MAPPING DEFORESTATION AND LAND COVER CONVERSION AT THE RAINFOREST MARGIN IN CENTRAL SULAWESI, INDONESIA

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ABSTRACT

The tropical rain forests in Indonesia are affected by socio-economic and ecological factors and processes that result in an increasing destabilisation of the rainforest margins. Optical satellite data have been explored to document changes in land cover throughout the past 30 years and to monitor the current status and dynamics of land cover and land cover conversion for an investigation area of 7,500 km^2 in Central Sulawesi. The purpose of the study is to evaluate available satellite data sets and to establish a transparent work flow for the monitoring of past and future land cover dynamics at a regional scale based on medium resolution satellite data. This includes rigorous radiometric calibration as well as advanced classification techniques. A time series of Landsat data (Landsat/MSS; Landsat/ETM+) have been radiometrically processed including sensor calibration, atmospheric correction (COST-model) as well as the correction of solar and topographic illumination effects. Land cover mapping has been performed using a comprehensive, context-based approach including image segmentation, fuzzy logic based class definitions (rule sets) and classification. Results of the change analysis show that forest degradation and deforestation within the study area in Central Sulawesi is occurring but at a significantly lower rate (-0.6%/year) than for the rest of the Indonesian Archipelago (-1.2%/year). Nevertheless, deforestation in Central Sulawesi has dramatically increased during the past few years, mostly due to illegal clear-cut logging which shows severe impacts on the environment (i.e. floods, landslides).

Keywords: Sulawesi, land cover conversion, classification, change detection.

INTRODUCTION

The SFB-552 *Stability of rainforest margins (STORMA)* sponsored by the Deutsche Forschungsgemeinschaft (DFG) examines the processes of destabilisation at the forest border and analyses factors and processes that may conserve tropical forest systems. Within this framework, remote sensing data analysis provides a spatial coverage of landscape pattern and delivers spatial and temporal data for the assessment and observation of land use systems and land cover change at the rain forest margin. Land use at the rain forest margin in Central Sulawesi is dominated by a range of agroforestry and agricultural systems that represent different stages of land use intensity and ecosystem biodiversity (1). Thus, changes in land use might help to explain environmental changes and their ecological and societal consequences (2). Within this context, remote sensing data may deliver spatial, spectral and temporal indicators of the land cover condition and type in tropical forest environments (3,4). The current work aims at the processing and analysis of medium resolution optical satellite data to monitor and map the extent and nature of land cover at the rainforest margins in Central Sulawesi, Indonesia. The main focus within the land cover mapping is on the estimation of the extent and rate of forest degradation and deforestation. There has been a lot of confusion about deforestation rates during the 90ies due to inconsistent definitions of the term deforestation. Deforestation is defined as the sum of both permanent and temporary human-induced removal of forest cover (5,6). This definition includes short-term removals by shifting-cultivation as well as selective and clear-cut logging activities and all other kinds of conversion of forest land to non-forest land. Considering this definition, remote sensing data provide spatial information about land cover which can be used in scenarios to predict and explain changes in land cover and land use.

Within this paper, the problems and opportunities of remote sensing based land cover mapping in the tropics will be discussed based on a data set of optical satellite data for the investigation area in Central Sulawesi. The Landsat system provides a temporal coverage of medium resolution satellite data with a nearly global coverage for land surfaces and still is indispensable for the majority of scientific and commercial projects and applications dealing with land use and land cover change. Within the current project, all available satellite data have been radiometrically calibrated taking into account top-of-atmosphere (TOA) reflectance, path radiance and solar as well as topographic effects. The projected and calibrated data yielded the input for the computational analysis and classification of the image data.

The goal of the research was to provide a transparent and reproducible processing and analysis work flow for the land cover categorization in a tropical environment based on a multi-temporal Landsat data set (Landsat/MSS; Landsat/ETM+).

STUDY AREA

The study area is located in Central Sulawesi, Indonesia and consists of the Lore Lindu National Park (LLNP) and five surrounding districts within the province of Central Sulawesi (Sulawesi Tengah). The province capital (Palu) is located at the northern border of the study area (Figure 1). The total investigation area covers approximately 7,500 sq. kilometres (0°50'S – 2°04'S and 119°40'E – 120°30'E) where 2,200 sq. kilometres constitute the LLNP, a natural forest reserve that is facing remarkable forest conversion activities along the forest and park boundaries. The Lore Lindu region is topographically diverse with mountain ranges reaching up to 2,600 m a.s.l. interspersed with narrow and outstretched valleys at different elevations and expositions.

