Mapping of the tropical forest cover of insular Southeast Asia from SPOT4-Vegetation images

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(*Received 23 July 2001; in final form 11 June 2002*)

Abstract. The objective of this study was to refine the methodology for a regional assessment of tropical forest cover in insular Southeast Asia from coarse resolution satellite images. SPOT4-Vegetation 10-day composites from 1998 to 2000 were used for the generation of a cloud free sub-regional mosaic image. Pixel selection was based on minimum values in the short-wave (monthly composites) and near-infrared spectral bands (annual composites), providing a maximum discrimination between forest and non-forest. A forest cover map was derived from digital classification of the dataset. The classification result was validated by comparison with the interpretation of 19 Landsat Thematic Mapper (TM) reference sites distributed over the sub-region. Forest area estimates were derived from the map and compared to Forest Resources Assessment 2000 data compiled by the Food and Agricultural Organization (FAO) of the United Nations. Results show that the new coarse resolution satellite sensor can provide sufficient information for mapping of tropical forest cover at the regional and sub-regional level.

1. Introduction

Tropical forests in Southeast Asia are still undergoing rapid changes (FAO 2001). The magnitude of the deforestation threatens whole ecosystems and their biodiversity, having a negative impact not only on the environmental, socio-economic and ultimately economic conditions of the countries, but also on the regional and global climates. Continuous monitoring of tropical forest cover is therefore more critical than ever. Appropriate action for the preservation of some of the last remaining contiguous areas of intact tropical forest can only be taken when based on up-to-date information on the status of forest cover. Satellite remote sensing can help in obtaining a synoptic view of the forest cover of a whole sub-region or region in order to understand and address the overall impact of deforestation in the tropics in a larger geographical context.

In the past, satellite images of coarse spatial resolution have been intensively tested for regional and global forest cover assessment and mapping (e.g. Malingreau *et al*. 1989, Achard and Estreguil 1995, Mayaux *et al*. 1998, Eva *et al*. 1999, DeFries 2000). In principle such satellite images can provide uniform and consistent forest

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International Journal of Remote Sensing
ISSN 0143-1161 print/ISSN 1366-5901 online © 2003 Taylor & Francis Ltd
http://www.tandf.co.uk/journals
DOI: 10.1080/0143116021000024113

cover information at this geographical level. Important key variables are 'forest cover extent', 'forest type distribution' and 'trends of change', but also single events of change need to be addressed when of large extent. However, the persistent presence of clouds and haze often made it difficult to obtain a regional view on forest cover in the tropics, particularly for insular Southeast Asia. Until recently, obstacles also resulted from the lack of operationally pre-processed satellite images. With the capabilities of recent coarse resolution satellite sensors and their data exploitation systems, such as the SPOT4-Vegetation instrument (Vegetation Users Guide 1998), one can cope with previous obstacles in a more operational and systematic way.

2. Forests and forest change in insular Southeast Asia

The forests of insular Southeast Asia represent some of the world's most valuable and productive tropical forests and also some of the richest ecosystems in terms of bio-diversity (Whitmore 1984). The majority of the forests are tropical evergreen rain forests with a great proportion of the highly productive and valuable Dipterocarp forests of Sumatra, Borneo and peninsular Malaysia. Fragile heath forests or 'Kerangas' can be found to a large extent in Borneo on acid substrates. Peat swamp forests—in the lowlands of Borneo and Sumatra and to a lesser extent on New Guinea—are not only unique ecosystems but contain valuable timber and store large amounts of carbon in their peat layer. Fresh water swamp forests occupy large areas of New Guinea, and some intact mangrove forests have remained particularly in Borneo and New Guinea. A few seasonal monsoon forests are located in the Philippines and in the south of Sulawesi and New Guinea.

The Food and Agriculture Organization (FAO) of the United Nations estimated the annual net loss of tropical forest for the period 1990–2000 at about 12.3 million ha (FAO 2001). The annual loss in tropical Southeast Asia reached more than 2.4 million ha during this period, more than half in Indonesia alone. The main reasons for these changes are uncontrolled and unsustainable logging practices (FLB News 2000), the conversion of forests to oil palm (Casson 2000) and to other forest plantations for pulp and paper production (Thompson 1996, WRM 2000). However, transmigration programs and uncontrolled migration have also played a significant role (Sunderlin 1998). Large forest losses also occurred due to the fires in 1997 and 1998 in Borneo (Hoffman *et al.* 1999).

