THE MULTI-SENSOR LAND CLASSIFICATION SYSTEM LCS: AUTOMATIC MULTITEMPORAL LAND USE CLASSIFICATION SYSTEM FOR MULTI-RESOLUTION DATA

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ABSTRACT:

Providing land use/land cover change maps through the use of satellite imagery is very challenging and demanding in terms of human interaction, mainly because of limited process automation. One main cause is that most of land use/land cover change applications require multi-temporal acquisitions over the same area, that introduces the need for accurate pre-processing of the dataset, in both geo-referencing and radiometry. Moreover, single multi-spectral images can be hundred of megabytes in size and therefore image time series are even more difficult to be handled and processed in real time. The approach here proposed foresees the use of a robust land cover classification system named SOIL MAPPER® to reduce input data size by assigning a semantic meaning (in the land cover domain) to each pixel of a single image. Land cover transitions and land use maps can be expressed as evolutions of land cover classes (features) on temporal domain. This permits to define 'trajectories' in the features – time space, that define specific transition or periodic behaviour. The target system, named Land Classification System, provides fully automatic and real time land use/land cover change analysis and includes fundamental sub-systems for accurate radiometric calibration, accurate geo-referencing (with geolocation within the pixel size) and accurate remapping onto an Earth fixed grid. The characteristics of the selected pre-classification system and Earth fixed grid allow general application across different sensors. Land Classification System has been prototyped over 15 years of global (A)ATSR data and foresees integration of over 3 years of regional ALOS-AVNIR-2 data.

1. INTRODUCTION

Land use and land cover change (LULCC) topics are going to become more and more critical subjects for the impact they have on the global climate. They are in fact linked to climate and weather in complex ways and are fundamental inputs for modelling greenhouse gas emissions, carbon balance, natural ecosystems and human environment evolution. Both human activity and natural phenomena can affect many of these processes, that are strictly correlated, influence each other and have strong impact and consequences on environmental, social and economic aspects as well as on human health. Land cover refers to everything that covers the land surface, including vegetation, bare soil, buildings and infrastructure, inland bodies of water, and wetlands. Land use refers, instead, to societal arrangements and activities that affect land cover (Mahoney et al., 2003).

Local-to-global scale LULCC studies and application has got great benefits from the use of remotely-sensed data, mainly due to the preferred point of view of satellite platforms for the periodic monitoring of the territory. Besides existing long time series of satellite data archives, there is an ever increasing availability of satellite images with global coverage from different sources and at different resolutions. As a drawback, single multi-spectral image can be hundred of megabytes in size and the real time utilization of these datasets for online analysis is a technological challenge by itself; that, paired with the high amount of time required for semi-automated image analysis suggests that fully automated pre-processing systems shall be used to improve satellite data exploitation and reduce the data volume at the same time.

In order to improve multitemporal satellite data usability for time series analysis, accurate image pre-processing operations shall be performed to make time series datasets homogeneous: the most important pre-processing steps are accurate geolocation and accurate radiometric calibration; digital numbers to radiance or surface reflectance conversion must be performed for quantitative analyses of multi-temporal images (Lu et al., 2004). Precise geolocation and image registration are to be addressed on a per-sensor basis, since each one has its geometric properties and correction factors.

The proposed generalised approach, named Land Classification System (LCS), aims at exploiting advanced applications for single image feature extraction, providing easy-to-use tools for land use and land cover change detection analysis over time series of data; such approach, to be readily usable by the scientific community and also by end users of land cover and land use maps, is also aimed at providing a computer aided modelling and land cover evolution analysis tool for definition of evolution models by domain experts and an high degree of automation for evolution models application in an effort to ease and speed-up the analysis of land use and land cover change phenomena, possibly in conjunction with other tools to find correlations among different factors influencing life on Earth like global climate.

In the following sections the methodological generic approach implemented on LCS is described, with specific emphasis on the critical subsystems. Moreover, a prototype application of LCS being implemented in the framework of the European Space Agency (ESA) Support by Pre-classification to specific Applications (SPA) is described; finally the preliminary results obtained during the SPA Project are discussed, with the clear aim of demonstrating the validity of the approach.

