From global to regional scale: Remote sensing-based concepts and methods for mapping land-cover and land-cover change in tropical regions

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Summary

A great number of studies have been dealing with land-cover mapping of tropical regions using earth remote sensing technology recently. This is partly due to a growing number of operational sensor systems for both scientific and commercial use and also because of an increasing demand for land-cover information relevant to global environmental issues and international policy instruments (e.g. the Kyoto protocol). Within this context, the present article discusses the state of the art of data processing and analysis for the assessment of broad scale land-cover and land-cover change in tropical regions. Current global scale land-cover maps are compared with regional satellite mapping products (Landsat/ETM+) for a test region in the humid tropics of Central Sulawesi, Indonesia.

The paper suggests the land cover classification system (LCCS) to be used as the conceptual basis for future land-cover analysis in Sulawesi because it delivers a consistent and comparable scale-independent class structure for satellite image-based land-cover mapping and monitoring. The results of the comparative analysis of land-cover and land-cover change document the inhomogeneity, inconsistency and hence high uncertainty of existing estimates. The outcome of the harmonized and generalized land-cover products for two base years (1992 and 2000) indicates considerable disagreements in area estimates and spatial distributions of land-cover classes for a single date that in some cases exceed the detectable changes between years.

Future work aiming at a long-scale operational land-cover mapping of tropical environments has to account for (a) a further harmonization of existing and planned land-cover definitions and products, (b) the regional validation of products and (c) the implementation of a multi-level standardized technical and conceptual classification workflow for ecosystem mapping and monitoring in tropical regions.

1 Introduction

Since the early 1980ies, information about land-cover has been recognized as being of utmost importance for the description and study of the environment (Watson et al. 2000). The main variable defining primary productivity and biodiversity of a land surface is the type of land-cover (Turner et al. 2005). Land-cover is the easiest detectable indicator of human interventions on the land and is a critical parameter for environmental databases of any kind.

Tremendous advances were made during the 1980ies in the use of remote sensing data to support research related to global change and sustainability. Land-use and land-cover change (LUCC) has become a key topic within global change research programs. The first international research program concerned with this topic was the International Geosphere-Biosphere Programme (IGBP). IGBP and ISCC (International Social Science Council) started up a core project on LUCC (Turner et al. 1995) that combined environmental and social science expertise in land-cover and land-use change analysis. After that, other programs funding research on land-use and land-cover such as the IAI (Inter-American Institute for Global Change Research), APN (Asian-Pacific Network for Global Change Research), START (Global Change System for Analysis, Research and Training), and GCTE (Global Change in Terrestrial Ecosystems) were initiated. Complementary to LUCC and GCTE, NASA developed its own land-cover and land-use change research program (NASA-LCLUC). Each of these programmes identifies land-use and land-cover change as the prior research topic (Townsend et al. 1994). The LUCC and GCTE core projects ended in 2005 but have been continued within the integrated "Global Land Project (GLP)" of the IGBP which aims at the identification, analysis and modelling of the character, causes and consequences of land system change (GLP 2005).

Tropical land-cover, especially the extent of tropical forests and the rate of deforestation, are of particular interest in environmental and socio-economical studies dealing with land-cover and land-use change. This can be documented by three major facts. 1) The tropical land surface is home to more than 55 % of the global human population (UN 2005) and hence human activities related to land-use, commercial structure and social structure constitute the ma-

jor driving forces of tropical deforestation; 2) Tropical ecosystems harbour a high biodiversity and thus deforestation and land-cover conversion contribute greatly to genetic erosion in tropical regions; 3) Tropical forests comprise a major terrestrial carbon sink and thus tropical deforestation contributes to global warming issues. In summary, the determination of reliable land-cover information constitutes a key input to any kind of spatially explicit analysis and scenario contributing to of one of these topics.

Several efforts to map land-cover in the tropics and monitor changes of forest cover have been undertaken in the past. Besides the problem of accurate assessment, these studies are not directly comparable due to differences in processing and analysis methods, land-cover class definitions and classification concepts. Another disadvantage of recent global land-cover maps (GLC2000, MODIS-IGBP) is the coarse resolution of 1 km^2 / pixel. This restricts the minimum detectable area of change and leads to mixed land-cover types resulting in a significant information loss especially in small-scaled heterogeneous landscapes that are common in Southeast Asia.

This paper deals with the problem of reliable and up-to-date spatially explicit information on land-cover and land-cover change in tropical regions. The introductory chapters provide an overview of the broad range of existing concepts for land-cover change analysis. Furthermore, a review of the most widely used and implemented techniques of image pre-processing, land-cover mapping and change analysis is given. In chapter 6 we present results of a regional study of land-cover monitoring in Central Sulawesi, Indonesia. Within this study different land-cover products are compared with regard to area estimates of land-cover and cover change for the base years 1992 and 2000. The comparison is based on area statistics and spatial distribution of harmonized and aggregated land-cover types. The quality of the global products is investigated by cross comparison with higher level land-cover products. The comparison delivers valuable information about the potential of coarse-scale mapping products for ecological and socioeconomic modeling and scenario analysis in tropical forest margin areas.

2 Basic principles of land-cover mapping and change detection

2.1 Concepts of land-cover characterization

Land-cover is defined as "the observed physical and biological cover of the Earth's land, as vegetation or man-made features" (Watson et al. 2000). In contrast, land-use describes the activities that people undertake in a certain land cover type (FAO 2003) and thus comprises a major driving factor of land-cover change (Meyer and Turner 1994).

In principle, land-cover mapping from satellite data is related to the amount of radiation that is recorded by a sensor on a platform in space for a

Table 1: Land-cover classes of IGBP and LCCS legends for insular Southeast Asia

IGBP class	LCCS class
Evergreen Needleleaf Forest	Forest cover, broadleaved, evergreen, closed and closed to open
Evergreen Broadleaf Forest	Forest cover, broadleaved, deciduous, mainly open (incl. Dry Dipterocarpus)
Deciduous Needleleaf Forest	—
Deciduous Broadleaf Forest	—
Mixed Forests	Mosaic: Forest cover / Other nat. vegetation or Cropland (incl.very degraded and open tree cover)
Closed Shrublands	Mosaics and Shrub Cover, shrub component dominant, mainly evergreen
Open Shrublands	Mosaics and Shrub Cover, shrub component dominant, mainly deciduous
Woody Savannas	Shrub cover, mainly deciduous, (Dry or burnt)
Savannas	Shrub cover, mainly deciduous, (Dry or burnt)
Grasslands	Herbaceous Cover (incl.alpine grassland) Sparse herbaceous cover > 3000m
Permanent Wetlands	Tree cover, regularly flooded, Mangrove Tree cover, regularly flooded, Swamp
Croplands	Cultivated and managed, non irrigated (mixed) Cultivated and managed, irrigated (flooded, rice, shrimp farms)
Cropland/Natural Vegetation Mosaic	Mosaics of Cropland / Other natural vegetation
Barren or Sparsely Vegetated	Bare Areas (Rock: Lime stone)
Urban and Built-Up	Artificial surfaces
Water Bodies	Water Bodies

certain area on the ground. Data acquisition is followed by processing, analysis and product generation (e.g. land-cover maps). However, each of these steps differs fundamentally between different environmental studies, even when they are carried out on the same region and / or topic.

