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Land Cover

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Global Terrestrial Observing System

Rome, 2009

Version 16
21 May 2009

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List of Acronyms

ALOS	Advanced Land Observing Satellite
ASAR	Advanced Synthetic Aperture Radar
AVHRR	Advanced Very High Resolution Radiometer
AWiFS	Advanced Wide Field Sensor
CBERS	China-Brazil Earth Resources Satellite Program
CEOS	Committee for Earth Observation Satellite
CORINE	Coordination of Information on the Environment
ECV	Essential Climate Variables
ENFIN	European National Forest Inventory Network
ENVISAT	Environmental Satellite
EOS	Earth Observing System
ERS-1 and 2	European Remote Sensing
ESA	European Space Agency
ETM+	Enhanced Thematic Mapper
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FAPAR	Fraction of Absorbed Photosynthetically Active Radiation
FRA	Global Forest Resources Assessment of FAO
FSI	Forest Survey of India
GCOS	Global Climate Observing System
GEO	Group on Earth Observation
GEOSS	Global Earth Observation System of Systems
GHG	Green House Gases
GLC2000	Global Land Cover 2000
GLCC	Global Land Cover Characterization Programme
GLCF	Global Land Cover Facility
GLCN	Global Land Cover Network
GLP	Global Land Project
GMES	Global Monitoring for Environment and Security
GOFC	Global Observations of Forest Cover
GOLD	Global Observations of Land Cover Dynamics
GOOS	Global Ocean Observing System
GTOS	Global Terrestrial Observing System
HRCCD	High Resolution CCD Camera
ICSU	International Council for Science
IGBP	International Geosphere-Biosphere Programme
IGOL	Integrated Global Observation of the Land
IGOS-P	Integrated Global Observing Strategy Programme
ILTER	International Long Term Ecological Research Sites

INPE	Brazilian Space Agency
IPCC	Intergovernmental Panel on Climate Change
IRS	Indian Remote Sensing
ISO	International Organization for Standardization
JRC	Joint Research Center
LAI	Leaf Area Index
LCCS	Land Cover Classification System
LCML	Land Cover Macro Language
LiDAR	Light Detection and Ranging
LISS	Linear Imaging Self-Scanning Sensor
LUCAS	Land Use/Cover Area Frame Statistical Survey
MERIS	Medium Resolution Imaging Spectrometer
MMU	Minimum Mapping Unit
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
PALSAR	Phased Array type L-band Synthetic Aperture Radar
PRODES	Programa de Cálculo do Desflorestamento da Amazônia
Radar	Radio Detection and Ranging
REDD	Reducing Emissions from Deforestation and Degradation
RS	Remote Sensing
SAFARI	Southern Africa Regional Science Initiative
SAR	Synthetic Aperture Radar
SPOT	Satellite Pour l'Observation de la Terre
TEMS	Terrestrial Ecosystem Monitoring Sites
TM	Thematic Mapper
UN	United Nations
UNCCD	United Nations Secretariat of the Convention to Combat Desertification
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
USGS	U.S. Geological Survey
VCF	Vegetation Continuous Fields
WGCV	Working Group for Calibration and Validation
WMO	World Meteorological Organization

Executive Summary

Land cover change is a pressing environmental issue, acting as both a cause and a consequence of climate change. Reliable observations are crucial to monitor and understand the ongoing processes of deforestation, desertification, urbanization, land degradation, loss of biodiversity, ecosystem functions, water and energy management, and the influence of land cover changes on the physical climate system itself. A number of disciplines (geography, ecology, geology, forestry, land policy and planning, etc.) use and refer to land cover and land cover change as one of the most obvious and detectable indicators of land surface characteristics and associated human induced and natural processes. Current and future IPCC Assessment Reports are based upon an uncertain understanding of the land surface dynamics and related processes. Applications of land cover and land dynamics in climate change-related Earth System Models and Impact Assessment Models need to be better linked and coordinated. The importance of these issues requires continuous monitoring systems and data.

Land cover is defined as the observed (bio)-physical cover on the Earth's surface. It includes vegetation and man-made features as well as exposed rock, bare soil and inland water surfaces. The primary units for characterizing land cover are categories (such as forest or open water) or continuous variables classifiers (e.g. fraction of tree canopy cover). Secondary outputs of land cover characterization include surface area of land cover types (hectares), land cover change (area and change trajectories), and observation by-products such as field survey data or processed satellite imagery.

Land cover in different regions has been mapped and characterized at various times and many countries have implemented some kind of land monitoring system (e.g. forest, agriculture and cartographic information systems and inventories). In addition, there are a number of continental and global land cover map products and activities. These activities have been building upon the availability of continuous global satellite observations since the 1980s.

With evolving technology, it has become increasingly feasible to derive land cover information from a combination of *in situ* surveys and earth observation satellite data at global, regional, and national scales. Inconsistencies exist between the different land cover map products or change monitoring systems, thus complicating our ability to successfully synthesize land cover assessments on regional and global scales.

Current data, products, and capabilities:

- There is a quasi-operational global land cover monitoring system which integrates information from three common observational scales: moderate resolution satellite data (e.g. MODIS- or MERIS–type satellite sensor); fine resolution satellite data (from Landsat- and SPOT-type satellite sensors), and *in situ* observations (or very high resolution remote sensing data). Continuity of observations and consistency for land cover characterization is required for all these scales.
- The UN Land Cover Classification System (LCCS) classifiers provide a comprehensive and flexible framework for thematic land cover characterization. LCCS classifiers enable compatibility to be achieved between existing datasets and for future global monitoring systems.
- Ongoing global mapping efforts (i.e. MERIS-based GlobCover and those using MODIS data) provide consistent and validated land cover data and land

cover change indicators worldwide at moderate spatial resolution.

- Land cover change estimates require multi-temporal fine resolution satellite observations. Archived image data (e.g. global Landsat data) and methods are available to implement a global land cover change monitoring system. Global assessments of historical forest change processes based on multiple data sources are available from regional and national programmes (e.g. the European CORINE, Brazilian PRODES) and international initiatives such as the Forest Resources Assessment of the FAO.
- An independent accuracy assessment using a sample of ground-reference data is an integral part of any land cover monitoring effort. Standard methods for land cover validation have been developed by the international community.

Recommendations

- Continuity and availability of data is required for all observations scales.
- Continuous monitoring of land cover conditions is recommended through periodic mapping cycles.
- The collection of ground reference data should be regular and sustained, and national agencies are encouraged to supply ground reference data in support of calibration and validation requirements.
- Further international development and adoption of land cover and land cover change mapping standards have been initiated and this process should be further encouraged.
- The international land observation community should continue the development and ensure the adoption of flexible land cover validation protocols.
- Consistent and synoptic data sets are required to represent the global land cover as an

Essential Climate Variable (ECV), this requires communication and cooperation between nations.

- UNFCCC Member nations are encouraged to support the continuity of existing observing systems and to promote further evolution of monitoring capabilities, both satellite and *in situ*.

1. Introduction

Land cover refers to the observed physical cover of the Earth's surface. Reliable land cover information is of crucial importance to: (1) understanding and mitigating climate change and its impacts; (2) sustainable development; (3) natural resource management; (4) biodiversity conservation, and (5) understanding of ecosystems and biogeochemical cycling. For example, land cover characteristics reveal ongoing processes of deforestation, desertification, urbanization, land degradation, loss of biodiversity and ecosystem functions, and water and energy management. *In situ* and satellite-based land observation efforts as well as different disciplines (geography, ecology, geology, forestry, land policy and planning, etc.) use and refer to land cover as one of the most obvious and detectable indicators of land surface characteristics and the associated human induced or naturally occurring processes.