1.1 Related work

Many approaches and methodologies exist for land cover change analysis: an extensive survey is provided in (Lu et al., 2004). Similar work for multi temporal analysis systems has been performed to provide targeted land cover change studies or develop databases of land cover (Homer et al., 2004). An interesting bi-temporal approach to land cover change analysis is provided by the Land and Ecosystem Accounting (LEAC) methodology whose main goal is to provide an easy and comprehensive access to land cover data, showing the 'stock' available for each land cover class in the different land cover data, and providing also the changes occurred in the periods between different land cover works, as land cover flows matrix (Haines-Young and Weber, 2006). The LCS approach however is not focused on a particular change pattern, land use typology or phenomena, it is instead proposed a generalized approach to land cover change analysis that, building on top of land cover maps stock, might serve as an interactive framework and tool for scientists to help quickly verify hypothesis and improve their research activities. Lastly, the system targets also decision makers to provide a practical surveying tool to systematically provide fast response in detection of features of interests.

2. METHODOLOGY

The LCS system is a generic tool for long-term time series of satellite data management for application in the LULCC field. The term "generic" refers to the wide applicability of the system to different type of satellite-borne sensor data, permitting also multi-sensor applications, and to different time frames; moreover it refers to its ability to fully exploit the multitemporal database for different LULCC phenomena analysis.

LCS creates time series of homogeneous satellite data making use of a robust land cover classification system named SOIL MAPPER®: this system process satellite data coming from different sensors in the same way, generating land cover classification maps with the same semantic meaning, thus permitting multi-temporal and multi-sensor applications.

The stock of classification maps, are then mapped on a common reference grid to allow worldwide pixel based multi temporal analysis of land cover to be performed in relatively small amounts of time since data compression, obtained through semantic feature extraction, delivers a map stock within 6 Terabytes, that is an amount of data readily manageable by modern computer systems.

The core change detection feature of LCS are the land cover evolution models and its model matching engine: in LCS, an evolution model is defined as a sequence of expected land cover classes along the temporal line; each land cover class – temporal reference pair constitutes an evolution model element. Land cover transitions can be represented by pairing elements which define expected land cover configuration in given points of the time line. A series of evolution model elements defines a land cover evolution pattern that can be matched with actual land cover time series data to determine if that data matches the modelled evolution pattern.

There is almost no automation in model definition and the model itself is designed to let the user precisely define each model element, also starting by a derived model from observer data, with tolerance margins in both feature and time domains. All the knowledge for multi temporal analysis is provided by domain experts in the form of evolution models.

The LCS methodology, explained hereafter in its critical subsystems, foresees three main elements that, chained together, aim at providing a consistent system for multi-temporal land cover data analysis: original data classification, Earth fixed reference system and land cover evolution modelling and matching. Moreover the layout of user interfaces suitable to ease analysis, define evolution models and perform automated model matching are described. Following subsections detail each main aspect of this methodology.

2.1 Common land cover classification system

SOIL MAPPER® is a fully automatic software that permits to generate land cover classification maps through the analysis of multispectral satellite data in the optical domain.
As input it requires multispectral remotely sensed (RS) images calibrated on Top of Atmosphere (TOA) physical values: TOA Reflectance values for Visible (VIS), Near Infrared (NIR), Short Wave Infrared (SWIR), Mid-Wave Infrared (MIR) bands and brightness temperature (BT) for Thermal Infrared (TIR) bands (Mantovani et al. 2009).

As output, it generates a preliminary classification map where each pixel is associated with one label belonging to a discrete set of spectral categories. Spectral classes detected by SOIL MAPPER® have a semantic meaning belonging to the following main categories: Vegetation, Bare soil / Built-up, Snow / Ice, Clouds / Smoke plumes, Water / Shadows, Outliers.

SOIL MAPPER® actually supports most common satellite optical sensors (from medium to very high resolution), like: MODIS, AVHRR, AATSR, MERIS, Landsat 5 TM/7 ETM+, ASTER, SPOT-4 HRVIR, SPOT-5 HRG, IRS 1-C/-D, IRS-P6, IKONOS, ALOS/AVNIR-2, QuickBird.

Recent developments to the system (MEEO, 2010) introduced an uniform classification output with similar number of semantic classes across sensors and standardised classification output that makes is suitable for LCS.

2.2 Earth Fixed Grid reference

LCS defines a multi level global Earth fixed reference on which all satellite data has to be remapped to perform multi-temporal sample-by-sample analysis. The multi-level mesh-grid has been set with a variable uniform angle sampling rate over the geographic coordinates system (Lat. Lon.) with level 0 set at 1/256th degree. Samples (grid elements) are grouped together in fixed size tiles of 64 by 64 samples called Tiles. At level 0 each Tile covers ¼ of degree in both Latitude and Longitude; each further level doubles the sampling rate in both dimensions (i.e. 1/512th degree at level 1 and so on). According to (Sahr et al., 2003), the LCS grid system is a congruent, unaligned discrete global grid system; cell data is provided by remapping of pre-classified images, that are then stored as raster format in the Tiles archive; the target grid level for each sensor depends on the Ground Sampling Distance (GSD) of the bands used for its classification.

