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# SATELLITE BASED MONITORING OF FOREST RESOURCES COMPLIANT WITH REDD+ AND ZERO DEFORESTATION

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**Abstract**

Natural Forests provide valuable ecosystem services and at the same time, direct and indirect human impacts affect these ecosystems. Especially in tropical countries with a high percentage of remaining natural forests, human induced land use change is one of the main drivers for increasing deforestation rates. The drivers, time scale and impact on forests are quite different between countries, but the necessity of a consistent, trustworthy and accurate monitoring of these resources is relevant to manifold stakeholders such as in the domain of land governance. The application of satellite imagery can greatly facilitate this need. The large area coverage and high spatial resolution of newly launched optical and radar satellite systems offer the opportunity to retrieve forest related information on a wall-to-wall basis. Satellite data based forest monitoring systems can provide evidence of most recent forest area and land cover changes with the capability to map historic events by incorporating archived data sets. Mapping forest extent and changes thereof is a crucial information requirement for managing the commons and customary land, forests and natural resources. The paper presents requirements, challenges and a methodological approach to implement National Forest Monitoring Systems (NFMS) at country level by incorporating user needs.

**Key Words:** Earth Observation, Forest Monitoring, REDD+, Sentinel, Zero Deforestation

## 1. Introduction

Satellite imagery provides an efficient means to retrieve information on the status and extent of forest resources and changes thereof. The large area coverage and high spatial resolution of newly launched optical and radar satellite systems offer new opportunities to remotely estimate and access land cover information on a wall-to-wall basis. At the same time the high temporal resolution and capacity to acquire data on a weekly basis improves the capability to detect most recent land cover changes such as deforestation and forest degradation events for National Forest Monitoring Systems (NFMS). The utilization of dense time series of multi-temporal and multi sensorial satellite imagery - which the European Space Agency (ESA) Sentinel missions data is well suited for - can address challenges caused by phenological changes of forest canopies between the seasons and data availability restrictions due to clouds. The scope for vastly improving the monitoring capabilities of the tropical dry and humid forest biomes with multi sensor EO data has implications for implementing robust and comprehensive monitoring systems at national level that can outperform globally available data sets of either coarse resolution or undefined accuracies. The technical specifications of forest monitoring products have to be defined according to the user and policy requirements. This paper will examine these requirements and analyze the required information on forest ecosystems. Section 2 will present existing technical challenges that have to be addressed and Section 3 will present a methodological approach to tackle these technical challenges. The methodological approach will specifically address the development of new algorithms, necessary validation procedures, the technical implementation and the knowledge transfer to Developing Countries. Within the last section of the paper conclusions will be drawn.

### 1.1 Policy Requirements

Global, international and national environmental or forest policies, programs and administrations do require spatial information on the forest area and forest area changes. A key international policy segment that requires countries to develop national forest monitoring systems is the United Nations Framework Convention on Climate Change (UNFCCC) policy on Reducing Emissions from Deforestation and Degradation (REDD+). Developing reliable Measuring, Reporting and Verification (MRV) systems are fundamental to the implementation of REDD+ in developing countries. This has been underscored in all the UNFCCC Conference of Parties (COP) Decisions since REDD+ has been negotiated. Countries that are willing and able to reduce emissions from deforestation and forest degradation are recommended by the UNFCCC COP to establish robust and transparent forest monitoring systems to account for anthropogenic forest-related greenhouse gas emissions by sources and removals by sinks. The methodological approach proposed by the Intergovernmental Panel on Climate Change (IPCC) for carbon emission accounting requires two basic data: (1) Activity Data (AD), i.e. area extent of the activity) and (2) Emission Factor (EF), i.e. carbon stock per unit area. Consequently, potential REDD+ countries need to estimate emissions and changes in forest carbon stocks from deforestation or forest degradation and have a means to establish reference emission levels, against which future emissions can be compared, as well as to address the displacement of emissions. It should be pointed out that neither the definition of forest nor the reference year for the baseline have been so far defined under REDD+.