In this context it appeared to be of interest to provide a new spatial assessment of the forest cover remaining in insular Southeast Asia at the beginning of the new millennium using the capabilities of the new coarse resolution sensor.

3. Materials and methods

3.1. *Data*

The study aimed at a pragmatic approach for the mapping of forest cover in insular Southeast Asia using satellite images of coarse spatial resolution, explicitly validating the results based on a sample of maps derived from satellite images of higher spatial resolution. Such an approach appeared feasible with the availability of SPOT4-Vegetation (VGT) standard products at 1 km spatial resolution for the following reasons:

- The almost daily acquisitions available for the whole of Southeast Asia offer improved spectral, spatial and geometrical qualities compared to former coarse resolution images.

- The 10-day composites (S10) are delivered in an operational way and permit a screening for cloud free pixels throughout the year while keeping the efforts of data storage and handling at a reasonable level.

The SPOT4-Vegetation instrument delivers images with a swath width of 2200 km and a spatial resolution of about one kilometre. The four reflective bands are located in the blue (0.43–0.47 μm), the red (0.61–0.68 μm), the near-infrared (NIR, 0.78–0.89 μm) and in the short-wave infrared (SWIR, 1.58–1.75 μm) range of the spectrum. The S10 composites combine 10 subsequent daily acquisitions with a pixel selection based on the maximum value of the Normalized Difference Vegetation Index (NDVI) found during this period (Vegetation User Guide 1998). All S10 composites from 1998 and 1999 were screened and all composites from April to September 1998 and from March to November 1999 were selected for further processing. For a few permanently haze-influenced areas data were also extracted from the January to March 2000 composites.

The results from visual interpretation of 19 Landsat Thematic Mapper (TM) satellite images, acquired around the year 1997 and distributed over insular Southeast Asia (figure 1), were available at a scale of approximately 1:100 000. Visual interpretation, and for most sites also field survey, were done by seven regional partners in the context of the 'TREES' (Tropical Resources and Environment monitoring by Satellites) project, a research activity of the European Commission's Joint Research Centre (Malingreau *et al*. 1995). Ten of the sites corresponded to full, the other nine to quarter Landsat TM frames.

3.2. *Creating a cloud-free mosaic*

All S10 composites were cloud and haze affected and a rigorous approach was chosen in order to create a good quality mosaic of the sub-region, taking the following steps:

– For a first cloud and haze reduction and for eliminating 'low-value' line errors occurring frequently in the SWIR channel thresholds were fixed for all S10 composites in the blue and the SWIR bands at $<7.5\%$ and $>6\%$ reflectance, respectively.

– Monthly mosaics (six for 1998, nine for 1999, three for 2000) were produced with pixel selection by the minimum value in the SWIR. This selection proved

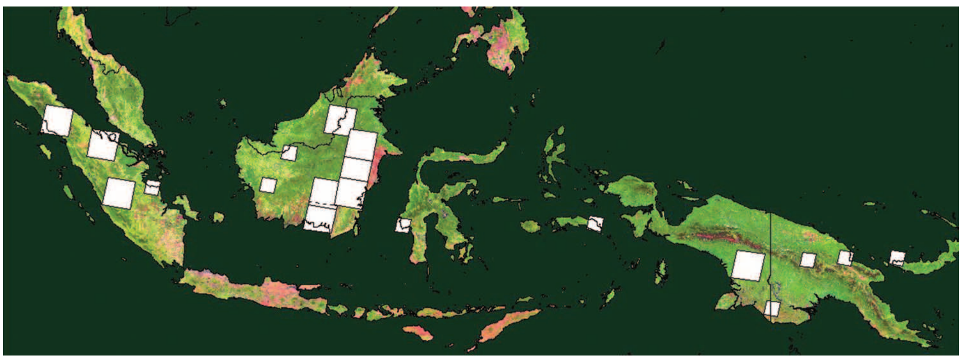

Figure 1. Location of TM validation sites overlaid on the SPOT4-Vegetation mosaic.

