 65 % and 71 % for the years 1990, 2000 and 2010, respectively. The higher uncertainty for mapping "change" reflects the fact that many "changed" mapping units are small and exact class thresholds even more difficult to determine. Nevertheless, taking the forest covered classes as one category in contrast to "Other Land", the overall accuracy even on the "change" polygons reaches 89 %, 86 % and 84 % for the years 1990, 2000 and 2010, respectively. In view of the fragmented landscapes and the seasonal variability of forest cover in Southeast Asia we consider the overall agreement

and mapping consistency as satisfying, providing a good indication of the achievable mapping accuracy.

4 Discussion

This study provides an updated and uniform regional view on extent and change of forest cover in Southeast Asia, making best possible use of available satellite remote sensing data. The results show a drop of the total forest cover of Southeast Asia from 268 Mha in 1990 to 236 Mha in 2010. This corresponds to a forest cover loss of ∼ 32 Mha (∼ 320 000 km^2) in only 20 yr, an area comparable to the size of Vietnam or about 6.5 % of the regions total "land" area.

Referring to the quantitative results there are only few studies one can compare to at regional levels. Most widely used is the database compiled by the FAO Forest Resources Assessment (FRA), based on country reporting and national forest inventories (FAO, 2010). The regional aggregation of these data results in "forest areas" of 281 Mha and 245 Mha for 1990 and 2010, respectively, both higher than our regional estimates of "forest cover". Several factors can be responsible for such difference: Firstly, the definitions of "forest cover" and "forest area" are not completely identical, because we do not consider aspects of "dominant land use" and "potential tree growth", contrary to the FRA. Secondly, the aggregation of national figures to regional levels holds uncertainties not easily to quantify, the error levels of the individual assessments are unknown and there are differences in methods, definitions and reference dates. Furthermore, our remote sensing based forest mapping approach tends to classify tree cover of heights just above the 5 m-class definition threshold (e.g. regrowth, dry deciduous forests-woodland formations) still to "Other Wooded Land" due to the similar spectral characteristics. National assessments might report these areas as "forest area", explaining therefore to some extent lower area estimates by this study.

At the sub-regional level of continental Southeast Asia this study estimates annual forest cover loss at 0.21 Mha and 0.48 Mha for the 1990s and 2000s, respectively (Table 3), whilst the corresponding FRA2010 figures are 0.47 Mha and 0.33 Mha. The discrepancies in change and its temporal distribution could not be put down to a specific reason. From this study's perspective, higher figures of forest loss in 2000–2010 can reflect partly the accelerated deforestation in some countries (e.g. in Cambodia and Laos), partly the fact that according to our "Tree Cover" definition we do not include young forest plantations in forest cover (e.g. extensive areas in Vietnam), therefore not counterbalancing forest loss (FAO, 2010). Also limitations in accurately assessing change in seasonal and dry forest cover on the continent can play a role. The canopies of these forests are to variable extent leafless during the dry season, often very open with transitions to woodland, and ground cover is frequently burned, making unambiguous class assignments from satellite imagery difficult. Underestimation of change for the first assessment period might have led to some extent to overestimation for the second period. For insular Southeast Asia there are obvious differences for Indonesia: our estimates of annual forest cover loss for the 1990s and 2000s are 1.15 Mha and 0.82 Mha (Table 3), compared to FRA2010 figures of 1.93 Mha and 0.51 Mha, respectively. A review of our sample sites did not explain these differences. However, for the period 2000–2010 our annual change estimate is rather in the range of those from other remote sensing studies, with 0.71 Mha for the period 2000–2005 (Hansen et al., 2009) or 0.88 Mha for the period 2000–2010 (Miettinen et al., 2011). The difficulty to accurately assess the forest cover destroyed during the 1997/1998 fires might have influenced the 1990s estimate of the national assessment, leading possibly to the very high change figure for the 1990s and accordingly to a lower figure for the following decade.

