Article

Monitoring Deforestation and Forest Degradation in the Bago Mountain Area, Myanmar using FCD Mapper

Myat Su Mon^{*1}, Tsuyoshi Kajisa^{*2}, Nobuya Mizoue^{*2} and Shigejiro Yoshida^{*2}

ABSTRACT

While deforestation in the tropics has been well mapped, there is little information on the extent and changes of forest degradation. This study aimed to investigate temporal and spatial patterns of both deforestation and forest degradation in three reserved forests of the central Bago mountain ranges, Myanmar, which have a long history of selective logging activities. We used Forest Canopy Density (FCD) Mapper and Landsat images (1989, 1999, 2003, and 2006) for the investigation. Over 17 years, more than 90% of the total area was kept as forests, defined as FCD $\geq 10\%$, but closed canopy forests (FCD $\geq 70\%$) greatly decreased from 98% to 53% of the total area. Medium canopy forests ($40\% \leq \text{FCD} < 70\%$) and open canopy forests ($10\% \leq \text{FCD} < 40\%$) increased. Gross forest degradation (change to lower FCD) was much larger than gross forest improvement (change to higher FCD) for all sites and periods, whereas differences in gross deforestation (forest to non-forest) and gross reforestation (non-forest to forest) were relatively small. As a result, a high annual net forest degradation rate of 2.5% was observed, although the annual net deforestation rate was relatively low at 0.2% between 1989 and 2006. Our findings on higher forest degradation throw the question about the sustainability of current harvesting levels of selective logging and/or extraction of non-wood forest products and shifting cultivation by local communities if no conservation or remedial measures are taken. This study revealed the importance of monitoring deforestation and forest degradation as well as the usefulness of the FCD Mapper.

Keywords: FCD Mapper, Landsat images, deforestation, forest degradation, reforestation, forest improvement

INTRODUCTION

Tropical forests are critical to the balance of economical, ecological, and environmental factors on our planet because of their high diversity. However, forests in the tropics are depleting at an alarming rate, thus leading to forest degradation and deforestation that have been threatening future sustainability (VEROLME *et al.*, 1999; RUDEL and ROPER, 1997; LAURANCE, 1999, 2007; PANTA *et al.*, 2008). Therefore, identifying forest degradation and deforestation at different spatial and temporal scales could provide useful information

for planning and sustainable management of forests (PANTA *et al.*, 2008)

Deforestation is loss of forest cover by conversion of forests to other land cover types (FAO, 2000, 2005); it can be relatively easily identified. However, identifying forest degradation, i.e., reduction in capacity of a forest or canopy cover and stocking within the forest to provide goods and services (FAO, 2000, 2005), is a subtle process (SOUZA JR *et al.*, 2003; PANTA *et al.*, 2008). Forest degradation also represents loss of various environmental functions of the forest, thus being similar to deforestation. While deforestation has been widely emphasized and analyzed in a large number of studies

Corresponding author: Myat Su Mon

^{*1} Laboratory of Forest Management, Department of Forest and Forest Products Sciences, Graduate School of Bioresource and Bioenvironmental Sciences, Kyushu University

^{*2} Faculty of Agriculture, Kyushu University
812-8581, Laboratory of Forest Management,
Kyushu University, 6-10-1 Hakozaki, Higashi-ku,
Fukuoka, Japan
Tel: +81-92-642-2867, Fax: +81-92-642-2869
E-mail: myatsumon@ffp.kyushu-u.ac.jp

using satellite remote sensing (ARMENTERAS *et al.*, 2006; LELE and JOSHI, 2008; PUYRAUD, 2003), the extent and rate of forest degradation have not been well documented (SUNDERLIN and RESOSUDARMO, 1996; SOUZA *et al.*, 2003; JOSHI *et al.*, 2006; PANTA *et al.*, 2008).

Remotely sensed estimation of forest canopy density (FCD) has been used to assess the level of forest degradation (TIWARI *et al.*, 1986; PRINCE, 1987; RINGROSE and MATHESON, 1986; FORD and CASEY, 1988; KLEINN, 2001; HADI *et al.*, 2004; JOSHI *et al.*, 2006; PANTA, 2008). Measuring the extent of forest degradation is much more difficult than measuring deforestation (DEFIRES *et al.*, 2007). FCD Mapper (RIKIMARU, 1996) is one of the methods used to quantify FCD as a continuous variable from 0 to 100% (JOSHI *et al.*, 2006). The results of FCD mapping give the stratification of forest cover and therefore outputs is reliable to assess both forest degradation and deforestation. The main advantage of using FCD Mapper is to eliminate the need to undertake time consuming of field measurement of FCD using densitometer or hemispherical photograph (RIKIMARU *et al.*, 2002; CHANDRASHEKHAR *et al.*, 2005; BAYNES, 2007; AZIZI *et al.*, 2008), which is necessary in other remote sensing (RS) technologies, such as artificial neural network, multiple linear regression and maximum likelihood classification method. Although FCD Mapper has been applied in different forest types in tropical regions, very few studies have attempted to monitor changes in forest degradation status using FCD Mapper (PANTA, 2003; ROY, 2004; JAMALABAD, 2004).

