Applied Vegetation Science 7: 153-162, 2004
© IAVS; Opulus Press Uppsala.

A new forest cover map of continental southeast Asia derived from SPOT-VEGETATION satellite imagery

Stibig, H.-J.[1*], Achard, F.[1,2] & Fritz, S.[1,3]

[1]*Institute for Environment and Sustainability, Global Vegetation Monitoring Unit, European Commission Joint Research Centre, TP440, I-21020 Ispra (Va), Italy;* [2]*E-mail frederic.achard@jrc.it;* [3]*E-mail steffen.fritz@jrc.it;* [*]*Corresponding author; Fax +390332789073; E-mail hans-juergen.stibig@jrc.it*

Abstract

Question: Can recent satellite imagery of coarse spatial resolution support forest cover assessment and mapping at the regional level?

Location: Continental southeast Asia.

Methods: Forest cover mapping was based on digital classification of SPOT4-VEGETATION satellite images of 1 km spatial resolution from the dry seasons 1998/1999 and 1999/2000. Following a geographical stratification, the spectral clusters were visually assigned to land cover classes. The forest classes were validated by an independent set of maps, derived from interpretation of satellite imagery of high spatial resolution (Landsat TM, 30 m). Forest area estimates from the regional forest cover map were compared to the forest figures of the FAO database.

Results: The regional forest cover map displays 12 forest and land cover classes. The mapping of the region's deciduous and fragmented forest cover remained challenging. A high correlation was found between forest area estimates obtained from this map and from the Landsat TM derived maps. The regional and sub-regional forest area estimates were close to those reported by FAO.

Conclusion: SPOT4-VEGETATION satellite imagery can be used for mapping consistently and uniformly the extent and distribution of the broad forest cover types at the regional scale. The new map can be considered as an update and improvement on existing regional forest cover maps.

Keywords: India; Kampuchea; Laos; Mapping; Monsoon forest; Myanmar; Remote Sensing; Thailand; Tropical forest; Vietnam.

Abbreviations: ASEAN = Association of Southeast Asian Nations; FAO = Food and Agriculture Organization of the United Nations; IUCN = International Union for Conservation of Nature; LCCS = Land Cover Classification System; MRC = Mekong River Commission; NDVI = Normalized Difference Vegetation Index; NIR = Near infrared; S10 = Ten day standard composites; SWIR = Short wave infrared; VGT = SPOT4-VEGETATION.

Introduction

The tropical forests of continental southeast Asia, extending from northeast India and the Chittagong hills of Bangladesh in the northwest to the Mekong delta and the Thai-Malaysian peninsular in the east and far south of the region, comprise tropical evergreen as well as seasonal monsoon forests. Since colonial times there has been high interest in these forests due to the presence of timber such as teak or rosewood (Collins et al. 1991). Forest resources have contributed to the rapid economic development of countries such as Thailand and they are still an important asset for national economies of countries such as Myanmar, Laos and Kampuchea (Collins et al. 1991; Anon. 1998a). Many people in the region depend on the forests, collecting edible and medicinal plants and wood for housing and cooking. Forests also provide hunting grounds and form a stabilizing element in the shifting cultivation systems of the numerous ethnic groups in the uplands (Anon. 2003a). The diverse demands on the forests have led, in the past, to severe forest loss and degradation, more recently fuelled by an increasing timber consumption of neighbouring countries such as China, Korea and Japan (Anon. 1998a). The importance of the remaining forests for soil and watershed protection, agricultural productivity and conservation of biodiversity is increasingly seen in a regional context (Anon. 2003a), demanding consistent forest cover information at a regional scale.

Forests in continental southeast Asia: ecological types, geographical extent and change

Forests in continental southeast Asia are characterized by a variety of evergreen, semi-evergreen and deciduous tree cover types, often in close proximity depending on soils, local site conditions and climate. Most parts of the region have a distinct dry season from December to April (northeast monsoon), with low cloud cover and monthly rainfall below 20 mm. In the rainy season from May to October (southwest monsoon) monthly average rainfall peaks reach ca. 300 mm in the Vientiane plain and more than 800 mm in the Chittagong area (Anon. 2004).

The main forest types of the region are briefly described hereafter, referring to sources given by Champion & Seth (1968); Whitmore (1984); Anon. (1989); Collins et al. (1991); Klankamsorn & Charuppat (1994); Rundel & Boonpragob (1995); Blasco et al. (1996), Spalding et al. (1997); Smith (2001). 'Moist tropical evergreen rain forests' (typical genera include *Dipterocarpus*, *Shorea*, *Parashorea*, *Hopea* and *Anisoptera*) are found on the peninsular of Thailand, as pockets in lower Myanmar, Kampuchea and Vietnam, on the Andaman islands and along the southern edge of the Himalayas. These forests are usually multi-storied and dense, the upper tree layer with heights of 45 m and above. The majority of evergreen forests in mainland southeast Asia, however, are 'semi-evergreen' and 'dry evergreen forests' (typical species include *Hopea ferrea*, *Anisoptera costata*, *Dipterocarpus alatus*, *Lagerstroemia* spp.) and contain a considerable number of deciduous tree species. Tree canopies are usually closed and 25 m - 30 m tall, a lower tree stratum may range from 5 m - 17 m in height. Evergreen tropical mountain forests grow at altitudes above 1000 m a.s.l. and comprise of, for example, the typical 'hill evergreen forests', which also contain temperate tree species (typical genera include *Quercus*, *Lithocarpus*, *Castanopsis*). 'Pine forests' can be mainly found in the mountain zones of the region (*Pinus kesiya*, *P. merkusii*, *P. dalatensis*), but also in the lowlands (e.g. Korat Plateau/Thailand). Non-tropical, evergreen coniferous and temperate broad-leaved mountain forests occupy the edges of the tropical biome at high altitudes, mainly in Myanmar and the Himalayan range.