Combining our results with the output on major change areas and main drivers of change, as compiled in parallel by expert consultation (Stibig et al., 2007b), underlines the high pressure and threats for the region's remaining forests (Fig. 7):

1. The conversion of forests to cash crops plantations has been ranked the most important driver of forest change in Southeast Asia. This is supported by the change patterns identified within our sample sites (Fig. 4). Main cash crops include in con-

tinental Southeast Asia coffee (e.g. S-Laos, central highlands Vietnam), tea (e.g. N-Thailand, Yunnan border area), sugar cane (e.g. N-Laos) as well as oil palm (e.g. S-Myanmar). For insular Southeast Asia the highest impact has been seen in the expansion of oil palm plantations, often on peat land, and mainly in eastern Sumatra, coastal Sarawak, central and northeast Kalimantan and southeast Papua, but also starting in Papua New Guinea (Fig. 7).

2. Non-sustainable selective logging has been ranked as the second important driver of change, causing forest degradation and initiating conversion processes. On the continent logging is an issue along the Annamite mountain range (Laos, Vietnam, Cambodia) and in northern Myanmar (Fig. 7). Our analysis of visible change patterns (Fig. 4) did not show major logging indicators in continental Southeast Asia, probably because forest cover is already fragmented and signs of logging are less visible in the deciduous and frequently logged-over forests on the continent. For insular Southeast Asia major logging-affected areas were identified in eastern Sarawak and central Kalimantan (Fig. 7), as also reflected by the change patterns of our visual analysis (Fig. 4). The extent of logging-affected areas identified for New Guinea (Fig. 7) may be taken as indication for the island becoming a new focus for timber logging, after decades of intense timber extraction on Sumatra and Borneo. Our quantitative analysis does not display huge change in forest area for New Guinea (Fig. 3), and the change patterns observed in the sample sites (Fig. 4) do not reflect a large spatial extent of logging. However, logging patterns may not be visible when logging intensities are still low and logging road networks are missing, considering that canopies in the humid evergreen forests quickly close after intervention. For a number of cases in continental and insular Southeast Asia the local experts classified logging as "illegal" and affecting protected areas, although the level of recent illegal logging in the insular sub-region was judged to be lower than in the past.

3. The conversion of natural forest canopies to fast growing tree plantations (e.g. *Acacia mangium* on Sumatra and Borneo) or to rubber plantations (e.g. in Cambodia, Laos and Thailand) has been ranked third in terms of importance for forest change in Southeast Asia.

4. At local levels important causes for change further include fires (e.g. Indonesia, Thailand), mining (e.g. Indonesia, Laos), urbanization (Myanmar), construction of hydropower dams (e.g. Mekong basin), road construction (e.g. Laos, Cambodia), shrimp farming (mangrove areas), fuel wood collection (Myanmar, Thailand, Vietnam), migration of ethnic groups (e.g. Myanmar) and resettlements (e.g. Laos). The impact of shifting cultivation (e.g. Myanmar, Laos) has been classified as "secondary" in the context of regional forest loss and compared to its role in the pre-1990s.

The magnitude of forest change in Southeast Asia in the last two decades and the continuing significance of the active drivers of forest change highlight the need for regional concepts for sustainable forest management and forest protection, not only for preserving some of the remaining intact tropical forests of Southeast Asia and for maintaining regional biodiversity, but also in order to deliver the forest and environmental services needed by a growing population.

Acknowledgement. We are grateful for having received the vast majority of Landsat satellite data from the United States Geological Survey (USGS). We are thankful for the support of the CEOS LSI Constellation team (US), and of ACRES (Australia), GISTDA (Thailand) and SPOT IMAGE (France) for providing additional satellite imagery from 1990 and 2000. We thank the European Space Agency (ESA) for providing 2010 imagery (AVNIR, KOMPSAT) in the context of the TROPFOREST project, and GISTDA (Thailand) for providing 2010 TM imagery from the Thai receiving station.

We would like to thank all the experts from national forestry institutions in Southeast Asia and PNG for their support in reviewing and "validating" the TREES mapping results in the context of regional workshops: S. Sophyra, L.Chivin and P. Sam (Forestry Adm. Cambodia), K. Chanthalasy, B. Luangphaseuth, H. Khamma and S. Siboun (Forestry Dep. Laos), San San Aye, A. Aung

Myint, P. Htut, and U. A. Myo Win (Forest Dep. Myanmar), S. Punkul (Royal Forest Dep. Thailand), Y. Jantakat (Suranaree Uni. Thailand), N. Phu Hung, L. Anh Hung and M. V. Tinh (FIPI, Viêt Nam), J. Wong-Basiuk (Sarawak Forestry Dep., Malaysia), J. A. Ignacio (ESSC, Philippinnes), R. Sari and Mr. Budiharto (MoF, Indonesia), A. Wijaya (CIFOR, Indonesia), J. Pokana (Office of Climate Change, PNG), and L. Li and T. A. Moe (AIT/UNEP RRC.AP, Bangkok).