Additionally, the IPCC Good Practice Guidance (GPG) for Land Use, Land Use Change and Forestry (LULUCF) defines 3 Tiers or levels of accuracy for reporting that have to be considered for operational REDD services. Tier 3 is the only approach that tracks forest and other land conversions on an explicit spatial basis, including gross deforestation and gross change into other land cover classes (FCCC/TP/2009/1). Thus, countries will need to know:

- The aerial extent of deforestation and forest degradation (hectares),
- For degradation, the proportion of forest biomass lost (percentage),
- Spatial location of deforestation or forest degradation events (which forest type),
- The carbon content of each forest type (tons of carbon per hectare), and
- The process of forest loss that affects the rate and timing of emissions.

Furthermore, the Corporate Sector collaborating increasingly with civil society and Non-Governmental Organizations (NGOs) are interested by concepts such as Zero Deforestation (ZD). At international and national level, ZD does not mean a complete stop to deforestation, but accepts that some gross deforestation can be counter-balanced by some plantations with an accepted potential loss of biodiversity in case forest re-growth is not achieved naturally. At local level, Zero or no deforestation should be understood as no deforestation of high carbon, high biodiversity forest and development should concentrate on heavily degraded areas. The ZD program and the effective evaluation of companies' commitments require two different kind of forest monitoring products. For the development of new plantations, companies that are committing to ZD have to restrict their expansions to locations of low carbon stocks and preserve areas of high ecological value. An efficient monitoring of forest resources is therefore required to help companies in confirming their ZD commitments and more important, to monitor protected areas. The two main forest monitoring products relevant for ZD can be summarized as:

- The aerial extent and amount of forest carbon stocks (tons of carbon per hectare),
- The process of forest loss in areas under protection (hectares).

The rationale for satellite based NFMS is not limited to the above-mentioned forest policy programs or similar initiatives. In fact, information of the forest extent and changes thereof is a crucial information requirement for overall management of the commons and customary land, forests and natural resources. The establishment of Indigenous peoples' tenure systems can build on such mapping results, which provide an objective representation of the landscape and its associated coverage. The spatial explicit representation and monitoring of land use classes, including forest, can be realized for large areas on a frequent basis by utilizing the full potential of satellite data.

**1.2 Specifications of Forest Monitoring Products**

NFMS are supported by the integration of regular updated map products capable to provide information with a level of detail and thematic completeness that meet stakeholder requirements. The mapping scale is related to the Minimum Mapping Unit (MMU) and to the applied national forest definition. A framework for applicable forest definitions for REDD+ is given within the Marrakech Accord. It defines applicable Thresholds for the minimum forest area (0.05 - 1ha), for the minimum tree height at maturity in situ (2-5m) and for the minimum percentage of crown cover (10-30%). In absence of a national forest definition many countries apply the forest definition of the Food and Agricultural Organization of the United Nations (FAO) which defines forests as: "Land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ." Thus, EO data used for the production process must have a geometric resolution that is sufficient for the production of maps with a MMU of 0.5 ha (i.e. the smallest geometric unit that can reliably be presented in a map).

Another important component for the definition of forest monitoring products is the range of thematic classes that have to be mapped. According to the IPCC Guidelines (2006) map products should provide information on:

- Spatial location and extent of unchanged forest areas
  - Forest Land remaining Forest Land
  - Non-Forest Land remaining non-Forest Land
- Changes into IPCC compliant land use classes.
  - Forest Land changed into Cropland
  - Forest Land changed into Grassland
  - Forest Land changed into Wetland
  - Forest Land changed into Settlement
  - Forest Land changed to Other Land

The assessment of the associated biomass and carbon stocks for these key categories forests remaining forest and forests converted into other land use are subject for terrestrial sample inventories (i.e. EF assessment).

The monitoring of the area changes of degradation is a bit more complex as this generally entails relatively dynamic processes as opposed to permanent land use changes. Using remote sensing data to monitor areas of forest degradation caused by the extraction of fuel wood for example is practically impossible to achieve. The concept of Intact Forest Landscapes can be used as a proxy to identify forest land without anthropogenic disturbance (GOFC-GOLD, 2016). Definitions for Intact and Non-Intact Forests are:

- Intact Forest: fully stocked (forest with a tree cover between 10% and 100% when the FAO Forest Definition is applied) but must be undisturbed, i.e. there has been no timber extraction.
- Non-Intact Forest: not fully stocked but tree cover must still be higher than 10% (when FAO forest definition is applied) to qualify as forest but the forest has undergone some level of exploitation or canopy degradation.