The first major efforts on land-cover mapping at the global to regional scale using earth observing data were initiated by the IGBP in 1990. These activities were driven by the need for information on the distribution of vegetation types and the disturbance of vegetation cover for climate and carbon cycle dynamics studies. The IGBP land-cover mapping studies were based on data from the Advanced Very High Resolution Radiometer (AVHRR) with a nominal resolution of 1 km and covered the period between 1992 and 1993. These data were processed to a global land-cover map and are available to the public (IGBP DISCover). A globally consistent land-cover legend was first defined by Running et al. (1994) and subsequently refined by IGBP core projects (Loveland et al. 2000). It consists of 17 classes and is currently used for the DISCover dataset as well as for present large scale land-cover maps such as the products of the Moderate Resolution Imaging Spectroradiometer (MODIS) land discipline group (Friedl et al. 2002).

Another approach to land-cover description is the Land-cover Classification System (LCCS) of the UN Food and Agricultural Organization (FAO) (Di Gregorio and Jansen 2000). LCCS is not based on a predefined list of class names, but instead uses a simple set of attributes and classifiers that are organized in a hierarchical manner (Bartholomé and Belward 2005). In the first stage of class characterization LCCS uses classifiers that describe the presence of vegetation, the edaphic condition and the nature of ground cover. The results of this "dichotomous phase" are eight land-cover classes (Di Gregorio and Jansen 2000). In the second stage, the modular-hierarchical phase of LCCS, the classes are further subdivided, based on environmental attributes (e.g. life form, land form, climate) and technical specifications (e.g. crop type). In this manner, the LCCS offers high flexibility to the user to describe and classify land-cover features at any desired scale and level of detail. Each of the classifiers and attributes that are used for the generation of a single land-cover class is associated with a unique code and thus every class is explicitly identifiable and is assigned a standard name by the classification system. The system offers the possibility to describe land-cover categories at a high level of detail, but also allows for the generalization and upscaling of complex land-cover maps to national or global levels.

LCCS has been applied to the maps of the Global Land-cover project (GLC2000) and also forms the conceptual basis for the class descriptions of the forthcoming Medium Resolution Imaging Spectroradiometer (MERIS) land-cover product GLOBCOVER. The GLC2000 legend is scale-dependent. At the global scale, it consists of 22 general land-cover types that are defined at the biome level. The legend for Southeast Asia contains 16 classes that inherit features of the major classes while classes that are not prevalent in the tropical biome are neglected. According to Bartholomé and Belward (2005),

the classes at the global level provide compatibility with maps that are based on the IGBP classification system. This means that any regional product that is based on the LCCS system can be compared to IGBP-based land-cover maps. In practice, this compatibility is not fully accomplished due to some inconsistencies in class definitions (see table 1 for a comparison of LCCS and IGBP legends). A workaround for the comparison of land-cover products that are based on different classification systems is the aggregation of the land-cover classes in two systems to a set of major land-cover types at the biome level (Giri et al. 2005).

Table 2 provides an overview of current and planned land-cover products covering insular Southeast Asia. These maps can be grouped into two categories: 1) maps based on global AVHRR data that have been generated during the 1990ies and use 1992 as the base year and 2) products for the base year 2000 from MODIS and VEGETATION using different classification concepts. In addition, table 2 includes the forthcoming GLOBCOVER product that is based on Envisat/MERIS. The year 2000 has been chosen as a benchmark for environmental, ecological and economic long-term analysis. The comparison of the land-cover product characteristics points to the general problem of inconsistency and thus incomparability between products that are generated by different workgroups. In addition to these products, the land-cover of insular Southeast Asia or its sub-regions are subject to a number of studies aiming at the characterization and delineation of land-cover types at the global to regional level (Sato and Tateishi 2004, Mayaux et al. 1998, Stibig et al. 2003)

2.2 Concepts of land-cover change analysis

All over the world terrestrial ecosystems are changing at multiple spatial and temporal dimensions. In the context of land-cover, change is defined as the "alteration of the physical or biotic nature of a site". As an example, the transformation of forest to cropland represents a change in land-cover whereas land-use change involves "alterations in the human management of land, including settlement, cultivation, pasture, rangeland and recreation" (Meyer and Turner 1994). Land-use induced land-cover change is one important factor affecting terrestrial ecosystems and human livelihoods and thus comprises a major driving factor of global change. Remote sensing studies are generally restrained to land-cover change analysis. Change can be either abrupt or gradual and thus can be described in categories (classes) or continuous variables. The complete replacement of one land-cover type by another is referred to as land-cover conversion, whereas slight changes affecting the attributes of a land-cover without changing the nature of the land-cover type are defined as land-cover modifications (Coppin et al. 2004).

Considering tropical environments, land-cover change is frequently caused by human-induced deforestation activities (Lambin 1997, Lu et al. 2005). The most general definition of deforestation is given in Watson et al. (2000) as the "sum of both, permanent and temporary human-induced removal of forest

Table 2. Current and planned global land-cover products covering insular Southeast Asia

