CONCEPTS AND PROCESSING TECHNIQUES FOR A GLOBAL SENTINEL 1-3 LAND COVER DYNAMICS AND CHANGE (LCDC) PRODUCT

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ABSTRACT

The present study proposes a concept and a joint processing chain for integrating the ESA's upcoming Sentinel 1-3 satellites to address the needs from a series of users. The framework considers the advantages of the single Sentinel systems in terms of the spatial, temporal and thematic detail for the generation of a global land cover dynamics and change (LCDC) product. In addition, a calibration and validation plan is discussed and open science issues to fully implement the product have been identified. In order to (i) address key user requirements and (ii) develop concepts and processing techniques for a global LCDC product that go beyond the current state-of-the-art, user requirements and available global state-of-the-art land cover efforts and retrieval approaches of similar nature and their shortcomings were considered.

1. INTRODUCTION

Land cover is one of the most important properties for observing, describing and studying the environment. Reliable land cover and land cover change observations are of crucial importance to: (1) understanding and mitigating climate change and its impacts; (2) sustainable development; (3) natural resource management; (4) conserving biodiversity; and (5) understanding of ecosystems and biogeochemical cycling. Although numerous satellites acquire data suitable for land cover monitoring, large-scale regional and global mapping and monitoring programs have not reached operational status for delivering internationally accepted land cover and, in particular, land cover change data to serve the many uses and applications [1].

Due to the availability of continuous global remote sensing datasets global land cover mapping has been evolving throughout the last 15 years. Large volumes of high-quality global near-daily multispectral imaging of the Earth's land surface at resolutions ranging from 250 to 1000 m has been provided by such as NOAA-AVHRR, MERIS, MODIS and SPOT-VGT. Derived global land cover products are commonly based on the multispectral signal and the change in those multispectral signals through an annual cycle. Three main recent global land cover products exist: MODIS land cover product [2, 3], Global Land Cover 2000 (GLC2000) project [4] and ESA-GobCover initiative [5, 6, 7]. Further global or large area land cover efforts are i.e. the ATSR World Fire Atlas (WFA) product [8] and the novel BIOMASAR growing stock volume product that is based on dense SAR intensity time-series [9]. The review of these available global land cover efforts reveals the several shortcomings. All global land cover products are single-year products that are based on single instruments. While the ESA-GlobCover project clearly demonstrates the operational capabilities to regularly deliver global land cover maps, the consistency of these still has to be assessed. In order to realize the full discrimination potential of current and future EO systems, a multi-sensor approach needs to be developed and tested. The main challenge is to ensure great spatial and temporal consistency over one complete year in order to be capable of delivering in the future a consistent long term land cover data set that is independent to the EO instrument lifetime.

To realize the full potential of the global Earth Observation (EO) archives and the upcoming Sentinel 1-3 that ESA together with its Member states have established over the last decades, the present study proposes a concept and a joint processing chain for integrating the ESA's upcoming Sentinel 1-3 satellites to address the needs from a series of users.

Therefore, chapter 2 provides an overview of the specific user requirements before the concepts and a joint Sentinel 1-3 processing chain for a global LCDC product is proposed in chapter 3. A calibration and validation plan for the LCDC product is discussed in chapter 4. The main open science issues for future scientific work that have been identified in order to implement the full concept are outlined in chapter 5. A conclusion is given in chapter 6.

2. SPECIFIC USER REQUIREMENTS

Specific user requirements have been widely assessed in the context of GMES land monitoring core service with the majority of the focus on Europe (Geoland 2, 2010). However, there are a series of mainly global user requirements that have not been fully considered. For example the climate science user community has requested land cover information consistent and comparable with other climate variables and in higher detail and accuracy than before [10].

The user survey of the recent assessment of the ESA land cover climate change imitative project [11] revealed some key needs that can be summarized. First there is a need for consistent time-series for monitoring land cover, land use and change with increasing emphasis on finer scales and focus on tracking human activities in and for forest, agriculture, urban areas. Efforts should be global and provide coordinated, consistent and validated information of regional and local relevance. Many users have need for "one" product based on "best" available information targeted at specific (science) user requirements. This implies a proper and comparative validation and accuracy reporting, the need to take advantage of all useful observation data sources, and that derived products provide flexibility and are developed with international collaboration and harmonization. Climate users in particular emphasize the consistency of land cover and other (i.e. biophysical variables).