Myanmar still has the largest forest cover, almost 50% of

the total land area, in mainland Southeast Asia (FAO, 2005). These forests are important sources of biodiversity. Myanmar will face serious problems in the very near future because of its high deforestation rate, i.e., 1.3% per year for 1990–2000 and 1.4% per year for 2000–2005 (FAO, 2005). Forest cover assessment in Myanmar has been mainly based on combined use of RS, geographical information systems (GIS), and ground forest inventory on national and regional scales. LEIMGRUBER *et al.* (2005) performed estimation of forest cover and focused on deforestation assessment throughout the country. However, there is dearth of detail and updated assessment on forest degradation, which makes it difficult for resource planners and decision-makers to implement effective conservation strategies for the remaining forest resources. This study aims to evaluate spatial and temporal patterns of forest degradation and deforestation, using the FCD Mapper and multi-temporal Landsat images in three reserved forests of the central Bago mountain ranges, Myanmar.

MATERIALS AND METHODS

Study Site

The study site was the central region of the Bago mountain ranges consisting of three reserved forests (RFs), namely Khapaung, Middle Nawin, and South Nawin RFs, covering an area of 1,074 km². The Bago mountain ranges located in the central part of lower Myanmar (Fig. 1), running from north to south, have renowned natural teak (*Tectona*

Fig. 1 Location of study sites: (a) Khapaung, (b) Middle Nawin, and (c) South Nawin reserved forests and sample plots measured FCD

grandis) bearing forests. Altitude ranges from 90 to 600m above sea level. The study areas mainly had an eastern or a western aspect. Occurrence of rainfall varies in intensity, depending upon the time of year; it is different between regions. According to some of the nearest meteorological stations, average annual rainfall was 1,917mm for eastern parts and 1,009mm for western parts during 1995 and 2006. Alluvial, red-brown forest soil and lateritic soil are common in the three RFs. Forest type occurred in the study area was commonly mixed deciduous forests, which are by far the most important forests in Myanmar. Under mixed deciduous forest types, moist upper mixed deciduous forest (MUMD) and dry upper mixed deciduous forest (DUMD) are widely distributed depending upon topography of the area. MUMD is characterized by the presence of bamboos, *Bambusa polymorpha* and *Cephalostachyum pergracile*. This forest type occurs on well-grained slopes and good quality soil. These forests contain the finest teak (*T. grandis*), usually associated with pyinkado (*Xylia xylocarpa*) and *Dipterocarpus* species. DUMD is characterized by the presence of bamboo *Dendrocalamus strictus* and occurs on ridge tops and hot aspects. *Bambusa tulda* is also found in stiff soil type of DUMD (KERMODE, 1964). Characteristic tree species of DUMD are very similar to that of MUMD. Economically important species such as teak (*T. grandis*), pyinkado (*X. xylocarpa*), padauk (*Pterocarpus macrocarpus*), taukkyan (*Terminalia tomentosa*), thitya (*Shorea oblongifolia*), and ingyin (*Pentacme siamensis*) are growing in two forest types of the study area.

Three RFs have been systematically managed under the selective logging system for teak and other hardwoods, known as the Myanmar Selection System (MSS). Under the MSS, a felling series is divided into 30 blocks of approximately equal yield capacity. Selective logging is carried out in one of these blocks every year and the whole forest is therefore worked over in the felling cycle of 30 years (DAH, 2004). Since forestry sector plays an important role in socio-economic development of the nation, increasing population and growing demand for timber, the study area was under shorter felling cycle (less than 30 years felling cycle) and subjected to repeated logging activities (BRUNNER *et al.*, 1998; FOREST DEPARTMENT, 1995a, 1995b, 2006a, 2006b). Land use history of shifting cultivation practiced by local communities with fallow periods over a 10-year rotation was also observed (TAKEDA *et al.*, 2005).

There is only one main road that passes through three RFs and joins two towns, namely Okktwin, Taungoo district and Paukhaung of Pyay district (Fig 1). Although the road condition is relatively good in Middle Nawin and South Nawin RFs, some parts are still under construction in Khapaung RF until 2009. Others are logging roads and that are especially used during summer for logging extraction purpose. The periphery of the study area was more likely to face forest depletion because of its location surrounded by a densely populated area, easily access, fertile soil for agriculture, and rich supplies of timber and bamboo (HTUN and MYINT, 2002;

THEIN *et al.*, 2007).