The research area is characterized by a humid tropical climate with mean annual temperatures between 25 and 26°C at sea level, high humidity (85-95%) and a mean annual precipitation >2,500 mm that is subject to a high variability due to the diverse topography (7). The annual precipitation distribution permits year-round agriculture. The land use is dominated by paddy rice cultivation in the valley bottom and coffee and cacao cultivation on sloping land. Maize, various legumes and fruits are cultivated on recently cleared areas and around people's houses. Furthermore, there is cultivation of coconut palms, cassava, peanuts and others.

DATA AND METHODS

Landsat data have been acquired over the study area for the time frame of 1972 to 2002. The data set that has been used for analysis within this investigation consists of four Landsat scenes: a Landsat/MSS scene of 28 October 1972 (WRS-1, Path 122 / Row 61) and three Landsat/ETM+ scenes of 20 September 1999, 24 August 2001 and 28 September 2002 (WRS-2, Path 114 / Row 61). The data have been received in level 1G-format (UTM 51M). The Landsat/MSS scene was geometrically adjusted using a 2nd order polynomial transformation with an average root mean square error (RMSE) of 0.3 pixel units. The Landsat/ETM+ scenes were geometrically processed using a parametric satellite orbital model (RMSE = 0.5) which compensates for distortions due to sensor geometry, satellite orbit and attitude variations, earth shape, rotation and topography (8). Overall, 65 ground control points (GCP's) were used to derive the model with Geomatica/OrthoEngineV9.1.

The reference data set for the geocoding procedures comprises topographic maps (1:50,000), D-GPS ground control points (Leica GS-50) and a local solar inclination map based on satellite header information of the respective image and digital elevation data (DEM) with an interpolated grid cell size of 30 m. The digital elevation model has been generated from digitised contour lines of the topographic maps. The local incidence angle (*i*) is defined as the angle between the surface normal of the smallest observed ground unit (pixel) and the direct solar irradiance. The cosine of the local solar incidence angle can be computed from the DEM as follows (9):

$$\cos i = \cos\theta_p \cdot \cos\theta_z + \sin\theta_p \cdot \sin\theta_z \cdot \cos(\phi_a - \phi_0) \quad , \qquad (1)$$

where θ_z and ϕ_a are the solar zenith and azimuth angles and θ_p and ϕ_0 are the surface slope and aspect angles.