The land surface in different regions of the world has been mapped and characterized several times, and many countries have some kind of land monitoring system in place (e.g. forest, agriculture and cartographic information systems and inventories). There are multiple examples of countries employing satellite data for national land cover and change assessments, for example in the context of reporting to the UN Framework Convention on Climate Change (UNFCCC). In addition, a number of global land cover mapping activities exist. They have evolved with the availability of continuous global moderate resolution satellite observations since the early 1990s and yielded numerous products in the 300 m – 1 km resolution range. Because most mapping projects are developed for specific applications and purposes, inconsistencies exist between the

different land cover map products or change monitoring systems that undermine the ability to successfully synthesize land assessments on regional and global scales. It is only recently that the UN Land Cover Classification System (LCCS) has been recognized and used to provide a basic level of thematic land cover standardization.

2. Definition and units of measure

Land cover is defined as the observed (bio)-physical cover on the Earth's terrestrial surface. It includes vegetation and man-made features as well as bare rock, bare soil and inland water surfaces (Di Gregorio, 2005). In current practice, many national and regional observation programmes and research institutes still do not distinguish between land cover and land use. Land use characterizes the arrangements, activities and inputs people have undertaken on a certain land cover type to produce, change or maintain it. Because of the implicit or explicit role of humans in land use characterization and mapping, it should be considered distinct and dealt with separately from land cover type, thus ensuring internal and external consistency and comparability.

The primary units for characterizing land cover are categories (e.g. Forest or Open Water) or continuous variables classifiers (fraction of Tree Canopy Cover). Secondary outputs include surface area of land cover types (hectares), land cover change (area and change trajectories), or observational by-products such as field survey data or geometrically and radiometrically corrected satellite image products. Categories

and classifiers must be defined consistently in order to identify land cover changes over time. Frequently it is essential to maintain the original data sources in support of land cover re-analysis with evolving technologies or changing standards or user requirements. In applications using land cover maps, the original land cover categories are often associated with specific attributes (e.g. average carbon stocks, degree of artificiality, or function in the hydrological system).

As noted above, many land information systems and classification legends mix land cover and land use concepts. Yet, the distinction between land cover and land use is fundamental to preventing confusion or ambiguity, in particular for more standardized concepts of land cover characterization. Though the meaning of land use varies among sectors, analysis of major existing class sets reveals that two parameters suffice: function that describes land use in an economic context, and activity that is defined as the combination of actions resulting in a certain type of product (Jansen, 2005). Land cover and land use transitions may be interoperable (i.e. a change from natural forests to crop agriculture or expansion of built-up areas as part of urban development processes), but this relationship does not hold for all circumstances as land use characterization includes considerations that go beyond land cover.

3. Existing measurement methods, protocols and standards

3.1 Standardized land cover characterization

Land cover mapping activities can be understood as a process of information extraction governed by rules of generalization. The degree of generalization, and thus the efficiency of representing reality in a two-dimensional form, is linked to three major factors. The "thematic" component refers to the land classification system and the adopted land cover legend. "Cartographic" standards include the spatial reference system, the minimum mapping unit (MMU) and the mapping scale. The "interpretation" process reflects the characteristics of the source data, the interpretation procedures, and the skill of their use. These factors affect the map products - their content, quality, flexibility and efficiency for specific applications.

It has become feasible and efficient to derive land cover information from *in situ* surveys and earth observation satellite data. Thus, extensive information on land cover has been produced in many regions of the world. The varying purposes, data sources, accuracies, spatial resolutions, and thematic legends of these efforts have resulted in a suite of more or less incompatible land cover datasets. Available global, regional, and national mapping products exist as independent datasets. For example, multiple definitions and thresholds for a particular land cover type, such as forests, result in different representations of forest class in the different land

cover maps. The lack of consistency has triggered the need for harmonization and standardized land cover monitoring.

Land cover information has to be compatible and comparable for multi-temporal analysis and map updates, within and among countries, within and between applications, disciplines and agencies, and across local to global scales (vertical and horizontal harmonization). In general, harmonization is a "bottom-up" process of emphasizing similarities and reducing inconsistencies between existing definitions of land cover to allow for better comparisons and compatibility between various land cover datasets (Herold *et al.*, 2006). Harmonization efforts should first address the terminology, or classifiers, used for the description of land cover and, once applied to systems and legends, the individual criteria used for creating land cover categories should be harmonized and applied in operational observing programmes.

The Land Cover Classification System (LCCS, Di Gregorio, 2005) and the related ontology specified in Land Cover Macro Language (LCML) currently is the most comprehensive, internationally applied and flexible framework for land cover characterization. It defines a system of diagnostic criteria (land cover classifiers) that provides standardization of terminology and not categories. At this level, existing land cover data can be much better compared. The Land Cover Data Macro Language is undergoing approval to become a standard of the International Standards Organization (ISO).

A translation of existing land cover legends and data into the LCCS language usually provides the first step in developing understanding needed to apply the classifier concept, and many existing global, regional and national land cover legends have been developed or translated using LCCS (see www.glcn.org). An agreement on a set of recommended classifiers provides the common ground for compatibility of land cover data. Current international consensus

on classifiers that meet global mapping land cover requirements include:

- Vegetation life form: trees, shrubs, herbaceous vegetation (may be separated into grasslands and agricultural crops), lichen and mosses, non-vegetated.
- Leaf type (needle-leaf, broad-leaf) and leaf longevity (deciduous, evergreen) for the different vegetation life forms.
- Non-vegetated cover types (bare soil or bare rock, built up areas, snow, ice, open water).
- Density of life form and leaf characteristics in percent cover.
- Terrestrial areas versus aquatic/regularly flooded.
- Artificiality of cover and land use.

The agreement and application of these classifiers have resulted in a number of generic land cover categories that should be considered in future mapping efforts:

- Trees (further separated by leaf type and leaf longevity).
- Shrubs (further separated by leaf type and leaf longevity).
- Herbaceous vegetation (further separated into grasslands and agricultural crops).
- Bare areas.
- Built up areas.
- Snow and/or Ice.
- Open water.

These categories are defined independently of the mapping scale, and any application of a minimum mapping unit will eventually result in mixed unit categories of these generic classes, i.e. through specifying cover percentages for the mapping units. Figure 1 illustrates the concept of moving from a terminology standard, to a thematic standard, and a cartographic standard, thus defining mapping categories from a common basis and common understanding. The figure also provides the basic
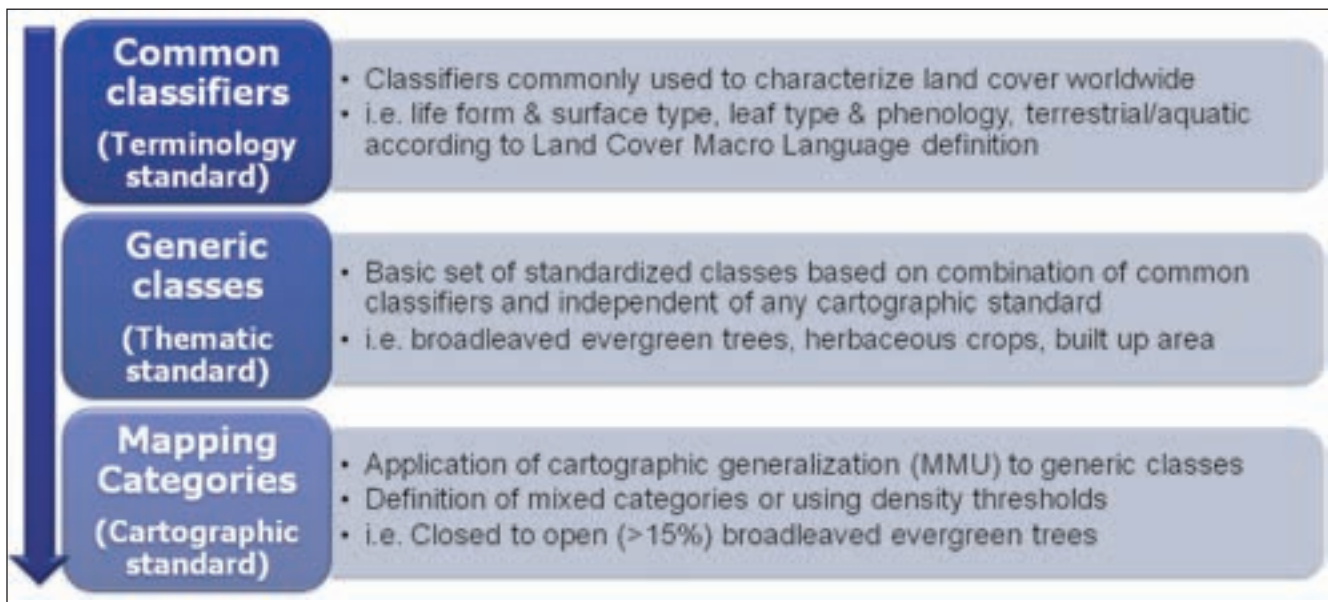
Figure 1. Concept of linking and characterizing land cover mapping categories through common classifiers, the definition of generic classes and the application of a cartographic standard