Over the last three decades, commercial forest plantations have been established in the three RFs. However, some older plantations in the Khapaung RF have already been exploited because of the construction of the Khapaung dam. In 2004, the Ministry of Forestry implemented a special afforestation project called the Bago Yoma Greening Project with the aim of conserving and protecting the remaining forest resources.

Procedures of FCD Mapper

The FCD Mapper, a semi-expert system was developed by the International Tropical Timber Organization and Japan Overseas Forestry Consultants Association and it produces FCD with the range of 0 to 100% (RIKIMARU, 1996; RIKIMARU and MIYATAKE, 1997). This comprises biophysical phenomenon modeling and analysis, utilizing data derived from four indices:

- I. vegetation index (VI), selected from the normalized difference vegetation index (NDVI), advanced vegetation index (AVI) or advanced normalized vegetation index (ANVI),
- II. bare soil index (BSI),
- III. shadow index (SI), and
- IV. thermal index (TI).

These four indices are calculated as new images from the raw Landsat bands 1-7. Based on the indices, FCD Mapper calculates a vegetation density (VD) which includes grassland and forest but excludes bare soil. Grass land is then separated from forest using a scaled shadow index (SSI) and finally FCD is calculated for each pixel of forested land. FCD Mapper produces these indices and integrates them into an FCD as an index ranging from 0 to 100 for each pixel of the final FCD image. The relevant formula and algorithms used in FCD Mapper are shown in Table 1.

The underlying principle for each of the above four main indices is that the VI has a positive relationship with the quantity of vegetation and therefore VI increases from grassland to forest. If there is more tree vegetation, there is more shadow and SI also increases as the forest density increases. If there is less bare soil or lower BSI, there will be a corresponding decrease in the TI. TI decreases as the vegetation quantity increases, i.e. TI is less inside the canopy of a forest due to blocking and absorption of the sun's rays and because of the cooling effect of evaporation from leaves.

Detailed methodology of FCD mapping is mentioned by RIKIMARU (1996), ROY *et al.* (1997), RIKIMARU *et al.* (2002), and CHANDRASHEKHAR (2005) and the FCD Mapper ver.2 user guide. Outputs of the FCD Mapper was then exported to ArcGIS 9.2 (ESRI Inc, USA) environments and used as a grid system of 30m × 30m for GIS analysis.

Table 1 Formula and algorithms used to calculate indices in FCD Mapper

Indices	Formula and algorithms
NDVI	$= (\text{Band 4} - \text{Band 3}) / (\text{Band 4} + \text{Band 3})$
AVI	$= [\text{Band 4} \times (256 - \text{Band 3}) \times (\text{Band 4} - \text{Band 3}) + 1]^{1/3}$, $(\text{Band 4} - \text{Band 3}) > 0$
ANVI	This index is synthesized index from NDVI and AVI by principal component analysis.
BSI	$= [((\text{Band 5} + \text{Band 3}) - (\text{Band 1} + \text{Band 4})) / ((\text{Band 5} + \text{Band 3}) + (\text{Band 1} + \text{Band 4}))] \times 100 + 100$
SI	$= [(256 - \text{Band 1}) \times (256 - \text{Band 2}) \times (256 - \text{Band 3})]^{1/3}$
TI	This index is calibrated from the value of thermal band.
VD	This index is calculated from the first principal component of VI and BSI.
SSI	This index is calibrated shadow index for the forested land.
FCD	$= (\text{VD} \times \text{SSI} + 1)^{1/2} - 1$

notes: NDVI: normalized different vegetation index; AVI: advanced vegetation index; ANVI: advanced normalized vegetation index; BSI: bare soil index; SI: shadow index; TI: thermal index; VD: vegetation density; SSI: scaled shadow index; FCD: forest canopy density %

Table 2 Images used for FCD assessment

No.	Year	Acquisition date	Satellites
1	1989	16-01-1989	Landsat TM
2	1999	30-12-1999	Landsat ETM +
3	2003	23-01-2003	Landsat ETM +
4	2006	15-01-2006	Landsat ETM +

Data Sources

Seven bands of Landsat data sets were taken as inputs for the FCD Mapper. This study used 133-47 Landsat TM for 1989 and Landsat ETM+ for 1999, 2003, and 2006 (Table 2). Wavelength and characteristics between Landsat TM and ETM+ are almost the same. JAMALABAD and ABAR (2004), ROY (2004) and CHANDRASHEKHAR *et al.*, (2005) also applied Landsat TM and ETM+ in FCD mapping and used the outputs to study the change detection of forest cover.

Data acquisition date is an important factor when using the FCD Mapper (ROY, 2004) because it models shadow, bare-soil and thermal indices for canopy cover estimation. To avoid seasonal variation in forest cover assessment, we selected four Landsat data sets that were acquired during the same season. It is extremely difficult to obtain images with the same acquisition date within the growing season of the study area, particularly in tropical regions where cloud cover is common (MAS, 1999). However, the data sets used in this study were acquired before leaf-off season, and these can provide effective results in estimating FCD.