to focus on green vegetation, i.e. vegetation with high water content. It also reduced the impact of clouds and haze and the artefacts occurring due to bi-directional and atmospheric effects in the original images, as reported also by Mayaux *et al.* (2000). At the same time 'high-value' line errors in the SWIR channel were excluded, however, shadows were retained. For each monthly mosaic a haze and cloud-shadow mask was produced through unsupervised classification for screening out still affected pixels from further processing. The geometrical location error between the composites remained in the range of one pixel.

– Based on the monthly products annual mosaics were then created for the years 1998 and 1999, the latter including also some pixels from the year 2000 composites. Pixel selection by the minimum value of the near-infrared band (NIR) gave preference to 'non-green' pixels and the mainly evergreen forests of insular Southeast Asia differentiated well from any other land cover with less or 'non-green' occurrence during the selected season. Areas burnt during the observation period were retained as such in the final product. The annual mosaics were then similarly merged, again applying a haze and cloud-shadow mask for further improvement of the mosaic.

The final image mosaic, hereafter referred to as the VGT mosaic, remained to a limited extent haze and shadow affected but was judged suitable for a sub-regional forest versus non-forest classification (Stibig *et al.* 2001). This is keeping in mind that only by covering a period from April 1998 to March 2000 could an exhaustive view on forest cover in insular Southeast Asia be obtained at all. Other mosaic-techniques (Cihlar *et al.* 1994, De Wasseige *et al.* 2000) as well as bi-directional and improved atmospheric corrections might lead to improved mosaics. However, the daily raw products were not available until recently and considering the effort required for data handling and processing, the approach chosen appeared to offer a good alternative for mapping forests in insular Southeast Asia.

3.3. *Classification*

An unsupervised classification algorithm (clustering and maximum likelihood classification) was applied to the VGT mosaic creating 60 spectral clusters. These spectral clusters were interpreted and labelled, using available information from the field, from satellite images and from existing maps as reference.

Before regrouping the spectral clusters into a few thematic forest and land cover classes some of the clusters were reassigned and split. This was done using the Global Digital Elevation Model GTOPO30 of the United States Geological Survey (USGS 1996) and the World Conservation Monitoring Centre's (WCMC) forest map (Iremonger *et al.* 1997) as stratification layers.

– All forest labelled pixels above 900 m elevation were reassigned to the cluster for mountain forest.

– A small percentage of forest pixels in the mountains, wrongly classified as water due to the influence of shadow, was reassigned to the forest class based on slope information (slope $>0°$).

– Bare rocks and alpine grasslands of New Guinea were partly contained in the spectral clusters labelled as burnt areas, because the final pixel selection procedure favoured dry phenological stages of vegetation and sparse vegetation. All pixels of these clusters above 1800 m elevation were therefore re-assigned to an additional cluster of alpine grassland, leading to a total number of 61 clusters.

– For improving the mapping consistency for mangrove and swamp forests all pixels labelled as forest were reassigned to mangrove and swamp forest respectively if indicated as such on the WCMC map.

– For the central part of southern Papua New Guinea (Gulf province) still remaining haze was found to bias the forest class towards the mosaic of forest and non-forest class. In order to correct for this impact the haze-affected sub-area was marked by visual delineation and pixels labelled within this sub-area as mosaic of forest and non-forest were reassigned to forest.

The 61 spectral clusters were finally regrouped to nine thematic forest and land cover classes and one class for all areas of 'no data' (table 1).

3.4. *Validation*

The data corresponding to the frames of the 19 interpreted Landsat TM images (figure 1) were extracted from the coarse resolution map and referenced to the UTM projection. For comparison of forest figures from the VGT classification and from the Landsat TM interpretations a location error in the range of one VGT 1 km pixel was accepted. One of initially 20 sites had been rejected because it had failed to meet the criteria.

A pixel-based comparison was performed for a first assessment of the VGT classification result and for obtaining an indication of the contents of the VGT forest classes in relation to the classes of the TM interpretations.