Since each Tile contains the same amount of pixels, the surface covered by the Tile varies with the sampling rate; depending on the sensor, precisely on its spatial resolution, that pixel size shall be under a threshold value, smaller than half of the original image pixel size in order to allow the pixel-based analysis and mitigate the displacement among the overlaid images due to systematic error into the original geo-referencing, hence defining the best fit level for that sensor. Reference grid resolution (Tile pixel resolution), across longitude, is computed at equator, taking into account that, for computational and archiving optimization reasons, the sampling rate is kept at a power of 2.

Grid Level	Ref. GSD	Pixel res.	Samples per deg.	Supported sensors
	m	m	#	
0	1000	434,84	256	(A)ATSR, MODIS
1	500	217,42	512	MODIS HKM
2	250	108,71	1024	MODIS QKM, MERIS
3	125	54,36	2048	LANDSAT TM TIR
4	60	27.18	4096	LANDSAT ETM+ TIR
5	30	13,59	8192	LANDSAT TM/ETM+ MS
6	15	6,79	16384	LANDSAT ETM+ PAN SPOT5, AVNIR-2
7	7	3,40	32768	-
8	3,5	1,70	65536	VHR MS
9	1,75	0,84	131072	VHR MS
10	0,8	0,42	262144	VHR PAN

Table 1. Grid parameters and supported sensor for levels 0-10

Table 1 lists grid parameters for levels zero to ten with reference GSD and name for a selected series of sensors. To avoid data loss during sampling, pixel threshold has been set at about half the original pixel size for medium resolution sensors at level zero, while for higher resolution the most suitable grid level is selected considering the power of 2, nearest to half of the original image resolution.

Tile mapping is the process dedicated to ingest the pre-classified scenes and remap them onto Earth Fixed Grid Tiles. The ingested scene has its original geo-reference system, thus, before applying any remapping process, a geo-referencing pre-process is required in order to avoid co-registration problems among images. It is then assumed that each input image to the ALCS system is accurately geo-referenced with accuracy below half of pixel size.

In the Tile mapping process, the original data is filtered taking into account the scope of LCS: tiles over sea are filtered out on the basis of a 4 valid pixels threshold (minimum amount of pixels detectable at supported sensor resolution) using the U. S. Geological Survey 1Km Land Sea Mask dataset (Eidenshink et al., 1994) for a per pixel coordinates test to assign each tile pixel to either the land or sea classes. Moreover all cloud and outlier pixels classes are also removed. Tile mapping is performed using the Nearest Neighbour remapping methodology.

2.3 Land Cover Evolution Models

LCS evolution model matching is a form of change analysis that, according to (Lu et al., 2004), falls in the “classification” category and especially it is a form, or extension, of the commonly used Post-Classification Comparison. The system lays on the basis that the evolution of land cover classification over time can lead to identification of land use typologies, and also effective identification of areas of rapid land-use and land-cover variation may allow contextual detection of major disturbances such as fires, insects and flooding. The key to the identification of relevant evolution patterns is the definition of a corresponding evolution model that can be systematically used to determine if an observed data series conforms to the model pattern.

2.3.1 LCS evolution model: is defined as a sequence of expected sets of land cover classes along the temporal line, each land cover set – temporal reference pair constitutes an evolution model element (see Figure 1 for a schematic representation). Transitions can be represented by pairing elements which define expected land cover configuration in given points of the time line comprising the transition. A series of evolution model elements defines a land cover evolution pattern that, stored in computer readable form, can be automatically matched with actual land cover time series to search for the modelled feature evolution pattern (evolution model matching). Relevant metadata associated to evolution models is: model name, model type (feature category), area of applicability, applicability to grid levels (accounts for typical size / resolution requirements of the modelled feature).

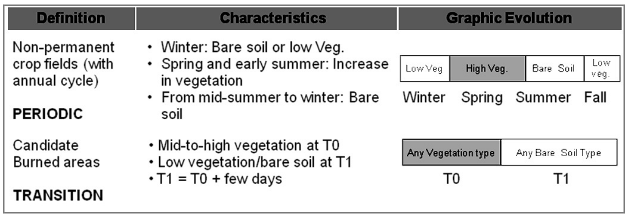

Figure 1 - Description of evolution models in the land clover / time domain for a periodic phenomenon and for a transition (non-periodic) phenomenon

The land cover class value defines the expected land cover type in a given model element. Multiple land cover class values can be defined, this is obtained by setting the class tolerance parameter in an evolution model element. An element can also have the “Not” flag enabled to invert the expected land cover class values.