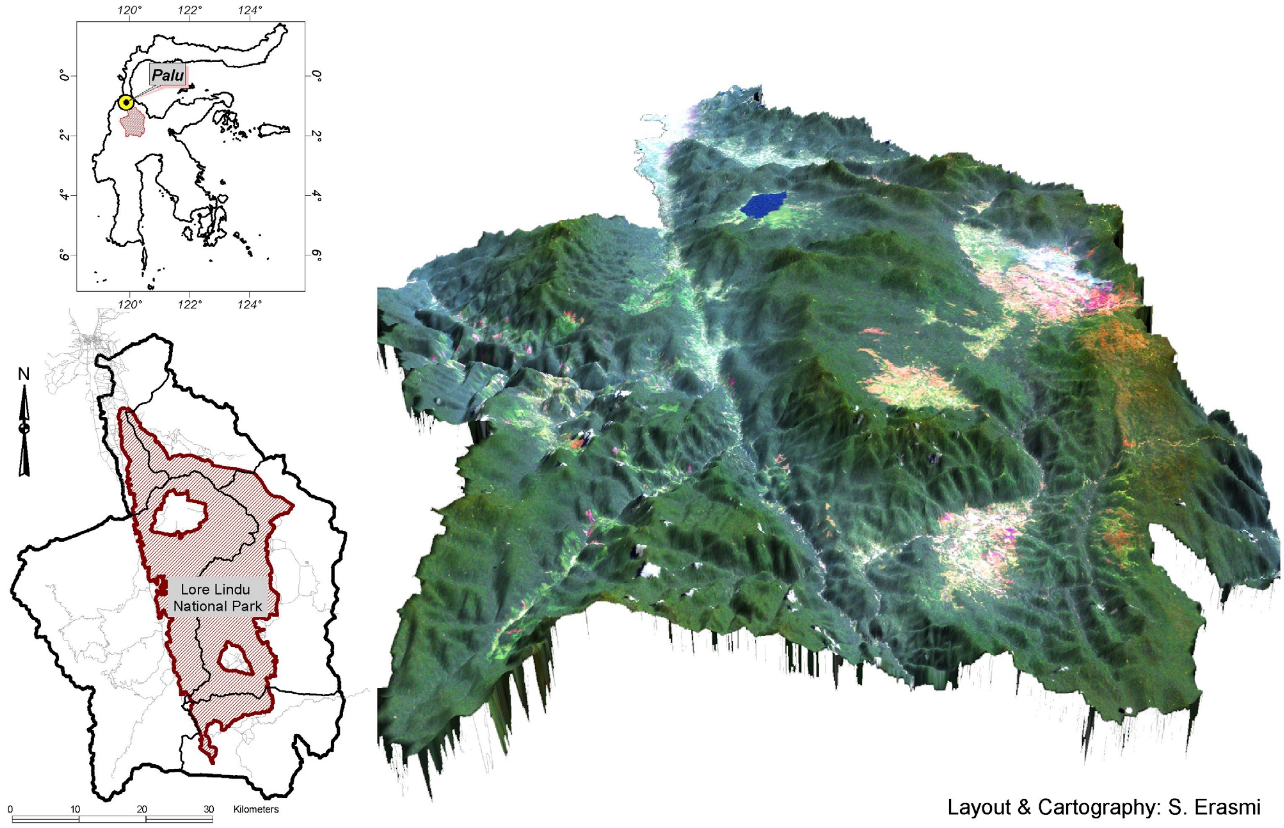

Figure 1: Overview of the study area surrounding the Lore Lindu National Park (LLNP) in the province of Central Sulawesi (right: Landsat/ETM+ color composite draped over digital terrain model)

The solar inclination map has shown to be of advantage for the detection of appropriate ground control points (GCP's) especially in rugged terrain compared to other GCP's taken from topographic maps. Subsequently, the geometrically congruent data set is converted to apparent at-satellite radiance using gain and offset coefficients provided by the data supplier.

Since atmospheric influences are particularly significant in tropical areas and vary both spatially and temporally, there is a need to account for these effects especially within multi-temporal studies of land cover change. Although physically-based models which require atmospheric data coincident with remote sensing observations are known to be most accurate (10), their overall applicability has been limited so far since these parameters are commonly not available for historical satellite data. Several image-based techniques have been developed in order to compensate for this shortcoming. We selected the improved dark object subtraction method (DOS) proposed by (11) which is also referred to as the COST model (cosine of the solar zenith angle "COS(ThetaZ)") to account for the contradicting effects of both path radiance and atmospheric transmittance. In addition, the algorithm incorporates a sun elevation and earth-sun distance correction.

Topographic normalization is commonly performed using the local solar incidence angle derived from a DEM (see above). After an evaluation of the existing methods (12,13) the C-correction method has been applied to normalize the current data set for topographically induced radiometric disturbances. Besides the standard methods which assume Lambertian reflectance, this empirical-statistical approach uses the gradient and intercept of the regression equation between non-corrected reflectance values and the local incidence angle.

The geometrically corrected and radiometrically calibrated imagery has been subset to the extent of the study area and clipped with the ancillary data (DEM, cosine map, area mask, spatial ground truth data) to form a geospatial database at a unique pixel resolution of 30 m. Within this study area, a focus area has been defined at a resolution of 15 m consisting of the pan-sharpened Landsat/ETM+ images and the same auxiliary data as above.

The qualitative analysis (classification) of the imagery is conducted with the purpose of mapping homogeneous areas of vegetation cover that represent the dominant land cover types within the project area. For this purpose an image segmentation is performed prior to image classification. The generalization of images always means a loss of information (14). This is why in most cases pixel-based classifiers are used to analyse medium resolution satellite data. On the other hand, pixel-based classifications always face the problem of mixed-pixels as well as salt-and-pepper features and thus in most cases require pre- or post-classification smoothing (15).

The entire classification procedure that is used within this study includes the following steps: 1. creation of a cloud mask for the entire data set; 2. segmentation of the imagery based on spectral and spatial attributes of the data sets; 3. definition of object classes and training sites; 4. fuzzy-logic classification of segmented images; 5. accuracy assessment; 6. change analysis based on area statistics.

Clouded and shadowed areas are computed using reflectance thresholds for the red and mid-infrared image channels for each data set respectively. These areas are neglected for further analysis. The image segmentation is performed to establish homogeneous areas within the images that are supposed to represent a distinct land cover type or object class, respectively. The image segmentation concept is based on homogeneity definitions in combination with local and global optimization techniques. The homogeneity of each image object is defined based on spectral and/or spatial information taken from the images (16). A scale parameter is used to control the average image object size. For the current Landsat data set a low scale factor (scale=5) was used. This resulted in an average object size of 4.7 hectares. The result of the segmentation procedure is a mosaic of image objects per image layer that deliver the input data set for further classification issues. The classification of the segmented image layers is based on a fuzzy logic approach that allows complex object feature descriptions and uses membership functions (rule-sets) to conduct rules for the determination of the membership degree, i.e. the likelihood of a certain object to belong to an object class based on spectral and/or spatial attributes (see 16 for details). An example for the definition of a rule-set using spectral and spatial data layers is given in Figure 2. As can be seen from this figure, the class description is not only generated using spectral values and ratios but also taking into consideration contextual information for each land cover category that is based on geospatial data and meta data.