The forest cover estimates obtained from the coarse resolution dataset were then validated by comparing with the estimates obtained from the visual interpretation of the Landsat TM images on the basis of entire full and quarter Landsat TM frames.

3.5. *Sub-regional forest cover assessment*

Forest cover estimates were obtained from the coarse resolution classification set for the sub-regional and the national level, after removing single and isolated pixels by a 3×3 spatial filtering process. These estimates were compared to the results of FAO's Forest Resources Assessment 2000 project (FAO 2001). Area figures refer to an equal area cylindrical projection (central meridian 120° E, standard parallel 0°), country boundaries were taken from the 1:3 000 000 ArcWorld database of the Environmental Systems Research Institute (ESRI 1992).

Table 1. Forest and land cover classes.

Evergreen montane forest	Non-forest vegetation
Evergreen lowland forest	Cropland
Mosaic of forest and non-forest	Burnt/dry/sparse vegetation
Mangrove forest	Water
Swamp forest	No data

4. Results

4.1. *Forest cover mapping*

The sub-regional forest cover map of insular Southeast Asia and the classes contained are displayed in figure 2. The map reflects the extent of tropical forest cover at the beginning of the year 2000 (Stibig *et al.* 2002). The spatial distribution of forest cover compares well to existing regional and also national forest and land cover maps.

Evergreen forest cover, including montane and lowland evergreen rain forests, heath forests, swamp forests and mangrove forests, could be well distinguished from other land cover as a result of the pixel selection procedure chosen. Spectral contrast appeared to be sufficient for a satisfactory separation of forests from bush and shrubs, included in the non-forest vegetation class. The few seasonal monsoon forests in the south of Sulawesi and Papua New Guinea and in the western part of the Philippines are contained in the evergreen forest cover, because these forests displayed neither strong seasonality nor significant spectral difference on the image mosaic used.

Swamp and mangrove forests showed up clearly on some individual S10 composites. However, the varying impact of haze and atmosphere over the observation period did not permit consistent mapping of these forest types based on the spectral properties only, suggesting the supportive use of the WCMC forest map as a stratification layer.

The mosaic of forest and non-forest class, hereafter referred to as forest mosaic class, was captured well, and mostly located at the edges of forest blocks. A further differentiation between forest types was not done for this class. A field survey in Eastern Kalimantan gave an indication of a high degree of degradation of the forest proportion contained.

The non-forest vegetation class contains bush, shrubs and grassland, but also cultivations of perennial crops (rubber, oil palm, coconut), while the cropland class comprises more intensively used land, partly with stages of bare soil, including tree crop plantations at premature stages.

The classification result documents the extent of the forest fires on Sumatra and

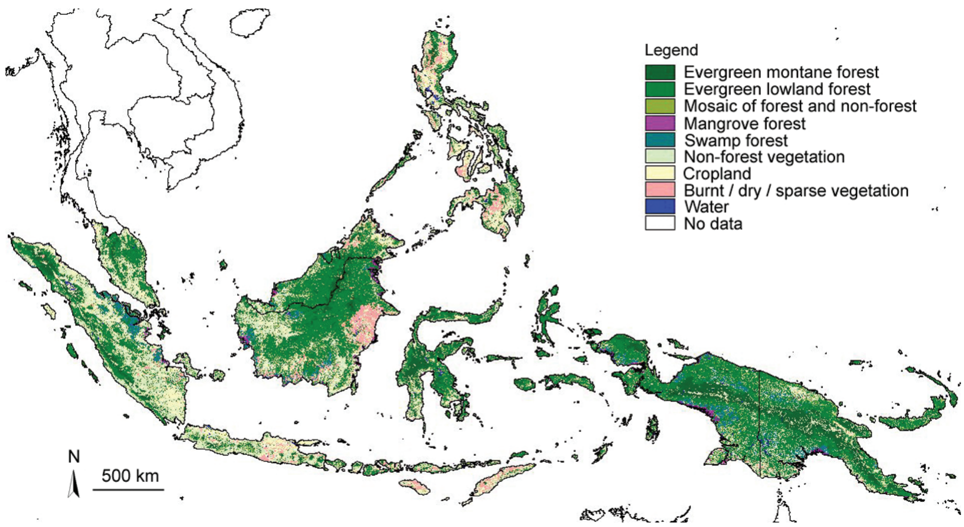

Figure 2. Forest cover map of insular Southeast Asia.