concept for the development of a legend that allows mapping to be consistently categorized internationally, while leaving the opportunity for provision of additional categorical detail, e.g. accommodating regional specific characteristics or national monitoring requirements. This general approach is suggested for all operational land cover observation activities. Instead of mapping categories, the data analysis may be performed at the level of individual classifiers (i.e. tree cover, shrub cover, herbaceous cover, etc.) and can entail specific density thresholds (e.g. tree cover 15-40 percent) or on a continuous range.

As a specific application of this concept, the GOFC-GOLD panel of GTOS in collaboration with the FAO will develop a globally exhaustive list of generic land cover classes that conforms to LCCS classifiers and can be regionally applied. This effort will provide a closed legend from a known and globally meaningful scheme, while leaving the opportunity for additional categorical detail to accommodate regional specific characteristics or national monitoring requirements.

3.2 Observing land cover

Multispectral and multi-temporal global, regional and national land cover data sets are currently produced by a range of space agencies, research institutes, and national agencies at "coarse" resolutions (250 m-1 km) for determining land cover type, and 'medium' resolutions (10-50 m) for determining type and detecting land cover change (Achard *et al.*, 2008, GOFC-GOLD, 2008). In addition, *in situ* data are acquired for monitoring of land cover, vegetation migration and related phenomena, and is also used as reference for calibration and validation of land cover and land cover change measurements by satellites.

3.2.1 *In situ*

In situ or field observations are important and accurate source of land cover data. Depending on the scale and purpose, a sampling design guides geo-referenced and GPS-based *in situ* observations and description of land cover characteristics. Such surveys

can provide statistical estimates of land cover area and, if repeated, changes for the sampled area. *In situ* observations easily provide measurements on both land cover and land use.

Ground-based observations are also a critical component of large-area land cover mapping and dynamics programmes, to support land cover interpretation of remotely sensed data and for the purpose of calibration and validation. For large-area projects, it is becoming increasingly common to use high spatial resolution airborne or satellite imagery. Samples derived from these image sources can be used to create datasets that allow for classification calibration and, if collected appropriately, robust and statistically sound validation. At the minimum, geo-located independent land cover classes are required to aid in the development of land cover maps based upon satellite imagery.

The following information are commonly required and acquired by *in situ* observations:

- Land cover type/category (e.g. forest) and/or
- Land cover characteristic (e.g. fraction of tree canopy cover)
- Change in land cover type/category and characteristics.

3.2.2 Satellite

In general, remote sensing data can be acquired from both airborne and satellite platforms and are based on a suite of measurements that can be used for land cover analysis. Spectral radiance is the primary variable used to determine land cover type from remote sensing data. Spectral pattern recognition procedures provide pixel or object-based analysis based on varying responses of different land cover types in multispectral satellite observations (such as Landsat) or hyperspectral sensor with a large number of continuous and narrow spectral bands. Remote sensing data acquired on multiple dates (multi-

temporal observations) recognize changes over time to assist in land cover characterization (phenology) or detection of changes.

Distance-resolved measurements are based on time delay between sensor and land surface. Such measurements are provided by active sensors, e.g. the Synthetic Aperture Radar (SAR), SAR interferometry, or LiDAR sensors. Compared to optical multispectral data, such measurements often depend more on the three dimensional structures (i.e. roughness, topography, vegetation structure) on the Earth's surface, thus providing additional information for land cover interpretation. Spatial pattern in the image data provides information on the texture and relationship of neighbourhood pixels that can be useful for identifying land cover.

In the current IPCC guidance given to countries for preparing their national Greenhouse Inventories, the sections "Remote sensing techniques" (2.4.4.1 of Penman *et al.*, 2003 and 3A.2.4 of Eggleston *et al.*, 2006) provide a synthetic outline of the type of remotely sensed data. These sections briefly discuss some of the strengths and problems of remote sensing techniques, including:

- the ability to provide spatially-explicit information and the possibility to cover large and/or remote areas that are otherwise difficult to access;
- the possibility of repeated coverage and the availability of archives of past remotely sensed data that can be used to reconstruct past time-series of land cover;
- the interpretation challenge, i.e. the images need to be translated into meaningful information on land cover and land use by visual or digital (computer based) analysis;
- the risk, depending on the satellite sensor, that acquisition of data is impaired by the presence of clouds and atmospheric haze;
- the need of ground reference data and for evaluating mapping accuracy;

- the fact that a complete remote sensing system for tracking land cover change may require combinations of different types of remote sensing data at a variety of resolutions.

Table 1 provides an overview of satellite sensors commonly used for land cover mapping and monitoring. The spatial resolution of the satellite imagery determines the minimum detectable size of individual patches – also referred to as Minimum Mapping Unit: fine resolution (circa 30 m) data allows detecting operationally over large regions (e.g. for a country) single patches of circa 0.5 - 1 ha. For detecting patches smaller than 0.1 ha very fine resolutions (< 5 m) are needed.

Wall-to-wall (an analysis that covers the full spatial extent of the study area) and sampling approaches are both suitable methods for producing estimates of land cover area change. The main considerations for choosing between wall-to-wall or sampling approaches are:

- wall-to-wall is a common approach if appropriate for national circumstances, in particular when a benchmark land cover map is needed;
- if resources are not sufficient to complete wall-to-wall coverage, statistically-based sampling is an efficient alternative, in particular for large areas to produce accurate estimates of land cover and land cover change. Recommended sampling approaches are systematic sampling and stratified sampling which can be combined.

Satellite imagery usually undergoes three main pre-processing steps before interpretation: geometric corrections, cloud removal and radiometric corrections.

Many methods exist to interpret satellite images (Franklin & Wulder, 2002; GOFC-GOLD, 2008). The selection of the method depends on available resources and whether image processing software is available. Visual image interpretation can be simple and robust, although it is a time-consuming method.

A combination of automated methods (segmentation or classification) and visual interpretation can reduce the work load. Automated methods are generally preferable where possible because the interpretation is repeatable and efficient. Even in a fully automated process, visual inspection of the result by an analyst familiar with the region should be carried out to ensure correct interpretation.

The use of ancillary variables or supporting spatial data layers is well established as a means to improve land cover classification outputs and their accuracy. For instance, digital elevation data can be used in the classification or as a stratification layer to differentiate land cover types that have known landscape positions. Further, temporal and spatial information can also be gleaned from image data to aid in classification. Temporal signatures can assist in the differentiation of cover types that appear spectrally similar in one season and different in another (e.g. deciduous forests). Spatial signatures, or additional contextual information, are also increasingly used to improve classification outputs, with known pixels/class associations used to aid in the determination of final class. A single class does not need to be the sole outcome of the classification process. Statistical information produced during the classification, such as distances in the statistical feature space, can be used to also identify the second most likely class, or the confidence a user should have in a given class. The production of continuous fields, whereby each pixel is composed of component classes, is a "soft" classification method that is highly flexible as it allows for the production of a wide range of classification outputs. Vegetation Continuous Fields (VCF) are especially relevant to coarse spatial resolution imagery that have an internal mixture of land cover types.