RESULTS

The geometric correction of the multi-temporal Landsat data set faced the problem of different geometric resolutions and different quality of meta data (sensor geometry, ephemeris data, etc.) of the two sensors. The Landsat/ETM+ data were corrected using standard parametric procedures and the full scene was geometrically corrected using a sensor model, a set of GCP's and a DEM with 30 m grid cell size. The same model could not be applied to the Landsat/MSS data because no satellite orbital data were available for this scene. The problem was solved using a 2nd order polynomial transformation from ground control points. The use of the solar incidence cosine image (cos i) as a reference for geocoding proved to be valuable when only little information is available for the whole region of interest, e.g. when field work can only be done within parts of the study area because of rugged terrain and dense vegetation cover. Moreover, within this example, the existence of rugged terrain showed to be useful when using the cosine image as reference because the local incidence angle map highlights the topographic features of the terrain.

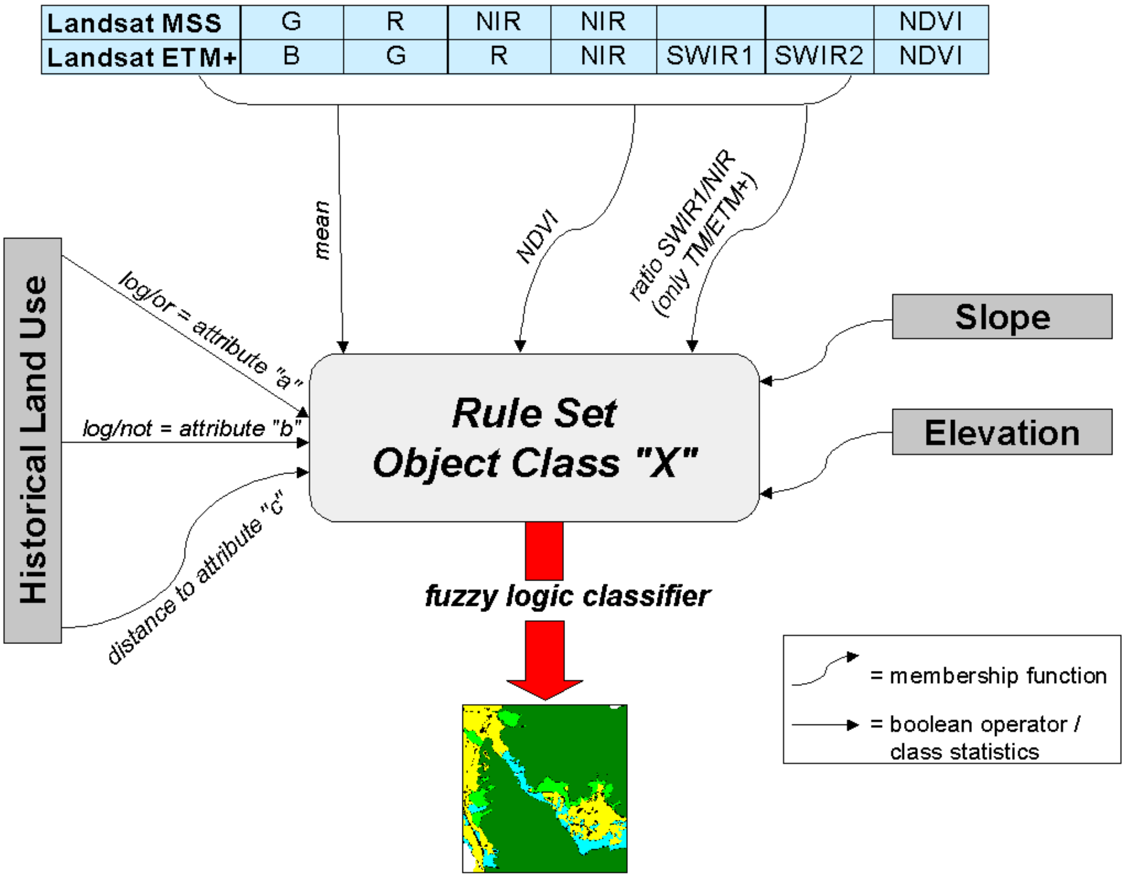

Figure 2: Rule set definition for the classification of the multi-temporal Landsat data set

