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Monitoring inter-annual land cover dynamics at the rainforest margin in Central Sulawesi, Indonesia

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ABSTRACT: A series of Landsat ETM+ satellite data has been analyzed with the aim of monitoring annual land cover changes at the rainforest margin in Central Sulawesi. The mapping system consisted of an object based classification approach and the implementation of socio-economic as well as agro-climatic constraints as a basis for the definition of rule sets about the spatio-temporal occurrence likelihood of land cover types. The resulting land cover maps have been evaluated with regard to the statistical accuracy and the overall data quality related to user requirements. The annual land cover change analysis shows a severe increase in tropical deforestation rates within the study area from a long term annual mean of 0.3% per year (1972 to 2002) to a rate of 0.56% per year for the study period of 1999 to 2002. The main drivers of forest conversion in the study region are identified as agricultural expansion of perennial cropping systems (cacao) and illegal clear-cut logging of natural forest at the rainforest margin.

1 INTRODUCTION

Tropical rain forests are regarded as the most complex, varied and species-rich terrestrial ecosystems on earth. Although tropical rain and moist forests cover only 7% of the planet's land surface, they are home for about 40% of all living species (Whitten *et al*. 2002). However, the earth is continuously losing its vital "green lung". It is estimated that about 146.000 km^2 of tropical forests have been lost each year between 1990 and 2000 (FAO 2001). Recent estimates of tropical deforestation reveal considerable differences in change rates between continents. Mean annual change estimates for the 1990s range from 0.38% (Latin America) to 0.43% (Africa) and 0.93% for Southeast Asia resulting in a global mean of 0.52% annual deforestation rate (Achard *et al*. 2002).

The insular state of Indonesia was still densely forested in 1950, but about 40% of its forests have been cleared until the beginning of the 21st century (FWI and GFW 2002). The speed of forest destruction is accelerating: While on average 10.000 km^2 were cleared each year during the 1980s, this rate has increased to 17.000 km^2 in the early 1990s and has finally reached the level of 20.000 km^2 p.a. since 1996 (FWI and GWI 2002). Furthermore, about half of the remaining forests are strongly affected by degradation due to human activities (FWI and GWI 2002).

Tropical deforestation is regarded as one of the major drivers of global environmental change. The driving forces of tropical deforestation are manifold and can be mainly categorized as infrastructural extension, agricultural expansion and wood extraction (Geist and Lambin 2002). The rainforest margin, which can be defined as the transition zone between natural forest and cultural landscape, comprises the region that is mostly affected by those driving forces. Thus, the consequences of processes that affect the stability of tropical forests (e.g. loss of biodiversity, changes in hydrological cycles, carbon stock loss, etc.) have to be analyzed with priority within this transition zone. If such analysis is intended at the national to regional level, it demands the availability of spatially explicit information about land cover and its change at scales that can be obtained from satellite data at medium to high spatial resolution. In the present study, a time series of Landsat ETM+ satellite data is analyzed with regard to the addressed topic of deforestation in the rainforest margin zone. From the methodological point of view, special emphasis of the work is on the establishment of a consistent analysis and validation workflow for multi-date satellite images that takes into account the complex pattern of land cover type and land use dynamics in the investigation area of Central Sulawesi, Indonesia. The main goal of the application of the developed method is the assessment of the amount of annual forest conversion at the rainforest margin.

2 STUDY AREA

The research area is situated in Sulawesi, which is the fourth biggest landmass of the Indonesian archipelago. The study region is located between 0°50'–2°04' southern latitude and 119°40'–120°30' eastern longitude. It comprises the districts Sigi-Biromaru, Palolo, Lore Utara, Lore Tengah, Lore Selatan, Kulawi and Pipiorke, which are part of the province Central Sulawesi. The study region covers a total size of 7.257 km^2. Its center is formed by the Lore Lindu National Park (2.214 km^2).

The terrain of the study region is very mountainous, ranging from less than 100 m to more than 2,500 m a.s.l. In 2000, the population density totalled to only 18 inhabitants per km^2 (BPS 2005). Villages are concentrated in the valleys, only few settlements can be found in the uplands.