The deciduous 'monsoon' forests of continental southeast Asia comprise the valuable 'mixed deciduous forests', stretching from northeastern India, through Myanmar and Thailand to Laos. The upper layer of these, usually closed, canopies reaches heights of ca. 30 m, with a secondary tree layer up to 20 m. Depending on site conditions and altitude, sub-types are referred to as 'moist upper mixed deciduous forest', 'dry upper mixed deciduous forest' and 'lower mixed deciduous forest'. Teak (*Tectona grandis*) can be dominant among a variety of other species (e.g. genera *Xylia*, *Terminalia*, *Dalbergia*, *Afzelia*, *Pterocarpus*, *Lagerstroemia*). 'Dry Dipterocarp' forests, representing the region's second main deciduous forest type, grow in dry site conditions and on poor soils, for example, in southern Laos and Cambodia. Tree heights range from 8 m - 25 m and the canopies are usually open, often associated with a grass layer. Dry Dipterocarp forests are characterized by a smaller number of species, the dominant of which are adapted to fire (e.g. *Dipterocarpus tuberculatus*, *D. intricatus*, *D. obtusifolius*, *Shorea obtusa*). Almost all species lose their leaves during the dry season. Gradual transitions to a savannah like wood and shrub cover are common and fires, mostly human induced, are frequent events. Locally, *Pinus* species are found in the dry deciduous forests and woodlands.

The region's mangrove forests (typical genera *Sonneratia*, *Avicennia*, *Rhizophora*, *Bruguiera*) are concentrated along the coastlines of the Bay of Bengal, the Gulf of Thailand and the deltas of the Irrawaddy and Mekong rivers; the 'Sundarbans' (Bangladesh/India) hold the world's most extensive mangrove area (dominant species *Heritiera fomes*, *Excoecaria agallocha*, *Ceriops decandra*). The swamp forest and woodland around the 'Great Lake' (Tonle Sap) in northwest Kampuchea consist of a mix of shrub and stunted trees (e.g. *Barringtonia acutangula*, *Diospyros cambodiana*, *Elaeocarpus* spp., *Hydnocarpus* spp., *Malotus* spp.).

During recent decades the tropical forests of continental southeast Asia faced significant depletion (e.g. Anon. 1993; Anon. 1998a; Achard et al. 2002), as evident from forest mapping and inventory results dating back to the 1960s (Table 1).

The causes of forest loss are documented in literature (e.g. Collins et al. 1991; Rundel & Boonpragob 1995; Anon. 1998a; Geist & Lambin 2001; Blasco et al. 2001; Smith 2001; Anon. 2003a, d). They include the

Table 1. Change of forest cover in continental southeast Asia from the 1960s to 2000[*].

Period	1960s-1970s		ca.1980		ca. 1990		ca. 2000	
	yr	%	yr	%	yr	%	yr	%
Country								
Kampuchea	-	-	1980[1)]	73	1990[1)]	67	1997[4)]	53
Laos	1969[1)]	60	-	-	1988[1)]	47	1997[6**)]	41
Thailand	1961[2)]	53	1978[2)]	34	1989[2)]	28	1998[4)]	29
Vietnam	1960[1)]	42	-	-	1988[1)]	28	1995[4)]	30
Myanmar	1955[3)]	58	-	-	-	-	1997[4)]	52
NE- India	-	-	-	-	1991[5)]	64	1999[5)]	63

[1)] Meyer & Panzer 1990; [2)] Klankamsorn & Charuppat 1994; [3)] Perrson 1974; [4)] Anon. 2001a; [5)] Anon. 2000; [6)] Anon. 2003a;
[*)] % of total land cover, 'forest land' estimates may include 'temporarily un-stocked' forest land; [**)] parts of the most north-eastern province not included.

over exploitation of forest resources by national and foreign enterprises, agricultural expansion and conversion to plantations (rubber, coffee, bananas) as well as shifting cultivation. The latter is traditionally practised by most ethnic groups in the mountain zones of north-eastern India, Myanmar, northern Thailand, Laos and Vietnam, but also in Kampuchea and the highlands of southern Vietnam. Population growth and economic development, resettlement of people, road and dam construction, fires and war took further toll. Mangrove forests were depleted by war, the extension of shrimp farming, charcoal production and changes of agricultural practices and drainage patterns (Sundarbarns), whilst fire wood collection affected the 'Tonle Sap' swamp forests.

Forest degradation, usually not reflected in forest area statistics, might affect areas even larger than those reported as deforested. Ca. 65% of Myanmar's monsoon forests were classified as heavily degraded by the beginning of the 1990s (Collins et al. 1991). Main reasons for forest degradation are unsustainable and illegal logging, the latter often associated with the increasing timber demand in Asia, but also with misguided forest policies, corruption and military involvement (Anon. 2003a; Currey et al. 2001; Anon. 2003c). The deciduous forests are further threatened by an increased frequency of forest fires, caused by land clearing, cattle grazing and hunting (Rundel & Boonpragob 1995).

Regular monitoring of the region's forest cover has become essential. Consistent and up to date information on forest cover at the regional level would not only be an asset for regional climate and vegetation modelling, but also for organizations implementing regional programs on sustainable development, environment and conservation, such as ASEAN, the MRC, IUCN or international development banks. Information on the forest pattern and potential fragmentation at the macro level can support regional planning in the field of transport and hydropower development, watershed protection and conservation area networking. It may further help to address issues such as the recent increase in the frequency of severe flooding or the concentration of forest loss and degradation along country boundaries (Anon. 2003a, c).