The Landsat TM image of 1989 was geo-referenced using topographic maps of scale 1:63360, published in 1945 by the Survey Department of Myanmar. Landsat images of 1999, 2003, and 2006 were geo-referenced using an image-to-image registration method where the 1989 image was taken as the master image and the root mean square error was 0.005 pixels.

Image preparation was conducted in ERDAS IMAGINE®9.1 (Leica Geosystems Geospatial Imaging, USA) before FCD mapping.

Assessment of Forest Cover Dynamics

Following the forest definition of FAO (FAO, 2000, 2005), we classified land into non-forest (NF) if $\text{FCD} < 10\%$ and forest if $\text{FCD} \geq 10\%$ based on outputs of FCD mapping. Based on URYU *et al.* (2008), forests were classified into the following three categories for analysis of change detection matrices: open canopy forests (OCFs; $10\% \leq \text{FCD} < 40\%$), medium canopy forests (MCFs; $40\% \leq \text{FCD} < 70\%$), and closed canopy forests (CCFs; $\text{FCD} \geq 70\%$). To analyze and to detect spatial and temporal patterns of forest distribution, we compared the results between three RFs over different periods: 1989–1999, 1999–2003, 2003–2006, and 1989–2006. Table 3 shows the definitions and rules applied in estimating net deforestation and net forest degradation of the study area.

Accuracy Assessment

Ground data was collected from August to October 2007 and January to February 2009 to coincide with the growing season of forest vegetation and acquisition of images. A purely random sampling design was applied to establish sample plots. Precise locations of the sample plots were recorded using

Table 3 Definitions and rules to calculate deforestation and forest degradation

Change types	Definition and calculation of changes
Gross deforestation	complete conversion of forest to non-forest, i.e., total number of pixels changed from CCF, MCF, and OCF to NF
Gross reforestation	re-establishment of forest from non-forest (PERALTA and MATHER, 2000; NAGENDRA <i>et al.</i> , 2006), i.e., total number of pixels converted from NF to OCF, MCF, and CCF
Net deforestation	gross deforestation – gross reforestation
Gross forest degradation	any change to lower FCD within a forest (SAXENA <i>et al.</i> , 1997; URYU <i>et al.</i> , 2008), i.e., total number of pixels converted from CCF to MCF or OCF as well as MCF to OCF
Gross forest improvement	any change to higher FCD within a forest, i.e., total number of pixels converted from OCF to MCF or CCF as well as MCF to CCF
Net forest degradation	gross forest degradation – gross forest improvement
Annual rate of net deforestation (%)	$\frac{\text{net deforestation}}{\text{total forest areas at initial year of assessment}} \times \frac{1}{\text{assessment periods}} \times 100$
Annual rate of net forest degradation (%)	$\frac{\text{net forest degradation}}{\text{total forest areas at initial year of assessment}} \times \frac{1}{\text{assessment periods}} \times 100$

notes: NF: non-forest; OCF: open canopy forest; MCF: medium canopy forest; CCF: closed canopy forest

Table 4 Error matrix for measured and estimated classes of forest cover

		Measured				Total	User's accuracy (%)
		NF	OCF	MCF	CCF		
Estimated	NF	4	2	0	0	6	67
	OCF	0	10	7	0	17	59
	MCF	0	2	22	11	35	63
	CCF	0	2	9	102	113	90
	Total	4	16	38	113	171	
Producer's accuracy (%)		100	63	58	90		
Overall accuracy (%)		81					
Kappa coefficient		0.62					

notes: NF: non-forest; OCF: open canopy forest; MCF: medium canopy forest; CCF: closed canopy forest

GPSMAP®60CSx (Garmin Ltd, USA) in a Universal Transverse Mercator coordinate system with common datum of World Geodetic System 84. Canopy density was measured at five points, i.e., four corners and the center of each plots (30m × 30m, 171 points) (Fig. 1), using a convex densiometer (Forestry Suppliers Inc, USA). Mean canopy density of each plot was calculated for accuracy assessment. Overall mapping accuracy was evaluated by scatter plot and an error matrix between measured and estimated FCD.

RESULTS

Accuracy of FCD Mapping

Fig. 2 shows the relationship between FCD measured using a convex densiometer in the field and FCD estimated using FCD Mapper with $R^2 = 0.81$. The error matrix of measured and estimated classes of forest cover (Table 4) shows the accuracy of the FCD Mapper in classifying forest cover, i.e., 138 of 171 observations were correctly classified with an overall accuracy of 81% and a kappa coefficient of 0.62.