The regional economy is dominated by agriculture (Maertens *et al.* 2002). Rice, cocoa and coffee are the most prevalent crops (G. Dechert 2003). Furthermore, coconut is cultivated on some locations. Large, partly undisturbed forests still exist, but have faced encroachments in the past few years.

3 DATA AND PRE-PROCESSING

The base dataset consists of three Landsat ETM+ scenes (WRS-2, Path 114/Row 61) of 20 September 1999, 24 August 2001 and 28 September 2002. The 2002 scene was orthorectified and projected to a rectangular reference system (UTM zone 51 south, WGS84) using 65 well distributed ground control points (GCPs) that were derived from 1:50.000 scale maps and a local solar incidence angle map that was computed from a

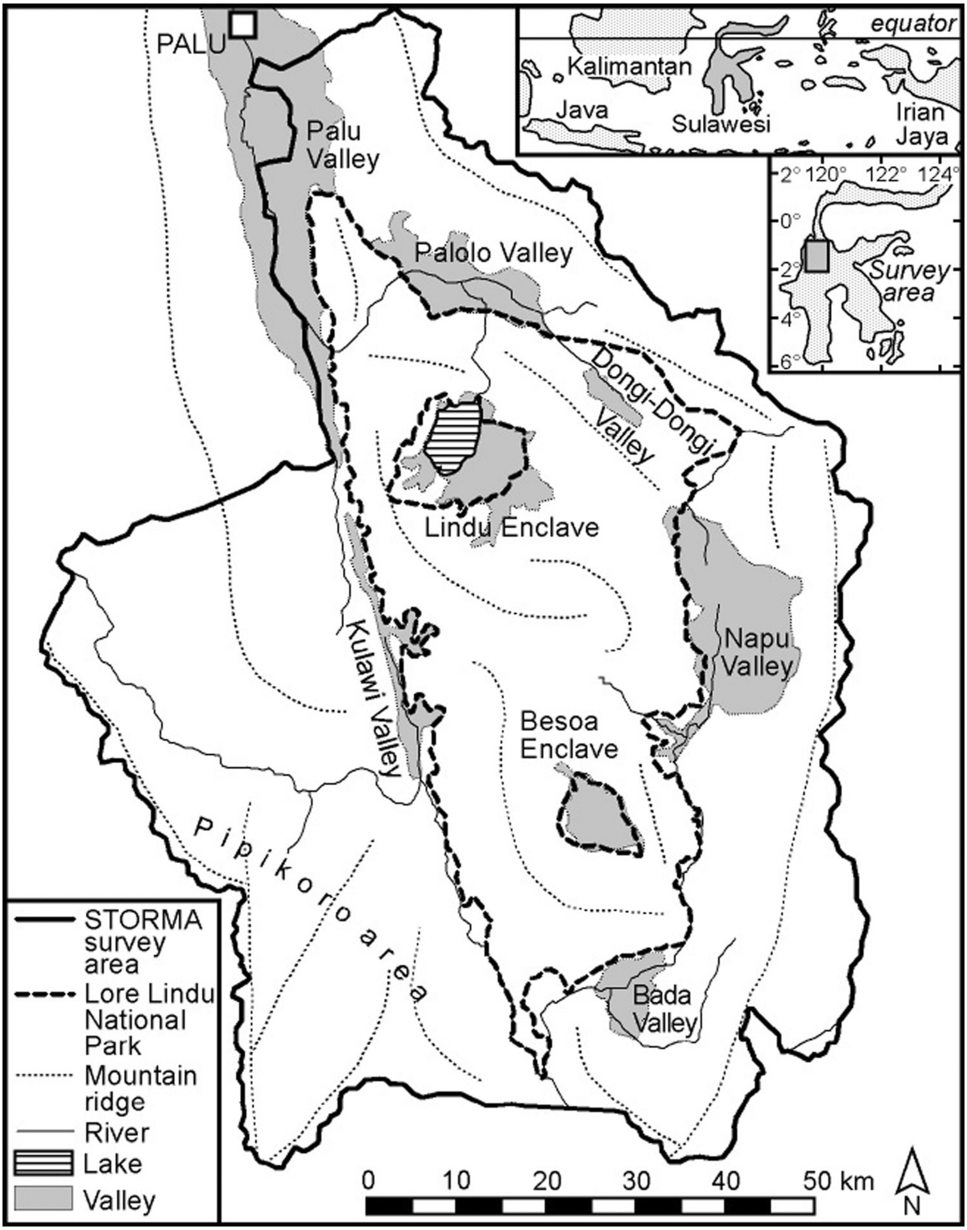

Figure 1. Overview of the study area in Central Sulawesi, Indonesia.

digital elevation model. This scene was then chosen as the absolute reference for co-registering and orthorectifying the remaining images.