However, there are few maps that provide a consistent view of current forest cover across the region. The aggregation of national data often suffers from incompatibilities of inventory methodology, forest definitions and reference periods, or from the lack of completeness and relevance to the present (Anon. 2001a). Existing regional forest cover maps, based on a mix of satellite imagery, aerial photography and field observations, either date back to the 1980s and 1990s (Collins et al. 1991; Blasco et al. 1996) or only partially cover the region (Anon. 2003b). Regional land cover information can also be extracted from global maps. The global data sets generated from coarse resolution satellite imagery (ca. 1 km) of the early 1990s (Loveland et al. 2000; Hansen et al. 2000) were recently complemented by new global maps of improved geometric and thematic detail (Friedl et al. 2002; Hansen et al. 2002; Bartholome & Belward In press). Regional forest cover maps of continental southeast Asia were also produced from coarse resolution satellite imagery from the 1990s (Defourny et al. 1994; Achard & Estreguil 1995; Anon. 1995). In our present study we aim to improve and update these regional products, giving a consistent regional overview on forest cover in continental southeast Asia.

Data and Methods

The study is based on SPOT4-VEGETATION (VGT) satellite imagery providing almost daily coverage of the whole region (88º - 111ºE, 5º - 30ºN) with four spectral bands and at a spatial resolution of ca. 1 km^2 (geographical projection, $112^{o\,-1}$ resolution). We used exclusively ten-day (S10) standard composites, generated from 10 consecutive days by selecting the image elements (pixels) using the maximum value of NDVI (Anon. 1998b).

All VGT S10 composites from the end of December to the end of March of 1998/1999 and 1999/2000 were utilized for obtaining sufficient cloud and haze free data over the whole region. Images from November and the beginning of December displayed clouds and fog in the valleys, those of the high dry season (April) were affected by atmospheric dust and smoke (burning of rice fields), burnt scars and strong seasonal effects. Most rainy season images were heavily cloud and haze covered.

Image processing and mapping followed a similar methodology as developed for insular southeast Asia (Stibig et al. 2003). The consecutive processing steps included (1) the elimination of pixels affected by clouds, haze and sensor errors from the S10 composites (empirically defined thresholds in the blue band > 10% and in the SWIR band < 5% of reflection factor); (2) the generation of monthly image composites (pixel selection by the minimum SWIR value); (3) the generation of the composites for the two dry seasons (pixel selection by the minimum value in the NIR band); and (4) the combination of the latter composites for obtaining an almost haze and cloud free regional image composite. Potential land cover change occurring during the 16-month observation period was assumed to be negligible. The 70 initial spectral clusters, resulting from unsupervised digital classification of the regional image composite, were labelled and interpreted within 11 geo-

Table 2. Geographical strata.

Strata	Geographical area
(1)	Himalaya range;
(2)	Plains of Bangladesh and NE India;
(3)	NE India, Bangladesh and W Myanmar mountain zone;
(4)	Plain of Myanmar and adjacent slopes;
(5)	Mountainous N Thailand and S Myanmar;
(6)	Peninsular Thailand-Myanmar;
(7)	Dry plains of NE Thailand;
(8)	Shifting cultivation dominated mountain zone of N Laos, S Yunnan, N Vietnam (incl. Hainan);
(9)	Annamite mountains (Laos, Vietnam);
(10)	Kampuchea and S Vietnam;
(11)	River deltas and Great Lake area (Kampuchea)

graphical strata, defined to account for the variability of climate, landscape and land cover in the region (Table 2). Allowing for individual class assignments within the strata and correcting for some obvious local misclassifications, the 135 resulting clusters were regrouped into 12 land cover classes.

Our reference data for class labelling consisted of (1) the GEOCOVER 1990 historical Landsat-TM satellite image mosaics (Anon. 2002); (2) a set of Landsat-TM prints of the late 1990s (1: 250 000 and 1:1 000 000 scales) and (3) field data collected from 1993 to 1997. The USGS GTOPO30 elevation model was used for defining elevation thresholds (Anon. 1996).

For the validation of our forest cover classes we were able to use independent mapping results derived from 18 Landsat-TM images from 1997/1998 at 30 m spatial resolution (Fig. 1). The 18 sites were part of a stratified systematic sample over the humid tropics,

Fig. 1. Location of Landsat-TM validation sites (seven full and 11 quarter frames)

established for the assessment of forest area change, giving higher selection probability to forested areas (Achard et al. 2002). The interpretation consistency of these maps had been assessed independently (Anon. 2001b) showing a satisfying agreement (ca. 92%) for the forest classes.

We compared forest area estimates from our map (VGT map) to those of the Landsat-TM interpretations for the 18 sites, calculated for whole sites and therefore minimizing the impact of geometrical registration errors (Klein et al. 1993). We further performed a simple count of Landsat-TM class proportions within the VGT forest classes (1-km^2 pixels) to obtain an additional, although rather indicative, appraisal of the mapping consistency achieved. All area estimates refer to the non-overlapping part of the Landsat-TM image frames and to a cylindrical equal area projection (central meridian: 99° E, standard parallel: 19° N, spheroid: WGS84).

Finally, we compared the regional and national forest area estimates derived from the VGT map to FAO figures, which are compiled from country inventory data and are used internationally as a reference (Anon. 2001a).