Borneo in 1998 in a remarkable way. 'Burnt' pixels occurring during the observation period are kept because they were preferred to the newly vegetated ones as a result of the pixel selection procedure applied. However, it was not possible to discriminate between burnt forest and other burnt vegetation or to differentiate consistently between dry or sparse vegetation on the other islands of the sub-region. However, we decided to retain the mixed class of burnt vegetation, dry vegetation, sparse vegetation as a separate category, because it provides an important indication on the impact of fires on the forests of Sumatra and Borneo.

4.2. *Validation*

Though the pixel-based comparison between the VGT and TM classes suffered from the geometrical position error in the range of one VGT pixel it provided an indication of the validity and content of the classes mapped from the coarse resolution image mosaic (table 2).

'Forest' on the VGT classification corresponded to 79% forest and 4% fragmented forest on the TM interpreted maps. About half of the VGT forest mosaic class (56%) was interpreted as forest on the TM images. On the other hand forest on the TM images was classified as 81% forest and 6% forest mosaic on the coarse resolution map. The comparison also shows that the majority of the TM fragmented forests, i.e. fragmented at the TM mapping unit level (50 ha), is still included in the forest class on the VGT.

The VGT non-forest vegetation class contains a forest proportion of some 25% on TM. Such a percentage was to be expected due to gradual transitions between forest cover and bush formations and the resulting spectral similarity particularly on images of coarse spatial resolution. The forest re-growth class on TM covered only about 4% of the total area and is by nature difficult to assign to forest or non-forest from satellite images. This class corresponded to some 60% to non-forest vegetation on the VGT data set and was not taken into account for further comparison.

The linear regression based on the 19 observation units (TM frames) is displayed in figure 3. Forest cover estimates from the VGT classification are based on the forest class (100%) and to 50% on the forest mosaic class. For the TM interpretations forest estimates include the areas of the forest and fragmented forest classes. The R^2 of the relationship is high (0.97). There is a trend of slightly overestimating forest area from the coarse resolution dataset compared to the TM visual interpretation results. Forest area estimates are very close when referring to the total land area of 255 643 km^2 covered by the 19 observation units: the estimates obtained were 63% of forest cover for the VGT classification and 62% for the total of the TM datasets.

Disregarding the contribution of the VGT forest mosaic class would have only a minor effect on the regression function ($R^2 = 0.96$) and would result in a slight underestimate of forest area compared to the TM estimates, yielding a VGT forest percentage of 60% instead of 63%.

Comparisons of forest cover estimates from coarse and high-resolution satellite images were addressed by several studies in the past using mainly NOAA AVHRR and Landsat TM data sets. Stone and Schlesinger (1990) found a trend of underestimating forest cover from coarse resolution satellite images for test sites over West Africa and Amazonia. Mayaux and Lambin (1995) showed that forest cover is rather overestimated from coarse resolution satellite data where forest cover is homogenous and rather underestimated where forest cover is fragmented.

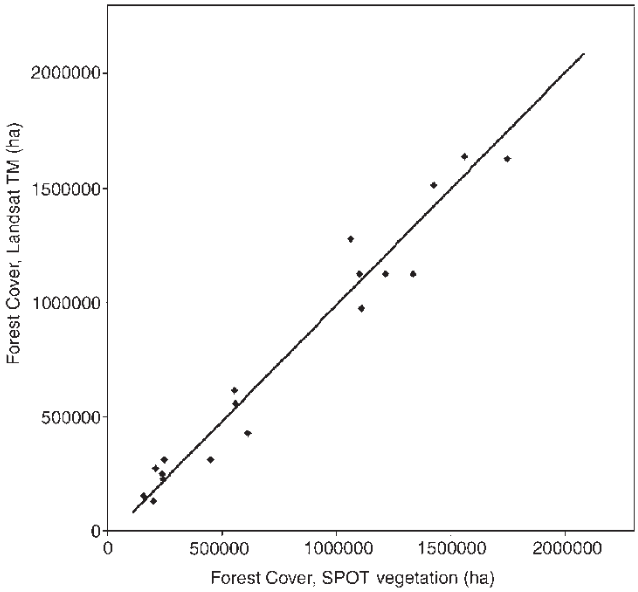

Figure 3. Relationship between forest cover estimates from VGT and TM for 19 observation units.