When it comes to the use Sentinel data there are three main priorities areas:

- Large area time-series processing with focus on a synergy of different Sentinel data streams: This requires methods for the operational processing of satellite (and in-situ) observations allowing for global coverage and continuous time-series data to address land dynamics and change. In parallel, historical satellite data archives need to be explored for large area monitoring over long time spans. Processing and cross-calibration should increase the synergy use among Sentinel 1-3 (all important for land) and Sentinel 2 and Landsat Data Continuity Mission (LDCM) to increase in terms of spatial, temporal and thematic detail.

- Deriving global fine-scale land change product that is also tracking anthropogenic land cover changes for forests, urban and agricultural areas. The evolution of such higher level thematic products should also take into account time-series analysis approaches to derive land dynamics and changes in a consistent and integrative way among land cover and biophysical variables, i.e. following the model of the MODIS product suite.

- Calibration and validation needs to be considered from the beginning since the current lack of suitable (in-situ) Cal/Val data are among the key gaps preventing serious observation progress it particular when processing and thematic products become more detailed and accurate. Both the processing scheme and the thematic product generation need to be underpinned by a suitable validation framework and reference network for Cal/Val sites. Thus, there is need to expand upon European and global networks with emphasis on Reference data for changes, dynamics and processes and to increase thematic quality by employing novel approaches (i.e. airborne, terrestrial LIDAR, sensor networks, citizen science).

3. NEW CONCEPTS AND PROCESSING TECHNIQUES

The development of new concepts and processing techniques that effectively integrate the advantages of the Sentinel 1-3 systems for the generations of a land cover dynamics and change (LCDC) product, requires an evaluation of the capabilities and limitations of the single Sentinel systems. Table 1 provides an overview of the Sentinel 1-3 system characteristics (including the Landsat Data Continuity Mission (LDCM)), which highlights main capabilities and limitations of the single systems (Tab. 1).

Table 1: Technical characteristics of Sentinel 1-3 and Landsat Data Continuity Mission (LDCM). Boxes marked in green highlight an advantage, the ones in red a disadvantage when comparing among the Sentinel satellites for global land change monitoring.

	Sentinel 1	**Sentinel 2 (+ *LDCM)***	**Sentinel 3**
Spatial detail	**Fine – Medium**	**Fine – Medium**	**Coarse**
Temporal detail	**Fine – Medium** 6 days repeat cycle 3 days rapid mapping	**Medium – Low** Sentinel 2: 5 days repeat cycle (depending on region/cloud coverage) LDCM: 16 days (depending on region/cloud cov.)	**Fine – medium** Near-daily acquisitions (depending on region/cloud coverage)
Thematic detail	Additional information for specific categories and dynamics (i.e. wetlands/water bodies, urban areas, agriculture, forest types/biomass) Serves as key data source in very cloudy tropical/coastal regions	Main data source for monitoring many land changes and dynamics	Additional information on vegetation dynamics (i.e. phenology, fires, snow cover etc.) not available from Sentinel 2

A joint Sentinel 1-3 LCDC product that satisfies the specific user requirements (see chapter 2) can benefit by combining the advantages in terms of the spatial, temporal and thematic detail of the single Sentinels 1-3 sensors (Tab. 1). This, however, requires full compatibility between the Sentinel 1-3 systems (incl. LDCM). Thus, coordinated procedures throughout the entire processing chain, including data acquisition and access, pre-processing and intercalibration, thematic product generation and Cal/Val procedures are fundamental.

The successful implementation of these coordinated procedures (in order to reach the desired compatibility between the Sentinels and dedicated missions, such as the use of a common DEM for geocoding/geometric calibration) in turn demands major research and development (R&D) activities for the entire processing chain that have not been done yet or are under development (see Chapter 5).