Results

Forest cover mapping

The forest cover classes mapped include evergreen lowland and mountain forests, deciduous forests and mangrove and swamp forests (Table 3). The new map presents the extent and distribution of these forest cover types for the year 2000 in the regional context, uniformly and compatibly across country boundaries (Figs. 2 and 3). At such a scale the map compares well to existing land cover maps of national or sub-regional scales (e.g. Anon. 2003b).

The main constraints in forest cover mapping related to (1) limitations of forest cover discrimination based on spectral reflectance; (2) the coarse spatial resolution; and (3) the application of accurate tree density or height thresholds:

1. The terms 'evergreen' and 'deciduous' refer to the predominant spectral appearance of forest cover during the dry season rather than to strict botanical definitions. Moist variants of mixed deciduous forests, containing portions of evergreen species and deciduous species which do not drop their leaves simultaneously, maintain an overall, evergreen appearance and are thus included in evergreen forest cover. Evergreen and semi-evergreen forest canopies could not be consistently differentiated. An unambiguous separation of forest and shrub cover could not always be

Table 3. Description of the forest and vegetation cover classes mapped.

Class name	Description
Evergreen lowland forests (< 1000 m a.s.l.)	Comprising all forests of predominant evergreen appearance during the dry season; including evergreen and semi-evergreen forest types, broad-leaved and coniferous species, and mixed deciduous forests of more or less evergreen appearance throughout the year
Evergreen mountain forests (> 1000 m a.s.l.)	All evergreen forest cover above 1000 m a.s.l; including, for reasons of geographical completeness, the non-tropical coniferous and broad-leaved forests in the Himalayas and at high altitudes in Myanmar
Deciduous forests	Tree canopies of predominant deciduous phenology during dry season; mainly mixed deciduous forests in central Myanmar and northern Thailand; mainly 'Dry Dipterocarp' forests in southern Laos, Kampuchea and southern Vietnam, with transitions to savanna-like woodland, locally including portions of dry grass or cropland
Mangrove forests	All major areas of mangroves; including degraded or fragmented canopies
Swamp forests and inundated shrubland	Mainly a tree-scrub layer surrounding the 'Great Lake' of central Kampuchea, in terms of physiognomy and height close to shrub cover, degraded by human activities; mapped by reassigning 'forest' labelled pixels within the predefined area
Fragmented and degraded evergreen forest cover	Forest mosaics and degraded tree cover, mainly resulting from shifting cultivation and repeated logging, respectively; in terms of spectral reflectance overlap with areas of regrowth and shrub cover
Evergreen wood and shrubland and regrowth mosaics	Shrub cover and regrowth of predominant evergreen appearance during the dry season including (1) shrub and regrowth patterns resulting from abandoned or less intense shifting cultivation, (2) tree cover of low height or sparse canopy, e.g. resulting from over-logging, (3) bamboo invaded areas; (4) forest remnants, not mapped at coarse spatial resolution
Deciduous wood and shrubland and regrowth mosaics	Shrub cover and regrowth of predominant deciduous appearance during the dry season; containing transitions to dry deciduous forests, but also fractions of dry grassland and cropland, not mapped at coarse spatial resolution
Mosaics of cropping and regrowth	Mainly intensive 'shifting cultivation', comprising recent burns, recent and last year's cropping, abandoned fields with regrowth, and forest remnants usually on steep and less accessible slopes
Other land	Consisting mainly of cropland, including upland crops (cash crops, mixed agricultural fields) and lowland crops (rice) in the irrigated plains and river deltas; including bare land and grassland, in the Himalayas also rocks, snow and ice
Rocks	Limestone formations with sparse tree cover (central Laos)
Water bodies / Sea	

achieved locally when mapping spectral clusters of regional extent.

2. Due to the coarse spatial resolution of the satellite data used, forest pixels may contain portions of non-forest and *vice versa*, as demonstrated in several studies (e.g. Achard et al. 2001). Based on our reference data we estimated the portion of forest contained in our fragmented forest class to be between 40% and 70%, in our wood and shrubland classes between 20% and 40%, and in our class of mosaics of cropping and regrowth between 10% and 30%.

3. We used the definitions of the FAO Land Cover Classification System 'LCCS' (Di Gregorio & Jansen 2000) as guideline for assigning the forest classes. Land is classed as forest when tree cover is > (10-20)% canopy density and tree heights of > 5 m. Tree cover, shrub cover and natural regrowth not matching these criteria were considered for this map as 'wood and shrubland'. However, these thresholds could only be applied approximately, given that tree height and canopy densities cannot be 'measured' from the satellite data used. From field knowledge, the minimum tree canopy density still taken as 'forest' on this map may range for evergreen canopies around, or slightly above, the upper LCCS margin (20%), whilst reaching the lower margin (10%) for deciduous forest cover.

Consequently, forest cover on this map may include open and degraded canopies, mature forest regrowth and local transitions to shrub cover, whilst areas mapped as wood and shrubland or regrowth mosaics may locally contain tree cover meeting the definition requirements for a 'forest'. Mapping of the region's dry deciduous forest remained difficult due to the spectral similarity to dry shrub cover and the visibility of ground vegetation, soils or burnt scars through the open tree canopies. Such difficulties had also been experienced with satellite images of higher spatial resolution (Anon. 1989).