Table 2. Cross comparison between VGT and TM classifications for the 19 locations (in thousand ha).

	VGT classes							
TM classes	Forest	Mosaics of forest and non-forest	Non-forest vegeta-tion	Crop-land	Burnt/ dry/ sparse vegeta-tion	Water	Non classi-fied	Total
Forest	12 078	954	1534	226	108	53	0	14 953
Forest fragmented	602	53	151	49	10	8	0	873
Forest regrowth	322	122	583	80	2	4	0	1112
Mosaics*	576	147	517	70	16	3	0	1329
Wood and shrub	81	5	23	3	24	6	0	142
Grassland	533	104	548	113	174	26	0	1498
Agriculture	633	236	2237	877	23	14	0	4021
Non-vegetated	149	43	264	136	25	7	0	624
Water	171	26	56	31	29	457	0	770
Not classified	73	0	6	0	0	0	164	243
Total	15 218	1690	5918	1586	411	577	164	25 564

*Mosaics of forest and non-forest.

The high agreement in area estimates from VGT and TM data displayed in this study is partly explained by the improved spatial and geometric quality of the SPOT4-Vegetation images, and partly by the homogenous spectral appearance of the mainly evergreen forests of the sub-region.

4.3. *Forest cover estimates for the sub-regional and national level*

Area counts for the main land cover classes are displayed in table 3 and the derived forest cover estimates are compared to those of FAO (FAO 2001) in table 4. We opted for a rather conservative estimate of forest cover from remote sensing and did not count any forest proportion of the VGT forest mosaic class, bearing in mind also the expected degree of degradation within the class.

Recalling that for forest cover assessment from coarse resolution satellites we aimed at the regional and sub-regional level, the forest cover estimate for insular Southeast Asia compares well to the sub-regional figure of the FAO 2000 assessment, differing by less than one percent (table 4).

There is more variability at the country level as would be expected in particular for the smaller countries. Reasons for deviations originate partly from the data used and partly from the approach applied:

– Our forest cover estimates refer to the actual 'forest cover' and not to 'forest land', as usually done by national forest inventories which may include 'temporarily' non-forested areas.

– The coarse spatial resolution integrates all vegetation cover within one square kilometre pixel and may over- or underestimate forest cover depending on the forest proportion contained.

Table 3. Area count for the main land cover classes (in thousand ha).

Country	Forest	Mosaic of forest and non-forest	Non-forest vegetation	Cropland	Burnt/dry/sparse vegetation	Water	Non classified	Total
Philippines	7401	1206	8337	6171	5564	909	20	29 608
Malaysia	18 382	1855	8819	2857	824	236	0	32 972
Indonesia	103 775	9213	47 012	15 563	11 797	2998	16	190 376
Brunei	465	12	64	15	22	10	0	588
Singapore	3	1	14	36	1	6	0	60
Papua New Guinea	32 009	2207	8615	1001	1065	402	255	45 554
Total	162 035	14 494	72 861	25 643	19 273	4561	292	299 158

Table 4. Forest area estimates from VGT (TREES map) and FAO (in thousand ha).

Area	VGT 2000 (thousand ha)	FAO 2000 (thousand ha)	Differences (thousand ha)	Differences %
Insular Southeast Asia	162 035	161 619	416	0.3
Indonesia, including E. Timor	103 775	105 493	−1718	−1.6
Malaysia	18 382	19 292	−910	−4.7
Papua New Guinea	32 009	30 601	1408	4.6
Philippines	7401	5789	1612	27.8
Brunei	465	442	23	5.3

*Difference in relation to FAO Forest Resources Assessment 2000.