The radiometric calibration of the satellite data included sensor calibration, atmospheric correction and solar / topographic correction. The sensor calibration used the gain and offset coefficients supplied by the USGS for the conversion of digital numbers (DN) to at-sensor-radiance. The validation of the sensor calibration showed a general underestimate of the NIR channels for the Landsat/MSS data especially for vegetated areas. At the present stage of the investigation, this problem could not be solved. The atmospheric and topographic correction led to the computation of surface reflectance values. The visual interpretation and statistical analysis of the terrain normalization data in contrast to the flat surface calibration underlined the necessity of a local solar incidence correction model (Figure 3). The solar and terrain corrected image statistics show no correlation between solar inclination and reflectance (r^2=0.0061). This means that the correction method well adjusts the effect of terrain-induced reflectance distortion. The chosen method for terrain correction (C-correction) is time-consuming because it requires empirical relations between reflectance and illumination to be established for selected test sites prior to the computation of horizontal surface reflectance. On the other hand, this empirical component is best accounted for the individual (non-Lambertian) behaviour of the reflectance distribution for different landscapes and land cover types within the present study.

The qualitative analysis of the Landsat time series used a combined approach of image segmentation followed by object-based fuzzy logic classification. The major problem of the land cover classification was the distinct definition of land cover (object) classes. This step always includes the definition of desired classes, the analysis of the class features of these classes (e.g. spectral and spatial attributes) and finally in most cases the reduction of the number of classes due to limited feature separability of the original classes. The final number and definition of object classes is then a compromise between requirements / demands of the project and actual information content of the data source. The second critical aspect in satellite image interpretation is the link between land cover categories and land use types. Table 1 shows an overview of the main land use types occurring in Central Sulawesi and the main aggregated land cover classes that could be derived from satellite image interpretation. The table shows the problems that occurred during the classification process within this study. A land cover category always has to aggregate different land use types due to their spectral properties. Within the presented project this problem mainly affected the definition and delineation of forest types and agroforestry systems at the rainforest margin.

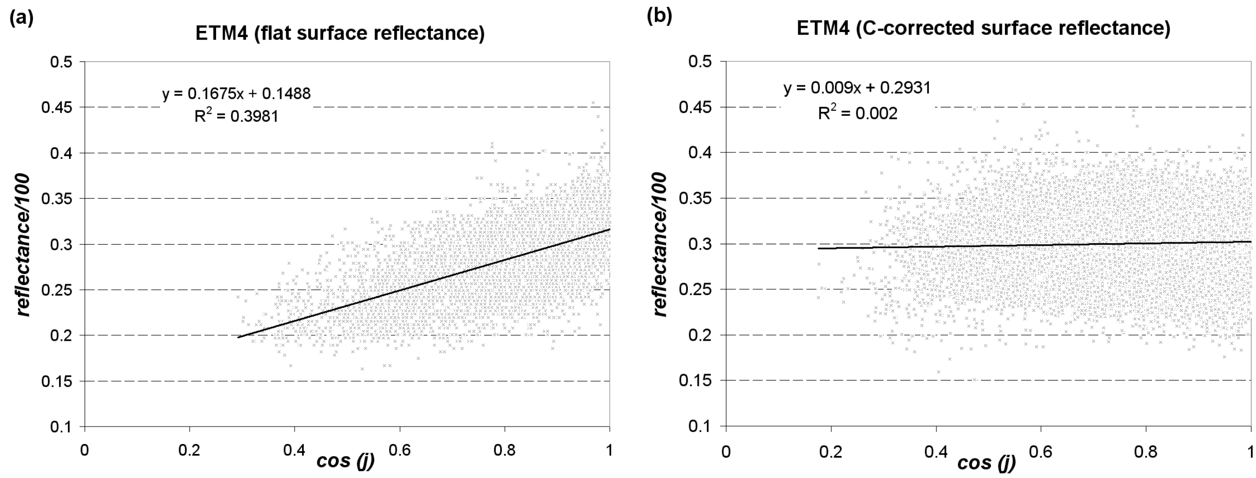

Figure 3: Comparison of "flat terrain" calibrated surface reflectance values (a) with solar and topographic corrected reflectance values (b) for a transect within a plot of homogenous dense forest

Table 1: Predominant land use types in Central Sulawesi and land cover categories for fuzzy logic classification (in brackets: land use types that contribute to / overlay with land cover classes by means of spectral properties and class definitions)