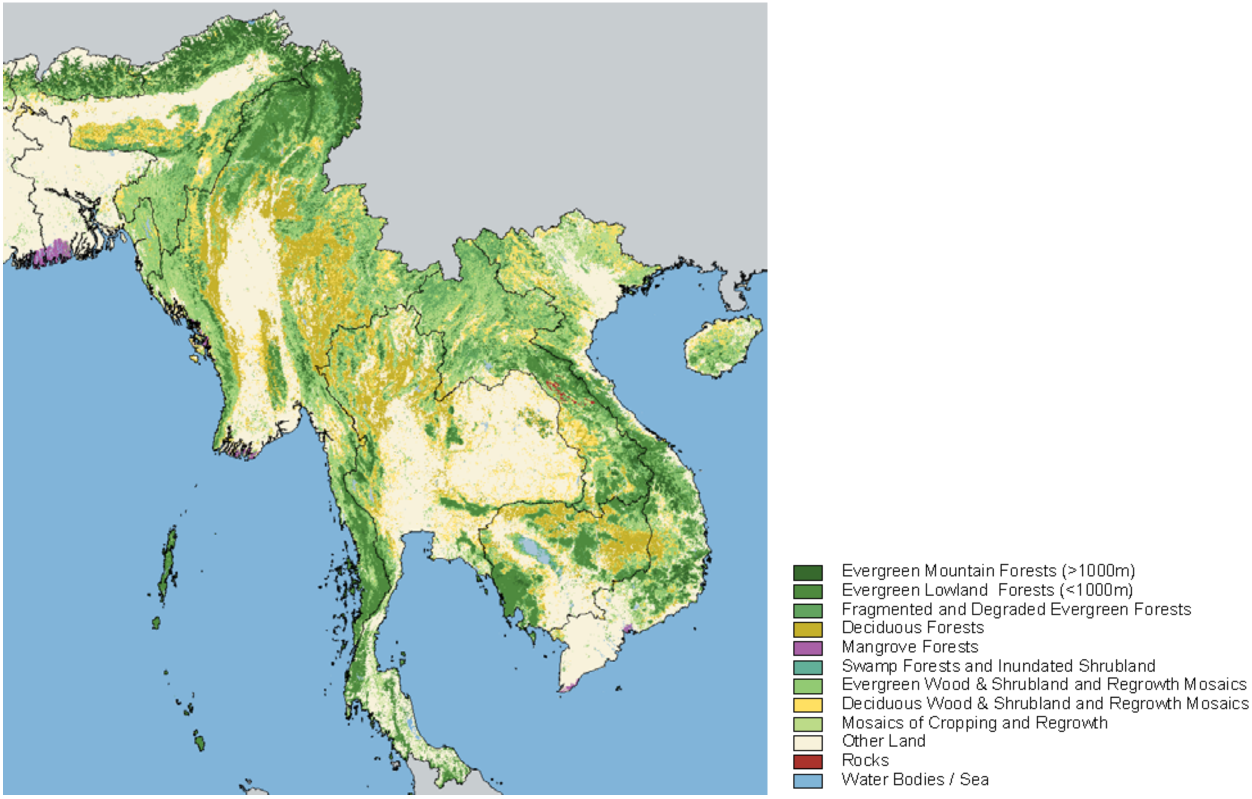

Fig. 2. Forest cover map of continental southeast Asia (geographical projection)

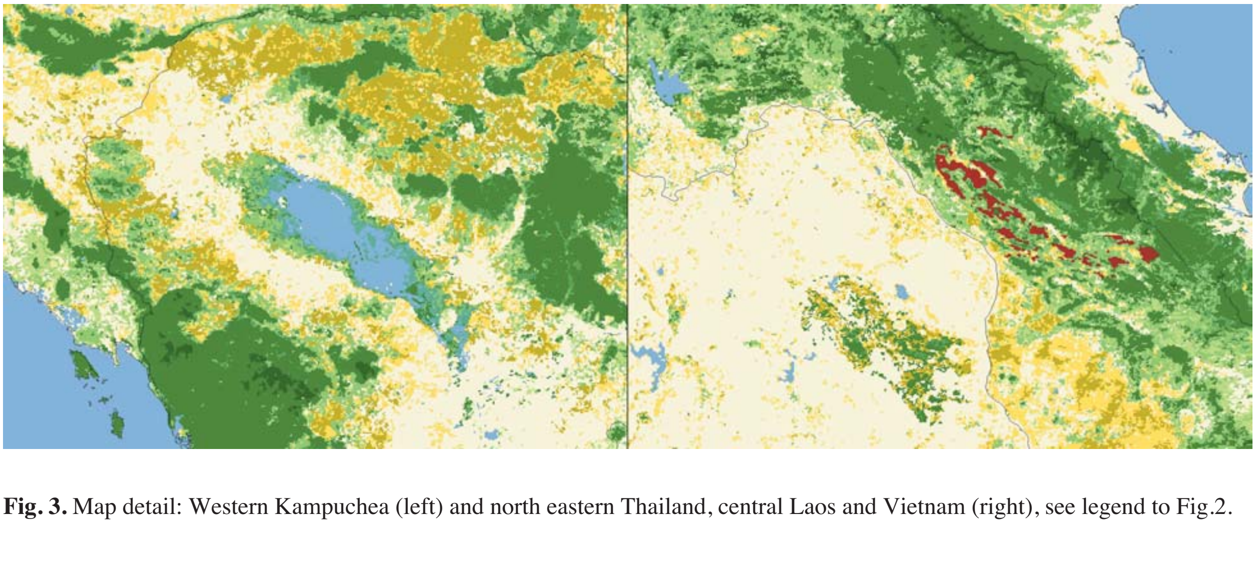

Fig. 3. Map detail: Western Kampuchea (left) and north eastern Thailand, central Laos and Vietnam (right), see legend to Fig.2.