Since the idea of Sentinel synergy has not been explored substantially and is something that will go grow over time, a stepwise implementation concept consisting of three synergistic levels and corresponding actions is being proposed. It goes beyond the current state-of-the art of global land cover product generation chains and GMES initial operations (Level 0) and that leads to a fully integrated observations system satisfying all user requirements (Level 3) is proposed. The three synergistic level (Level 1, Level 2 and Level 3) and respective actions to for data acquisition and access, pre-processing and intercalibration, thematic product generation and Cal/Val procedures that go beyond Level 0 are proposed (see Tab. 2 for details):

- <u>Level 0 – Current state of the art</u>
- <u>Level 1 – Synergy product opportunities:</u> addressing few key user needs and opportunities with focus on integrating different satellite derived information on the product level
- <u>Level 2 – Interoperable time-series processing:</u> provide processing level 2 and 3 large area Sentinel 1-3 (and LDCM) time-series that can feed into analysis for the LCDC product
- <u>Level 3 – Integrated observing system:</u> operation of coordinated acquisitions, interoperable processing, integrated thematic product generation and operational Cal/Val for land dynamics and change worldwide with local relevance

The realisation of Level 1 and Level 2 rely on a joint Sentinel 1-3 processing chain that is automated from level 1b imagery time-series until the final LCDC product. Based on the requirements and actions described for synergistic Level 1 and Level 2 a processing chain is proposed (Fig. 1). Synergy Level 3 suggests focused action related to interoperability, product generation and improvements of operational Cal/Val. It consists of all image processing steps (incl. optional Sentinel 1 InSAR module) and opportunities that are required to satisfy synergy Level 1 demands (Fig. 1, blue) starting from level 1b time-series imagery, pre-processing to generate level-2 time-series, feature extraction (level 3) until the final LCDC product. In addition the proposed chain features processing steps/opportunities that are required for synergy Level 2 (Fig. 2, orange).
Advantages, recent scientific activities and identified research gaps related to the proposed processing opportunities required for synergy Level 2 are further discussed in the subsequent.

- Multi-sensor fusion of Sentinel 2 and Sentinel 3 time-series will enable to overcome infrequent high spatial Sentinel 2 observations (e.g. due to cloud cover, data gaps), while more frequent coarse resolution Sentinel 3 time-series are available. The aim is to generate Sentinel 2 time-series featuring the temporal resolution of the available Sentinel 3 time-series. Several fusion methods that use data blending techniques for the production of synthetic Landsat time-series on the basis of infrequent Landsat images and dense MODIS time-series provided reliable results. The results are synthetic Landsat time-series with both, high spatial and temporal resolution [12]. These data blending techniques could be applied to Sentinel 2 and Sentinel 3 to produce Sentinel 2 time-series with the temporal resolution of the available Sentinel 3 time-series. A semi-physical fusion approach that can be applied to predict Sentinel 2 reflectance by utilizing Sentinel 3 BRDF and Albedo land surface characteristics has been developed and successfully applied by [13], using Landsat ETM+ and MODIS data in cloudy areas and to fill the ETM+ SLC-off data gaps. Both fusion techniques, however, require a radiometric inter-calibration of the Sentinel 2 and Sentinel 3 time-series.
- Multi-sensor time-series feature extraction: Available techniques and approaches for multi-sensor time-series feature extraction of Sentinel 1 and Sentinel 2 like time-series as well as of Sentinel 2 and Sentinel 3 like time-series are rather limited. This clearly identifies a research gap and the need for R&D (see Chapter 6). However, the results of several studies show the high potential for the integration of Sentinel 1 and 2 time-series for monitoring diverse

cropping management systems in tropical [14] and temperate environment [15]. [14] for example, integrated multi-temporal Envisat ASAR and dual-temporal Landsat ETM+ imagery for monitoring small scaled landscape patterns in tropical regions and showed that to be capable of detecting intensively managed perennial and intra-annual rice and cocoa cropping systems with a reasonable accuracy. The land cover assessment results proved that a SAR-optical multi-temporal data approach is being preferred over single-temporal or single-sensor techniques. In addition, studies showed methods are available to be applied for Sentinel 1 and 2 multi-sensor feature extraction, such as the Support Vector Machine (SVM) based multi-sensor (SAR: Envisat ASAR, ERS; optical: Landsat TM) based land cover change detection [16]. One of the few available methods that can be applied to Sentinel 2 and 3 for multi-sensor feature extraction consists of an advanced decision tree approach for monitoring forest cover loss by combining Landsat and MOIDS like time-series information [17].

Table 2: Proposed concept for different synergy levels for the joint operation of Sentinel data for global land change monitoring. Boxes marked in light green represent joint operations/actions that demand minor R&D activities, while dark green ones represent joint operations/actions that demand major R&D activities for a successful implementation of the respective synergistic level.