In the humid tropics, atmospheric effects are particularly strong and can seriously affect the radiometric quality of optical satellite data. Since atmospheric impacts vary both spatially and temporally, there is a need to account for these effects especially within multi-temporal studies of land cover change. We used the improved dark-object-subtraction method proposed by Chavez (1996) (also referred to as the COST-model) to account for the diametrical effects of both path radiance and atmospheric transmittance. The correction model was combined with sensor calibration, sun illumination and sun-earth distance normalization in a streamlined model to convert uncorrected digital numbers (DNs) to atmospherically corrected reflectance. The final step of radiometric processing involved the removal of variations in spectral reflectance due to topographic distortions using a stratified normalization technique based on the Minnaert-correction model (Twele & Erasmi 2005).

Prior to classification, the image pixel values have been aggregated to homogeneous units (image objects, resp. segments) using a region growing approach (segmentation). The homogeneity of each image object and hence the criteria for generating a segment were defined based on the panchromatic channel of the Landsat ETM+ images. A scale parameter was used to control the average image object size. For the current Landsat data sets a scale factor of 5.0 to 5.3 was used. The slight variation of the scale factor is due to changes in the image statistics between the years and hence the heterogeneity of the objects. This resulted in an average object size of 2 hectares. The result of the segmentation procedure is a mosaic of about 340.000 homogeneous image objects for every data set that delivers the input geometry for further classification issues.

The creation of segments is a decisive step in the object-oriented analysis of remotely sensed data, because the quality of its outcome directly affects the quality of the following classification (Meinel & Neubert 2004). Within this study, the objective of using image segmentation prior to classification was to generate objects that represent the small-scaled patchiness of the land cover pattern in the investigation area and at the same time reduce the overall amount of image objects to be analyzed. Further to this, the creation of objects enables the definition of rules about the relation of objects to other objects as well as the analysis of spatial relationships between image objects and ancillary data (e.g. digital elevation models, thematic maps).

4 METHODS

The classification and change analysis concept consists of six main components: (1) a land cover legend; (2) field data (reference and validation); (3) a classification algorithm; (4) post-classification analysis; (5) change detection and (6) accuracy assessment. The land cover classification system (LCCS) comprises a global concept of land cover categorization that can be adapted from the supra-national to the regional/local level (Di Gregorio and Jansen 2000). The land cover legend has been defined based on a hierarchical classification system. The main advantages of the hierarchical classification approach are its high flexibility and the easy integration of *a priori* knowledge, which are both strengths of object-oriented image analysis. The initial class set includes 17 land cover types (see Knieper 2006 for a detailed description of the classes). These classes are aggregated to eight classes that represent the major land cover characteristics within the area under investigation (Broadleaved Evergreen Forest, Cropland: Plantations (Cacao, Coffee), Cropland: Plantations

(Coconut, Clove), Cropland: Paddy, Mosaic of Cropland/Tree Cover/Other Natural Vegetation, Wetlands, Grassland, Natural Water Bodies). The class aggregation accounts for the problems of uncertainty in change analysis and is on the other hand tailored to the demands of the project partners concerning socio-economic and ecological modeling of the environment.

The classification algorithm 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 Baatz and Schäpe 2000 for details).

Each class inherits the rule set of its parent class and contains additional definitions. At each node of the classification tree, the most suitable parameters are used for the determination of thresholds that discriminate the classes. Within the present classification, the core part of the rule set was built up by spectral and textural attributes from the multispectral image channels of the Landsat ETM+ data sets as well as ancillary thematic information about topography, infrastructure, agro-climatologic and socio-economic drivers and constraints of land cover and land cover change.

The post-classification implies the application of multi-year conditional rules that reduce the occurrence of pseudo-changes between two images. The rules are based on expert knowledge about historical and present land use and recent regional land use statistics (BPS 2005). Finally, the change analysis is based on a post-classification image subtraction approach and area statistics.