The capture of change, or dynamics, in land cover is important and may be considered by type, magnitude or area, among others. Consistent

Sensor & resolution	Examples of current sensors	Common minimum mapping unit	Cost for data acquisition	Utility for land cover monitoring
Coarse optical (250-1000 m)	SPOT-VGT (1998-) Terra-MODIS (2000-) Envisat-MERIS (2004-)	~ 100 ha ~ 10-20 ha	Low or free	Consistent global annual monitoring to identify phonological pattern, basic land cover types, large changes and locate "hotspots" for further analysis with finer resolution data
Moderate optical (10-60 m)	Landsat TM or ETM+, SPOT HRV IRS AWiFs or LISS CBERS HRCCD	0.5 - 5 ha	Some free, otherwise <$0.001/km² for historical data $0.02/km² to $0.5/km2 for recent data	Primary tool to map major land cover types and changes and associated estimate area estimates
Fine optical (<5 m)	IKONOS QuickBird Aerial photos	< 0.1 ha	High to very high $2 -30 /km²	Detailed surveys and mapping, validation of results from coarser resolution analysis, and training of algorithms
Synthetic Aperture Radar (SAR) (10-60 m)	ERS-1 and 2, ENVISAT ASAR, RADARSAT, ALOS/PALSAR TERRASAR-X	0.5 - 5 ha	Depending on sensor and distribution agency	Additional information for mapping specific land cover types and for covering consistently cloudy areas

Table 1: Utility of common remote sensors at multiple resolutions for land cover monitoring

change assessment methodologies need to be used between the repeated time intervals to obtain accurate results. Fine spatial resolution change can provide dynamics information that is relevant at the landscape or management level, although physical and technical limitations remain in the generation of such products for large areas. Coarse spatial resolution data, while conferring less detail at a pixel level, have the advantage of capturing large areas in short time periods, thus allowing for change products to be developed over shorter temporal intervals. The combination of such coarse and fine spatial resolution data provides opportunities for large area monitoring in

a systematic and meaningful fashion (Achard *et al.*, 2007).

Satellite remote sensing can provide accurate information on land cover. Land use is considered a secondary observation variable that may or may not have a distinct relationship with land cover. To move from primary land cover to land use observations additional information is usually required, i.e. local expert interpretations, higher resolution data or ground-based observations (Cihlar and Jansen, 2001).

A thorough consideration of accuracy and its independent assessment using a sample of higher quality data should be an integral part of any land cover monitoring system. If the sample for the higher

quality data is statistically balanced (e.g. random, stratified, systematic), a calibration estimator (or similar approach) gives better results than the original survey. Accuracy assessment should lead to a quantitative description of the uncertainty of the land category identification and of the associated area or change observed. Different components of the monitoring system affect the quality of the outputs. They include:

- the quality and suitability of the satellite data (i.e. in terms of spatial, spectral, and temporal resolution);
- the interoperability of different sensors or sensor generations;
- the radiometric and geometric preprocessing (e.g. correct geolocation);
- the cartographic and thematic standards (e.g. land category definitions and the MMU);
- the interpretation procedure (e.g. classification algorithm or visual interpretation);
- post-processing of the map products (dealing with missing values, conversions, integration with different data formats, e.g. vector versus raster), and
- the availability of reference data (e.g. ground truth data) for evaluation and calibration of the system.

Given the experience from a variety of large-scale land cover monitoring systems, many of these error sources can be properly addressed during the monitoring process using widely accepted data and approaches:

- Suitable data characteristics: Landsat-type data, for example, have been proven useful for national-scale land cover and land cover change assessments for MMU's of about 1 to 5 ha[1]. Temporal inconsistencies from seasonal variations that may lead to false change (phenology), and different illumination and atmospheric conditions can be reduced in the image selection process by using same-season images or, where available, applying two images for each time step.
- Data quality: pre-processing suitable for most regions is provided by some satellite data providers (e.g. global Landsat Geocover mosaics). Geolocation and spectral quality should be checked with available datasets, and related corrections are mandatory when satellite sensors with no or low geometric and radiometric processing levels are used.
- Consistent and transparent mapping: the same cartographic and thematic standards and accepted interpretation methods should be applied in a transparent manner using expert interpreters to derive at the best national estimates. Providing the initial data, intermediate data products, documentation for all processing steps, as well as interpretation keys and training data along with the final maps and estimates, supports a transparent consideration of the monitoring framework. Consistent mapping also includes a proper treatment of areas with no data (e.g. from constraints due to cloud cover).

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1   As operational examples:

- the European CORINE project, based on the photo-interpretation of Landsat satellite images over European Union territory, uses a Minimum Mapping Unit (MMU) of 5 hectares for changes between 1990 and 2000 (EEA, 2004).

- The PRODES project of Brazilian Space Agency (INPE) has been producing annual rates of deforestation since 1988 using a minimum mapping unit of 6.25 ha (INPE, 2008).

- The Forest Survey of India (FSI) has been assessing the forest cover of the country on a two year cycle since early 1980s with a minimum threshold of 1 ha (FSI, 2008).

3.3 Summary of requirements and gaps

In summary of sections 3.1 and 3.2, the following important criteria should be considered for selecting land cover observation data and land cover product development:

- adequate land categorization scheme;
- appropriate spatial resolution;
- appropriate temporal resolution for estimating of land conversions;
- availability of accuracy assessment;
- transparent methods applied in data acquisition and processing;
- consistency and availability over time.

Integrated Global Observation of the Land (IGOL, Townshend *et al.*, 2008) defines detailed land observations requirements for land cover and advocates existing requirements and gaps. IGOL advocates sustained and integrated observations on all three major scales of land cover observations: moderate and fine resolution satellite data, and *in situ* (Figure 2). An operational global observ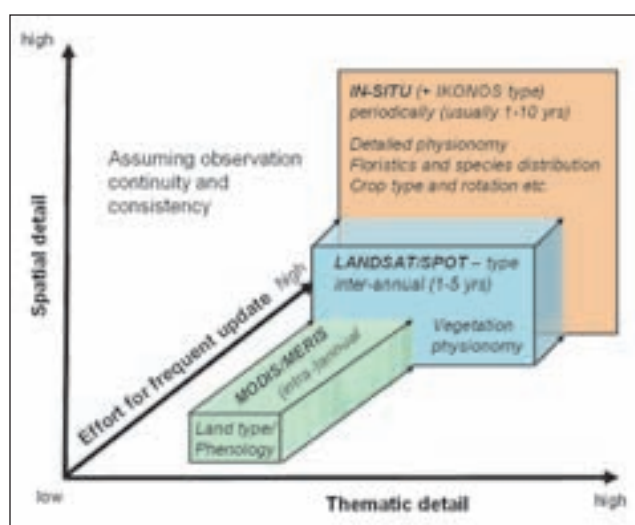ing system for land cover integrates information from these three different scales, i.e. MODIS or MERIS –type satellite sensor (moderate resolution), from Landsat and Spot-type satellite sensors (fine resolution satellite data), and *in situ* observations (or very high resolution satellite data). Measurements on these different scales have their strengths and weaknesses for monitoring in terms of spatial and thematic detail they provide, and for the efforts needed for regular temporal updates. An integrated system combines their advantages to provide world-wide consistency and links the local and global observation levels.

Based on the IGOL requirements and current consensus among the international land observation community the following requirements and gaps can be highlighted:

a. Availability of baseline observations

The implementation of the framework assumes observation continuity at all scales. Existing and archived data sources are not yet fully exploited for land cover monitoring. For observations to be useful for global land cover monitoring the following requirements should be considered:

i. Consistent global coverage.
ii. Non-discriminatory, straightforward access to global data.
iii. Continuity in measurements over time.
iv. Observations appropriate for the detection of land changes in all environments.
v. Large amounts of well calibrated or cross calibrated measurements.
vi. Room for technological advances.