Product	GLCC	UMD land-cover	GLC2000	MODIS land-cover	TREES	GLOBCOVER
Sensor	AVHRR	AVHRR	SPOT Vegetation	MODIS	SPOT Vegetation	MERIS
Timeframe of data collection	April 1992 - March 1993	April 1992 - March 1993	Nov. 1999 - Dec. 2000	Oct. 2000 - Oct. 2001	March - Sept. 1998 March - Nov. 1999	Jan. 2005 - Dec. 2005
Input data	Monthly NDVI composites	Monthly NDVI composites and metrics	Spot VGT1 S1	MOD43 (nadir BRDF- adjusted reflectance)	Spot-VGT1 S10	MERIS Level 2
Spatial Resolution	1km	1km	1km	1km	1km	300m
Map Projection	Goode's Homolosine	Goode's Homolosine	Geographic	Sinusoidal	Geographic	Geographic
Classification technique	Unsupervised clustering	Supervised classification (decision tree)	flexible classification system depending on partner institution	Supervised classification (decision tree)	N/A	N/A
Classification scheme (legend)	IGBP (17 classes)	Simplified IGBP (14 classes)	LCCS (16 classes for SE Asia)	IGBP (and others)	TREES 9 classes	LCCS
Intended update schedule	Annual*	Annual*	2005 (GLOBCOVER)	Annual*	–	N/A
Detailed description of product	Loveland et al. (2000)	Hansen et al. (2000)	Bartholomé and Belward (2005)	Strahler et al. (1999) Friedl et al. (2002)	Stibig et al. (2003)	N/A
Data access	http://edcdaac. usgs.gov/glcc/ glcc.asp	http://glcf. umiacs.umd.edu/ data/landcover/	http://www.gvm. jrc.it.glc2000	http://edcimswww. cr.usgs.gov/pub/ imswelcome/	http://www.gvm. sai.jrc.it/Forest/ defaultForest.htm	http://www.gvm. jrc.it/tem/pro- ducts.complete.htm

* no updates available at time of paper submission + Version 1.2 of GLCC has been updated by version 2.0 in 2004 but is based on the same data set (1992-1993)

cover". This definition includes short-term removals by shifting-cultivation as well as selective and clear-cut logging activities and all other kinds of conversion or modification of forest land. Lund (1999) restricts the term deforestation to "the long-term or permanent removal of forest cover and conversion to a non-forested land-use". Besides human induced alteration, land-cover change can also be caused by long-term changes that are related to climate change, geomorphological (soil erosion) and ecological processes (vegetation succession) as well as inter-annual climate variability (Lu et al. 2004). Within the present study, deforestation is only addressed in terms of short- to long-term forest conversion (e.g. changes in forest or land-cover type).

Detailed descriptions of change detection concepts can be found in Coppin et al. (2004), Lu et al. (2004) and Singh (1989). The most important point in determining the appropriate concept is the decision for a spatial and temporal scale for the intended investigation. Vegetation cover changes seasonally, inter-annually or between any other points in time (directional change). The change concept can either rely on two different images (bi-temporal) or on a set of images covering a complete time trajectory (time series analysis). Bi-temporal change detection concepts have to take into account the dates of image acquisition as the most important factor that may bias the resulting change. This is especially of interest in areas showing significant phenological differences in vegetation status or seasonal / intra-seasonal land-use patterns. Hence, bi-temporal change analysis is only meaningful if acquisition dates are comparable, phenological cycles follow distinct seasonal patterns and if they cover the interval length of the change process that is observed. In practice, bi-temporal change analysis is the dominating concept for change analysis in tropical areas (Achard et al. 2002, Alves et al. 2003, Castro et al. 2003, Erasmi et al. 2004). In most cases, the choice of a data pair for bi-temporal analysis is more related to the availability of appropriate satellite image data than to the above mentioned factors. To overcome the limitations of bi-temporal analysis, recent approaches in satellite based ecosystem analysis focused on the analysis of temporal profiles of image data covering seasonal, annual and inter-annual observation periods. These change concepts require a time series of remote sensing data that are transformed into indicators of ecosystem characteristics (e. g. spectral vegetation indices). Time series-based change detection has recently been successfully implemented for regional and global studies of climate induced land-cover changes (Friedl et al. 2002, Zhang et al. 2004) and for the assessment of the variability of inter-annual net primary productivity of tropical ecosystems (Turner et al. 2005).

Overall, the most important challenges for remote sensing-based ecosystem change analysis are (1) the detection of land-cover modifications in addition to conversions; (2) the detection of abrupt as well as gradual changes in land-cover; (3) the detection and separation of spontaneous, seasonal and annual changes from inter-annual changes and long-term trends; (4) the scale dependency of change estimates derived from satellite images at different spatial resolutions; (5) the precise geometric co-registration of multi-temporal im-

ages and time series of satellite data; (6) the development of an appropriate change detection method; (7) the adoption of a consistent and hierarchical classification concept.

2.3 Remote sensing sensors and systems for land-cover mapping

As described in the previous section, the success of land-cover studies is directly related to the availability of satellite imagery at the desired spatial and temporal resolution. Concerning the spatial resolution of existing satellite systems, three main categories of sensors can be defined: (a) coarse to medium-resolution sensors (> 250 m); (b) high-resolution sensors (> 10 m); (c) very high-resolution sensors (< 10 m). These spatial resolutions can be linked to studies at different level of detail: (a) global to landscape level ($< 1:200.000$); (b) regional level ($< 1:25.000$); (c) local level ($> 1:25.000$). In general, the temporal resolution of optical satellite sensors is a function of the spatial resolution, due to sensor limitations (instantaneous field of view) and repetition rate of a sensor system. This means that an increase in the temporal resolution will most likely reduce the spatial resolution available for analysis. In addition to these characteristics, the choice for a satellite system also de-
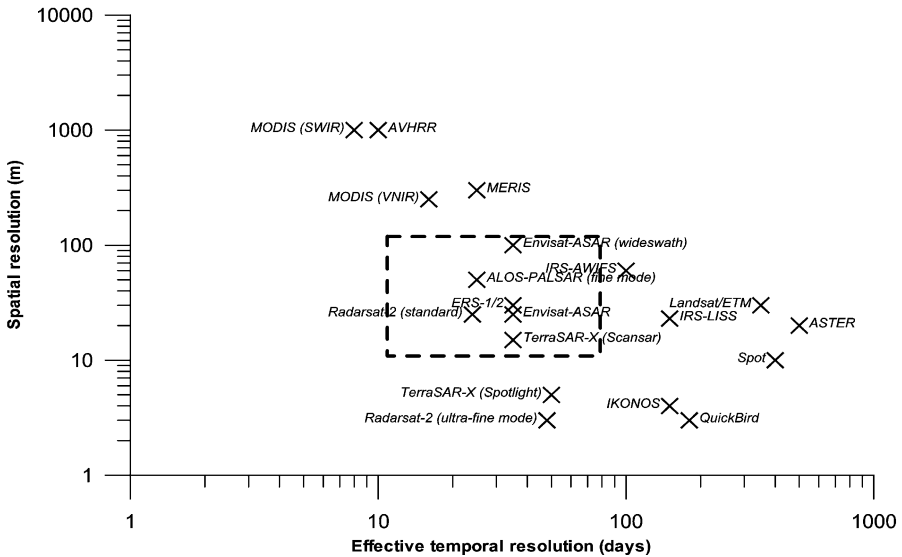
Fig. 1. Effective temporal and spatial characteristics of current and future multispectral and SAR earth observation satellite sensors for humid tropical regions (dotted rectangle highlights desired resolution configuration for operational tropical land-cover monitoring