The value of a mapping and change analysis product based on remotely sensed data is most often expressed in terms of accuracy of the mapping results. Accuracy assessment has to be based on a validation data set that is usually gained on the basis of ground truth data. Records of ground surveys have been performed in 2004 and 2005 and are used as the core reference and validation data set. Additional sample points for the validation data set of 1999 and 2001 were collected from pan-sharpened very high resolution satellite images (Quickbird, Ikonos) using a simple random sampling scheme. Altogether, 998 sample points were collected whereas one half was used as reference data in order to assess the classification.

The Kappa coefficient was used as the main indicator for the quality of the classification results. The producer's accuracy was applied as an indicator in order to examine the accuracy of single classes (Congalton 1991):

$$\text{Kappa coefficient} = \frac{n \sum_{k=1}^{m} n_{kk} - \sum_{k=1}^{m} (n_{k+} \times \; n_{+k})}{n^2 + \sum_{k=1}^{m} (n_{k+} \times n_{+k})}; \quad \text{Producer's accuracy} = \frac{n_{kk}}{n_{+k}}$$

where n is the total number of samples, m terms the number of classes, k marks a single class, n_{kk} is the number of correctly classified samples of a class, n_{k+} terms the total number of reference samples assigned to class k and n_{+k} marks the total number of samples classified as class k in the classification.

5 RESULTS

5.1 *Land Cover 2002*

The largest part of the STORMA research area is covered with forest, comprising 84.1% of the total size. This proportion even increases to 96.4% inside the Lore Lindu National Park.

The classification results reveal a strong contrast between mountain slopes which are strongly dominated by forest cover and valleys that are usually used as cropland. Besides slope angle, altitude is an important factor that has a positive impact on forest cover. Above 1.250 m a.s.l., the STORMA research area is almost entirely forested, whereas forest cover has virtually disappeared on elevations up to 250 m.

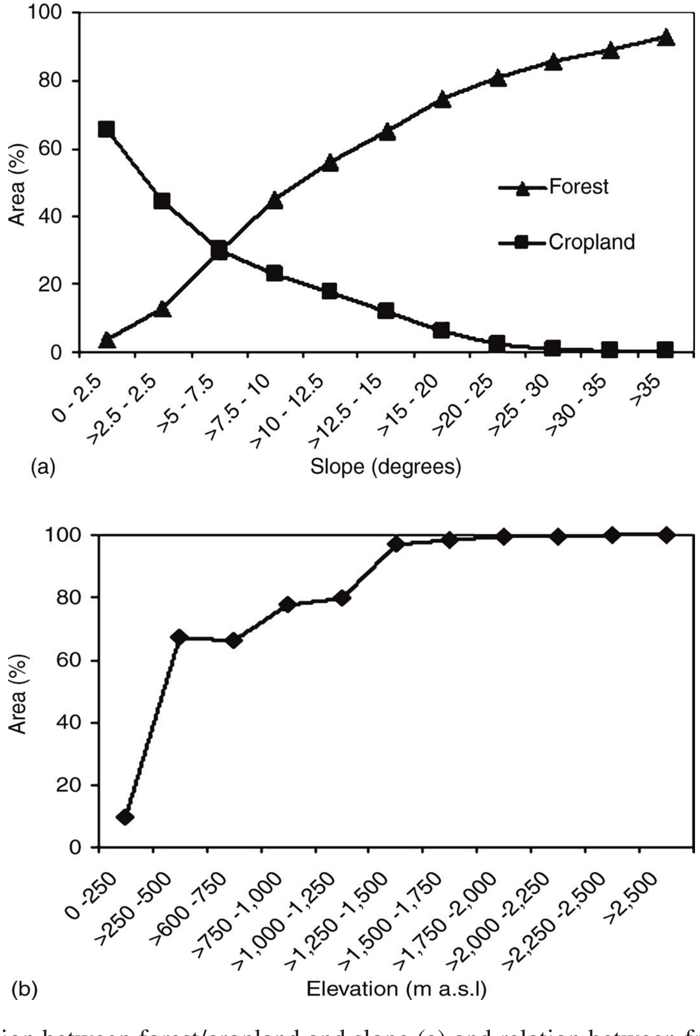

Figure 2. Relation between forest/cropland and slope (a) and relation between fraction of forest cover and height (b).