No	Land use type	Land cover (object) class
1.	Natural Forest	
2.	Secondary Forest	Natural Forest (1,2,3,4,5,13)
3.	Managed Forest	
4.	Tree Plantation	
5.	Bushland	Open Forest / Agroforestry (1,2,3,4,5,10,11,12,13)
6.	Grassland	
7.	Degraded Grassland (*alang-alang*)	
8.	Fallow / Reed	Perennial Crops / Plantations (4,10,11,12,13)
9.	Meadow	
10.	Coffee	Annual Crops (14,15,16,17,5)
11.	Coconut	
12.	Cacao	Grassland (6,7,8,9)
13.	Clove	
14.	Maize	Water (15,16,17)
15.	Paddy Rice	
16.	Rain Fed (Upland) Paddy Rice	Built Up (15,16,17)
17.	Rivers / Channels / Lakes / Fishponds	
18.	Settlements (incl. Homegarden, Infrastructure, etc.)	

The number of identifiable land cover classes could be increased by incorporating auxiliary data taken from the image itself (e. g. texture) or from other spatial data sources (e.g. height, slope, distance to features, historical land use map, etc.).

As a result of the knowledge-based class definitions and fuzzy logic classification process, within this study, eight land cover classes could be separated for the 1972 and 2002 data sets with an average membership probability of 0.93 (1972) and 0.87 (2002), respectively (see Figure 4). In 2002, natural forest comprises 67 % of the total study area whereas the cultivated land covers 28 %. Cultivated land includes agricultural fields and plantations (paddy, annual crops, perennials) as well as forest areas that are cultivated in the form of agroforestry systems (mainly cacao under shade trees), forest gardens or selective timber extraction at diverse intensity levels. Another 4 % of the total area comprises extensively used grasslands, the remaining part consists of built-up area and water surfaces (Table 2). The area statistics of the change analysis for the data set approves the developments of land cover conversion within the study area during the 30-year time period that have previously been reported from socio-economic studies at the village and regional level within the framework of the *STORMA*-project. According to (17) the area under cultivation increased by about 58% within the time period of 1982 to 2002 (based on a village survey). The satellite analysis shows an average increase of 55 % for cultivated land for the time period 1972 to 2002.