The method employs the EO derived Forest Cover Maps of different epochs and adapts a series of spatial criteria to distinguish Intact from Non-intact Forests. The increase of the Non-intact Forest area over time provides the area of degradation. The stratification of Intact and Non-intact Forest is then the basis for a terrestrial sample inventory measuring the average biomass and carbon stock per hectare. The difference in carbon stock per hectare between both strata will be the Emission Factor for the degradation change area for the investigated epoch.

Companies and NGOs involved in the ZD process require further information on different types of vegetation with different levels of carbon stocks. The process needs six biomass related classes ranging from high density forest to cleared/open land. Such information can be assessed with direct biomass assessment methods using L- and P-band of radar data.

## 2. Technical Challenges

Despite the fact that EO has markedly advanced in recent years regarding both, satellite sensors and algorithm development for data analyses, existing technical challenges still hinder a full implementation of accurate operational NFMS. The NFMS has to be capable to serve the various requirements of stakeholders, the user specified forest and land use definitions, required accuracies and the different technical specifications of available satellite sensor systems. Statistical robust methodologies for accuracy assessments is another essential component. It is at the same time important that the system can be adapted to changing requirements and different forest ecosystems.

The number of suitable satellite sensors systems for forest monitoring applications vastly grew during the last years. An important milestone for the development of satellite data based applications was the release of the Landsat archive and the open data policy of United States Geological Survey (USGS) and National Aeronautics and Space Administration (NASA). The European Space Agency (ESA) jointly developed the Sentinel satellite constellation of which two satellite systems are of special importance for the monitoring of forest resources. The Sentinel-1 satellite constellation, acquire radar-based information from the earth surface at a high spatial resolution. The Sentinel-2 satellite pair acquire imagery in the optical domain with spectral bands of up to 10 m spatial resolution and a revisit time of 5 days. Figure 1 shows an example of a Landsat 8 image subset and two image subsets from Sentinel-2.


*Figure 1: Example of a Landsat 8 image (left) compared to Sentinel-2 10 m imagery (middle & right images) taken over a monitored area in Peru. The time difference between the Sentinel-2 images is 20 days only. A forest clearing in the upper right part of the image is clearly visible. The area size is approximately 17 ha. This example highlights the need for a high temporal satellite data coverage and fast processing algorithms.*

The volume of data to be handled via these sensors is considered to be exceptional; for example for every 10,000 km² Sentinel-2 will generate about 1 Giga Byte due to the improved spatial resolution and number of spectral bands. When the increased revisit time of Sentinel-2 is taken into account, the sensor will generate 12 times as much data than that of Landsat 8. Together with the historic and current data of the Landsat missions, Sentinel data provides vast opportunities for forest cover and change mapping. Harnessing this amount of data and realizing its potential requires specific and sophisticated approaches.

Dense time series data stacks can be built with available data and analyzed with new algorithms that incorporate phenology, seasonality and land use practices in the mapping procedure. These new data opportunities require at the same time a computational infrastructure capable to handle intense data volumes with the requirement of efficient processing chains in order to provide mapping results in a timely manner.

Other challenges to operationalize NFMS in tropical countries and especially in the tropical dry forest biome are related to the gradual transition between the forest and grassland or cropland categories. This includes the relatively low canopy closure on large areas with bare soils, shrubs and thickets visible through the tree canopy gaps, which causes confusion of the spectral signals; this leads to higher uncertainty of the area assessments. Many of the species in the dry forests in Africa also are deciduous with leaf fall in the dry season that poses a problem, as the optimal satellite images for the forest mapping can only be obtained in the winter season where the data is cloud free but at the same time trees are without leaves and therefore are difficult to be detected. During this season, the forests have a very low canopy reflectance and therefore the mapping produces higher inaccuracies. The dry forests biome covers approximately 42% of sub-tropical and tropical forested regions in the world (Murphy and Lugo, 1986) and in West-, East- and Southern Africa it covers approximately 17.3 million km² and is home to about 505 million people, which highlight the importance to provide accurate and trustworthy forest and land use information. Countries in the southern African regions such as Zambia, Zimbabwe and Malawi have some of the highest deforestation rates in Africa and globally. Malawi for example has an annual deforestation rate of 1.0% - 2.8% and is ranked 4$^{th}$ in the world and the first in southern Africa (MNRE, 2013). There are however several challenges for mapping these dry forest ecosystems. Especially the improved temporal, spectral and spatial resolution of freely available Sentinel data is an important component to tackle these challenges.