Fig. 2 Scatter plot of measured and estimated FCD%

Forest Cover Change

Fig. 3 shows spatial distribution of four classes of forest cover in each year, and Table 5 indicates percentages of forest cover classes for three RFs. In 1989, almost all land (98%) of the three RFs was covered with CCF, whereas NF comprised only 1% of the total area. Forest cover changes were more

prominent in the Middle and South Nawin RFs compared to the Khapaung RF. In the former two RFs, CCF largely decreased to around 30% between 2003 and 2006, whereas MCF increased from 1% to approximately 60% between 1989 and 2006. On the other hand, Khapaung maintained a relatively high percentage of CCF (62%) in 2006, whereas the percentage of MCF was 30%. Changes in NF were relatively

Fig. 3 Forest cover classified by FCD of three RFs for 1989, 1999, 2003, and 2006

Table 5 Percentage of four forest cover types in each year

Study sites	Year	NF (%)	OCF (%)	MCF (%)	CCF (%)
Khapaung	1989	1.0	0.3	0.6	98.1
	1999	1.8	2.8	2.2	93.1
	2003	2.3	3.8	4.5	89.4
	2006	3.8	3.7	30.5	62.1
Middle Nawin	1989	0.8	0.4	1.0	97.8
	1999	1.6	7.5	10.9	80.0
	2003	1.4	9.0	14.8	74.8
	2006	7.2	8.0	58.5	26.2
South Nawin	1989	1.1	0.5	1.2	97.2
	1999	2.3	7.5	9.8	80.5
	2003	1.7	10.7	20.2	67.3
	2006	6.0	7.8	55.6	30.7
Total	1989	1.0	0.3	0.7	98.0
	1999	1.9	4.1	4.5	89.5
	2003	2.1	5.5	8.1	84.3
	2006	4.6	4.9	38.0	52.6

notes: NF: non-forest; OCF: open canopy forest; MCF: medium canopy forest; CCF: closed canopy forest

small in all three RFs with a percentage of much less than 10% in 2006. Among different periods, changes during the latest period, i.e., from 2003 to 2006, were the most prominent.

Since each forest cover map has four classes, sixteen different classes were involved in change detection matrix. They were categorized into five groups: no change, gross forest degradation, gross deforestation, gross reforestation, and gross forest improvement. Table 6 shows percentages of five categories of forest cover change for each RF and period. Among the three RFs, the Khapaung RF had a larger number of no change areas and less gross forest degradation. For all RFs and periods, gross degradation was always much higher than gross forest improvement, thus resulting in net forest degradation; differences between them were larger in later periods. Gross deforestation was also larger than gross

reforestation in most cases, thus resulting in net deforestation, except for the period 1999–2003 in the Middle and South Nawin RFs. It should be noted that gross degradation was much larger than gross deforestation in all periods and RFs.

Tables 7 and 8 show annual net deforestation and forest degradation, respectively. The highest deforestation rate of 1.96% occurred in the Middle Nawin RF during the period 2003–2006, followed by that of 1.45% in the South Nawin RF. As expected from Table 6, there were two cases of negative net deforestation rates, i.e., net deforestation in the 1999–2003 periods. Forest degradation rates were always much higher than deforestation rates; the highest forest degradation rates were found in the latest period of 2003–2006, with a maximum forest degradation rate of 16%.

Table 6 Percentage of forest cover change types for four periods

Study sites	Periods	No change (%)	Gross forest degradation (%)	Gross deforestation (%)	Gross forest improvement (%)	Gross reforestation (%)
Khapaung	1989–1999	92.5	4.7	1.6	0.5	0.7
	1999–2003	86.8	6.7	1.8	3.4	1.3
	2003–2006	65.1	27.7	3.0	3.6	0.6
	1989–2006	62.7	33.7	3.1	0.2	0.3
Middle Nawin	1989–1999	79.2	17.9	1.5	0.8	0.6
	1999–2003	74.6	14.4	1.1	8.6	1.3
	2003–2006	38.1	49.0	7.7	4.7	0.5
	1989–2006	27.0	65.7	6.8	0.2	0.3
South Nawin	1989–1999	79.6	16.6	2	0.9	0.9
	1999–2003	68.5	21.1	1.2	7.4	1.8
	2003–2006	48.7	37.8	5.9	7.2	0.4
	1989–2006	31.4	62.2	5.4	0.5	0.5
Total	1989–1999	88.8	8.3	1.6	0.6	0.7
	1999–2003	82.5	9.7	1.6	4.7	1.5
	2003–2006	58.9	32.2	4.1	4.2	0.6
	1989–2006	53.2	42.2	4.0	0.2	0.4

Table 7 Annual net deforestation rate (%) of three reserved forests

Study sites	1989–1999	1999–2003	2003–2006	1989–2006
Khapaung	0.08	0.12	0.50	0.17
Middle Nawin	0.08	–0.05	1.96	0.38
South Nawin	0.12	–0.14	1.45	0.29
Total	0.09	0.06	0.85	0.21