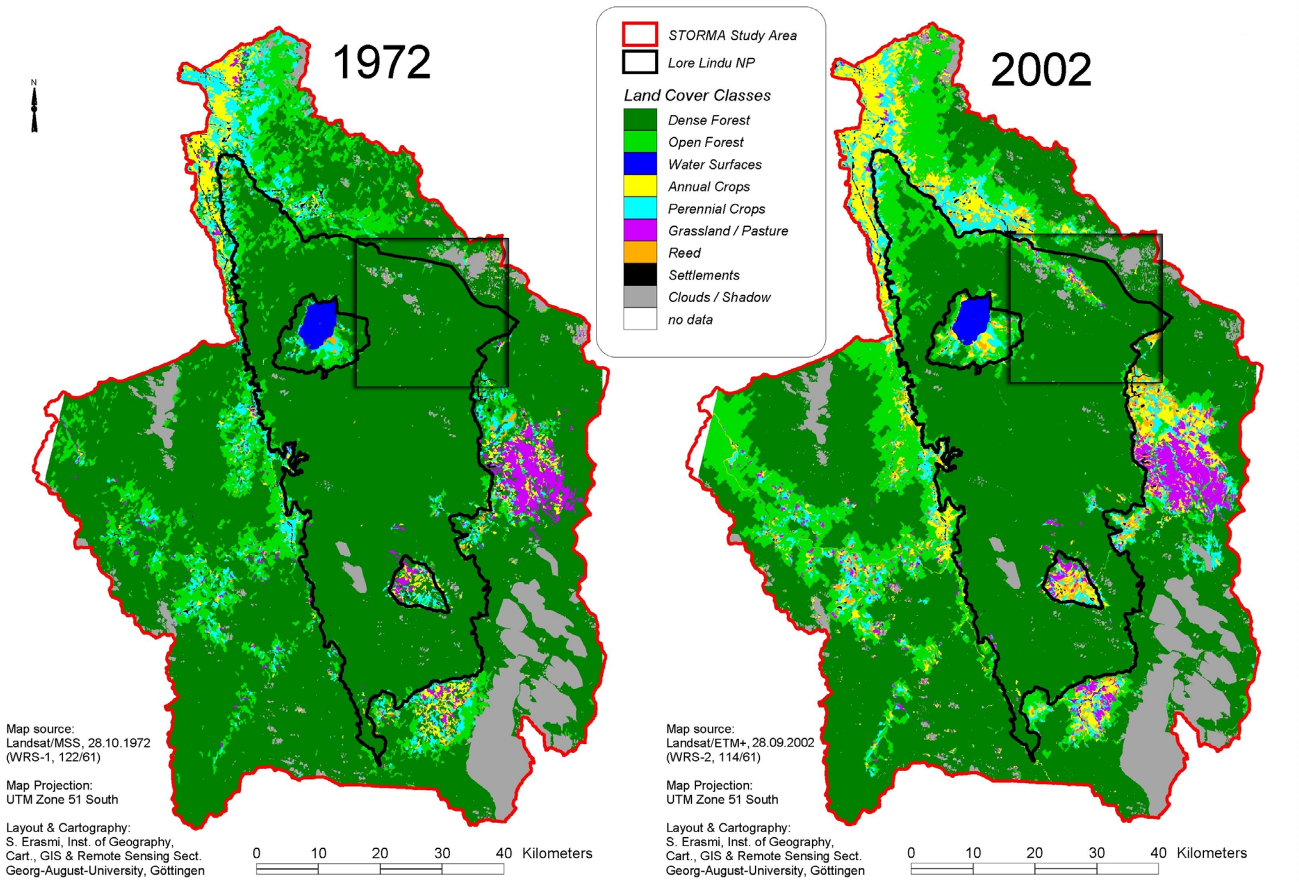

Figure 4: Land cover maps of the STORMA study area for 1972 (a) and 2002 (b) resulting from segmentation and fuzzy logic classification of Landsat/MSS and /ETM+ imagery taken over Central Sulawesi, Indonesia (the rectangle shows the image subset used in Figure 5)

The main historical and present land cover conversion activities are: 1) an expansion of the agricultural area especially in upland areas, 2) the conversion of formerly forest areas into agroforestry systems and into cocoa and coffee plantations and 3) selective and clear-cut logging activities. The changes are mainly characterized by an extension and intensification of the land cultivation and conversion at the forest margin. In recent years, these activities in many cases exceeded the border of the Lore Lindu National Park and caused dramatic changes in the landscape pattern that may have long-term effects on species richness of flora and fauna in one of the most important centres of endemism in the world (1). At present, the forest conversion is dominated by vast clear-cutting operations that are driven by the timber industry, the carelessness of local and national authorities and private benefits of migrants. This led to a loss of more than 2200 ha of natural forest only within the north-eastern part of the LLNP during the period 1999 to 2002 (see Figure 5).

Table 2: Area statistics for the 1972 and 2002 Landsat data sets covering the aggregated land cover classes for the STORMA study area of Central Sulawesi, Indonesia

Class	**Area 1972 [km^2]**	**% Cover-age**	**Area 2002 [km^2]**	**% Cover-age**	**Change 1972-2002 [km^2]**	**% rel. Change 1972-2002**	**Annual change rate [%]**
Natural Forest	5259	78.5	4468	66.7	-791	-17.7	-0.6
Open Forest / Agroforestry	727	10.9	1107	16.6	380	34.3	1.1
Perennial Crops	322	4.8	338	5.1	16	4.7	0.2
Annual Crops	180	2.7	415	6.2	235	56.6	1.9
Grassland	155	2.3	291	4.4	137	47.1	1.6
Built-Up	21	0.3	25	0.4	4	16.0	0.5
Water	34	0.5	42	0.6	7	16.7	0.6