– Visual comparison with TM images showed that the gradual transitions from forest to non-forest, such as bush and re-growth of secondary vegetation, cannot always be depicted based on spectral properties only. The similar appearance can lead to misclassification of forest cover and explains some of the differences when comparing to terrestrial forest assessments, which include for example also height parameters for the definition of forest.

– Bi-directional effects and remaining haze may have contributed to misclassification at the level of individual pixels.

Finally, the FAO forest cover estimates used for comparison are derived from national forest inventories, which bear also a number of error sources. Forest inventories often differ in terms of inventory method, definition of forest, accuracy, date of reference and inventory intervals. Updated figures are sometimes available only for parts of a country while for the remaining area outdated figures are used. The FAO figures are therefore considered as best reference but may not always reflect the actual forest cover of a country at highest accuracy.

For Indonesia, Malaysia, and Papua New Guinea the discrepancies remained below 5%. Forest estimates would be slightly higher for Indonesia if the forests burnt in 1998 were still included. The estimates for Brunei are displayed for completeness in spite of the fact that the size of the country is too small for any land cover assessment by coarse resolution satellite images. Some areas of bush, re-growth or tree crops have been obviously included in the forest class, as reflected by a number of isolated pixels classified as forest in the non-forested parts of the countries. The overestimate for the Philippines (almost 28%) appears high in relation to the FAO 2000 estimate. The absolute difference is about 1.6 million ha. The official statistics of the Forest Management Bureau (DENR 2002) of the Philippines display 10 million ha of 'forest land', which is not considered as forest cover. It was most probably in these parts of 'forest land' with mixed agriculture and degraded forest remnants where misclassifications occurred at the one kilometre spatial resolution level, leading to this overestimate. Singapore was not included in the comparison at the country level because of its small size and its low forest cover of only about 2000 ha, where analysis from coarse resolution satellite images was not considered appropriate.

5. Conclusions

The study shows that the SPOT4-Vegetation satellite system offers the possibility of obtaining a regional view on tropical forest cover and that the data exploitation system implemented can cope largely with the obstacle of persistent cloud cover.

Creating the image mosaic based on a pixel selection by minimum values in the short-wave and near-infrared bands provided a good separation of forest and non-forest in the case of insular Southeast Asia.

The derived sub-regional forest cover map offers an actual and uniform overview and estimate of the extent of forest cover throughout the sub-region. Baseline forest cover estimates can be reached even at the national level for countries of a certain area extent and when thoroughly interpreted.

Regular forest cover assessment at the regional and sub-regional level is important for understanding the magnitude and impact of deforestation in a regional context. The new coarse resolution satellite images can make a significant contribution to a continuous regional forest monitoring system, providing baseline information as input for regional forest policies and conservation strategies, but also for carbon assessment and climate modelling.

The approach described presents a possibility for a relatively quick assessment of forest cover for the cloud contaminated region of insular Southeast Asia, where a large number of images acquired over a period of time is required in order to achieve an acceptable basis for forest cover mapping.

Acknowledgment

This is to acknowledge the contribution of regional partners and institutions performing field survey and visual interpretation from Landsat TM satellite images for 20 monitoring and validation sites in the framework of the EU JRC TREES project: BIOTROP (Southeast Asian Regional Centre for Tropical Biology)/IPB (Agricultural University), Bogor/Indonesia (Upik R. Wasrin); CIFOR (Centre for International Forestry Research), Bogor/Indonesia (R. Dennis and I. Kuriawan); FOMISS (Forest Management Information System Sarawak), Kuching/Malaysia (J. Wong-Basiuk); IFFMP (Integrated Forest Fire Management Project), Samarinda/Indonesia and Max Plank Institute, Germany (A. Hoffman and L. Christy); PUSPICS (Centre for Remote Sensing and Integrated Surveys), Gadjah Mada University-Bakosurtanal, Yogyakarta/Indonesia (D. Hartono); RSS (Remote Sensing Solutions), München/Germany (F. Siegert and V. Boehm); UNITECH (Papua New Guinea University of Technology), Lae/Papua New Guinea (M. Govorov and J. Suat).

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