Table 8 Annual net forest degradation rate (%) of three reserved forests

Study sites	1989–1999	1999–2003	2003–2006	1989–2006
Khapaung	0.42	0.82	8.96	1.99
Middle Nawin	1.72	1.47	16.10	3.88
South Nawin	1.58	3.51	11.35	3.66
Total	0.76	1.27	10.35	2.50

Fig. 4 Total exploited timber volume (1,000m³) from three RFs (1990–2007)

DISCUSSION

The FCD Mapper was designed for foresters and resource managers to easily collect information on forest canopy with reducing costs and saving time (RIKIMARU *et al.*, 1997). In the other words, FCD Mapper eliminates large amount of ground data which are not always easily available. This study demonstrated to detect forest cover change, deforestation, and forest degradation using FCD Mapper. This study achieved an overall mapping accuracy of 81%, which is an acceptable level of FCD mapping in comparison to other studies [71% (PANTA, 2003) and 50% (JOSHI *et al.*, 2006) in Nepal, 83% (JAMALABAD and ABAR, 2004) and 84% (AZIZI *et al.*, 2008) in Iran, and 80% in India (CHANDRASHEKHAR *et al.*, 2005)]. Performance of the FCD Mapper in forest cover assessment provided satisfactory accuracy, thus showing that it can be used to assess forest degradation as well as deforestation.

During the 17-year period, the three RFs maintained a high percentage of forest cover (more than 90%) and the annual net deforestation rate was 0.2% in total, thus being much smaller than the 1.3% or 1.4% values estimated by the FAO (2005) and similar to the estimate (0.3%) by LEIMGRUBER *et al.* (2005). On the other hand, we found that a high degree of forest degradation occurred in all study sites, with an annual net degradation of 2.5% in total. The high percentage of CCF in 1989 gradually decreased in all areas, whereas MCF significantly increased. These findings imply that forest degradation may be more problematic than deforestation in the study sites.

We found that there were differences in deforestation and forest degradation among different RFs and periods. Among the three RFs, forest degradation was larger in the Middle and South Nawin RFs for all periods. As mention in study area, one reason might be because the two RFs are more accessible in terms of road conditions and distance from the road and human settlements in compare with Khapaung RF (Fig. 1). These RFs are therefore more susceptible to fuelwood collection and encroachment by surrounding communities.

Among different periods, forest degradation was very rapid during 2003–2006, i.e., 10% in total. Changes in the harvesting volume could be one of the reasons for this. According to records of timber exploitation over 10 years, exploited timber volume was highest during 2003–2004 (Fig. 4). Accordingly, conservation activities including checking annual allowable cuts for selective logging activities for each management unit should be implemented based on updated inventory data, and enrichment planting should be conducted for open and degraded forest areas.

The Bago mountain ranges have been managed for timber production and non-wood forest products (NWFPs) by the Forest Department (FOREST DEPARTMENT, 2006a, 2006b). Sustainable forest management for long-term benefit was attempted in the forestry sector by introduction of a rehabilitation project, the Bago Yoma Greening Project (FOREST DEPARTMENT, 2004). In this project, both silvicultural treatments in natural forests and socio-economic development were considered in promotion of conservation activities. Assessment and monitoring of forest cover changes using remote sensing data with FCD Mapper as demonstrated in this study will be useful to evaluate and improve effectiveness of this kind of conservation activities.

CONCLUSION

We found that the FCD Mapper is useful technique for monitoring and assessing deforestation and forest degradation, which are significant problems in planning and implementation of sustainable forest management. The study area still had a large percentage of forest area, more than 90% of the total area, over the 17 years considered. However, gross forest degradation was much larger than gross forest improvement, thus resulting in high net forest degradation, especially in recent years. These findings call for conservation activities to improve current land use practices, such as commercial logging and shifting cultivation practices in the study area. This study provides baseline information related to dynamics of forest cover. Future studies should be conducted

to identify factors causing deforestation and forest degradation, and find remedial measures for future sustainable forest management.