We are further grateful for the support of regional experts for identifying regional patterns and drivers of forest change in the context of two sub-regional workshops in Jakarta and Vientiane in 2007: V. Ambia (Forest Authority, PNG), M. Boccucci (World Bank, Indonesia), R. Dennis (CIFOR/SEKALA, Indonesia), D. Gaveau (WCS, Indonesia), M. Jaeger (EC-FLEGT, Indonesia), E. Meijaard, (Nature Conservancy, Indonesia), Y. K. D. Muliastra (SEKALA, Indonesia), J. Schade, (DFS, Germany), F. Siegert (RSS, Germany), Fred Stolle (WRI, US), Ib. K. Wedestra (EC- FLEGT, Indonesia), J. B. Weingart (Leyte State Univ., Philippines), J. Wong (Sarawak Forest Dep., Malaysia), Y. H. Yap (Forest Dep., Malaysia).

S. Bhumibhamon (Mae Fah Luang University, Thailand), N. Cox (WWF, Mekong Basin), P. M. Cuong (FIPI, Viêt Nam), C. Feldkötter (GIZ, Laos), C. Inthavong (Dep. Land Use Planning, Laos), S. Jaenne (World Bank, Laos), H. Khamma (Dep. Forestry, Laos), C. MacAlister (MRCS), T. A. Moe (UNEP RRC.AP Thailand), T. Ngwe (Forest Dept., Myanmar), A. Rasphone (MRCS, Laos), H. Rath (MRCS, Laos), F. Rock (GIZ, Laos), S. Teang (Forestry Adm., Cambodia), R. B. Tennent (GFS, Cambodia), V. A. Tuan (VTGEO, Vietnam), W. Wisesjindawat (MRCS, Laos).

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Table 1. Use of satellite imagery for sample sites in Southeast Asia.

Satellite Sensor	TM	ETM	SPOT HRV	ASTER	ALOS AVNIR	KOMP-SAT	DEIM-OS	RAPID EYE
(Spatial Resolution) Year	(30 m)	(30 m)	(20 m)	(15 m)	(10 m)	(20 m*)	(22 m)	(10 m*)
1990	408	–	8	–	–	–	–	–
2000	4	410	2	–	–	–	–	–
2010	302	69	–	1	33	1	1	7

* Resampled.

Table 2. Forest cover and change from 1990 to 2010 in Southeast Asia[a] (areas in Mha).

	STATUS Area (SE)	Change 1990–2000 Area (SE)	Change 2000–2010 Area (SE)
Forest Cover 1990	268.0 (6.6)		
Forest Cover 2000[b]	250.6 (6.7)		
Forest Cover 2010	236.3 (6.7)		
Gross Forest Cover Loss		−20.4 (1.9)	−17.7 (1.9)
Gross Forest Cover Gain		+2.9 (0.5)	+3.2 (0.7)
Net Change Forest Cover		−17.5 (2.6)	−14.5 (2.5)
Net Change OWL[c]		+10.6 (1.8)	+7.1 (1.6)

[a] Incl. PNG and Solomon Isl.
[b] Average from two period estimates.
[c] OWL = Other Wooded Land.

Table 3. Forest cover and annual change in Southeast Asia and sub-regions (areas in Mha).

Sub-region	Forest Cover 1990 Area	2000[a] Area	2010 Area	Annual Net Change 1990s Area (SE) Change % (SE)	Annual Net Change 2000s Area (SE) Change % (SE)
SE-Asia[b]	268.0	250.6	236.3	1.75 (0.26) 0.67 % (0.10)	1.45 (0.25) 0.59 % (0.10)
Continental SE-Asia	78.7	76.5	71.7	0.21 (0.08) 0.27 % (0.10)	0.48 (0.13) 0.65 % (0.18)
Insular SE-Asia[b]	187.9	173.0	163.5	1.51 (0.26) 0.84 % (0.14)	0.96 (0.22) 0.57 % (0.13)
Indonesia[c]	123.8	112.4	104.4	1.15 (0.24) 0.98 % (0.21)	0.82 (0.21) 0.76 % (0.19)

[a] Average from two period estimates.
[b] Incl. PNG and Solomon Isl.
[c] Including East-Timor.