There are important differences in the usefulness of existing data sources depending on the following characteristics:

i. Observations are being continuously acquired and datasets archived by national or international agencies.

Figure 2: A framework for integrated global observations of land cover and vegetation (from Herold et al., 2008)

ii.   There is general understanding on the availability (i.e. global cloud-free coverage), quality and accessibility of the archived data.

iii. Data are being pre-processed (i.e. geometrically and radiometrically corrected) and are made accessible to the monitoring community.

iv.   Pre-processed datasets are available in international or national mapping agencies for land cover and change interpretation.

v.   Sustained capacities exist to produce and use land cover datasets within countries and for global assessments (e.g. in developing countries).

Ideally, all relevant land cover observations (satellite and *in situ*) should meet these requirements to be considered useful for the overall aim of UNFCCC. For example, the commitment to build and operate Landsat 8 (NASA, US) and Sentinel 2 (ESA) are major achievements to ensure continuity beyond 2012.

b. Availability of data for calibration and validation

Despite the importance of *in situ* or very high-resolution observations, this observational domain is the least advanced for global monitoring. *In situ* or local measurements are often not dedicated for larger area analysis efforts and currently remain unavailable or unused for monitoring land cover as ECV. As a minimum, a sustained global network of calibration and validation sites needs to be established, building upon some of the existing networks. The collection of *in situ* data should be ongoing, and national agencies are encouraged to supply data in support of monitoring and to meet calibration and validation requirements.

c. Continuous monitoring

There are commitments of observing agencies for coordination of observations that should be further encouraged to provide continuity and availability of data for all observations scales. However, available data are used for single mapping efforts rather than for continuous monitoring of conditions in periodic mapping cycles. Thus global mapping efforts, e.g. MERIS-based GlobCover (Arino *et al.*, 2008, Bicheron *et al.*, 2008) and those from MODIS need to move to ongoing operations to provide consistent land cover data and land cover change indicators worldwide at moderate resolutions. An operational validation and verification system should be part of these efforts, and the international land observation community should help to coordinate and cooperate to provide useful and flexible land cover validation protocols.

d. Land cover versus land use and land change

Observation strategies and methods vary for observing land cover, land use or associated changes. Standard procedures exist for observation of land cover. Further international technical consensus should be developed for the area of observing land cover change, land use, and land use change (Wulder *et al.*, 2003). In particular the requirements for estimating, accounting and reporting on land use change and forestry using the IPCC guidelines and guidance (Penman *et al.*, 2003; Eggleston *et al.*, 2006) and the global forest resources assessments by FAO rely on land cover and land use change information.

e. Towards more standardized land cover characterization

The observation framework described in Figure 2 assumes that measurements taken at the various scales are comparable and compatible. A number of steps should be taken to ensure consistency for future mapping and monitoring efforts:

■   Further international consensus on the adoption of evolving land cover mapping standards (LCCS classifiers and generic classes).

- Existing legends should be revisited in the context of evolving land cover standards.
- Land cover legends should be developed using the LCCS and the common set of classifiers. Based on these general descriptions, more thematic detail can be specified that meets the mapping requirements without losing compatibility on a broader level.
- There is a need to explore how a harmonized land cover product can be linked to, or can benefit from, existing mapping initiatives at both finer and coarser scales (i.e. *in situ* and global) and vice versa.

f. Further technical guidance on remote sensing approaches

Several initiatives are currently underway to move towards operational land cover monitoring. The approaches used by the international community or by countries (i.e. for their GHG inventories) still seem diverse. This highlights that some basic level of consistency would be needed among the different methodologies and to ensure:

- Better description of characteristics of satellite imagery (e.g. spatial and temporal resolution, cost and availability) to be used in relation to the definition selected by the country (minimum land area). This has also implications for the accuracy.
- Existing standard image classification methodologies, with a special focus on land use identification (based on IPCC land use categories).
- Integration of different data types, i.e. more information on potential and problems of methods for combining *in situ* observations with satellite data.
- Indication of cost of data processing and analysis.
- Better description of specific issues and problems related to the detection of active fire and burned areas with satellite remote sensing techniques.

Given the increasing role for evolving monitoring technologies, there is a need for more formalized technical guidance and support and for capacity development, building upon established international networks. For example, dedicated technical inputs were provided to the negotiations of the UNFCCC on reducing greenhouse gas emissions from deforestation in developing countries (REDD) as key mitigation option for the post-Kyoto climate agreement (DeFries *et al.*, 2007). A sourcebook of methods and procedures to estimate and account for carbon emissions from forest loss in an operational, verifiable, transparent and efficient manner has also been developed (GOFC-GOLD, 2008).

g. Assessment of accuracy of land area change

Despite a number of successful case studies, there are no uniform methods for the accuracy assessment of land cover/land use change and associated area estimates. The GOFC-GOLD community, having developed consensus guidelines to validate single date land cover maps, has already started the process of developing such internationally agreed-upon approaches for the case of land cover and use change.

h. Support modelling the Earth system, and climate change and policy impacts

Applications of Earth System Models and Impact Assessment Models to understand and forecast climate change impacts and to evaluate potential mitigation and adaption strategies require improved land cover, land cover change and land use datasets. There is a strong need for effective coordination between the land observation and the modelling communities to better address land use change issues, specifically to reduce uncertainties in understanding and modelling the global carbon cycle, and for related impact and policy assessments.

4. Contributing networks and agencies

The Global Terrestrial Observing System (GTOS, www.fao.org/gtos/) is a programme for observations, modelling, and analysis of terrestrial ecosystems to support sustainable development. GTOS facilitates access to information on terrestrial ecosystems so that researchers and policy makers can detect and manage global and regional environmental change. The GTOS is sponsored by the FAO, ICSU, UNEP, UNESCO, and WMO. The GTOS has two "sister programmes": the Global Ocean (GOOS) and Global Climate (GCOS) Observing Systems. The GTOS is the mandated organization to coordinate ECV observations in the terrestrial domain and the associated development of reporting guidelines and standards.

Global Observations of Forest Cover and Land Dynamics Panel of GTOS (GOFC-GOLD, www.fao.org/gtos/gofc-gold/) is a coordinated international effort working to provide ongoing space-based and *in situ* observations of forests and other vegetation cover, for the sustainable management of terrestrial resources and to obtain an accurate, reliable, quantitative understanding of the terrestrial carbon budget. GOFC-GOLD provides a forum for users of satellite data to discuss their needs and for producers to respond through improvements to their programmes; providing regional and global land datasets; promoting globally consistent data processing and interpretation methods; promoting international networks for data access, data sharing, and international collaboration, and stimulating the production of improved products (Townshend & Brady, 2006).

The Group on Earth Observation (GEO) resulted from three ministerial-level international earth observation summits. It aims to build and maintain a Global Earth Observation System of Systems (GEOSS). GEOSS will build on and add value to existing earth observation systems by coordinating their efforts, addressing critical gaps, supporting their interoperability, sharing information, reaching a common understanding of user requirements, and improving delivery of information to users (GEOSS, 2005). As high-level political process (74 member states and 51 participating organizations as of August 2008), GEO has defined nine areas where society directly benefits from earth observations Disasters, Energy, Health, Climate, Water, Weather, Agriculture, Ecosystems, and Biodiversity. According to the ten-year GEO implementation plan, land cover observations are important for all of these areas (GEOSS, 2005). Although being global in scope, GEO seeks to stimulate national and regional implementation activities. GEO's main strategy is improved international coordination and a number of relevant forest and land cover monitoring related tasks are carried out by existing agencies and networks (Herold *et al.*, 2008).

The Integrated Global Observation Strategy-Partnership (IGOS-P) is organized through a series of themes including Oceans, Carbon, Water Cycle, Coasts and Natural Hazards. In 2004 it was decided that IGOS-P should have an additional theme so that international agreement could be reached concerning all land requirements outside of those covered by other established themes. This new theme is known as Integrated Global Observations of the Land (IGOL). Following the requirements laid out by the GEO, IGOL defines detailed observations requirements for the land domain (Townshend *et al.*, 2008). At the present time while GEO is evolving, there is clearly considerable overlap between IGOS-P and GEOSS and many IGOS-P themes are in transition to GEO tasks and activities.