Cropland comprises only 5.2% of the STORMA research area. It is almost completely situated in settled valleys up to 1.250 m a.s.l. Cocoa and coffee are the most widespread crops covering a total of 18.998 ha, especially in the Palolo basin. However, patches of this cropland type can be found in each of the valleys. Rice is the second most widespread crop covering 15.995 ha of the survey region. Vast areas of paddy fields are concentrated in the Palu valley, the Palolo basin, the Besoa valley and in the Lindu enclave. Once again, patches of this cropland type are situated in each of the settled valleys. Coconut and clove plantations cover 2.601 ha. Vast cultivation areas concentrate in the Palu valley. Only few patches of this cropland type can be found on other locations.

Cropland patches are also located at several locations inside the Lore Lindu National Park. In total, 1.532 ha (0.7%) of the park area are used as cropland, mainly for cocoa and coffee plantations (1,283 ha), which are mainly located south of the Palolo valley.

With a total size of 22.040 ha, grassland accounts for 3.0% of the survey area. Large grassland plains are located in the southern valleys of Napu, Besoa and Bada, where agricultural cultivation is less intensive than in the northern basins. The local forest borders are usually very sharp and abrupt. Next to these three southern valleys, the steep slopes of the Palu valley are strongly dominated by grassland. Besides, small grassland patches accumulate in forest margin zones at many locations, probably caused by human encroachment.

The class Mosaic of Cropland/Tree cover/Other Natural Vegetation covers 6.3% (46.038 ha) of the STORMA survey region. This mixed class evolved from the problem of misclassification of large areas of extensive agricultural cultivation. The interpretation of multi-year satellite data pointed out that these areas are under shifting cultivation practices and hence show complex spatio-temporal patterns of land cover modification. The occurrence of the land cover type is concentrated at valley margins and in the mountainous Pipikoro region, and generally indicates low intensity agricultural practices in remote areas. Further to these areas, the class also includes mixed areas of small scaled heterogeneous landscape patches (e.g. house gardens, mosaics of shrubland/cropland).

5.2 *Quality Assessment*

The collection of accurate ground truth data for accuracy assessment is often a challenge, especially in remote and mountainous tropical areas. The samples of this work were not distributed evenly in the total survey region. Therefore the reference data are not fully representative. But since the sample points cover both extensive forested areas as well as cultivated land in an appropriate proportion, they can be regarded as a satisfying compromise concerning representativeness and amount of work. The overall accuracies and Kappa coefficients of the classifications are illustrated in Table 1. The comparison of classification results before and after applying multi-year conditional rules only shows a slight increase in classification accuracies. A more obvious enhancement can be seen for the classes plantations and paddy since these classes are mostly affected by the multi-year rules (Table 2).

5.3 *Land Cover Change*

The total area covered with forest has dropped off by 10.530 ha in the survey region between 1999 and 2002. This corresponds to a rate of 1.7% for the investigated time

Table 1. Kappa coefficients and overall accuracies of the classification results.

	without multi-year rules		with multi-year rules	
Classification date	overall acc. (%)	Kappa	overall acc.(%)	Kappa
1999	85.0	0.758	83.2	0.729
2001	81.4	0.702	82.6	0.723
2002	77.4	0.671	77.9	0.679

Table 2. Producer's accuracies for selected classes (in %).

	without multi-year rules		with multi-year rules	
Classification date	Cacao, Coffee	Paddy	Cacao,Coffee	Paddy
1999	76.1	84.5	67.6	91.5
2001	74.6	77.5	80.3	81.7
2002	72.4	75.0	78.2	84.2

period of three years. Inside Lore Lindu National Park, the loss amounts to 1.3% for the same period. Deforestation has accelerated since 2001: The area affected by forest loss between 2001 and 2002 is almost five times higher than the one for the period of 1999 to 2001. Insular clearings took place in the vicinity of all settled valleys. By contrast, the forest loss on higher elevations was insignificant. The largest clearings inside the park area are located in the Dongi-Dongi valley. This basin was nearly untouched at the beginning of 2001 but has been subject to large-scale deforestation since 2001 along a road crossing protected areas of the Lore Lindu national park. The total forest loss in the Dongi-Dongi area amounts to an area of 1.229 ha for the investigated period.