## 3. Methodological Approaches

The requirements for a sustainable NFMS can be described with four main components as follows:

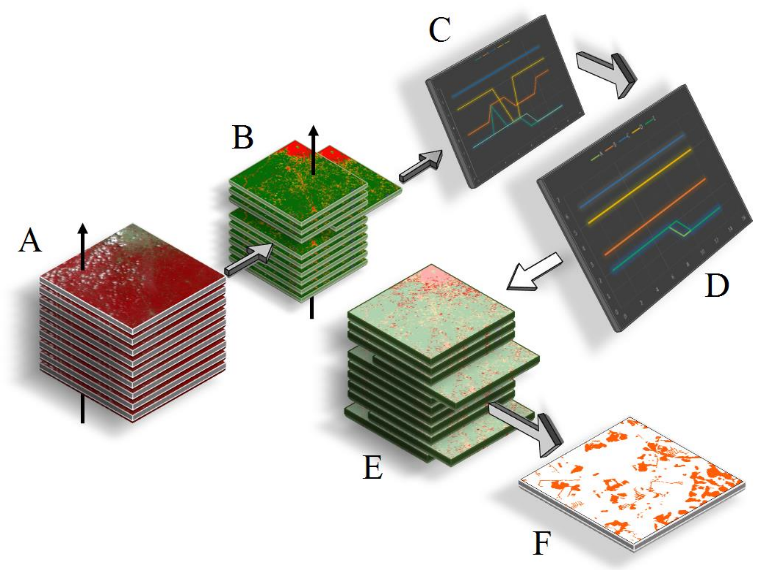
- Robust and accurate algorithms;
- Assessment of map accuracy;
- Technical implementation and its infrastructure;
- Knowledge transfer and capacity building.

The first component comprises processing algorithms that are capable to handle various kind of EO data, handle intensive data volumes, produce reliable mapping results and that are capable to meet various needs of stakeholders. The second component comprises all quality assurance measures. Especially the verification of user required mapping accuracies and product standards have to be considered in an appropriate manner. The third component is the technical implementation within a high-performance computing environment, which specifically addresses the challenge of processing the intensive data volume in a timely manner. The fourth and at the same time a crucial component to implement a sustainable NFMS in developing countries is the capacity to exploit the capabilities of such a system and provide accountable verification of land cover and changes thereof in order to fulfill continuing reporting requirements. These components build the sound basis of a sustainable NFMS.

### 3.1 Development of Algorithms

Recently launched satellite systems did set the stage for exploiting the information content of dense time series. The integration of different data sources into one streamlined workflow requires innovative and computational efficient processing algorithms. New approaches for data harmonization and trustworthy verification procedures have to be implemented and applied. Instead of analyzing single images from specific points in time, new algorithms exploit information from the entire time series by incorporating knowledge about phenological dynamics and local land use practices. Tracking features over the entire year improves the robustness and completeness of the mapping approach.

The proposed system design utilizes dense multi-temporal and multi-sensoral EO time series to overcome existing technical challenges (see Figure 2).




**A:** Preparation of multisource satellite data (pre-processing).
**B:** Classification of each single EO data input. Creation of chronologically ordered dense time series.
**C:** Analyses of image segments throughout the entire time line.
**D:** Optimisation of each image classification by applying logical rule sets and perform consistency checks (e.g. phenology).
**E:** Improved wall-to-wall land cover information for entire data stack.
**F:** Identification of land cover changes.