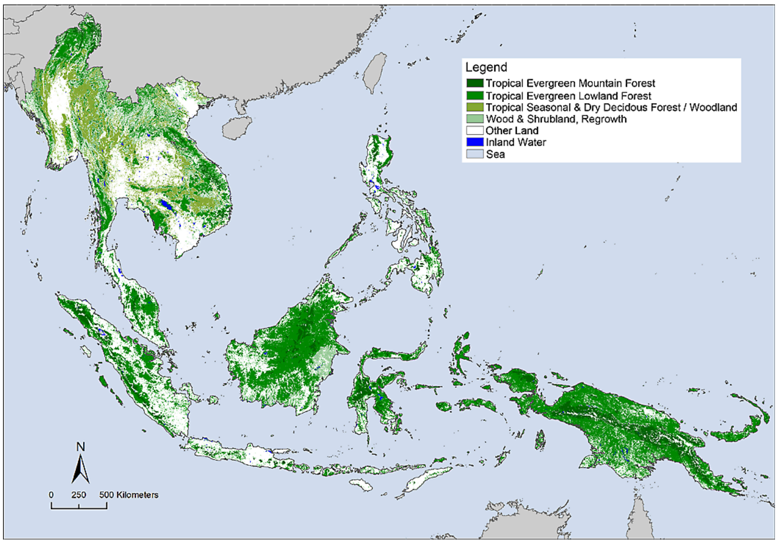

Fig. 1. Regional extent of tropical forest in Southeast Asia (incl. Papua New Guinea) derived from SPOT VEGETATION 1 km data of the year 2000 (Stibig et al., 2007a).

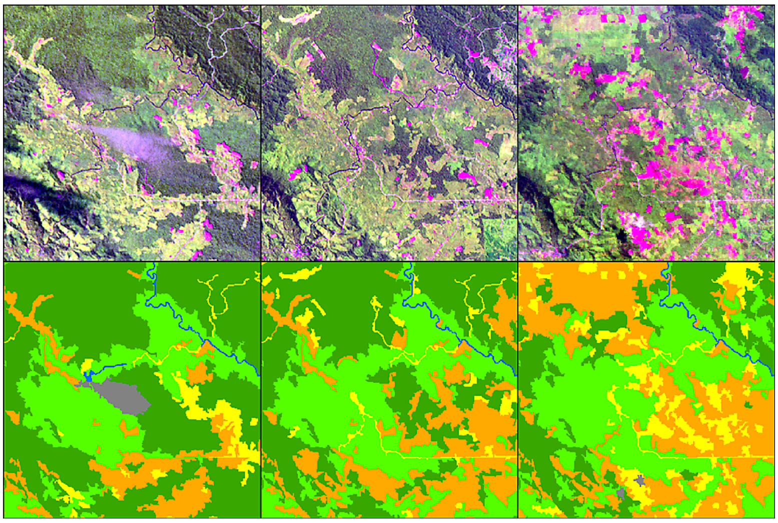

Fig. 2. Example of image and mapping results for a sample site (10 km × 10 km) on Borneo (0° N, 101°). Top: landsat TM and ETM+ satellite imagery for reference years 1990 (left), 2000 (middle) and 2010 (right). Bottom: corresponding land cover maps: dark green = "Tree Cover", bright green = "Tree Cover mosaics", orange = "Other Wooded Land", yellow = "Other Land", dark grey = Cloud, Smoke; blue = "Water".