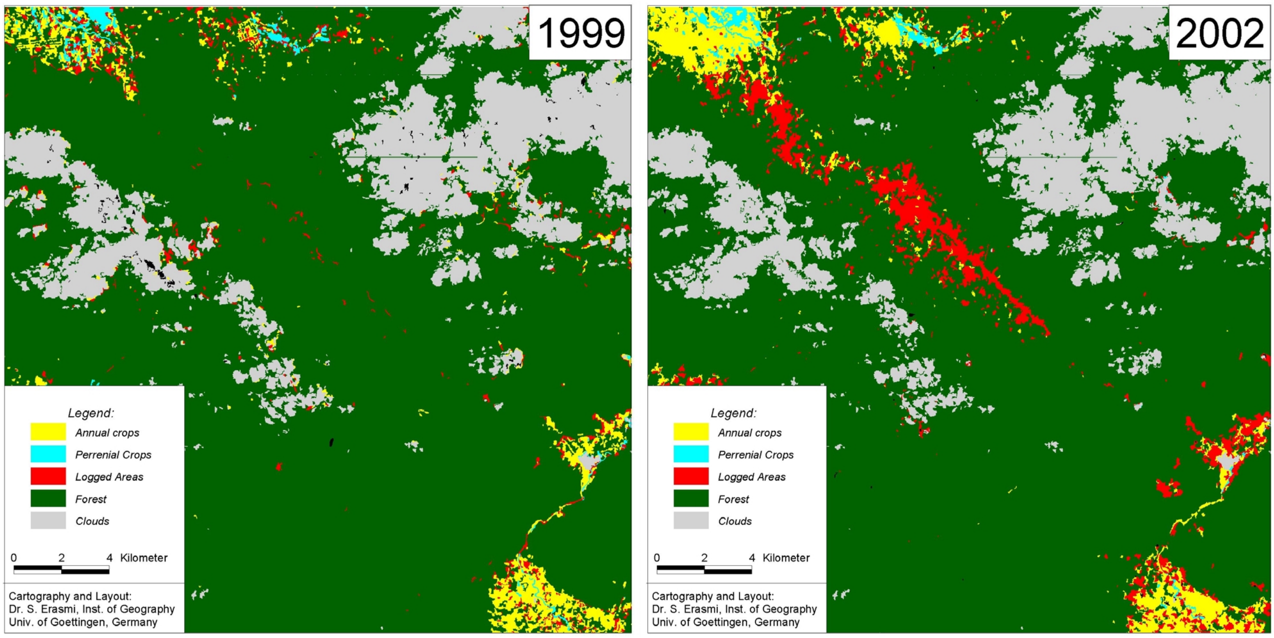

Figure 5: Land cover maps of the STORMA focus area for 1999 (a) and 2002 (b) resulting from segmentation and fuzzy logic classification of Landsat/ETM+ imagery taken over Palolo Valley, Central Sulawesi, Indonesia (see Figure 4 for the exact location of the subset)

CONCLUSIONS

In this study a processing and analysis work flow for a time series of Landsat imagery in a tropical environment is presented. This includes geometric correction, radiometric calibration, land cover classification and change analysis. Concerning the radiometric calibration, the results indicate that it is necessary to consider topographic effects on spectral reflectance. Surface reflectance data have to be corrected for terrain disturbances prior to image classification because of the significant dependence of reflectance values on solar incidence angles. The presented method for topographic normalization (*C-correction*) yielded promising results.

The proposed context-based classification procedure proved to be highly effective for the mapping of land cover and land cover conversion at the regional level. Despite the low resolution of Landsat images, the segmentation approach showed to be useful in categorizing surface sub-areas prior to the computation of landscape attributes from multi-source data sets. Within this study the object-oriented approach at a minimal aggregation level was preferred to the pixel-based procedures, because it takes into account the spectral as well as the spatial similarities of an object within a multi-source data set.

The results of the land cover mapping and change analysis were compared to actual and recent statistical forest assessments at a local and a regional level. The outcome is that the Landsat based land cover mapping provides necessary and reliable information about land cover conversion at the regional level. The area statistics and deforestation rates computed from the satellite analysis correspond well to the investigations at the district level and furthermore show the inhomogeneous spatial distribution of land conversion processes within the study area. Moreover, it is documented that the overall deforestation rate of the area under investigation is significantly lower (-0.6%/year 1972-2002) compared to other estimates for Sulawesi (-1.7%/year 1985-1997, taken from (18)) and the whole Indonesian Archipelago (-1.2%/year, 1990-2000, (19)) within comparable time periods. These discrepancies may be explained with the varying time periods that have been used but mainly are the result of the different data sources that build the basis for the estimates at the national and global levels. For instance, the data of the Indonesian forest cover and deforestation rates are derived from reports, photographs and satellite imagery with the help of several institutions (e.g. Regional Physical Planning Programme for Transmigration, RePPProT, World Conservation Monitoring Centre, WCMC, National Forest Inventory (NFI) and the Government of Indonesia in collaboration with the World Bank). Concluding, the following advantages of the presented Landsat data analysis can be stated. The object-oriented and context-based classification workflow with rule set based class descriptions offers an opportunity for an objective and transparent definition of land cover units from optical satellite data. The satellite derived maps may be related to field observations at the village or regional level and thus account for the heterogeneous, small-scale landscape pattern at the intensively cultivated rain forest margins.

The most critical factor in interpreting satellite images remains the fact that spatial mapping of land cover categories is only usable to derive *land use* types to a certain extent and thus limits the informational value of satellite-based mapping for deforestation monitoring. But on the other hand, satellite mapping of *land cover* units remains the most important input source for spatial modelling of factors and processes that determine *land use* change. Further research will therefore focus on the transferability of the suggested calibration processing chain and class descriptions to other spectral data sets and thus the establishment of robust and reproducible work flows to ensure the successful application of current and future remote sensing data and systems for the assessment of land cover and land use change at the regional scale in tropical rain forest margin areas.

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