pends on the spectral resolution (bandwidth, number of channels) and nature

of radiation source (optical, radar, lidar). Figure 1 provides a broad overview of selected multi-spectral optical and SAR (synthetic aperture radar) satellite sensors that are used for earth observation purposes at present. The shown temporal coverage for optical sensor systems does not represent the nominal coverage of the observing system based on its repetition rate, but accounts for the effective mean availability of imagery for humid tropical areas due to atmospheric disturbances and cloud coverage. In contrast to this, the temporal coverage of SAR satellite sensors is identical with its repetition rate due to the ability of radar waves to penetrate clouds. The summary shows that, in general, regional to local level mapping and monitoring is mainly related to observation systems with less frequent coverage whereas frequent observations of seasonal, annual and inter-annual phenomena (time series analysis) often require medium to coarse-resolution satellite systems. The lack of available systems in the intermediate space (high acquisition frequency, high spatial resolution) may be accounted for by using spaceborne imaging SAR systems. As illustrated in figure 1, satellite SAR sensors may comprise a key data source for land-cover observations in tropical areas. So far, only few studies have accounted for this opportunity and revealed the potential of the synergetic use of optical and radar data for the mapping and monitoring of land-cover in the tropics (Sano et al. 2005, Siegert et al. 2001). An explanation for this fact is that despite the operational availability of SAR satellite data, still too little is known about the relation of SAR signals to vegetation properties.

3 Pre-Processing of satellite data

3.1 Single-time and bi-temporal mapping

Land-cover studies that are carried out based on single images mainly require accurate geometric registration to a reference system or co-registration to other spatially explicit data sources for geospatial analysis purposes in a geographical information system (GIS). Geometric accuracy of (co-) registration is of utmost importance to any form of land-cover mapping or change analysis and should be accounted for at the sub-pixel level. Mis-registration at the pixel level may lead to significant differences in area or change estimates and, hence, may cause pseudo-events in change detection or geospatial modelling. Radiometric consistency is not needed in the case of single image analysis if isolated empirical studies are intended, because land-cover maps are created individually for a single area and a single date. The challenges for radiometric image pre-processing increase with the number of images that are being processed and analysed.

In the case of bi-temporal analysis, major causes for the alteration of the sensor signals that are recorded and converted into digital numbers (DNs) are the variability of atmospheric constituents and topography. Radiometric processing always aims at the normalisation of these effects by the use of models

that in general invert the signal to DN conversion and eliminate the noise that is apparent in the signal or, in other words, maximize the signal to noise ratio (SNR). In general, there are two types of radiometric pre-processing: (a) relative radiometric calibration and (b) absolute radiometric calibration. Detailed summaries of pre-processing techniques for land-cover mapping and change detection are available from Cihlar (2000) and Coppin et al. (2004). Simple relative radiometric normalisation approaches are linear regression algorithms, or pseudo-invariant feature-based techniques. These methods rely on image based statistics and perform a relative normalisation of spectral image layers. Most of these methods use invariant features that are assumed to retain their spectral characteristics over long periods of time (e. g. empirical line calibration). More sophisticated radiometric calibration approaches aim at the computation of the absolute intensity of radiance reflected or emitted by a surface. These models are grouped in image-based atmospheric correction methods (Chavez 1996, Twele and Erasmi 2005) and physically based methods (radiative transfer models). A study by Songh et al. (2001) revealed that the complexity of a radiometric calibration technique does not necessarily improve the accuracy of a classification or change detection analysis. This only implies qualitative analysis of the land surface. If further quantitative analysis (biophysical ecosystem variables) from calibrated remote sensing data is intended, an accurate and robust absolute atmospheric correction method should be applied.

3.2 Time series computation

Satellite image analysis that is based on a time series of observation dates generally requires the same pre-processing workflow as has been explained in the previous section. Adequate geometric accuracy is obligatory for change analysis in time profiles. Current sensor systems already account for this necessity and provide precise geo-located products to the user community (Terra/Aqua-MODIS, Envisat-MERIS, Spot-VEGETATION). The radiometric calibration of time series data has mainly to deal with the removal of clouds and other atmospheric effects (e. g. water vapour content, aerosols) that are inherent in a single image. Since the existence of clouds constitutes a major problem in tropical land surface remote sensing, the development of methods to minimize or remove these effects is imperative for land-cover analysis. A simple but robust approach to reduce the amount of cloudy and atmospherically contaminated image pixels is the generation of temporal composites based on a constant number observation dates. The processing and archiving facilities of the currently available satellite systems that deliver daily image data already, developed and implemented such compositing techniques in standard pre-processing workflows and provide the compositing results as an operational data product (Terra/Aqua-MODIS, Spot-VEGETATION, NOAA-AVHRR). In most cases, these temporal composites rely on the maximum vegetation index value within a given period of time (several days or weeks). Maximum

value composites (MVC's) are very simple to use and have been applied to early temporal profiling satellite data sets (e. g. AVHRR Pathfinder; Holben 1986). Newer approaches further account for the influence of the viewing geometry (panoramic distortions, sensor off-nadir angle) (Huete et al. 2002, Duchemin et al. 2002). Global imaging sensor systems are operated at a wide field of view, which results in signal alterations in off-nadir areas. These effects are mainly caused by the directionality of the reflectance behaviour of natural objects and are described for every land surface object by its bi-directional reflectance distribution function (BRDF).

Table 3 summarizes the temporal composite products that are currently available for insular Southeast Asia. All land-cover products that are summarized in Table 2 are based on one of these compositing techniques or use enhanced techniques that have been developed complementary to the basic methods. These recent approaches are mainly driven by the fact that even the BRDF-adjusted composite for MODIS and VEGETATION products (Schaaf et al. 2002, Duchemin et al. 2002) does not yield uniform results for the globe and can further be improved for specific regions, especially the tropics, where cloud coverage and atmospheric disturbances are eminent (Cabral et al. 2003, Carreiras and Perreira 2005, Hagolle et al. 2004).