	Data acquisition and access	**Pre-processing and inter-calibration**	**Thematic product generation**	**Cal/Val procedures and networks**
Level 0: Business as planned by GMES IO				
Level 1: Synergy product opportunities: addressing few key user needs and opportunities with focus on integrating different satellite derived information on the product level	Use available data acquisition and access schemes	Use available pre-processing schemes and add where needed so data products derived can be compared and integrated: • Comparable geolocation among Sentinel 1-3, and Sentinel 2 and LDCM • Radiometric intercalibration as much as already available/ongoing	Apply joint data analysis algorithms to address key opportunities in specific regions: • Tropical forests: using Sentinel 1 as temporal gap filling for Sentinel 2 data gaps (cloud cover) for monitoring tropical forest changes (REDD) • Wetlands: Using Sentinel 1 and 2 data in conjunction for assessing flooding and water body dynamics in wetlands • Agriculture: Synergy of Sentinel 1-3 for tracking agricultural dynamics • Urban areas: Address the need for multiple data sources to identify and monitor urban areas worldwide • Phenology and fire: Integration of Sentinel 2 and 3 time-series data to monitor vegetation seasonal dynamics and active fires/burned areas	Use and expand exiting Cal/Val networks with some expansion towards better representation of change and dynamics and focus on thematic product priorities
Level 2: Interoperable times series processing: provide processed level 2 and 3 large area times-series S1-3 (and LDCM) that can feed into analysis for land dynamics and change products	Use of available data acquisitions but develop targeted common data catalogue and selection of interoperable/multi-sensor time-series products (like MODIS web-service for time-series)	System includes joint processing procedures: • Common input to processing, i.e. land water mask, DEM, comparable products i.e. radiometric corrections for Sentinel 2 and Sentinel 3 (i.e. cloud screening/atmospheric correction, BRDF correction, compositing), calibration coefficients focus on temporal consistency and stability (also for using historical archives) • Re-processing of archives to derive consistent long-term time-series adding to Sentinel 1-3 and LDCM, i.e. Landsat archive, ERS 1+2, ASAR, MERIS, MODIS, SPOT VGT, AVHRR	• Apply joint data analysis algorithms to address key opportunities in specific regions as specified in level 1. • Research into dedicated algorithms making use of the advanced global pre-processing products and long-term times series from historical archives.	Significantly expand upon existing networks for quantitative Cal/Val of time-series processing products and land dynamics

Level 3: Integrated observing system: operation of coordinated acquisitions, interoperable processing, integrated thematic product generation and operational Cal/Val for land dynamics and change worldwide with local relevance	Operating Sentinel 1-3 and LDCM as a system of systems to optimize acquisitions for tracking land dynamics and change, and access through common data catalogue of interoperable/multi-sensor time-series and thematic products	Operational use of the procedures implemented in level 2 for near-real time processing	Implement a series of consistent and interoperable thematic products describing land dynamics and change on Sentinel 2/ LDCM spatial resolution with fine temporal detail and addressing various thematic areas: • Land cover/use change (incl. those of level. 1) • Phenology of vegetation and snow • Fire and burnt area • Biophysical variables (i.e. LAI, fAPAR) • Long-term vegetation trends (i.e. treeline) • Albedo, LST	Develop a truly global Cal/Val reference and sensor networks providing joint and operational for time-series and different thematic land dynamics products