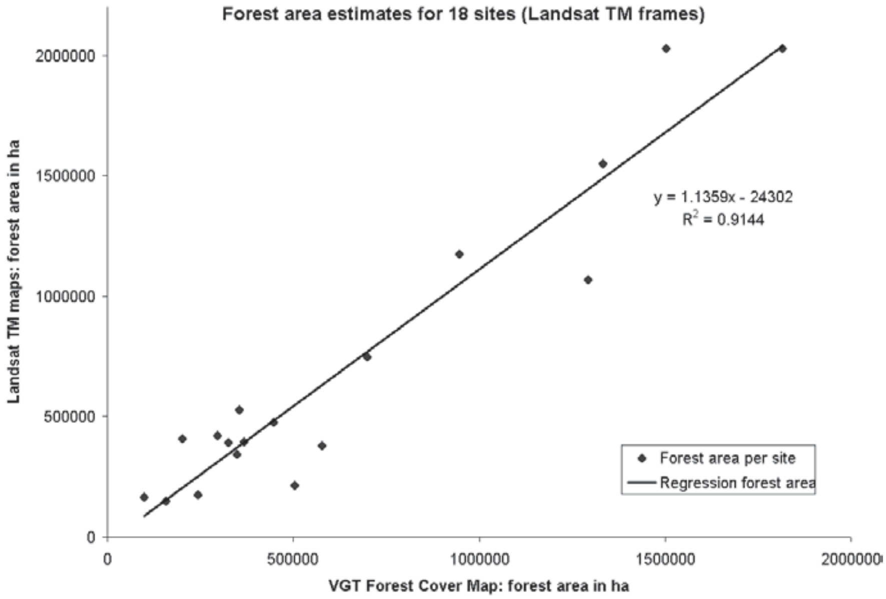

Fig. 4. Comparison of forest area estimates from VGT and Landsat-TM derived maps for 18 validation sites

Validation

We compared, for the 18 validation sites, our VGT forest area estimates to those derived from the Landsat-TM maps. The portion of forest in our mosaic classes, previously expressed as a range, was simplified to a single percentage value by taking the middle value of the range. Thus, we assigned 100% of forest cover to the forest classes, 55% to the fragmented forest class, 30% to the wood and shrubland dominated classes and 20% to the mosaics of cropland and regrowth class. Similarly, we applied to the fragmented Landsat-TM classes the forest fractions determined by the consistency study, with 75% and 25% of forest cover for the fragmented forest and the mosaic classes, respectively. A linear regression established for the area estimates obtained from both data sets displays a high correlation ($R^2 \sim 0.91$) and a tendency to slightly underestimate forest cover from the VGT map (Fig. 4). Referring to the total land area covered by the 18 sites (ca. 233 000 km^2), the forest area would be estimated at 49% by the VGT map and 54% by the Landsat-TM maps. Potential forest change between the years 1997 and 2000 was neglected. Considering the spatial resolution of our map and the region's complex land cover patterns the discrepancy of forest area of some 10% appears to be a satisfying result.

The direct pixel count of Landsat-TM class proportions within the VGT classes remains indicative, because of possible geometric location errors of up to one pixel (1 km). However, it shows that the VGT evergreen forest class compares reasonably well (83%) to forest on the Landsat-TM maps, whilst up to 35% of the VGT deciduous forest class might consist of other land cover, reflecting the difficulties in mapping of deciduous forest cover (Table 4). For the validation sites the forest portions contained in the shrub cover dominated classes appear higher than estimated *a-priori*.

However, we did not further derive correction factors for forest fractions or for calibrating forest area estimates because (1) of a possible impact of geometric

Table 4. Landsat-TM land cover proportions (in %) within VGT classes.

	VGT classes						
	Evergreen forest	Fragmented & degraded evergreen forest	Deciduous forest	Evergreen wood & shrubland, regrowth mosaics	Deciduous wood wood & shrubland, regrowth mosaics	Mosaics of cropping & regrowth	Crop & other land
Landsat-TM classes							
Forest & fragmented forests	83	69	65	52	43	39	10
Mosaics	2	10	13	12	13	16	5
Shrubland	10	12	7	16	8	19	29
Other Land Cover	5	9	15	20	36	26	56
VGT class area in 1000 ha	5596	1844	2350	5531	1617	2027	4376

Table 5. Comparison of regional and sub-regional forest area estimates.

	FAO 2000 database			Forest cover map (VGT) Reference year 2000	
	Reference year	Forest area $\times 10^6$ ha	Land area %	Forest area $\times 10^6$ ha	Land area %
Region	--	--		101.1	36
Greater Mekong Sub-Region		80.9	43	75.2	39
Myanmar	1997	34.4	52	31.7	48
Thailand	1998	14.8	29	14.3	28
Laos	1989	12.6	54	10.0	44
Kampuchea	1997	9.3	53	8.8	49
Vietnam	1995	9.8	30	10.2	31

location errors on the calculation of forest fractions and (2) our validation sites do not statistically represent the region's land cover proportions as they are concentrated in the forested areas. For example, the calculated forest portions in the VGT non-forest classes (Table 4) are likely to be higher within our validation sites than for the total region.

Forest area estimates

Keeping, therefore, to our initial class descriptions, the VGT map would estimate the total forest area at ca. 101×10^6 ha or 36% of the total land covered (Table 5). For the core countries ('Greater Mekong sub-region') the total forest area would be estimated at ca. 75×10^6 ha or 39% of the total land, compared to 81×10^6 ha or ca. 43% from the FAO database (Anon. 2001a). Even for individual countries, the VGT forest area estimates remain quite close to the FAO data, except for the case of Laos, where the VGT map estimate is closer to the more recent figure reported earlier (Table 1).