4 Techniques of land-cover mapping and change detection

Satellite image classification, the assignment of a discrete object attribute (e.g. land-cover type) to a single image unit (pixel or object), is one of the earliest application fields of digital image processing and analysis in remote sensing. Two types of approaches have evolved and are used to this day as the basic options for digital image classification. These types are based on different general concepts about the previous knowledge of the area that is to be classified (Cihlar 2000). Supervised classification uses a priori knowledge about the surface types that is used to create representative signatures which are applied to the entire area of interest. The unsupervised classification concept does not take into account prior information about cover type and distribution. The assignment of clusters to land-cover types is done a posteriori, based on available ground truth information. A number of enhanced techniques have evolved from these two classification techniques, including decision tree classifiers, neural networks and fuzzy logic classification (Coppin et al. 2004).

In addition to the analysis of the spectral dimension, the spatial domain contains also valuable information about land-cover features, especially when high spatial resolution satellite data are available. The most utilized approaches comprise texture analysis and other spatial measures based on image segments.

Table 3. Vegetation index composite products available for Southeast Asia

Product	MODIS MOD13	SPOT-VGT S10	SPOT-VGT D10	AVHRR 1km	AVHRR GIMMS
Sensor	Terra/Aqua MODIS	SPOT-Vegetation-1/2	SPOT-Vegetation-1/2	AVHRR	AVHRR
Temporal coverage	April 2000 - present	April 1998 - present	July 2001 - present	April 1992 - May 1996	July 1981 - Dec. 2003
Spatial resolution	250/500/1000m	1km	1km	1km	8km
Map projection	Sinusoidal	Equirectangular/ Plate Carée (Lat/Lon)	Equirectangular/ Plate Carée (Lat/Lon)	Goode's Homolosine	Geographic
Compositing period	16 days	10 days	10 days	10 days	1 month
Compositing algorithm	MODIS VI compositing algorithm	Maximum value composite (MVC)	Bidirectional composite (BDC)	Maximum value composite (MVC)	Maximum value composite (MVC)
Detailed product description	Huete et al. (2002) Schaaf et al. (2002)	Holben (1986)	Duchemin et al. (2002)	Holben (1986)	Tucker et al. (2005)
Data access	http://edcimswww.cr. usgs.gov/pub/imswel come/	http://free.vgt.vito.be/ index.php	http://free.vgt.vito.be/ index.php	http://edcdaac.usgs. gov/1KM/1kmhome page.asp	http://glcf.umiacs. umd.edu/data/gimms/

If area distributions of land-cover classes are to be compared over time, a classification of all image pixels for each point in time is obligatory. Consequently, the multi-temporal dataset is classified separately and a pixel-by-pixel comparison is employed. Subsequently, changes in area distribution of all land-cover classes can be calculated and the history of land-cover development can be analysed and interpreted under different (e.g. social, ecological) perspectives.

However, land-cover studies frequently deal with single, sometimes drastic change phenomena such as deforestation, forest fires, landslides and floods. In this case, mapping all image pixels is neither necessary nor feasible with respect to time requirements. Therefore, it is possible to use special techniques which are developed to highlight the specific change phenomena. The most popular of these methods utilize image algebra or image transformations to convert multi-temporal spectral reflectance to a feature space that highlights changes. Comprehensive reviews of change detection techniques can be found in Coppin et al. (2004), Lu et al. (2004) and Lu et al. (2005).

If land-cover mapping aims at the detection of gradual changes in land-cover (e.g. forest thinning, selective logging or reforestation), mapping land-cover modifications in a continuous manner is desirable. The most common approach to derive such information from multispectral remote sensing data is the computation of fractions of land-cover types within a pixel (e.g. fraction of vegetation) or of biophysical attributes over time (Lambin 1999).

5 Land-cover and change analysis in Sulawesi

It is evident from numerous studies (Achard et al. 2002, Erasmi et al. 2004, FAO 2003, FWI & GFW 2002) that substantial land degradation and land-cover conversion at the rainforest margin in Southeast Asia has taken place during the past decades and significantly increased during recent years. Regional studies based on satellite data state an annual loss of forest cover of 0.6 % for the time period 1972 to 2002 for Central Sulawesi (Erasmi et al. 2004). National estimates for Indonesia assume a loss of forest of 1.2 % to 1.7 % per year (FAO 2003, FWI & GFW 2002).

These discrepancies in deforestation estimates allude to the problem of data comparability and scale dependency for socio-economic and ecological modelling. Within this context, a study has been carried out for a test region in Central Sulawesi that evaluated the satellite data products and land-cover mapping concepts that have been explained above.

5.1 The land-cover classification system for Sulawesi

The comparison of the IGBP and LCCS classification system for insular Southeast Asia revealed some problems that are mainly caused by the different class definition concepts.

Figure 1

for evergreen broadleaved forest use different height thresholds (shrubland: IGBP=3 m, LCCS=2 m; forest: IGBP=5 m, LCCS=2 m).

Fig. 2. Subsequent land-cover specification for tropical forest areas in Sulawesi using the modular hierarchical classification system (LCCS)

The flexibility and hierarchical concept of LCCS were the major criteria for the decision to adopt this system as a fundament to create a consistent land-cover classification system for Sulawesi. The first and lowest level of the hierarchical multi-level system comprises the land-cover classes that have been defined within the GLC2000 project for insular Southeast Asia. These class definitions already account for the specifics of tropical land-cover and are tailored to general tropical vegetation types (Table 1). Land-cover analysis at this level is limited to large area observations, temporal trajectory analysis and comparison of results from different regions. At the next and more detailed level, the initial classes are subdivided into more detailed descriptions of the

land-cover that is dominant in the area under investigation. Other classes that are less important within the area remain unchanged. At this level regional analysis of land-cover is performed, aiming at a more complex characterization of tropical landscape patterns. The third and highest observation level again contains more detailed descriptions of land-cover units. At this stage, a description of local land-cover phenomena is carried out with regard to the characterization of land-use intensity gradients at the rainforest margin. An example of the specification of land-cover classes within this modular concept is given in Figure 2 for broadleaved evergreen forest areas.

The concept has been adapted to satellite-based mapping approaches for the investigation area in Central Sulawesi. Land-cover analysis based on this classification system guarantees consistent and comparable land-cover information at multiple scales. Land-cover mapping results at higher levels can be transferred to lower levels by means of aggregation of land-cover classes at any time without class overlap or inconsistencies.