LITERATURE CITED

- ARMENTERAS, D., RUDAS, G., RODRIGUEZ, N., SUA, S. and ROMERO, M., (2006): Patterns and Causes of Deforestation in the Colombian Amazon. *Ecological Indicators* **6**: 353-368
- AZIZI, Z., NAJAFI, A. and SOHRABI, H., (2008): Forest Canopy Density Estimating using Satellite Images, *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. Vol. XXXVII. Part B8. Beijing
- BAYNES, J., (2007): Using FCD Mapper Software and Landsat Images to Assess Forest Canopy Density in Landscapes in Australia and the Philippines. *Annals of Tropical Research* **29**: 9-20
- BRUNNER, J., TALBOTT, K. and ELKIN, C., (1998): Logging Burma's Frontier Forests: Resources and the regime. World Resource Institute. Washington, DC. ISBN: 1-56973-266-3
- CHANDRASHEKHAR, M.B., SARAN, S., RAJU, P.L.N. and ROY, P.S., (2005): Forest Canopy Density Stratification: How Relevant is Biophysical Spectral Response Modeling Approach?, *Geocarto International* **20**: 15-21
- DAH, S. E., (2004): Teak and Forest Management in Myanmar: Myanmar's Natural Teak Forests are being Supplemented Increasingly by Plantations. *ITTO Tropical forest Updated* **14**: 12-13
- DEFRIES, R., ACHARD, F., BROWN, S., HEROLD, M., MURDIYARSO, D., SCHLAMADINGER, B. and SOUZA Jr, C. D., (2007): Earth Observations for Estimating Greenhouse Gas Emissions from Deforestation in Developing Countries. *Environ. Science and Policy*: 385-394
- FAO., (2000): Forest resources assessment 2000. Food and Agriculture Organization of United Nations, Rome
- FAO., (2005): Forest resources assessment 2005. Food and Agriculture Organization of United Nations, Rome
- FORD, J.P. and CASEY, D.J., (1988): Shuttle Radar Mapping with Diverse Incidence Angles in the Rainforest of Borneo. *Int. J. Remote Sensing* **9**: 927-943
- FOREST DEPARTMENT, (1995a): Forest Management Plan (1996-1997 to 2005-2006), Pyay District, Bago Division. Myanmar (Text in Myanmar)
- FOREST DEPARTMENT, (1995b): Forest Management Plan (1996-1997 to 2005-2006), Taungoo District, Bago Division. Myanmar (Text in Myanmar)
- FOREST DEPARTMENT, (2004): Bago Yoma Greening Project (2004-2005 to 2008-2009). Forest Department, Myanmar (Text in Myanmar)
- FOREST DEPARTMENT, (2006a): Forest Management Plan (2006-2007 to 2015-2016), Pyay District, Bago Division. Myanmar (Text in Myanmar)
- FOREST DEPARTMENT, (2006b): Forest Management Plan (2006-2007 to 2015-2016), Taungoo District, Bago Division. Myanmar (Text in Myanmar)
- HADI, F., WIKANTIKA, K. and SUMARTO, I., (2004): Implementation of Forest Canopy Model to Monitor Forest Fragmentation in Mt. Simpang and Mt. Tilu Nature Reserves, West Java, Indonesia. 3rd FIG Regional Conference Jakarta, Indonesia, October 3-7
- HTUN, K. and MYINT, W., (2002): Traditional and Current Land Use in South Nawin Watershed in Paukkaung Model Forest, Myanmar. Newsletters: News on the Model Forest Approach to Sustainable Forest Management. Food and Agriculture Organization of United Nations
- JAMALABAD, M. S. and ABKAR, A.A., (2004): Forest Canopy Density Monitoring using Satellite Images. Geo-Imagery Bridging Continents XXth ISPRS Congress, Istanbul, Turkey
- JOSHI, C., LEEUW, J.D., SKIDMORE, A.K., DUREN, I.C.V. and OOSTEN, H.V., (2006): Remotely Sensed Estimation of Forest Canopy Density: A Comparison of the Performance of Four Methods. *International Journal of Applied Earth Observation and Geoinformation* **8**: 84-95
- KERMODE, D.W.D., (1964): Some Aspects of Silviculture in Burma Forest. Forest Department, Rangoon, Myanmar
- KLEIN, C., (2001): A Cautionary Note on the Minimum Crown Cover Criterion in Forest Definitions. *Can. J. For. Res.* **31**: 350-356
- LAURANCE, W.F., (1999): Reflections on the Tropical Deforestation Crisis. *Biol. Conserv.* **91**: 109-117
- LAURANCE, W.F. (2007): Forest Destruction in Tropical Asia. Special Section: Asian Biodiversity Crises, *Current Science* **92**: 1544-1550
- LEIMGRUBER, P., KELLY, D.S., STEININGER, M.K., BRUNNER, J., MUELLER, T. and SONGER, M.A., (2005): Forest Cover Change Patterns in Myanmar (Burma) 1990-2000. *Environmental Conservation* **32**: 356-364
- LELE, N. and JOSHI, P.K., (2008): Analyzing Deforestation Rates, Spatial Forest Cover Changes and Identifying Critical Areas of Forest Cover Changes in North-East India 1972-1999. *Environ Monit Assess.* DOI. 10. 1007/s 10661-008-0472-6
- MAS, J.F., (1999): Monitoring Land-cover Changes: A Comparison of Change Detection Techniques, *Int. J. Remote Sensing* **20**: 139-152
- NAGENDRA, H., PAREETH, S. and GHATE, R., (2006): People Within Prak-forest Villages, Land-cover Change and Landscape Fragmentation in the Tadoba Andhari Tiger Reserve, India. *Applied Geography* **26**: 96-112
- PANTA, M., (2003): Analysis of Forest Canopy Density and Factors affecting it, using RS and GIS Techniques (A Case Study from Chitwan District of Nepal). ITC Master Thesis
- PANTA, M., KIM, K. and JOSHI, C., (2008): Temporal Mapping of Deforestation and Forest Degradation in Nepal: Application to Forest Conversation. *For. Ecol. and Manage.* **256**: 1,587-1,595
- PERALTA, P. and MATHER, P., (2000): An Analysis of Deforestation Patterns in the Extractive Reserves of Acre, Amazonia from Satellite Imagery: A Landscape Ecological Approach. *Int. J. Remote Sens.* **21**: 2,555-2,570
- PRINCE, S.D., (1987): Measurement of Canopy Interception of Solar Radiation by Stands of Trees in Sparsely Wooded Savanna (Sudan). *Int. J. Remote Sensing* **8**: 1747-1766
- PUYRAVAUD, J.P., (2003): Standardizing the Calculation of the Annual Rate of Deforestation, *For. Ecol. Manage.* **117**: 593-596
- RIKIMARU, A., (1996): LAMDSAT TM Data Processing Guide for forest Canopy Density Mapping and Monitoring Model. ITTO workshop on Utilization of Remote Sensing in Site Assessment and Planning for Rehabilitation of Logged-over Forest. July 30-August 1, Bangkok, Thailand
- RIKIMARU, A. and MIYATAKE, S., (1997): Development of Forest Canopy Density Mapping and Monitoring Model using Indices of