The total area of paddy fields decreased by 3.2% from 1999 to 2002, whereas the area covered with plantations for coconut and clove increased by 9.1%. The area under cocoa and coffee cultivation rose by 64.6%. The expansion of cultivation area for cocoa and coffee took place especially at the margins of the Palu and Palolo valley as well as the

Table 3. Area statistics of aggregated land cover types based on Landsat ETM+ analysis.

Land cover type	Area 1999 (km^2)	Area 2001 (km^2)	Area 2002 (km^2)
Broadleaved Evergreen Forest	6208.5	6190.5	6103.2
Cropland: Plantations (Coconut, Clove)	23.8	26.3	26.0
Cropland: Plantations (Cocoa, Coffee)	115.4	161.9	190.0
Mosaic of Cropland/Tree Cover/ Other Natural Vegetation	395.0	403.7	460.4
Wetlands	26.5	27.5	21.3
Grassland	241.1	223.7	220.4
Cropland: Paddy	165.1	145.9	160.0
Natural Water Bodies	81.1	76.9	75.3
Total:	7256.5	7256.5	7256.5

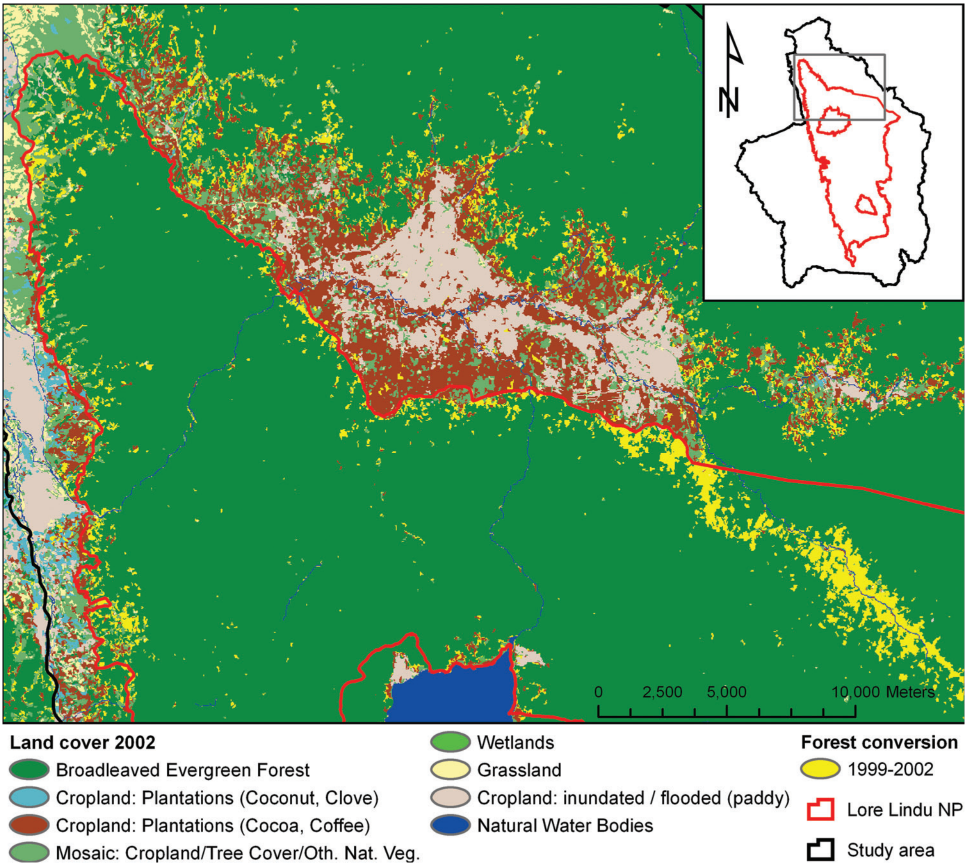

Figure 3. Final land cover map for 2002 and superimposed areas of deforestation between 1999 and 2002 (yellow).

Lindu enclave and the northern Napu basin. The creation of arable land did not stop at the park borders. A multitude of small cropland patches can now be found in the outer zone of the national park.