5.2 Land-cover area comparison based on global products

Despite the inconsistencies of the IGBP and LCCS classes, the IGBP classes have been translated into the LCCS system for insular Southeast Asia as shown in Table 1. This made a direct quantitative comparison of the MODIS and the GLC2000 land-cover products possible. Figure 3 shows the resulting area fractions of the LCCS classes for the MODIS land-cover compared to the GLC2000 land-cover classification. Most obvious discrepancies are apparent for the classes "broadleaved evergreen forest" and "mosaics of cropland / other natural vegetation". Other findings by Hansen and Reed (2000) and Giri et al. (2005) also reported major differences in forests as well as in shrublands and savannas that are mostly related to the different class definitions of forest, resulting in an overlap of forests in the LCCS system with savannas / shrublands of the IGBP land-cover classes. In the specific case of Sulawesi, the discrepancies cannot solely be explained by these class inconsistencies. In contrast to other reported results (Hansen and Reed 2000, Giri et al. 2005) the forest area in the MODIS land-cover product is 20 percent above the estimates of the GLC2000 product (MODIS: 81.5 %; GLC2000: 61.5 %). The second major difference in area fractions is found for the "mosaics of cropland / other natural vegetation" class. The amount (in percent of total area) nearly compensates for the shift of forest cover rates between the two maps (MODIS: 7.9 %; GLC2000: 24.0 %). The area statistics also reveal some noticeable differences between the estimates for "cultivated areas" as well as "tree cover and other natural vegetation mosaics". The fractions and differences for the remaining classes that are found in the investigation area are below 1 % and neglected in this discussion.

The large overestimation of forest cover in the MODIS land-cover classification compared to the GLC2000 product is surprising, because the class definition of the IGBP legend for forest is based on a threshold of 60 % tree
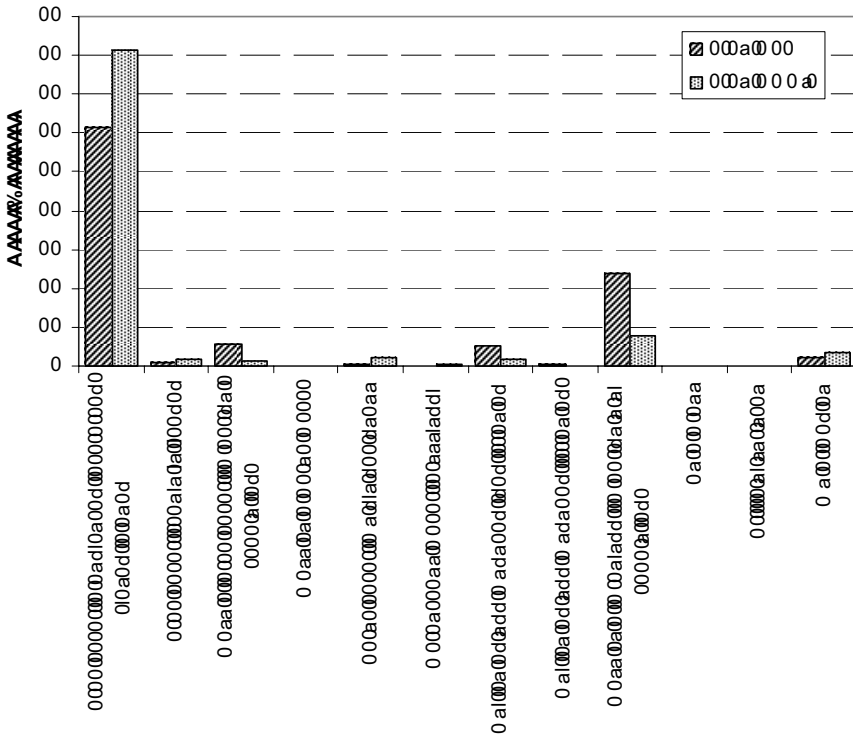
Fig. 3. Occurrence of LCCS land-cover classes based on the GLC2000 and MODIS land-cover products for Sulawesi

cover in contrast to only 15 % for the LCCS. Based only on this fact, the simple translation of the IGBP forest class to the LCCS system that has been accomplished here must lead to an overestimation of forest area in the GLC2000 product. Since the opposite is observed in this study, it cannot be argued that the different area estimates are simply based on different class definitions or inconsistencies in legend translations. This has been further approved by the comparison of the two classifications at the biome level, using only seven aggregated land-cover classes based on the LCCS class definition scheme (Figure 4). Additional investigation thus concentrated on the validation of the two products for a regional study site in Central Sulawesi.

5.3 Comparison of global products with regional studies

There are several options to validate satellite-based land-cover products. The approach for the GLC2000 data sets was based on the participation of international, national and regional experts from more than 30 countries. Within this consortium, the land-cover maps were produced at the regional level and
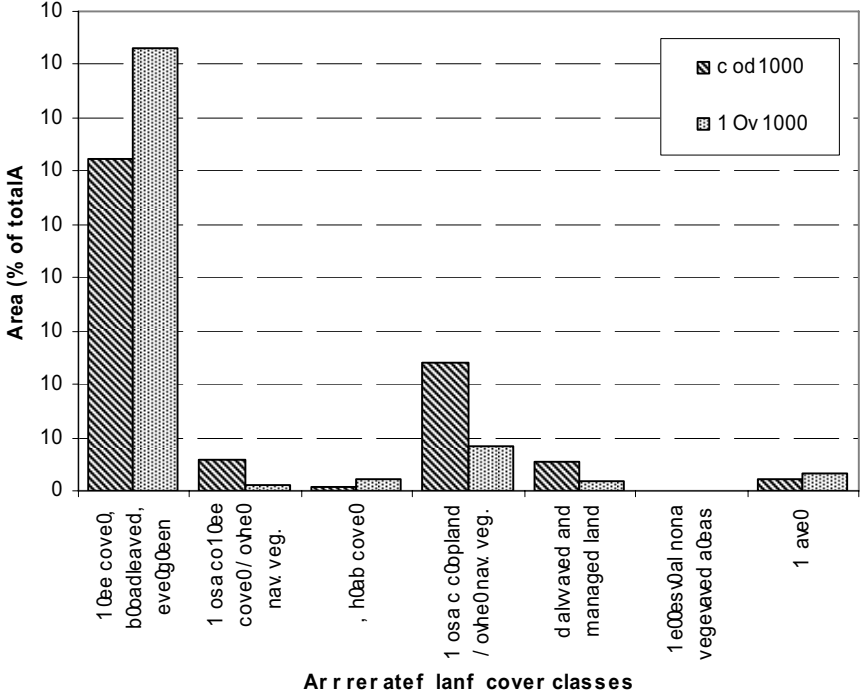
Figure 3 Area statistics based on aggregated LCCS land-cover classes for the GLC2000 and MODIS land-cover classifications of Sulawesi

later transferred to the continental and global scale using the hierarchical LCCS classification scheme. This bottom-up classification concept already accounted for a regional validation by a team of experts that created maps at higher levels. All input data sources, the classification scheme and methodology were adapted to the needs of the participating institutions and optimized for the land-cover types that are found in the respective regions. In contrast to this, the MODIS product uses a top-down approach to characterize land-cover. The MODIS land-cover product is based on a consistent classification methodology that uses a supervised decision tree classifier and is adopted for the entire terrestrial surface. A validation using results from regional studies and high-resolution satellite data has not been carried out within the project.