The Committee on Earth Observing Satellites (CEOS) was set up to coordinate global earth observing activities among the space agencies. CEOS implementation is organized in working groups. The Working Group on Calibration and Validation's Land

Product Validation sub-group (CEOS WGCV) is of particular importance for the land cover observation domain.

Within the UN system the Food and Agriculture Organization (FAO) and the United Nations Environment Programme (UNEP) are primarily involved in land cover observations. For example, FAO, at the request of its member countries, regularly monitors the world's forests and their management and uses through the Forest Resources Assessment Programme (FRA). Every 5 to 10 years since 1946, FAO has provided a periodic global picture on existing forests, derived trends and statistics. FRA 2005 is the most comprehensive assessment to date. Although FRA has been primarily using national statistics, the FRA 1990 and 2000 employed a combination of earth observation data and national data to estimate transitions between several woody biomass categories for Africa, Asia and Latin America. For FRA 2010 a comprehensive global remote sensing survey is intended (FAO, 2006).

The UN Global Land Cover Network (GLCN) has been driving the national implementation of the evolving land cover standards. GLCN developed from FAO's Africover and Asiacover initiatives. The approach is to bring all national land mapping entities together and develop strategies on how the standards can be implemented at a national level. As one of its main activities, the GLCN is leading the development and implementation of UN Land Cover Classification System.

Several space agencies are leading global efforts to land cover observations. Activities include US sponsored initiatives like NASA's land cover and land use change programme (http://lcluc.umd.edu/), the US Geological Survey (http://edc2.usgs.gov/glcc/), and Global Land Cover Facility based at the University of Maryland (glcf.umiacs.umd.edu). They develop and distribute satellite data and land cover information with a focus on determining the location, extent, and drivers of land cover changes around the world. The European Space Agency, and in particular its Data User Element (dup.esrin.esa.it) are providing continuous global land cover observations (e.g. through GlobCover that will start with data in 2002 and continue beyond 2009; Bicheron *et al.*, 2008, Defourny *et al.*, 2009). The EU-led initiative GMES (www.gmes.info/) is developing earth observation-based services for Europe and is evolving more engagement and support to the global land cover observation domain.

5. Available data

5.1 *In Situ*

An example in this category is LUCAS, the European Land Use/Cover Area Frame Statistical Survey (Eurostat, 2003). LUCAS is based on an area frame survey (sample of geo-referenced points examined *in situ* by surveyors) carried out in 2001, 2003, and 2006. Many countries (e.g. almost all European countries, Brazil, Canada, India, Russia, USA) already have or are planning to implement recurrent sample plot-based national forest inventories that might be used as *in situ* information in support of remote sensing approaches. Collaboration is increasing through the FAO efforts that provide support to developing countries, and through several harmonization programmes (driven e.g. by the European National Forest Inventory Network, ENFIN).

However, it is acknowledged that for many parts of the globe these types of data may not yet exist. Options for alternate acceptable or useful data sources will be developed, resulting in a prioritization of information to be used. When considered spatially, this prioritization will indicate locations/regions most in need of the collection of data to support land cover mapping. The temporal element of the

field observations must also be considered. Ideally continuous collection of field observations of some sort will occur from before mapping is initiated and continue through the mapping effort. This enables gathering of field observations for calibration of a given map product, but through the continued data collection also facilitates the validation of the outputs and for assessment of change products that may be developed.

The following are among the global and regional networks that collect *in situ* land cover data that might also be used for validation purposes:

- International Long Term Ecological Research Sites (ILTER) - 195 Terrestrial Sites;
- Terrestrial Ecosystem Monitoring Sites (TEMS) - 146 Terrestrial Sites;
- IGBP Land Cover Validation Confidence Sites - 413 Terrestrial Sites;
- EOS Land Validation Core Sites - 31 Terrestrial Sites;
- SAFARI 2000 Validation Sites - 20 Terrestrial Sites;
- FLUXNET Network - 266 Terrestrial Sites;
- BIGFOOT Network - 19 Terrestrial Sites;
- GLC 2000 land cover validation Sites – 1 253 Terrestrial Sites;
- GLOBCOVER land cover validation sites ~ 4 000 sites.

Although these networks provide some useful land cover information, they are insufficient to provide the minimum information for calibration and validation of global land cover products. Significant investments in global coordinated *in situ* data acquisitions (coordinated by CEOS WGCV and GOFC-GOLD) are required to provide sustained observation data for observing land cover as ECV.

5.2 Satellite

Appendix A provides an overview of available global land cover datasets. Different data sources and approaches have been used to map global land cover worldwide using 250 m-1 km satellite data. There are currently no global available land cover products on finer spatial scales.

Global, 1 km Annual Land Cover Type

Data requirements:
1. A repeatable classification algorithm that can be applied uniformly across all regions of the Earth.
2. Use of the highest spatial resolution achievable for global land cover maps.
3. Annually updated maps: since the classification error rate is higher than the annual rate of land cover change (and consequently changes observed are often due to algorithm errors or changes in training), a consistent and repeatable classification system is needed.
4. The highest classification accuracy possible. Accuracies associated with specific classes should not be less than 65 percent correctly classified, and classification accuracies should not vary widely due to geographic location.
5. A statistically rigorous validation strategy that assesses overall classification accuracy and accuracy within classes.

Technical approach:
- Input data algorithms must be processed to minimize variations among and within sensors.
- To support supervised classification algorithms, high-resolution training datasets are needed; creation of such datasets requires protocols for geographic and ecological sampling, minimum patch size, quality assessment, and procedures for detecting land cover change in any given patch.
- Use of a validation strategy that uses a probability-based sample design with adequate samples to estimate overall accuracy and class-specific

accuracy at continental and if feasible, regional scales.

Global, Decadal, mid-Decadal, 30 m Land Cover Type

Data requirements:

1. Based on a flexible land cover classification scheme with categories relevant for assessing a wide range of environmental applications. In particular, attention should be devoted to classes that are poorly represented in coarse-resolution output products, and those classes reflecting human land use (e.g. urban types, agricultural types, impervious surfaces).
2. A spatial resolution of 30 m with temporal updates every 3-5 years.
3. Overall and regional accuracies exceeding 90 percent at the highest level of aggregation.
4. Validation should be based on the use of a probability-based sampling strategy.

Technical approach:

■ The use of computer-assisted methods enables a cost-effective approach to creating accurate, high-resolution products.

■ Validation must be statistically rigorous. Finding suitable sources of validation can be problematic; high resolution satellite imagery and aerial photography may be costly but are useful.

Global Continuous Fields

Data requirements:

1. The use of explicit physiognomic-structural definitions that are easily incorporated into UN Land Cover Classification System and that enable the derivation of a mutually exclusive and exhaustive land cover classification.

2. (Modular) vegetation trait definitions that allow for their direct incorporation into global, continental and regional scale biogeochemical, hydrological and other natural resource and ecological modelling exercises.
3. An algorithm that yields the highest accuracy possible.
4. Annual or more frequent monitoring for those VCF layers suitable for change monitoring, and five-year intervals for layers not likely to exhibit change.
6. Spatial resolution of 500 m or higher to permit large area monitoring of key vegetation change dynamics (e.g. deforestation).
7. Quality assessment mechanisms for each observation or pixel.
8. Validation protocols for both VCF layers and derived change products.
9. The temporal frequency of the VCF layers and change products are envisioned as x and y, respectively.

Technological approach:

■ A supervised algorithm to ensure repeatability. Tree-based algorithms meet key criteria of repeatability, transparency, and a high level of accuracy.

■ Training data should be derived from high-resolution data sets (5-50 m) for calibrating the algorithm.

■ Vegetation life form definitions used should be compatible with the LCCS.