*Figure 2: Workflow for processing dense time series of High Resolution EO data for mapping forest disturbances.*

In order to gain improved mapping results the temporal trajectory and image quality is incorporated in the mapping procedure. Storch et al. (2016) applied this approach on a large study site in Malawi. The strong phenological effects of the tropical dry forests and the frequent cloud cover during the leaf-on season causes special technical challenges for mapping land use and changes thereof. The acquisition date and cloud cover have an impact on the reliability of a classification result. Therefore, a higher reliability can be assigned to images taken during the vegetation period. By incorporating local expert knowledge on natural and human induced land cover dynamics the plausibility of single map results within a map sequence can be analyzed and misclassified map elements be corrected. A region specific rule set is therefore containing information on natural reforestation periods and agricultural practices. The combination of an *a-priori* scene rating into different classes of reliability and the subsequent plausibility check improves the overall map accuracy.

### 3.2. Validation of Map Accuracy

Generally, maps derived from remote sensing contain classification errors, even though the presented methodology eliminates most of these errors by incorporating the reliability and plausibility information in the entire processing chain. The residual inaccuracies of mapping results can be caused by many factors such as quality and suitability of satellite data, interoperability of different sensors, radiometric and geometric processing, cartographic and thematic standards, and image interpretation procedures, post-processing of the map products and finally the availability and quality of reference data. The qualitative assessment of map accuracy is very often under emphasized in implementing NFMS projects. Especially for REDD+ MRV projects and many other applications where the reliability of the derived mapping results is critical, the application of accuracy assessments should be mandatory. This entails class specific thematic accuracy measures, confidence intervals for the area estimates, and/or an adjustment of the initial area statistics considering known and quantified biases to provide the best estimate. The accuracy assessment has to be based on independent reference data, applying statistical sampling to measure overall accuracy, errors of omission and commission for each class. For the implementation of robust accuracy assessment methods, three primary components need to be defined: the Sampling Design, determines the spatial location of the reference data, the Response Design describes how the reference data is obtained and an Analyses Design defines the accuracy estimates. “Best Practices” for these steps are provided by Strahler et al. (2006).

The sampling design specifies the sample size, sample locations and the reference assessment units (i.e. pixels or image blocks). Different sampling schemes can be used in collecting accuracy assessment data including: simple random sampling, systematic sampling, stratified random sampling, cluster sampling, and stratified systematic unaligned sampling.

In large area forest monitoring projects simple random sampling would be sufficient for the accuracy assessment, but a usual drawback of a simple random sampling is that some areas can be omitted. This can be overcome by combining a random sampling approach with a systematic grid, which ensures that the whole area is sampled (Sannier et al. 2014). An additional challenge of random sampling occurs when change classes have to be assessed. This is because the areas of change are often locally concentrated and have the risk of not providing a sufficient amount of change samples for each kind of land cover change category. The more detailed the classes, the more samples have to be collected.

Another aspect, which is important for the selection of an efficient sampling method, is the availability and accessibility of reference data. The most cost efficient source of reference data for large areas is Very High Resolution (VHR) EO data, which is available from archives in full scenes (approx. 11 by 11 km) or in less expensive mini-scenes (e.g. 5 by 5 km). To cover the entire area and in order to build a representative reference data set a two-stage sampling design with Primary Sampling Units (PSUs) and Secondary Sampling Units (SSU) has proven as very efficient for large area forest monitoring projects. In the first stage a sample of 5x5km VHR satellite image frames (PSUs) is randomly selected. In the second stage a set of sampled points per image and class are selected (SSUs).

The above sampling design is effective and at the same time cost efficient when the area coverage of the PSUs is in the range of 1% of the total area. The sample size of the SSU is determined by the need to express accuracy in an error matrix. On empirical grounds a minimum of 50 samples per map class are required to adequately populate an error matrix. Larger area maps or more complex maps should receive 75 to 100 accuracy assessment sites per class (Congalton and Green, 2009). These sample sizes yield stability and reliable results.

The calculation of the necessary number of SSUs at a certain level of confidence is described in Goodchild et al. (1994). The principles of selection PSUs and SSUs are illustrated in Figure 3 using an example of Cameroon.