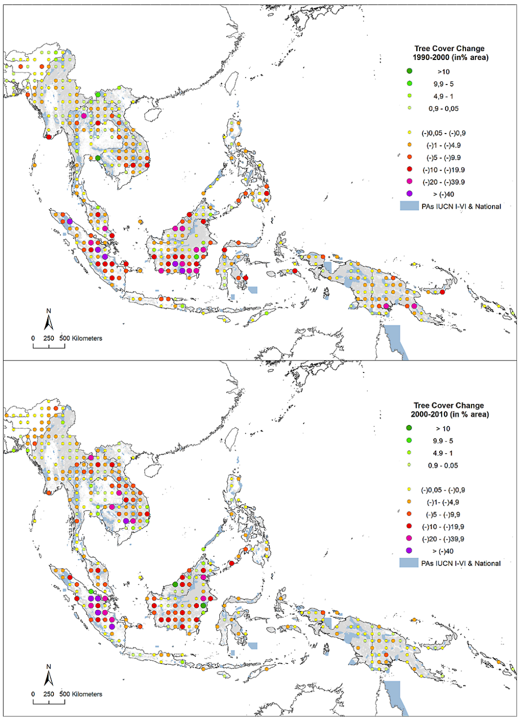

Fig. 3. Spatial distribution of forest cover change in Southeast Asia: change in forest cover per sample site (in % of land area, clouds excluded). IUCN I-VI and National Protected Areas from IUCN and UNEP (2009). Background map (grey): forest cover 2000.

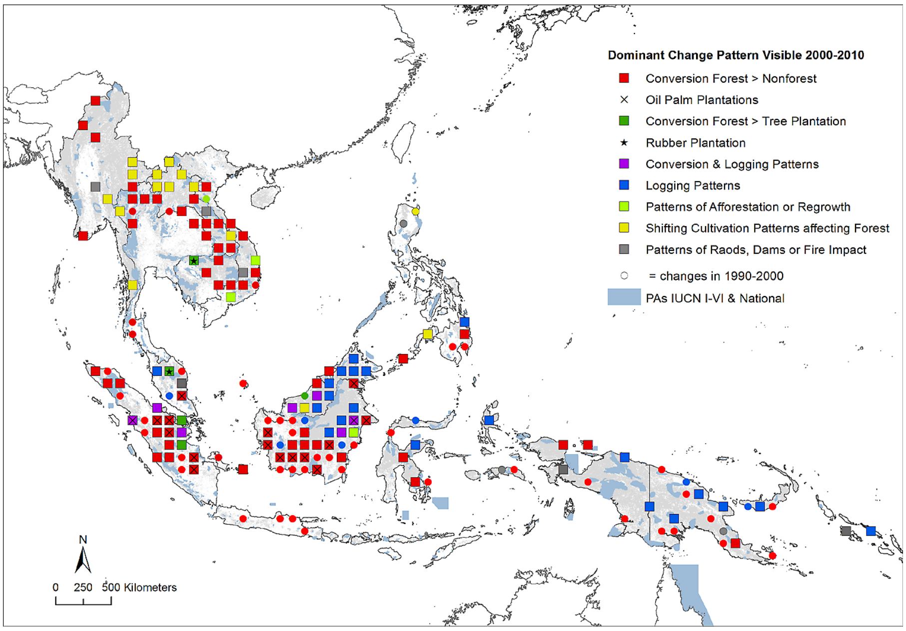

Fig. 4. Dominant type of forest change patterns as visually identified from satellite imagery within the sample units. Background Map (grey): Forest cover 2000.

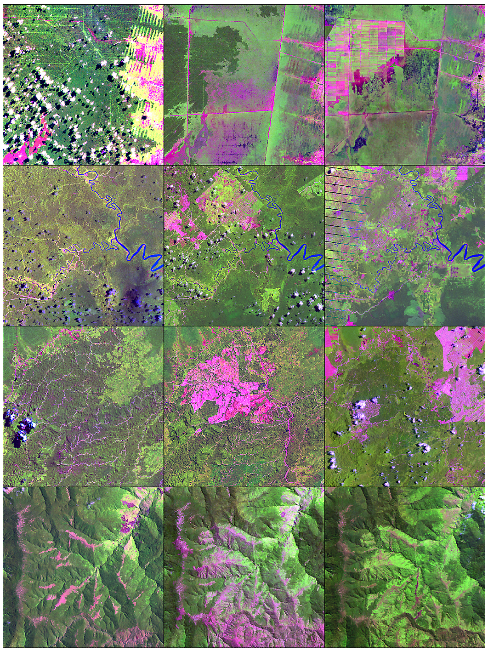

Fig. 5. Examples of forest change patterns from insular Southeast Asia, taken from Landsat TM/ETM imagery for 1990–2000–2010 for selected sample units. Top row, site S03-E114, S-Kalimantan: conversion of former peat swamp forest to agriculture and oil palm; row 2, site N04-E117, N-Kalimantan: conversion of lowland forests to oil palm plantations; row 3, site N03-E113, N-Sarawak: plantation establishment of fast growing trees for pulp and paper: bottom row, site S08-E147, PNG: impact of fires.