■ Probability-based sample design for assessing product accuracy should be based on the direct observation or measurement of the respective vegetation trait.

Inter-annual Land Cover Change and Disturbance

Data requirements:

1. Medium resolution data (pixel size less than ~50 m) are required to create accurate maps of land

cover conversion and many types of ecosystem disturbance, including anthropogenic changes.

2. Land cover change should be monitored at two separate temporal resolutions: updates on intervals of five years or less to assess long-term trends in land-cover change; and annual updates to detect major annual variations at the regional scale in terms of deforestation and regrowth (these changes strongly impact carbon sinks and sources).

3. Land cover change products for this purpose should collect information on three themes: (1) conversion of land cover from one type to another; (2) ecosystem disturbance events without change in land cover type, and (3) quantitative data on changes in vegetation cover due to land cover conversion, disturbance, recovery, or long-term ecological trends.

Technical approach:

▪ Algorithms should explicitly account for atmospheric and seasonal variability among images. Atmospheric correction to surface reflectance may reduce atmospheric variability, and provide a physical basis for further analyses.

▪ Several image interpretation approaches have proven to be effective for assessing changes in land cover, as long as sufficient training data exist. Mapping land cover conversion requires algorithms that use direct radiometric comparisons across time. Multi-date supervised classification has been effective for this purpose.

▪ Different algorithms for specific regions, processes, or parameters, rather than a single algorithm for all land cover change, should be considered.

6. Towards standardization of satellite derived products

To overcome the heterogeneity in the characteristics of global land cover datasets (Appendix A), the international community lead by GLCN, GTOS/ GOFC-GOLD and CEOS WGCV has been fostering harmonization and more standardized land cover monitoring (Strahler *et al.*, 2006). Product comparisons and initial comparative validation exercises have been performed (Herold *et al.*, 2008), providing better understanding and some of the technical foundations for more standardized satellite-based land cover monitoring in the future.

For observing land cover as an ECV, several areas require attention: coordinated observations, integrated and standardized mapping, and independent quality assessment. Any ECV monitoring efforts have to ensure saliency and legitimacy in addition to technical credibility. An international coordination mechanism among key actors worldwide (users, producers, science, regional/national experts) is essential to ensure that land cover products are accepted internationally and by the UNFCCC.

Coordinated observations

An operational global land cover monitoring integrates information from different observation scales, i.e. integrating coarse and fine scale satellite data and *in situ* data. ECV monitoring assumes the use of all useful data sources - from historical archives, present assets and future monitoring programmes in a seamless and consistent manner. Acquisitions and the derivation

of standard products should be coordinated among space agencies (e.g. with support of GEO, CEOS).

Integrated and standardized mapping and monitoring

There is need for both maps (static and updated) and dynamic monitoring products at different spatial and temporal scales (Table 2). These outputs require different sets of observations and monitoring approaches. The development and derivation of the mapping products need consistency in land cover characterization to be interoperable as part of an integrated global observing system. The broad areas and topics requiring international consensus are outlined in this document. There is also a need to ensure synergy with other ECV observation products (i.e. Fire, biophysical parameters, Snow Cover) that are directly related to land cover characteristics.

Independent quality assessment

There is need for an independent quality assessment to ensure that the required standards are met, and that uncertainties are quantified and reduced as far as practicable. Considering the suite of important land cover information (Table 2), there is expected to be a diversity of products contributing to ECV monitoring. While diversity and redundancy is useful for building a sustained global land cover monitoring system and to ensure flexibility in incorporating evolving technologies, there also needs to be an independent assessment mechanism led by the international community. This mechanism should provide a comparative assessment and validation of individual products and work towards synergy to ensure that a common framework is used for global assessments, and that the "best global estimates" are made available based on the current stage of

Name	Spatial resolution	Frequency of product update	Maturity
Mapping of land cover			
Land cover maps	250m - 1 km	annual	pre-operational
Fine-scale land cover and land use maps	10-30 m	3-5 years	pre-operational (for land cover)
Global land cover reference sample database	In-situ/1 m	1-5 years	pre-operational (CEOS, GOFC-GOLD)
Monitoring of dynamics and change			
Global land cover dynamics and disturbances	250m - 1 km	intra-annual/ long-time series	pre-operational (for several processes)
Fine-scale land cover and land use change	10-30 m	1-5 years	pre-operational (for land cover)
Monitoring areas of 'Rapid change'	1-30 m	1-2 years or less	pre-operational (for some change processes)

Table 2: Characteristics of land cover mapping and monitoring products useful for observing land cover as an ECV

knowledge, data and information. The basis for such efforts consists of sustained global network of calibration and validation sites, international agreement and standards and approaches for land cover characterization and validation, and an internal coordination mechanism, currently lead by GOFC-GOLD and the Land Validation sub-group of the CEOS WGCV.

7. Conclusions

The international community has been working towards harmonization and standardization of global land cover observations for more than a decade. The achievements, basic considerations and assumptions, available observations and datasets, and suggestions on how to observe land cover as ECV are summarized in this document. The framework and level of maturity for available observations and mapping standards is sufficient for a systematic implementation of a consistent and sustained global land cover observing system that, given the implementation of recommendations made in this document, could evolve to full operational mode in the near future.

8. Recommendations

8.1 Standards and methods

Further international development and adoption of land cover and land cover change mapping standards have been initiated and this process should be further encouraged to ensure that land cover measurements taken on all of these scales are comparable and compatible. A number of steps should be taken to ensure consistency for future mapping and monitoring efforts, including:

- Further international consensus discussions on the adoption of evolving land cover mapping standards (LCCS, LCML classifiers and generic classes);
- Existing legends should be revisited in the context of the evolving land cover standards;
- Land cover legends should be developed using the common set of classifiers. Based on these general descriptions, more thematic detail can be specified that meet the mapping requirements without losing compatibility on a broader level;
- There is a need to explore how a harmonized land cover product can link to, or benefit from existing mapping initiatives on both finer and coarser scales (e.g., *in situ* and global) and vice versa.

To foster this process, the international land observation community should intensify coordination and cooperation towards useful, flexible and validated global land cover information. Particular effort should be focused on the implementation of an operational global land cover validation system, and on specifications for a global high resolution land cover product and land change monitoring and associated accuracy assessments.

Based on international agreement, standardized and basic land cover information products and observations should be made available to all users, also allowing the definition of detailed thematic products and services that build upon publicly available datasets.

8.2 Other recommendations

- The interaction between the observation community and the political community needs to be established as a continuous process to ensure the achievement of the long-term observation goals and the further development of for saliency and legitimacy of ECV monitoring efforts. The

current priorities and prominent processes mainly focus on issues of forest observation. Future attention may be required for the observation of other domains, i.e. related to agriculture or urban areas.

- Continuity and availability of data is required at all observation scales. Current shortcomings include limited access to available data in existing archives, and the lack of coordinated global observations for both satellite and *in situ* data. National and international space agencies are urged to make long-term commitments to acquire and ensure availability of baseline datasets. Priority should be given to the development of a consistent, pre-processed, global, and free-of charge Landsat dataset for the year 2010 that extends the existing 1990, 2000 and 2005 datasets. In the future, better synergistic use of optical and active remote sensing (i.e., Radar and LiDAR) data sources will improve land cover characterization.

- Geographic and thematic gaps exist in the collection of *in situ* and reference data that are necessary for land cover/use surveys and for the calibration and validation of satellite data analysis; reduction of these gaps should be addressed in future efforts. Continuous monitoring of land cover conditions is recommended through periodic mapping cycles.

- Although some countries maintain operational, satellite-based land cover monitoring systems (i.e. India, Brazil, Australia, EU, US, Australia), the capacities in many countries to produce and use land cover datasets are limited. Significant efforts should aim to build and strengthen existing capacities, with an emphasis given to the stronger involvement of developing countries in the anticipated post- 2012 climate agreement. UNFCCC Member nations are encouraged to support the continuity of existing observing systems and to promote further evolution of monitoring capabilities, both satellite and *in situ*. This requires

communication and cooperation between nations to develop consistent and synoptic data sets are required to represent the global land cover as an Essential Climate Variable (ECV), this.