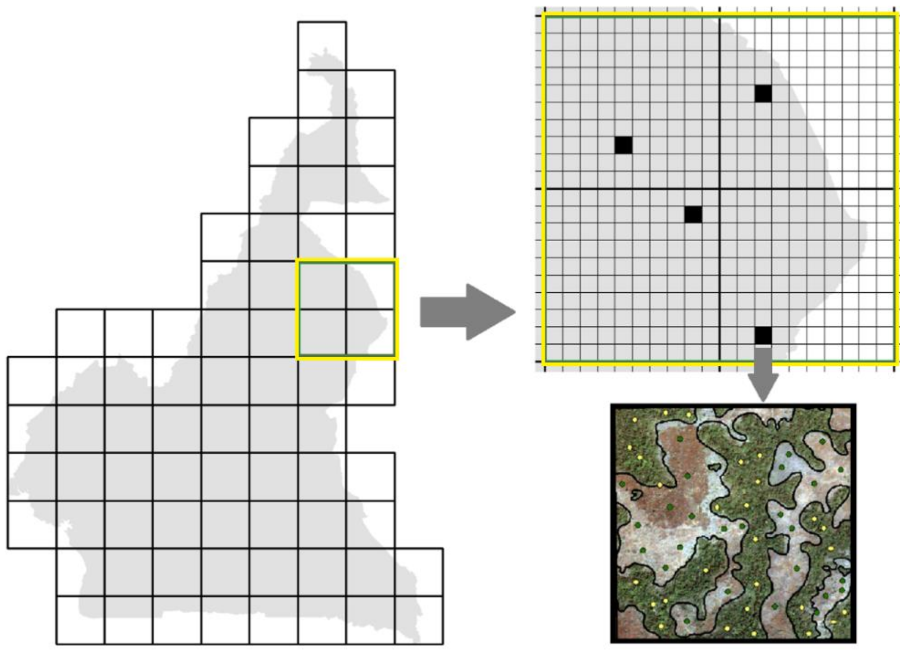


*Figure 3: Example of the systematic random sampling design. A large grid covers the entire study area and within each of these grid cells one Primary Sampling Unit (PSU) is randomly selected (upper right image). Thus, a spatially balanced distribution of reference samples across the entire study area is achieved. The PSUs are visually interpreted and finally a random sample of Secondary Sampling Units (SSUs) is collected (lower right image). At these locations, the produced map values are compared to the interpretation result.*

The response design is the methodology to obtain reference data from the sample units (Stehman & Czaplewski, 1998) to be used for the definition of agreement between map labels and reference labels. Generally, ground reference information shall come from data of higher quality, such as areal images or VHR satellite images. However, collecting reference data on the ground by means of intensive fieldwork is both costly and time consuming and in the scope of most operational forest monitoring projects not feasible. Forest monitoring map products are usually derived from historic and current High Resolution (HR) data of Landsat, SPOT, RapidEye or Sentinel-2 satellites with spatial resolutions varying from 5 m to 30 m on the ground. Therefore, significantly higher resolution imagery from WorldView, Quickbird, Ikonos, Orbview, Pléiades or GeoEye that provides resolutions of 1 meter and higher is used for validation. The spectral resolution of the available images is also of importance depending on the map products. VHR panchromatic satellite images may be usable for the validation of forest maps but experience shows that it is much better to use multi-spectral images. The HR satellite data used for map generation is also useful as reference for consistency checks when no other ground data sets are available especially for the historical forest cover maps going back in time till 1990.

Once the VHR scenes are randomly selected as PSUs for the current and historic epoch(s), the SSUs are randomly selected in order to generate a reference for the change classes. At this stage it needs to be defined what the SSU should be: points, pixels, pixel cluster or polygons. The advantages and disadvantages of the different SSU types are discussed in Stehmann and Czaplewski, (1998). Point samples as SSU have been proven as best practice in many operational forest monitoring projects. The sampling points which are overlaid onto the map and reference data have to be interpreted by an experienced expert and assessed as classified correctly or incorrectly. During the interpretation process, the MMU is taken into account and superposition errors and problems with class borders are mitigated.

Contingency tables, confusion or error matrices are derived by comparing the reference information of the samples with their corresponding classes on the map. Confusion matrices are showing the number of samples which are correctly and not correctly classified. This allows the calculation of the user and producer accuracies for each class as well as the overall accuracy figure. In particular, omission and commission errors should be equally spread if area statistics are to be extracted directly from thematic maps. The values in an error matrix can be used to calculate confidence intervals and to quantify the uncertainties for each class at defined confidence levels (usually 95%). Further on, it is possible to use information on bias in the map to adjust area estimates. The calculation of confidence intervals is described by Congalton and Green (2009).