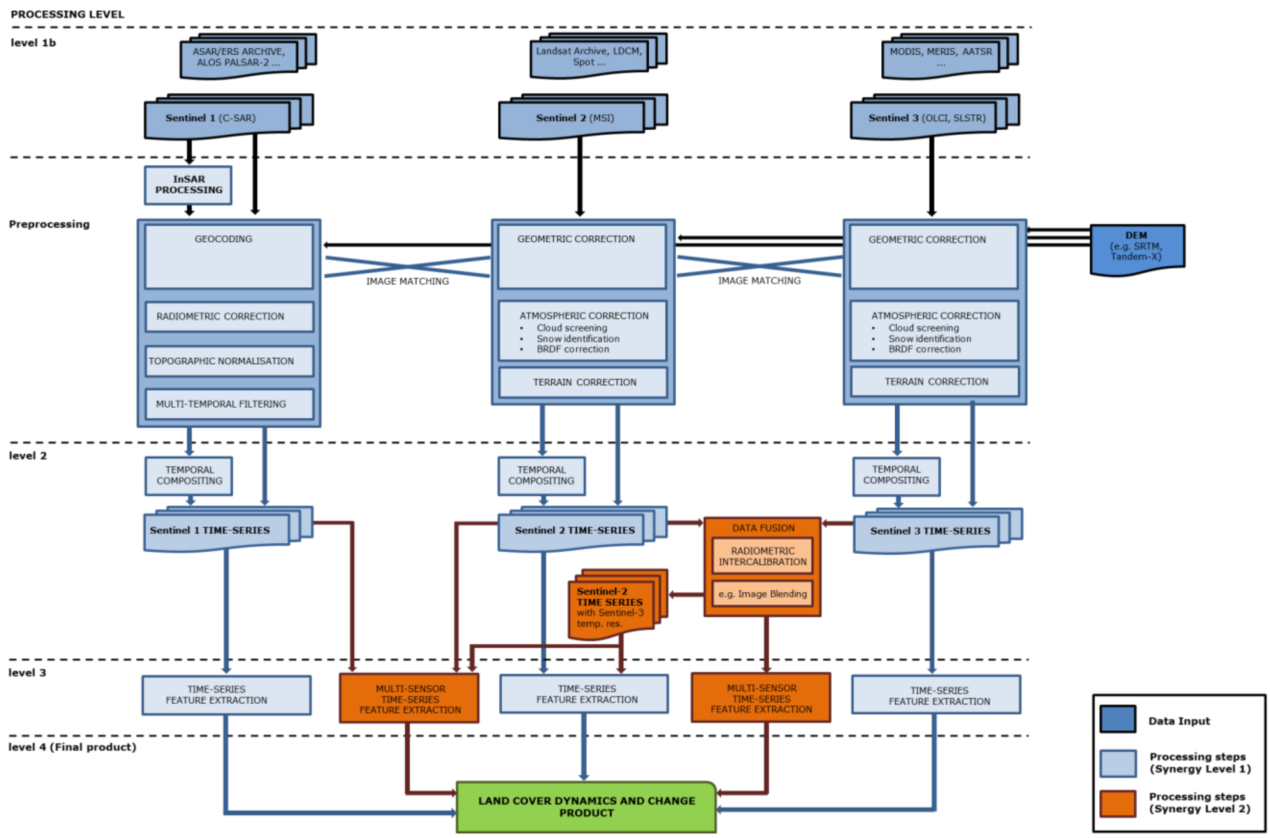

Figure 1: Proposed Sentinel 1-3 processing chain for the generation of LCDC product.

4. CALIBRATION AND VALIDATION

The calibration and validation (Cal/Val) plan for the proposed LCDC product should include calibration and validation of the entire processing chain from processing level 1b until level 4 (final product). For the basic Cal/Val plan, it is suggested to follow established and standardized Cal/Val strategies, dedicated methods, standards, protocols and tools of existing global Cal/Val networks, such as those provided by the Land Product Validation (LPV) subgroup of the CEOS Working Group on Calibration and Validation (WGCV) [18, 19, 20]. For validation activities both, direct validation sites (e.g. CEOS/LPV core sites [21]) and indirect validation sites (e.g. FLUXNET [22]) should be considered to ensure a largest possible validation site network.

It is important to perform joint Cal/Val activities and to use common Cal/Val sites for Sentinel 1 (SAR) and Sentinel 2 and 3 (optical). In order to safeguard the required independency between the calibration and the validation process, different set of sites should be used.

The Cal/Val plan for the LCDC product should in particular focus on the Cal/Val of the joint Sentinel 1-3 time-series processing (level 1b – level 2; see Fig. 1). Thereby, the evaluation of the geolocation accuracy and the geometric and radiometric intercalibration accuracy are of capital importance for multi-sensor time-series feature extraction (level 3; see Fig. 1) and for the final integration of extracted features from Sentinel 1-3 to generate the LCDC product (level 4; see Fig. 1). Calibration and validation of the internal time-series stability and robustness should be conducted at time-invariant sites, such as the CEOS/LPV desert surface core sites [21].

Considering the proposed synergy level (see Tab. 2) of the LCDC product it reveals that an increasing synergistic level and its related pre-processing and thematic product generation chain increases the demand for more advanced Cal/Val activities.

The validation of the final LCDC product focus primarily on the evaluation of the thematic class accuracy and on change and change area. Unlike existing global land cover product validation concepts that evaluate the thematic accuracy of the land cover classes, the validation of the proposed LCDC product requires the additional efforts to include the validation of land cover changes and dynamics for which appropriate validation strategies and standards have to be developed.