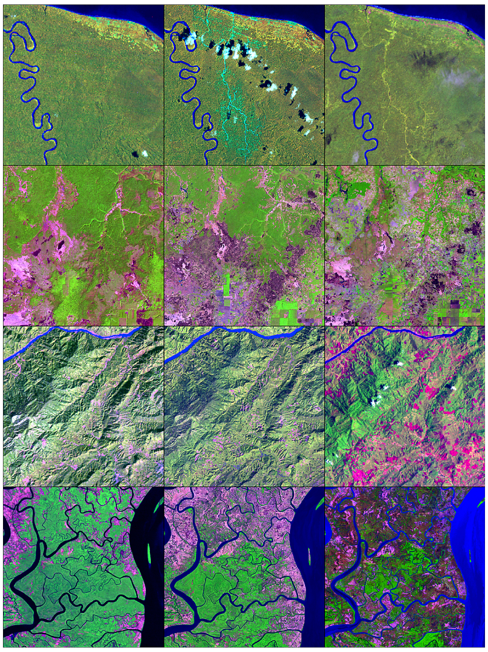

Fig. 6. Examples of forest change patterns from Papua and continental Southeast Asia (Cambodia, Laos and Myanmar), taken from Landsat TM/ETM imagery for 1990–2000–2010 for selected sample units. Top row, site S02-E139, Papua/Indonesia: logging; row 2, site N12-E106, Cambodia: agricultural expansion and rubber plantations; row 3, site N20-E102, Laos: shifting cultivation; bottom row, site N16-E095, Myanmar: mangrove forest conversion for aquaculture.

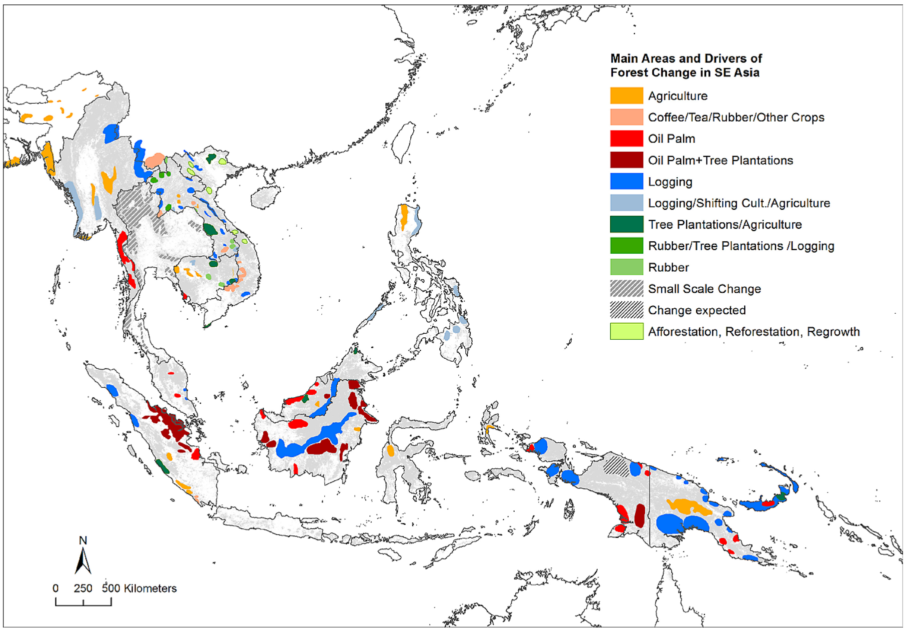

Fig. 7. Regional pattern of main areas and drivers of forest change in Southeast Asia, as identified by expert consultation. Background map (grey): forest cover 2000.