**3.3 Technical Implementation and Infrastructure**

With the launch of Sentinel-1A/B and Sentinel-2A/B a new era of frequent coverage of the earth surface by high resolution satellite imagery was initiated. Together with the Landsat and other satellite missions it is now possible to built-up dense time series with sufficient spectral and geometrical resolution which allows new analysis methods for improved land cover mapping. The high temporal resolution of multi-source satellite imagery is recognizing the natural seasonal changes of vegetation cover which can then be considered in the extraction of human induced changes of forest cover. Furthermore, dense time series enable a compensation of data gaps caused by clouds and make an early detection of deforestation and forest degradation events possible. However, the data volumes on dense time series data stacks from Sentinel and other satellite systems are, compared with traditional processing methods (mono- and bi-temporal analysis), tremendously increasing and therefore require a sophisticated IT infrastructure to compute wall-to-wall land cover maps. In the practical world of providing operational EO based monitoring services it has been proven more efficient to make use of cloud processing options instead of purchasing, maintaining and constantly upgrading existing IT infrastructure. Currently, there are many commercial providers for cloud IT infrastructure like the most known ones Amazon Cloud and Google Cloud; in Germany there are T-Systems and others but there are also several public financed platforms under development as e-g. CODE-DE (Germany) or C-DIAS (EU). The advantages of using cloud processing environments are scalability according to the required processing tasks and direct access to EO and other data. Costs for data processing are only due for payment during the service request and is therefore adjustable to the needs of a specific project. Web based processing platforms can be accessed by multiple users at the same time, which enables them to work on the same environment. Data backup capabilities are provided by the cloud infrastructure providers and are generally scalable to the needs of the project.

### 3.4 Knowledge Transfer and Capacity Building

REDD+ implementing countries as well as many other users need to have capacity to operate MRV systems. The handling of huge data volumes and the application of complex processing algorithms which are needed for the implementation of NFMS pose an infrastructure and capacity challenge for Developing Countries. Thus technology transfer and capacity building are major pillars of development cooperation programmes but however, the status of having up-to-date hard- and software is almost always lacking behind the requirements of fast developing technology. Working on cloud-based processing chains can be an opportunity for improved technology transfer and capacity building to Developing Countries. Figure 4 illustrates the components of cloud based processing chains and the interactions of Service Providers with Users from Developing Countries. The Service Providers are designing the application oriented processing chains in the cloud based infrastructure in terms of configuring the necessary computing power and functionality to discover, select, process, and classify the desired information from EO and ancillary data.