5. OPEN SCIENCE ISSUES

In conjunction with the proposed stepwise implementation concept and processing chain for a LCDC product using a synergy of Sentinel products, different open issues for future scientific work have been identified. However, the demand for research and development (R&D) is moderate for the implementation of the proposed synergy Level 1, but clearly increase with increasing synergistic level (Level 2 & 3).
With respect to the successful implementation of the proposed higher synergy Level, the following R&D activities are proposed:

<u>Data acquisition and access:</u>

- GMES needs to increase its efforts for consistent global land monitoring and large area processing and analysis
- ➔ GMES should have an data acquisition strategy that covers all areas in sufficient temporal detail and provide them with an open data access policy world-wide; considering that this may need to be adjusted to allow for better synergy among the different Sentinel data streams and also considers other sensors such as the LDCM to follow the system of systems idea of the Group on Earth Observations (GEO)

<u>Pre-processing and inter-calibration</u>
<u>A) Time-series processing</u>

- Optical remote-sensing approaches for Sentinel 2 and 3 time-series feature extraction and monitoring of different land cover types and dynamics are currently being studied, but in several regions restricted data availability (e.g. frequent cloud cover in tropical regions) limits the applicability of optical-based methods.
- ➔ Research activities should focus on synergistic optical and SAR (intensity & coherence) time-series processing to track and understand dynamics and changes over different land cover types worldwide

<u>B) Multi-sensor time-series feature extraction</u>

- Multi-sensor (SAR & optical) time-series approaches for Sentinel 1, 2 and 3 that overcome the limitations of single-sensor approaches are lacking
- ➔ R&D should focus on the development of systematic time-series analysis that effectively integrates optical and SAR (intensity & coherence) multi-sensor time-series for feature extraction

<u>Thematic product generation for different user needs</u>

- All existing global land monitoring efforts are single-sensor, single-year and single-variable approaches!
- ➔ Using robust time-series analysis features and longer time-series, efforts should be put in developing proper methods for deriving a series of series of novel Sentinel-based thematic products targeted at specific user communities and their needs, for example those not covered by current GMES services addressing the monitoring of Essential Climate and Biodiversity variables, global climate change policies, or monitoring for impacts of urbanization and for food security.
- ➔ Efforts should also look into how different observation variables can be observed in more consistent manner towards a more integrated land monitoring, i.e. deforestation causing and can be understood as a change in land use, land cover and in biophysical variables (i.e. LAI, albedo) depending on the user community.

<u>Calibration and Validation framework</u>

- Most existing sites and networks have limitation for calibration and validation of seasonal strongly dynamic land cover classes, because they generally represents only a minor fraction of the entire growth cycle (usually maximum leaf development) and most global validation networks provide land cover information, but do not provide information on dynamics and change and areas affected

- ➔ Global calibration sites should be updated and expanded to include land cover dynamics information. This requires the frequent measurements of Cal/Val sites over the entire season
- ➔ Global validation networks should expand to track change over time and area at and around the validation sites and augmented reference data collection also including information coming from citizen observers.

6. CONCLUSION

A concept and a joint processing chain for integrating Sentinel 1-3 data has been proposed to address the needs from a series of users. The framework considers the advantages of the single Sentinel systems in terms of the spatial, temporal and thematic detail for the generations of a global land cover dynamics and change (LCDC) product.

We provide a discussion on the current status and background for global land monitoring in order to (i) address the key user requirements and (ii) to develop concepts and processing techniques for a global LCDC product that go beyond the current state-of-the art, user requirements and available global state-of-the art land cover efforts and retrieval approaches of similar nature and their shortcomings.

Approaches for using Sentinel synergy have not been explored substantially for land change analysis. To allow for a stepwise implementation, a concept consisting of three synergistic levels and corresponding actions is proposed. It goes beyond the current state-of-the art of global land cover product generation chains and GMES initial operations and leads to a fully integrated observations system. We present three synergy levels (Level 1, Level 2 and Level 3) and respective actions for data acquisition and access, pre-processing and intercalibration, thematic product generation and Cal/Val procedures that go beyond Level 0.

Achieving the higher-level synergy products requires further investments in the areas of:

- Data acquisition and access
- Time-series processing
- Multi-sensor time-series feature extraction
- Thematic product generation for different user needs
- Calibration and Validation framework

that are described in more detail.

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