The two products (MODIS land-cover, GLC2000) have been validated within the current study using a land-cover map of a test site in Central Sulawesi, Indonesia. The site covers approximately 7.200 square kilometres and is dominated by broadleaved evergreen natural forest and land cultivation of different intensities at the forest margins. The validation dataset consists of a Landsat/ETM+ based land-cover map that has been validated by local
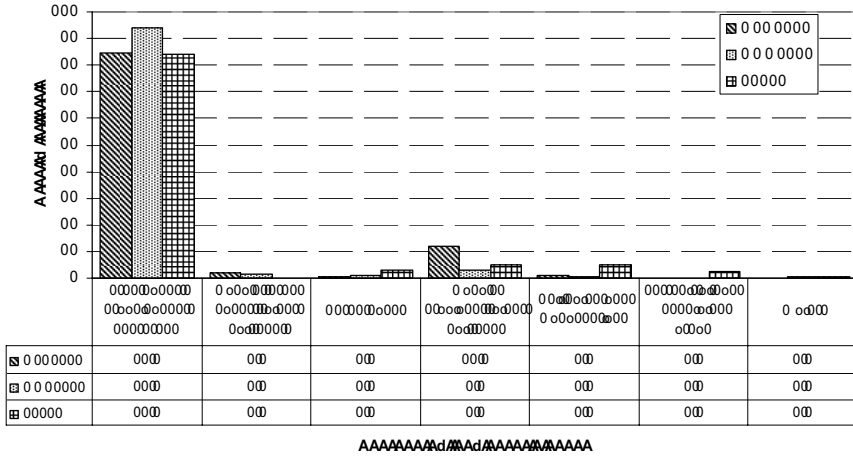
Fig. 5. Area statistics for aggregated classes of Landsat-based classification compared to GLC2000 and MODIS land-cover products (STORMA project area, Central Sulawesi)

and regional experts (producer's accuracy: 87,7 %). All data products have been created using the LCCS legend or translated from other systems and have been aggregated to the major land-cover types that are prevalent in the study area. Figure 5 shows the results of the area statistics calculations for the three land-cover maps. It is apparent that the GLC2000 map better reflects the results of the regional study. The forest areas can be estimated with a total difference of only 10 square kilometres (0.1 % of total area). The "cropland / natural vegetation mosaic" areas are larger in the GLC2000 land-cover map whereas the cropland area is larger in the regional land-cover map. This can be explained by the small-scaled landscape pattern of annual and perennial crops, grassland and agroforestry systems that are mixed up when using lower resolution satellite images. Considering the MODIS regional validation, forest areas are strongly overestimated (94 % of the study area). The remaining area is shared by the other six classes, which leaves no space for interpretation of agreement or disagreement with the regional map. A comparison of the spatial distribution of the forest areas from GLC2000 and MODIS clearly shows the areas of disagreement between these two products (Figure 6). Inconsistencies mainly occur at the transition zones between natural forest and cultivated land and hence in the areas that are of primary interest in most studies with regard to the stability of rainforest margins.
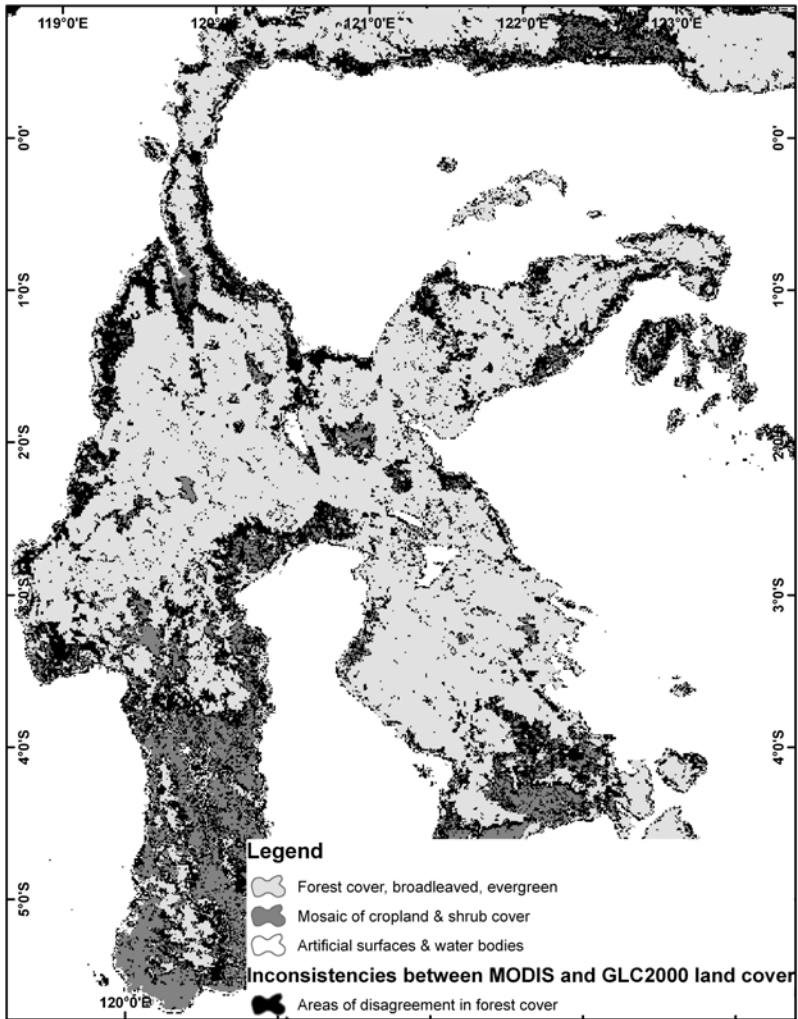
Fig. 6. GLC2000 land-cover map for Sulawesi including areas of disagreement between GLC2000 and MODIS land-cover (in magenta)
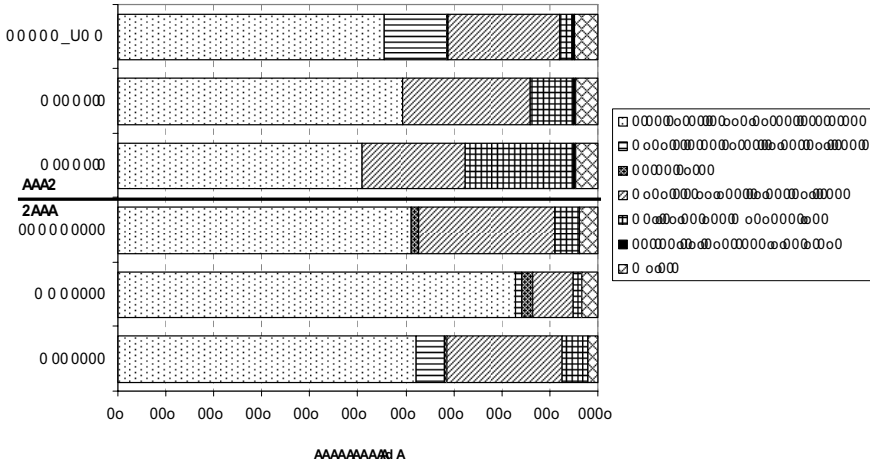
Fig. 7. Area statistics of land-cover change for Sulawesi based on global products for the years of 1992 and 2000