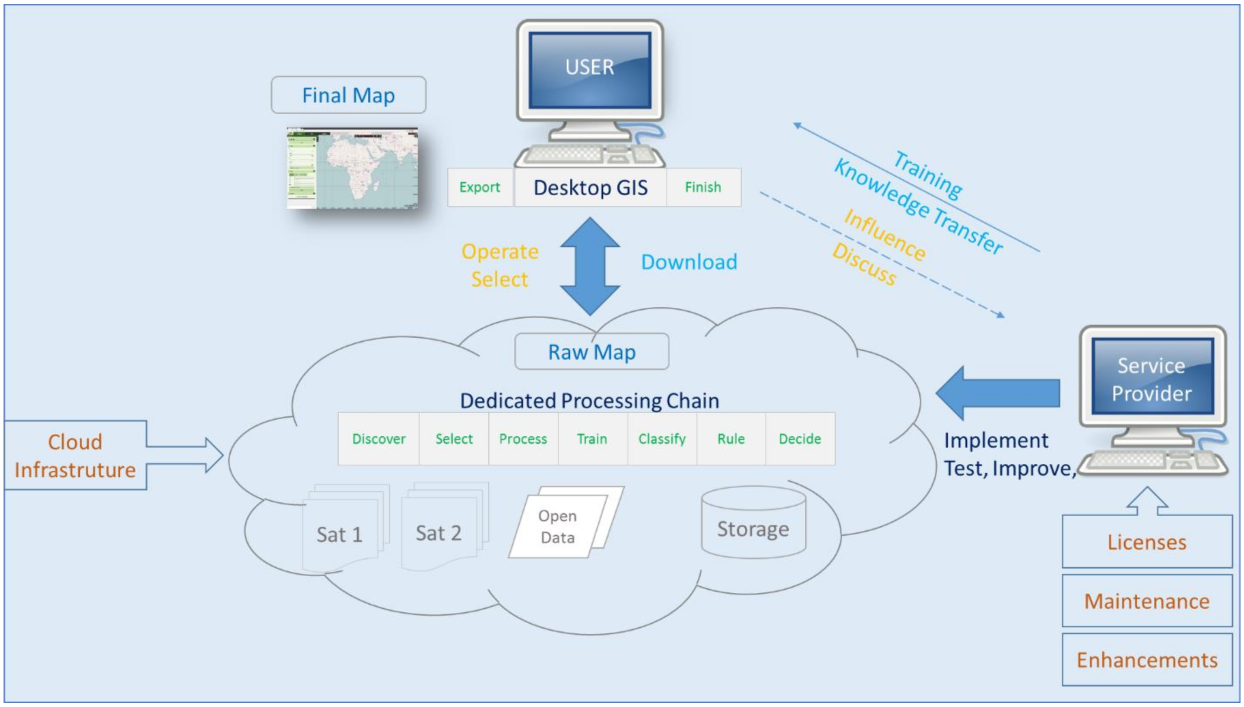



*Figure 4: Components of cloud based processing chains and interactions of Front End Users in Developing Countries and Service Providers.*

The Service Provider has the opportunity to continuously test and improve the algorithms and processing tools in the cloud infrastructure. The necessary EO data are usually already on the cloud platforms and can be complemented by the Service Providers if needed so that transfers of huge data sets is not anymore necessary. The only hard- and software requirements on the side of the Users Front End are restricted to a Desktop GIS and a web interface with the functionalities to operate, select, analyze, upload country specific ancillary data and download processed results and which is in most cases are feasible to implement. The benefit for users in Developing Countries can be summarized as follows:

- no sophisticated IT-infrastructure is needed,
- access to up-to-date technology,
- no obstruction to technology transfer by outdated hard- and software.

All the necessary skills to operate the cloud based processing chains can be trained via capacity building and technology transfer workshops. The Users in the Developing Countries can decide in which intensity they would like to operate the processing chain and therefore which kind of capacity building is needed.

## 4. Conclusion

REDD+ participating countries need to provide rigorous methodologies and validated results in order to receive financial compensation for conserving their forest areas. Deforestation and forest degradation has manifold drivers, which are diverse between tropical countries. The expansion of plantations is one of these key drivers and the ZD program currently aims to address this. Spatial explicit information on the land cover is required for these two programs in the forest domain. Furthermore, the provision of evidence on historic and current changes of ecosystems and urban areas is a fundamental requirement for a sustainable management of resources. With the availability of new sensors such as the Sentinel data having spatial resolutions of up to 10 m and a frequent coverage of the world surface by open accessible satellite imagery, map production requires scalable and adaptive solutions. The huge data volume and countrywide coverage need a computational infrastructure that exceeds the capabilities of single workstations. This can be resolved via using cloud based platforms for EO data storage, access and processing. This is also advantageous to the users in developing countries as it resolves the problem of computational infrastructures, and further supports their participation in the creation of forest and land cover maps as well as their monitoring.

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## 7. Figures

Figure 1: Example of a Landsat 8 image (left) compared to Sentinel-2 10m imagery (middle & right images) taken over a monitored area in Peru. The time difference between the Sentinel-2 images is 20 days only. A forest clearing in the upper right part of the image is clearly visible. The area is approximately 17ha. This example highlights the need for a high temporal satellite data coverage and fast processing algorithms.

Figure 2: Workflow for processing dense time series of High Resolution EO data for mapping forest disturbances

Figure 3: Example of the systematic random sampling design. A large grid covers the entire study area and within each of these grid cells one Primary Sampling Unit (PSU) is randomly selected (upper right image). Thus, a spatially balanced distribution of reference samples across the entire study area is achieved. The PSUs are visually interpreted and finally a random sample of Secondary Sampling Units (SSUs) is collected (lower right image). At these locations, the produced map values are compared to the interpretation result.

Figure 4: Components of cloud based processing chains and interactions of Front End Users in Developing Countries and Service Providers