Each element has a temporal reference that defines a point along the timeline, either fixed or related to the previous element, where its land cover class is expected (the data sampling point of the model matching); in particular, three temporal parameters are provided: Date, Time Since Previous element (TSP) and time tolerance. All parameters are specified in unit of days, and thus the entire system is designed to work at day resolution.

The Date parameter references a date in the timeline where the element lies; this parameter can be set only on the first element of an evolution model, thus indicating the starting point of the model. Different specification for the first element Date defines different kinds of models as follows: a blank Date (no date specified) defines a non periodic model, that can be matched at any point along the timeline as a sliding temporal window; a complete date specification defines a fixed model that can be matched only at its fixed temporal reference; a partial date (i.e. without the year) defines a seasonal model that can be matched at any subset of points in the temporal line identifiable by setting the unspecified parts of the date as matching input.

TSP defines the sampling point of an element as the number of days after the previous element along the evolution model sequence, hence it is not applicable to the first element for which it is fixed to zero; Using TSP to locate elements along the timeline lets the user easily define non periodic models and apply them at any point in the timeline.

Time Tolerance (TT): defines the radius in days of a temporal interval, centred on the element's sampling point along the timeline in which the actual data can be validly sampled. That allows coping with the possibility of missing data at the element's sampling point, such as cloudy acquisitions or data gaps due to satellite revisit time. Moreover, any element of the evolution model can be set to be "Persistent", that means the expected land cover type must persist in actual data for the entire Time Tolerance of the element.

2.3.2 Model matching algorithm: key feature of LCS is automated model matching that takes as its input a single area of interest and a variable amount of details, depending on the Date specification of the actual model, for one or more time periods over which matching is to be preformed. For this description we assume a single time period, in case of multiple periods, the process herein described is simply iterated over each one to deliver one result set for each period.

Taking into account the definition of an evolution model and the various options for its parameters, the simplest form of model matching is the match of a fixed model, that is tested only at a fixed point along the temporal line. This matching is performed by testing, over each grid element (here called also simply pixel) covering the area of interest, the value of relevant pixels in the stock maps archive, according to every element that composes the evolution model, verifying each pixel with the expected value in the model.

In particular, for each element, pixel data is first searched at the exact day of sampling specified by the element and, in case that data is missing the search interval is recursively extended one day in both directions to search for data within the TT. This search interval does not influence the marching outcome, unless the element is defined as persistent, that is any available data closest to the sampling point, within the TT, is used for matching with the expected set of classes for the element.

Model matching can bring four different results for each pixel, mapped on a result map with different colors for immediate visual analysis, as follows:

- No data (Black): for any element there is no data available within the classified tiles stock.
- Match (Green): for all model elements data is available and, actual pixel value fits with the main land cover class expected value of the model.
- Match within Tolerance (Yellow): for all model elements data is available and, for all observations not providing a Match result, the observed class is among the set of classes listed in the class tolerance set.
- Not match (Red): for all model elements data is available and, for at least one element, actual data does not match neither the main class, nor any of the classes in the tolerance set.

Seasonal models are matched in the same way as fixed models but any time range input detail for the model starting date can be freely specified to a full date, hence fixing the model. Each set of different values of the details specifying a full date (multi period matching), delivers its related result map.

The most general form of evolution model matching, called Non Periodic Model Matching, is designed for automated detection of the broadest evolution patterns typologies, including unpredicted events like sudden deforestation / fires, flooding and other single or multi transition phenomena whose position in the temporal line cannot be pre determined by nature. These models are characterised by an empty Date specification on their fist element, hence matching these models require as input the full specification of star and end dates of each temporal range. The non periodic matching is then performed as a repetition of the fixed model matching above for each day in the time period, the model can thus be seen as sliding along the temporal line. The date of application (start of the sliding window) slides from the time period start date, to its end date minus the model duration.