5.4 Change analysis based on global products

The change analysis was based on a comparative post-classification analysis of the existing global land-cover products for insular Southeast Asia. The computation of change statistics and the results of change analysis are strongly dependent on reliable and consistent data for at least two base years. In this study five land-cover products have been compared (see Table 2 for product details) with regard to feasibility and consistency of area estimates for the tropical land-cover of Sulawesi. The results of the area calculations based on aggregated classes are shown in Figure 7. A comparison of the area distribution reveals some remarkable aspects. The revision of the GLCC product (version 2.0) leads to a considerable increase in forest cover. At the same time, cultivated land decreases to less than half of the previous estimate for the GLCC version 1.2. The AVHRR_UMD map includes the "Mosaic: Tree cover / other natural vegetation" class while this class is not apparent in the other AVHRR-based products for the base year 1992. In general, the area estimates for forest cover show an increase in forests during the time period of 1992 to 2000 even if the strong overestimation of the MODIS product is neglected in the comparison. Moreover, there seems to be no increase in land cultivation. The consequence of these results would be that tropical ecosystems in Sulawesi regenerated during the past decade. This finding is contradictory to all assessments and field observations at the local, regional and global level and is abandoned from further interpretation. The reason for the implausible area estimates is rather to be seen in the inconsistencies of data sources, methodologies and classification concepts of the different studies.

As a consequence of these findings, further change analysis based on the existing land-cover products has not been conducted within this study.

6 Discussion and conclusions

A comparative analysis of the global land-cover products for Sulawesi has been carried out. The data set for the comparison consisted of five land-cover maps covering two base years (1992 and 2000). The analysis for the base year 2000 included the MODIS land-cover and the GLC2000 product. Area statistics for these two products show a strong overestimation of forest areas in the MODIS land-cover classification. In comparison, the present study underlines the high consistency of forest cover estimates from GLC2000 land-cover with regional land-cover mapping from high-resolution satellite data for Central Sulawesi. Moreover, cropland is mixed up with natural forest cover in the MODIS product, whereas the GLC2000 map better delineated cultivated land from natural forest areas. The spatial analysis of area distributions for the main land-cover classes reveals large areas of disagreement between MODIS and GLC2000, especially near the rainforest margins. Overall, the GLC2000 is superior to the MODIS product considering the investigation area in Sulawesi. This conclusion is not surprising because of the lack of regional validation studies for the MODIS land-cover data. The data were not intended for regional or local applications, thus the data have not been optimized for those purposes. On the other hand, the GLC2000 data demonstrate the feasibility of integrating global land-cover data sets into regional studies and the importance of regional studies for the verification of global land-cover products.

The GLC2000 concept will be adapted to the forthcoming GLOBCOVER data set in a similar manner. This scheme presumes that GLOBCOVER data will provide a land-cover map that is comparable to the GLC2000 and may deliver the basis for a consistent change analysis in tropical regions. Nevertheless, the classification and validation strategy of GLC/GLOBCOVER is not operational due to the large number of involved partners and institutions at different operating levels. In contrast, the MODIS classification methodology is consistent and repeatable. It aims at the provision of a global data set every six months, but the intended update schedule has not been accomplished up to now.

The MODIS and GLC2000 data sets have also been compared with the global data sets for the base year 1992 (GLCC, AVHRR_UMD). The comparative analysis for the Sulawesi area confirms the problem of inconsistency with regard to data sources, classification methods and concepts. Even if the data source of a land-cover product is identical, the processing and analysis differs fundamentally, thus making it difficult to compare the results (Hansen and Reed 2000, Giri et al. 2005). The results of the present study for Central Sulawesi conclude that the area disagreements between products for a single

year can be of the same dimension as estimated changes of land-cover between years.

Considering land-cover classification systems, the LCCS comprises a basis for the definition of land-cover legends at multiple levels, using a hierarchical tree concept and a combination of environmental and technical attributes of land-cover. The concept has been successfully adapted to the land-cover types for the tropical environment of Central Sulawesi. The advantage of the LCCS system is that it is flexible and adaptable to biome specific characteristics while the IGBP consists of an irreversible number of major land-cover classes. Hence the LCCS is more useful for multi-level investigations from local to global scale. In contrast, the IGBP class definitions are restricted to global monitoring issues.

Future work will aim at the generation of consistent data products for change analysis. These attempts have to account for a robust pre-processing chain focussing on data harmonization (spectral, spatial and temporal fitting). If data harmonization is achieved at a certain level, standardized classification workflows can be established and adapted to the different data sets. The overall scope of future studies of land-cover assessment within the project will be on the routine mapping of tropical ecosystems which comprise a hot spot region with regard to global change. It is obvious that future work should therefore focus on the integration of single isolated mapping approaches and aim at developing a comprehensive and reliable operational monitoring concept for tropical environments.

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