In general, the VGT forest area estimates tend to be lower than the FAO figures. This may partly result from the loss of detail and from effects of spatial aggregation associated with the coarse spatial resolution (Woodcock & Strahler 1987; Townshend & Justice 1988). There are also other explanations for lower estimates from our map compared to FAO figures: (1) national forest figures refer to 'forest land', including 'un-stocked' forest areas; (2) the forest area estimates refer to different reference years; (3) regrowth, young forest plantations and bamboo invaded areas, classified as shrub cover on the VGT map, may have been counted as forest by national inventories; (4) the difficulty of accurately mapping deciduous forest cover, at regional and national scales, may contribute to differing estimates; (5) our estimated portions of forest within the VGT fragmented and non-forest classes might tend to be low (although partly compensated for by not accounting for non-forest portions in the VGT forest classes).

Conclusions

With the present forest cover map of continental southeast Asia we provide a comprehensive and updated overview on the distribution of forest cover in the region for the year 2000. The main patterns of evergreen and deciduous forest cover depicted compare well to those of existing sub-regional maps. The combination of digital processing and classification with visual class labelling was found appropriate, compensating the loss of reproducibility by the input of regional knowledge on forest and land cover types. Difficulties in mapping regional forest cover from the coarse resolution satellite data related to forest fragmentation and land cover mosaics, to the mapping of deciduous forest cover in general, and to the gradual transitions between forests and regrowth or shrub formations.

Forest area estimates derived from our map compare at the regional level reasonably well to data of the FAO database. However, such 'non-calibrated' figures should be considered as preliminary estimates, useful as a reference in the regional context and for large geographical units. A detailed assessment of forest fractions and remnants in the non-forest classes and a forest area 'calibration' derived from measurements within a representative sample of high resolution satellite imagery could improve area estimates (Mayaux et al. 1998).

The map could serve as a baseline for spatially documenting large-scale forest cover change and long-term trends, as demonstrated for insular southeast Asia (Stibig & Malingreau 2003). The coarse spatial resolution, however, remains a limiting factor for local applications and for monitoring of annual or small-scale deforestation and degradation processes, common in the region.

Acknowledgements. The data set for the forest cover map of continental southeast Asia was prepared in the context of the JRC's TREES project and finalized during the GLC2000 project. The digital data are available at URL: http://www.gvm.jrc.it/Forest/defaultForest.htm. The map served as an input layer to the GLC2000 map over southeast Asia.

References

Anon. 1989. *Classification and mapping of vegetation types in tropical Asia*. Report, FAO, Rome, IT.

Anon. 1993. *Forest resources assessment 1990 – Tropical countries*. FAO Forestry Paper 112, FAO, Rome, IT.

Anon. 1995. Land cover assessment and monitoring. Environment Assessment Technical Reports 1-10, UNEP Environmental Assessment Program – Asia Pacific, Bangkok, TH.

Anon. 1996. *GTOPO30 Global Elevation Model (CD)*. United States Geological Service, Eros Data Centre, Sioux Falls, US. URL: http://edcdaac.usgs.gov/gtopo30/gtopo30.html.

Anon. 1998a. *Asia-pacific forestry towards 2010*. Report, FAO, Rome, IT.

Anon. 1998b. *VEGETATION user guide*. URL: http://www.spot-vegetation.com/vegetationprogramme/Pages/TheVegetationSystem/userguide/userguide.htm.

Anon. 2000. *State of forest report 1999*. Forest Survey of India (FSI). Ministry of Environment & Forest, Dehra Dun, IN.

Anon. 2001a. *Global forest resources assessment 2000*. Main Report. FAO Forestry Paper 140, FAO, Rome, IT.

Anon. 2001b. *Consistency assessment of the TREES II high resolution exercise*. JRC Report No. AJ/08/2000, prepared by Instituto Agronomico per l'Oltremare Florence (IAO), Ispra, IT.

Anon. 2002. *GEOCOVER 1990*. NASA. URL: https://zulu.ssc.nasa.gov/mrsid/mrsid.pl.

Anon. 2003a. *State of basin report: 2003*. Mekong River Commission, Phnom Penh, KH.

Anon. 2003b. *People and the environment atlas of the Lower Mekong Basin*. (CD), Mekong River Commission, Phnom Penh, KH.

Anon. 2003c. *A conflict of interest – The uncertain future of Burma's forests*. Briefing Document, Global Witness, London, UK.

Anon. 2003d. *Tonle Sap freshwater swamp forests*. WWF. URL: http://www.worldwildlife.org/wildworld/profiles/terrestrial/im/im0164_full.html.

Anon. 2004. *World climate: Weather rainfall and temperature data*. World Climate. URL: http://www.world climate.com/.

Achard, F. & Estreguil, C. 1995. Forest classification of Southeast Asia using NOAA AVHRR data. *Remote Sens. Environ*. 54: 198-208.

Achard, F., Eva, H. & Mayaux, P. 2001. Tropical forest mapping from coarse resolution satellite data: production and accuracy assessment issues. *Int. J. Remote Sens*. 22: 2741-2762.

Achard, F., Eva, H., Stibig, H-J., Mayaux, P., Gallego, J., Richards, T. & Malingreau, J.P. 2002. Determination of deforestation rates of the world's humid tropical forests. *Science* 297: 999-1002.

Bartholome, E. & Belward, A.S. In press. GLC2000: a new approach to global land cover mapping from earth observation data. *Int. J. Remote Sens*.