The match is tested for any day in the temporal range until a match is found; when a match is found, to avoid duplication of the same match that will be reported multiple, the next test is moved forward of an entire sliding window This non periodic matching can detect more than one match occurrence of the model in the given period if it reoccurs; to provide an immediate visual feedback over this reoccurrence, the first three occurrences of Match are marked with different tones of the result colour. Match result options have the same labels as the fixed matching but slightly different meaning as follows:

- Match: is reported when at least one matching test returns a Match at any given date within the temporal period. Depending on the number of occurrences, this is marked with different tones of green.
- Match within tolerance (Yellow): is reported when no Match is returned and at least one fixed match produces a Match with tolerance.
- Not Match (Red): is reported when no matching produced a Match or a Match with Tolerance and at least one test produced a Not Match.
- No Data (Black): is reported when all tests along the temporal interval return No Data.

Coloured result maps are displayed by the system over a dynamic reference map for immediate visual analysis of the results but also a GeoTIFF version of the map is produced and a comma separated values file format has been designed for further results analysis with other software tools.

2.4 User Interface

The LCS methodology defines key concepts of a framework for land cover change analysis and, to be effectively useable by end users, requires also a graphic user interface (GUI) to provide online analysis of its data archive, aid in definition of Evolution Models and ease of access to its automated matching engine. These functionalities are achieved through the use of Rich Web Technologies, that make the GUI a dynamic data manipulation tool to interactively access and analyse the multitemporal data. LCS foresees three different web-based interfaces, each one dedicated to serve a different typology of users: Administrators, Domain Experts and Standard users.

Domain Expert is the role of users that have the ability to perform land cover change analysis and to derive land cover evolution models from observed data; to these users LCS provides the Expert user Visual Analysis Tool (EVAT) interface including graphical tools for visual analysis of time series data (Figure 2) and graphical design evolution models (Figure 3).

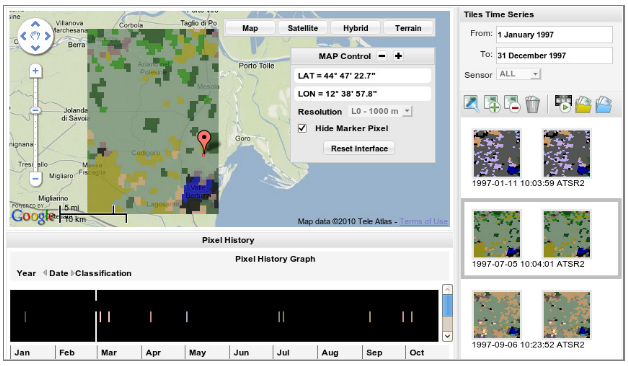

Figure 2 – Time series analysis tools (EVAT)

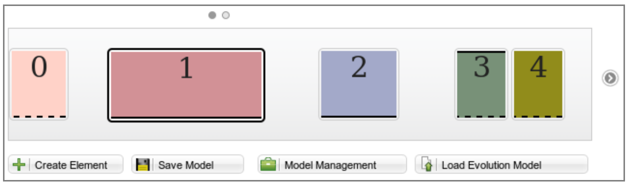

Figure 3 – Evolution Model editing tool (EVAT)

Standard user role is assigned to all users that are not interested in the evolution model edit or stock classification map analysis, hence the Visual Analysis Client (VAC) interface for these users provides ready access to LCS model matching engine by allowing selection of matching inputs: evolution model, area of interest and temporal intervals. It allows immediate visual analysis of the results map, overlaid on a scalable geographic map and also exporting these results for offline analysis or integration with other analysis tools.

Finally, administrators are a fundamental typology of users for any software system that includes access control features, different user roles and system control features like LCS data ingestion processing. The Operator Panel Interface (OPI) is the web interface for that user category and provides control over several system aspects like: user management, system status and data ingestion policies. Data ingestion in LCS is managed on a per sensor basis and the minimum control unit is one month. Overall ingestion status and input control is thus provided in tabular form with one cell per month.

3. RESULTS

For the entire ATSR-2 and AATSR data archive a prototype of LCS (named ALCS) has been implemented and a preliminary validation performed on bi temporal models over a study area with well documented large scale flooding phenomena and consequent influence on vegetation.

3.1 LCS Application to ATSR2-AATSR data: ALCS

An LCS application prototype over fifteen years (A)ATSR data (June 1995 - June 2010 an continuously updated from ESA rolling archive) has recently been implemented including all parts of the described methodology, data from the (A)ATSR Multimission Archive at NERC Earth Observation Data Centre (NEODC) at Rutherford Appleton Laboratory have been mapped, at grid level 0, into Tiles stored in the system that are accessible through the Web-based LCS interfaces.