- Vegetation, Bare Soil and Shadow. 18th Asian Conference on Remote Sensing, October 20-24, Malaysia
- RIKIMARU, A., ROY, P.S. and MIYATAKE, S., (2002): Tropical Forest Cover Density Mapping, *Tropical Ecology* **43**: 39-47
- RINGROSE, S. and MATHESON, W., (1986): Monitoring Desertification in Botswana using Landsat MSS Data: with Consideration as to the Nature of the Infra-red Paradox. In: Millington, A.C., Mutiso, S.K., Binns, J.A. (Eds.), *African Resources*, vol. 1. Appraisal and Monitoring. University of Reading, UK, 18 pp
- ROY, P.S., (2004): Forest Fire and Degradation Assessment using Satellite Remote Sensing and Geographic Information System, *Satellite Remote Sensing and GIS Applications in Agricultural Meteorology*: 361-400
- RUDEL, T. and ROPER, J., (1997): The Paths to Rain Forest Destruction: Cross National Patterns of Tropical Deforestation, 1975-1990. *World Dev.* **25**: 53-65
- SAXENA, A.K., NAUTIYAL, J.C. and FOOT, D.K., (1997): Analyzing Deforestation and Exploring the Policies for its Amelioration: A Case Study in India. *Journal of Forest Economics* **3**: 253-289
- SOUZA Jr, C., FIRESTONE, L., SILVA, L.M. and ROBERTS, D., (2003): Mapping Forest Degradation in the Eastern Amazon from SPOT 4 through Spectral Mixture Models. *Remote Sens. Environ.* **87**: 494-506
- SUNDERLIN, W.D. and RESOSUDARMO, I.A.P., (1996): Rates and Causes of Deforestation in Indonesia: towards a Resolution of the Ambiguities. Center for International Forestry Research. Occasional paper no. 9. ISSN 0854-9818
- TAKEDA, S., SUZUKI, R. and THEIN, H.M., (2005): Three Years Monitoring of Shifting Cultivation Fields in Karen Area, the Bago Mountains, Myanmar. Nihon Shinrin Gakkai Taikai Koen Yoshishu (CD-ROM)
- THEIN, H.M., KANZAKI, M., FUKUSHIMA, M. and MINN, Y., (2007): Structure and Composition of a Teak-bearing Forest under the Myanmar Selection System: Impacts of Logging and Bamboo Flowering. *Southeast Asian Studies* **45**: 303-316
- TIWARI, A.K., MEHTA, J.S., GOEL, O.P. and SINGH, J.S., (1986): Geo-forestry of Landslide-affected Areas in a Part of Central Himalaya. *Environ. Conserv.* **13**: 299-309
- URYU, Y., *et al.*, (2008): Deforestation, Forest Degradation, Biodiversity Loss and CO2 Emissions in Riau, Sumatra, Indonesia. WWF Indonesia Technical Report, Jakarta, Indonesia
- VEROLME, H., MOUSSA, J.H. and JULIETTE, M., (1999): Addressing the Underlying Causes of Deforestation and Forest Degradation-case studies. In: *Analysis and Policy Recommendations*. Biodiversity Action Network, Washington, DC, USA

(Received 18 May 2009)

(Accepted 5 September 2009)