The land cover class *Mosaic of Cropland/Tree Cover/Other Natural Vegetation* was affected by distinct shifts in its spatial distribution. In the Pipikoro area, blocks of this land cover changed their positions between 1999, 2001 and 2002, thereby causing forest loss but also forest regrowth. This phenomenon indicates shifting cultivation practices, in which forest areas were burnt, used for cultivation and finally left. The Palu valley is the second location where distinct land cover shifts can be observed. Especially the eastern slopes were strongly affected by shifts of the local land cover gradient (i.e. grassland on low elevations, forest on ridge tops and a mosaic of cropland, tree cover and other natural vegetation between). The land cover zones shifted 2 km westwards on northern locations from 1999 to 2001, whereas they moved about 1.5 km eastwards on the northern peak of Lore Lindu National Park. This phenomenon was probably caused by interannual weather variability at the semiarid slopes of the Palu valley.

The total area of grassland dropped off by 8.6%, probably as a consequence of interannual weather variability (see above). However, it increased from 1.123 ha to 1.629 ha inside the Lore Lindu National park, in fact almost completely after August 2001. Small grassland patches can now be found at several locations in the park's margin zones, indicating clear-cuttings and expanding agricultural use into protected area.

6 DISCUSSION AND CONCLUSIONS

The combination of an object-oriented analysis approach with a hierarchical classification scheme and a multi-year change concept has proven to be an effective way for the analysis of multi-year satellite data for the assessment of land cover and land cover change in the project area of Central Sulawesi.

The object-oriented classification approach and the definition of rules enables the incorporation of a multitude of non-spectrally based information into the classification system. This was especially helpful in handling spectral similarities of tropical land cover units. The integration of additional knowledge, such as information about topography, agro-climatic and socio-economic constraints, considerably enhanced the overall quality of the land cover map in terms of homogeneity and plausibility of the occurrence of objects and classes. Further refinements of classification quality could be achieved by implementing post-classification rules based on multi-year land use scenarios. Nonetheless, the integration of *a priori* and *a posteriori* knowledge must be performed very carefully, because it might significantly influence classification results.

The hierarchical classification scheme of the LCCS comprises a valuable fundament for the definition of consistent land cover classes that can be transferred into the object hierarchy of the classification algorithm. However, the change analysis in this study was carried out at a high level of class aggregation due to limitations in the spatial resolution of data sources on one hand and the requirements of the end-product users (socio-economic and hydrological modeling groups) on the other hand.

The results of the land cover change analysis generally indicate a loss of natural forest area towards cropland and especially a strong increase in the cultivation of perennial cropping systems (mainly cacao). This strong increase confirms findings that are based on field observation and household census data (Faust *et al*. 2003, Weber 2005). The deforestation rate of 0.56% per year for the period 1999 to 2001 is far beyond earlier reports of the long term deforestation rate within the study area that is less than 0.3% per year (Erasmi *et al*. 2004). This increasing speed of deforestation during the past years is the consequence of recent land use conflicts that are mainly related to the illegal expansion of arable land into the national park, driven by local peasants (Faust 2001, Faust *et al*. 2003). Controversially to the good correlations between household statistics and satellite based land cover data for the cacao areas, the mapped paddy areas considerably underestimate the values that are reported by regional statistics (BPS 2005). The reason for this is the incapability of the available satellite data to monitor the phenological stages and seasonal characteristics of rice crops and intermediate fallow periods. On the other hand, the regional statistics may also include some uncertainties. Apart from this, the general trend in the area estimation shows a stagnation and slight decrease in paddy areas that can mainly be explained by conversion activities from paddy to cacao cropland (Sitorius 2002).

Finally, it is concluded that the application of a well defined and adaptable classification workflow based on image objects is well suited for the analysis of multi-temporal Landsat ETM+ satellite data in conjunction with ancillary thematic information layers. Satellite based land cover classification in tropical regions is always hampered by inadequacies in weather conditions. The combined use of optical and radar satellite data might help to reduce this problem and close the gap from annual to more frequent earth observations such as phenological, seasonal and annual land cover dynamics at the regional level. In any case of satellite based mapping, the end-product of land cover classification has to pass a certain level of statistical accuracy but primarily has to comply with the user needs in terms of data quality.

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