The ALCS Prototype has been designed as a modular system that has been deployed on a computer system of five machines for computation and a storage array for hosting the Tiles. The system provides 38 cores dedicated to model matching that deliver a fast response for regional area analysis. Like its web interfaces, ALCS distributes computation leveraging the Apache web server that is installed on each of the four processing servers to receive HTTP requests from the core model matching system.

3.2 ALCS Application Case Study

The case study selected as first complete test from the end user point of view has been the flooding phenomenon occurred on the Iraq Marshlands (Lolli, 2010). This area has seen important changes during the period from 2000 to 2009. The reasons for this choice are mainly based on having an available area whose history shows in the last ten years significant changes in several environmental restoration areas. These marked changes are visible on a large scale and well monitored continuously by satellite. Furthermore, given the limited accessibility and vastness of the Iraqi marshlands, satellite data has proven to be a key source of valuable information on prevailing environmental conditions in the region.

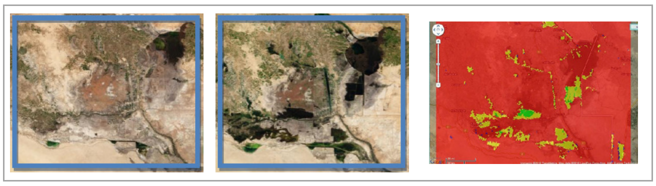
Figure 4 – True color MODIS images of study area in 2003 (left), 2004 (center) and the resulting not-water to water map for the 2003-2004 period.

Among the models created and tested for this study, the models not-to-vegetation and not-to-water, representing the bi-temporal change from not vegetation land cover classes to vegetation and from not water land cover classes to water (see Figure 4) have demonstrated their capability to identify both qualitatively and quantitatively the dimension of the flooding phenomenon over yearly periods. The confirmation about that this change has been well detected comes from the comparison between the results of this case study and the results carried out by the United Nation Environment Programme on the same area (Patrow et al. 2006).

4. CONCLUSIONS AND FUTURE WORK

The here proposed methodology, represents a step forward with respect to current approaches to LULCC analysis that are generally focused on bi-temporal analyses, with a strong limitation in the capability of extracting information and forecasting trends. The possibility to perform a real multi or hyper-temporal study of a phenomenon, with obvious consequences on its understanding, is still not exploited at all. The classification process for many of the current approaches is very labor intensive, frequently being a supervised or semi-automated classification requiring visual interpretation. This implies that most LULCC data products are released several years after the satellite images were taken, and thus, out of date to a certain extent when they are released. Nonetheless, LULCC provides a very valuable method for determining the extents of various land uses and cover types, such as urban, forested, shrubland and agriculture.

LCS is designed to perform a real multi or hyper-temporal study of a phenomenon, with obvious consequences on its understanding and to solve several limitations of similar bi/multi temporal analysis methods like:

- temporal limitations, most of applications are bi - temporal or restricted to few temporal frames while LCS efficiently provides online analysis of the entire 15 years (A)ATSR time series;
- spatial limitations: LCS is worldwide applicable;
- rapid updating limitations, many applications release their products with significant delays with respect to the date of data acquisition and/or elaboration while LCS can deliver very fast results over targeted areas of regional extent.

Moreover, since the proposed system avoids direct use of multispectral images, being based on the application of land cover evolution models directly to its stock of classified maps, there is no need for huge data transfers or processing on demand since LCS leverages the high data compression ratio delivered with association of a discrete valued semantic meaning in place of the original multi spectral data. LCS allows end users to easily apply evolution models to any area of interest over multiple periods and also provides computer aided evolution modeling with interactive series analysis tools to assist in detecting relevant patterns of land cover change to identify related phenomena.

4.1 Future work

The ALCS prototype implementation shows the potential of this methodology application to long time series that can be extended to many different sensors at different resolutions: the next data source foreseen for integration in the prototype systems is a selection AVNIR-2 datasets hosted by the European Space Agency to fully discover the potential of the LCS multi resolution grid system

Future activities foresee the involvement of selected users from several institutions with interest in LULCC to test the effectiveness of the system and its user interfaces in a short term validation campaign.

During the ALCS prototype implementation, several subjects of further study have been identified, such as: the possibility to use area of applicability information and an evolution model ranking system to automatically chose and apply the best version of semantically equivalent (same feature label extracted) models; even for data with image geo-location and registration issues, LCS could still detects the core of a modelled feature, provided it is large enough and not completely dispatched (no overlapping region) at the analyzed resolution.

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