Blasco, F., Bellan, M.F. & Aizpuru, M. 1996. A vegetation map of tropical continental Asia at scale 1:5 million. *J. Veg. Sci*. 7: 623-634.

Blasco, F., Aizpuru, M. & Gers, C. 2001. Depletion of the mangroves of continental Asia. *Wetl. Ecol. Manage*. 9: 255-266.

Champion, H.G. & Seth, S.K. 1968. *The forest types of India: a revised survey*. Manager of Publication, New Delhi, IN.

Collins, N.M., Sayer, J.A. & Whitmore, T.C. 1991. *The conservation atlas of tropical forests: Asia and the Pacific*. Macmillan Press, London, UK.

Currey, D., Doherty, F., Lawson, S., Newman, L. & Ruwindrijarto, A. 2001. *Timber trafficking. Illegal logging in Indonesia, South East Asia and international consumption of illegally sourced timber. Report*. Environmental Investigation Agency (EIA) and Telapak Indonesia, Washington, DC, US.

Defourny, P., Pradhan U.C., Vinay, S. & Johnson, G.E. 1994. Overview of South-east Asia land cover using NOAA AVHRR one kilometre composite. *Geocarta Int*. 4: 45-52.

Di Gregorio, A. & Jansen, L.J.M. 2000. *Land cover classification system – LCCS: classification concepts and user manual*. FAO, Rome, IT.

Friedl, M.A., McIver, D.K. , Hodges, J.C.F., Zhang, X.Y., Muchoney, D., Strahler, A.H., Woodcock, C.E., Gopal, S., Schneider, A., Cooper, A., Baccini, A., Gao, F. & Schaaf, C. 2002. Global land cover mapping from MODIS: algorithms and early results, *Remote Sens. Environ*. 83: 287-302.

Geist, H.J. & Lambin, E.F. 2001. *What drives tropical deforestation? A meta-analysis of proximate and underlying causes of deforestation based on sub-national case study evidence*. LUCC Report Series No. 4, CIACO, Louvain-La-Neuve, BE.

Hansen, M.C., DeFries, R.S., Townshend, J.R.G. & Sohlberg, R. 2000. Global land cover classification at 1 km spatial resolution using a classification tree approach. *Int. J. Remote Sens*. 21: 1331-1364.

Hansen, M.C., DeFries, R.S., Townshend, J.R.G., Sohlberg, R., Dimiceli, C. & Carroll, M. 2002. Towards an operational MODIS continuous field of percent tree cover algorithm: examples using AVHRR and MODIS data. *Remote Sens. Environ*. 83: 303-319.

Klankamsorn, B. & Charuppat, T. 1994. *Deforestation in Thailand*. Royal Forest Department, Bangkok, TH.

Klein, C., Dees, M. & Pelz, D.R. 1993. *Sampling aspects in the TREES project: Global inventory of tropical forests*. Final report to the Joint Research Centre, No. 4014-92-10 ED ISP D, University Freiburg, Freiburg, DE.

Loveland, T.R., Reed, B.C., Brown, J.F., Ohlen, D.O., Zhu, Z., Yang L. & Merchant, J.W. 2000. Development of a global land characteristics database and IGBP DISCover from 1 km AVHRR data. *Int. J. Remote Sens*. 21: 1303-1330.

Mayaux, P., Achard, F. & Malingreau, J.P. 1998. Global tropical forest area measurements derived from coarse resolution satellite imagery: a comparison with other approaches. *Environ. Conserv.* 25: 37-52.

Meyer, G. & Panzer, K.F. 1990. *Regional renewable natural resources and land use inventory and monitoring*. Report PN: 90.2098.3-03.120, Federal Republic of Germany-Interim Mekong Committee for Coordination of Investigations of the Lower Mekong Basin, GTZ, Eschborn, DE.

Persson, R. 1974. World forest resources. Review of the world's forest resources in the early 1970s. Research Notes 17, Royal College of Forestry, Stockholm, SE.

Rundel, P.W. & Boonpragob, K. 1995. Dry forest ecosystems of Thailand. In: Bullock, S.H., Mooney, H.A. & Medina, E. (eds.) *Seasonally dry tropical forests*, pp. 93-123. Cambridge University Press, Cambridge, UK.

Smith, J.D. (ed.) 2001. *Biodiversity, The life of Cambodia – Cambodian biodiversity status report 2001*. Cambodia Biodiversity Enabling Activity, Phnom Penh, KH.

Spalding, M.D., Blasco, F. & Field, C.D. (eds.) 1997. *World mangrove atlas*. International society for mangrove ecosystems (ISME). Okinawa, JP.

Stibig, H.-J., Beuchle, R. & Achard, F. 2003a. Mapping of the tropical forest cover of insular Southeast Asia from SPOT4-Vegetation images. *Int. J. Remote Sens.* 24: 3651-3662.

Stibig, H.-J. & Malingreau, J.P. 2003b. Forest cover of insular Southeast Asia mapped from recent satellite images of coarse spatial resolution. *Ambio* 32: 469-475.

Townshend, J.R.G. & Justice, C.O. 1988. Selecting the Spatial Resolution of Satellite Sensors required for Global Monitoring of Land Transformations. *Int. J. Remote Sens.* 9: 187-236.

Whitmore, T.C. 1984. *Tropical rain forests of the Far East*. 2nd ed. Clarendon Press, Oxford, UK.

Woodcock, C.E. & Strahler, A.H. 1987. The factor of scale in remote sensing. *Remote Sens. Environ.* 21: 311-332.

Received 6 April 2004;
Accepted 28 August 2004.
Co-ordinating Editor: J. Franklin.