- While standard procedures exist for the monitoring of land cover and to some extent for land cover change, monitoring strategies and methods vary for observing land cover changes and land use. The technical community needs to provide a better description of satellite imagery characteristics, existing standard interpretation methodologies, and methods for integrating different data sources for such purposes.

- Further emphasis should be given to better coordination between the land observation and modeling communities, to better address land change issues inherent in the global carbon cycle, and for related impact and policy assessments. Among the requirements is the need for better conceptual and thematic treatment of land cover and land use, their heterogeneity, and uncertainty of land information in Earth system models. This focus will be facilitated by soon-to-be-available global land cover data that will provide higher spatial detail, and by the robust accuracy measures to be available for all new maps. This issue may require modeling of meteorological and land surface processes on different scales, and is of particular relevance for the incorporation of heterogeneous and spatially clustered land change processes.

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Appendix A: Overview of existing global land cover databases and approaches

Dataset	Objective	Data	Classification system	Interpretation/map production approach	Validation	Data release policy
IGBP DISCover (part of the Global Land Cover Characterization Programme (GLCC))	■ Goal was to provide a global status-quo land cover map to improve the reliability of global-scale environmental assessments ■ No land cover change mapping was intended	AVHRR (1992–93), 1 km	■ IGBP based land cover classification (17 classes) ■ Additional legends: ■ Global Ecosystems (96 classes) ■ USGS Land Use/ Land Cover (24 classes) ■ Simple Biosphere Model (20 classes) ■ Simple Biosphere Model 2 (11 classes) ■ Biosphere Atmosphere Transfer Scheme (20 classes) ■ Vegetation Lifeform (8 classes)	■ Global land cover database: developed on a continent-by-continent basis ■ Continental database: unique elements based on the specific geographic aspects of each continent, there are a common set of derived thematic maps produced through the aggregation of seasonal land cover regions. ■ Computer-assisted image processing interpretation, multitemporal unsupervised classification of NDVI data ■ Classification process is not automated but more similar a traditional manual image interpretation. Human interpreter make the final decisions regarding the relationship between spectral classes defined using unsupervised methods and landscape characteristics that are used to make land cover definitions.	Probability-based sampling with interpretation of Landsat TM or SPOT Application of two methods: ■ "Core sample" of single pixels at each site (random stratified sampling of 15 classes, with a target of 25 samples per class ■ "Confidence sample" consisting of an area of about 20 by 20 km, positioned with the core sample pixel at one corner, which was delineated into land cover polygons on the fine resolution imagery by a photointerpreter	Open access, data for free

Dataset	Objective	Data	Classification system	Interpretation/map production approach	Validation	Data release policy
Continuous Fields Tree Cover Project (AVHRR)	▪ To develop methodologies for global representation of vegetation characteristics and ▪ To produce continuous fields of vegetation characteristics at 1km which are accessible to the global change research community	AVHRR (1992–93), 1 km	▪ Proportional cover scale	▪ Automated classification procedure ▪ Using training data and phenological metrics with a regression tree to derive global percent cover ▪ Using Landsat MS images to train the linear mixture models for vegetation characteristics permitting estimation of endmember values ▪ The spectral response of the AVHRR data is then unmixed using the endmembers and estimates of leaf longevity, leaf type and percent tree cover are identified	▪ No information available	Open access, data for free
University of Maryland global Land Cover Product	▪ To develop methodologies for global land cover classifications that are objective, reproducible, and feasible to implement on data from additional years and ▪ To produce a global land cover classification at 1 km spatial resolution accessible to the global change research community	AVHRR (1992–93), 1 km, 8 km, 1 deg.	▪ eleven major land cover types based on interannual variations in NDVI ▪ These types were selected primarily to conform with the cover types required as input to climate models	▪ Developed on a continent-by-continent basis ▪ Automated unsupervised classification procedure ▪ Training data and phenological metrics that describe the temporal dynamics of vegetation over an annual cycle ▪ The metrics have the potential to be used as input variables to a global land cover classification	▪ The data set has not been systematically validated	Open access, data for free

Dataset	Objective	Data	Classification system	Interpretation/map production approach	Validation	Data release policy
MODIS Land Cover Products (MOD12)	■ To provide a suite of land cover types useful to global system science modellers by exploiting the spectral, temporal, spatial, and directional information content of MODIS data	MODIS/ Terra (since 2000), 1 km	■ Application of following classification schemes: ■ IGBP based land cover classification (17 classes) ■ UMD (14 classes) ■ LAI/FAPAR (9 classes) ■ PFT (12 classes)	■ Supervised classification approach using a decision tree classification algorithm in conjunction with boosting ■ Top-down approach: image classification for the whole globe ■ Using a global suite of training sites interpreted primarily from Landsat Thematic Mapper (TM) data	■ No probability-based sampling ■ Utilizing confusion matrixes based on cross-validation using unseen training sites ■ Using IGBP confidence sites	Open access, data for free
Continuous Fields Tree Cover Project MODIS	■ To support change detection studies at the global scale ■ To continue with and improve the continuous fields product series, formerly retrieved from AVHRR data now using more detailed spatial/spectral characteristics of the MODIS data	MODIS/ Terra, (2000-2005), 500 m	■ Proportional cover scale	■ Automated classification procedure using a regression tree algorithm ■ Using high-resolution imagery (Landsat ETM+, IKONOS) to derive global training data ■ Using training data as dependent variable, predicted by independent variables in form of annual MODIS metrics ■ Employing these training data and phenological metrics with a regression tree to derive global percent cover ■ Outputs from the regression tree are further modified by stepwise regression and bias adjustment	■ Initial validation efforts ■ Interpretation of field data along with IKONOS and Landsat ETM+ data ■ Establishment of test areas with size of an ETM+ image ■ Crown cover maps of IKONOS images are binned to ETM+ cells to map percentage crown cover for 30m pixel ■ The retrieved ETM+ crown cover map is averaged to a 500-m resolution to validate the MODIS map	Open access, data for free

Dataset	Objective	Data	Classification system	Interpretation/map production approach	Validation	Data release policy
Global Land Cover Map for the year 2000 (GLC 2000)	■ To provide harmonized regional and global land cover map database ■ Addresses the need for improved land cover information deriving from a number of initiatives, in particular the ecosystem-related international conventions (UNFCCC, UNCCD, and the Millennium Ecosystem Assessment)	SPOT Vegetation (2000), 1 km	■ 23 global classes based on LCCS, regional and global	■ 19 regional products produced by regional GLC2000 partners, with a regionally specific legend ■ GLC 2000 data interpreters designed individual classification procedures ■ Harmonisation and merging of regional products to one global product with generalized legend (bottom-up approach)	■ Probability-based sampling with interpretation of Landsat ■ Application of two methods: ■ Confidence-building method (quality control based on a comparison with ancillary data) and ■ Stratified random sampling for quantitative accuracy assessment using Landsat-based local land cover interpretations	Login/password required, data for free
GLOBCOVER	■ Building upon GLC2000 experience, develop a processing system to derive moderate-resolution consistent global land cover map for 2005-2006 ■ Set up an international partnership to produce and use such products in continuous manner for multiple global and regional applications	ENVISAT/MERIS (2005/6) 300 m	■ 22 global classes based on LCCS, regional and global	■ A priori stratification to split the world in 22 equal-reasoning regions ■ For each region, per-pixel classification algorithm to derive homogeneous land cover classes ■ Per-pixel temporal characterization through temporal metrics and classification ■ Labeling rule-based procedure using best available products and experience of an international experts network	■ Probability-based sampling with interpretation of Landsat ■ Data, Google Earth, and NDVI time series for more at more than 3000 sample locations worldwide. Full validation report available	Open access, data for free