FINAL PUBLISHABLE SUMMARY REPORT

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TIM PEARSON

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1 INTRODUCTION

1.1 Purpose and scope

This document comprises part of the Final Report of the REDD-FLAME project. It is submitted together with a plan for the use and dissemination of foreground and a report on societal implications, using the REA's SESAM online application.

Section 2 provides a summary description of the project context and the main objectives.

Section 3 provides a description of the main science and technology results/foregrounds.

Section 4 provides a description of the potential impact and the main dissemination activities and the exploitation of results.

1.2 Intended audience / Classification

This document is intended for general distribution. It is therefore classified as 'Public'.

1.3 Abbreviations and Acronyms

AP	Alternating Polarisation (Envisat ASAR mode)
CDS-SCI	Coordinated Data Access System – Services Coordinated Interface
EC-GA	European Commission Grant Agreement
ESA	European Space Agency
EU	European Union
FCT	Forest Carbon Tracking (GEO Task)
FLAME	Fast Logging Assessment & Monitoring Environment
FP7	7th Framework Programme (EC)
FTP	File Transfer Protocol
GMES	Global Monitoring for Environment and Security
GSC-DAP	GMES Space Component Data Access Portfolio
ICP	International Cooperation Partner
NGO	Non-governmental Organisation
PMP	Project Management Plan (D1)
REA	Research Executive Agency (EC)
REDD	Reducing Emissions from Deforestation and Forest Degradation (UN)
SAR	Synthetic Aperture Radar
SDD	System Design Document (D4)
STD	System Technical Description (D12)
UN	United Nations

URD	User Requirement Document (D2)
(V)HR	(Very) High Resolution
WP	Work Package

2 PROJECT CONTEXT AND OBJECTIVES

2.1 Context

Deforestation

Recent analysis of low resolution satellite data indicates that 27.2Mha (105,000 square miles) of tropical rainforest were cleared from 2000 to 2005, an area representing 2.36% of global tropical forest cover [3]. The Intergovernmental Panel on Climate Change (IPCC) estimates that the cutting down of forests is now contributing close to 20 per cent of the overall greenhouse gases entering the atmosphere. Forest degradation also makes a significant contribution to emissions from forest ecosystems. Therefore there is an immediate need to make significant progress in reducing deforestation, forest degradation, and associated emission of greenhouse gases.[1]

Deforestation also results in loss of biodiversity. The Convention on Biodiversity (CBD) requires close monitoring of forest fragmentation because of the clear links it has to habitat conservation and species survival. Furthermore, maintaining forest ecosystems can contribute to increased resilience to climate change.[2]

Tropical peat swamp forest (PSF) ecosystems, of special concern given the large amounts of carbon stored in the ground, are being logged and converted at alarmingly high rates. Over the past decade and a half, much of the remaining PSF on the island of Borneo has been drained for conversion to agricultural land. The dry years of 1997-8 and 2002-3 saw huge fires in these areas. A study for the European Space Agency (ESA) found that the peat swamp forests are a significant carbon sink for the planet, and that recent fires may have released up to 2.5 billion tonnes of carbon into the atmosphere. The Nairobi conference of the UNFCCC recognised these findings, to the extent that ‘avoided deforestation’ in such areas is now eligible under the carbon crediting scheme. Protection of PSF ecosystems in this manner contributes to economic sustainability as well as environmental conservation.

Logging

Small-scale forest clearance is often just the precursor to wholesale deforestation. Such activities may be associated with illegal mining, road building or clearance for shifting cultivation. Once this first step is achieved, larger operations can follow and clear greater areas more easily: it establishes access and opens up the forest canopy, facilitating clearance using larger machinery.

Exceeding legal harvesting quotas or harvesting outside of legal concession areas is a key problem. However, legality of timber is not necessarily a guarantee of sustainability of forest management, either from economic, social and/or environmental points of view [4].

Monitoring systems

Various national and international guidelines, commitments and responsibilities (e.g. UN-REDD, GEO, Kyoto) require a precise assessment of changes in tropical forest cover and related carbon stock. Large-scale land cover classification and change mapping are nowadays quite common: yearly updates on land cover provide such information on national or sub-continental scales, but miss small-scale deforestation and degradation that will have a large scale impact months or years later. Examples are the PRODES (Monitoring of the Brazilian Forest by Satellite) and DETER (Detecção de Desmatamento em Tempo Real) systems implemented in Brazil, which map the

[1] UN-REDD Programme Fund, www.undp.org/mdtf/un-redd/overview.shtml

[2] UN-REDD Programme, www.un-redd.org

entire country in relatively coarse detail and update once or a few times per year, depending on cloud cover.

There is therefore a need to implement new systems that identify small areas of development within the forest as early as possible, in order to minimise their impact and prevent uncontrolled deforestation.

A system designed to detect small-scale logging operations will, by definition, also be suitable for recognising early signs of other forms of deforestation and forest degradation. Hence there is scope to scale up any such system as part of a universal forest monitoring initiative at national or regional level. Such a system could also be used to provide inputs for carbon emission assessments.

Contribution of Earth Observation

Earth Observation satellites provide large area coverage over most of the surface of the globe. They are therefore ideal for obtaining a synoptic view, and particularly valuable in areas that are difficult, expensive or dangerous to access on the ground or by aircraft.

By virtue of its ability to see through cloud, imaging radar is of significant advantage in tropical regions that are typically obscured from optical image sensors by quasi-permanent cloud cover. Furthermore, the ability to acquire data at night doubles the potential number and frequency of imaging opportunities. Availability of high-resolution radar sensors has recently increased: since 2007 there is a good choice of radar band, spatial resolution, monitoring frequency and areal coverage (see Table 2.1 and Figure 2.1). Investigating the potential for using these high-resolution sensors for small-scale hotspot monitoring in combination with other sensors and data, has been a primary objective of REDD-FLAME.

Mission/ Instrument	In operation	Frequency (Band)	Polarisation	Revisit	Swath width
JERS-1 SAR	1992-1998	1.27GHz (L-band)	HH	46 days	75km
ERS-1 SAR	1992-2000	5.6GHz (C-band)	VV	35 days	100km
ERS-2 SAR	1995-2011	5.6GHz (C-band)	VV	35 days	100km
RADARSAT-1	1995-2013	5.3GHz (C-band)	HH	3-24 days	45-500km
Envisat ASAR	2002-2012	5.6GHz (C-band)	Single or dual	3-35 days	100-400km
ALOS PALSAR	2006-2011	1.27GHz (L-band)	Single, dual or quad	3-46 days	20-350km
RADARSAT-2	2007-date	5.3GHz (C-band)	Single, dual or quad	3-24 days	10-500km
TerraSAR-X	2007-date	9.65GHz (X-band)	Single, dual or quad	11 days	10-100km
COSMO-SkyMed	2007-date	9.6GHz (X-band)	Single or dual	1-16 days	10-200 km
Sentinel-1	2013 on	5.405GHz (C-band)	Single or dual	12 days	80-400 km

Table 2.1 Comparison of SAR mission characteristics

REDD-FLAME project partners are established experts in remote sensing change detection and forest classification and have considerable experience of research into techniques using radar data. The challenge that this project aimed to address is the implementation of these techniques in an operational system that has the potential to be integrated as part of a national or regional forest monitoring centre.

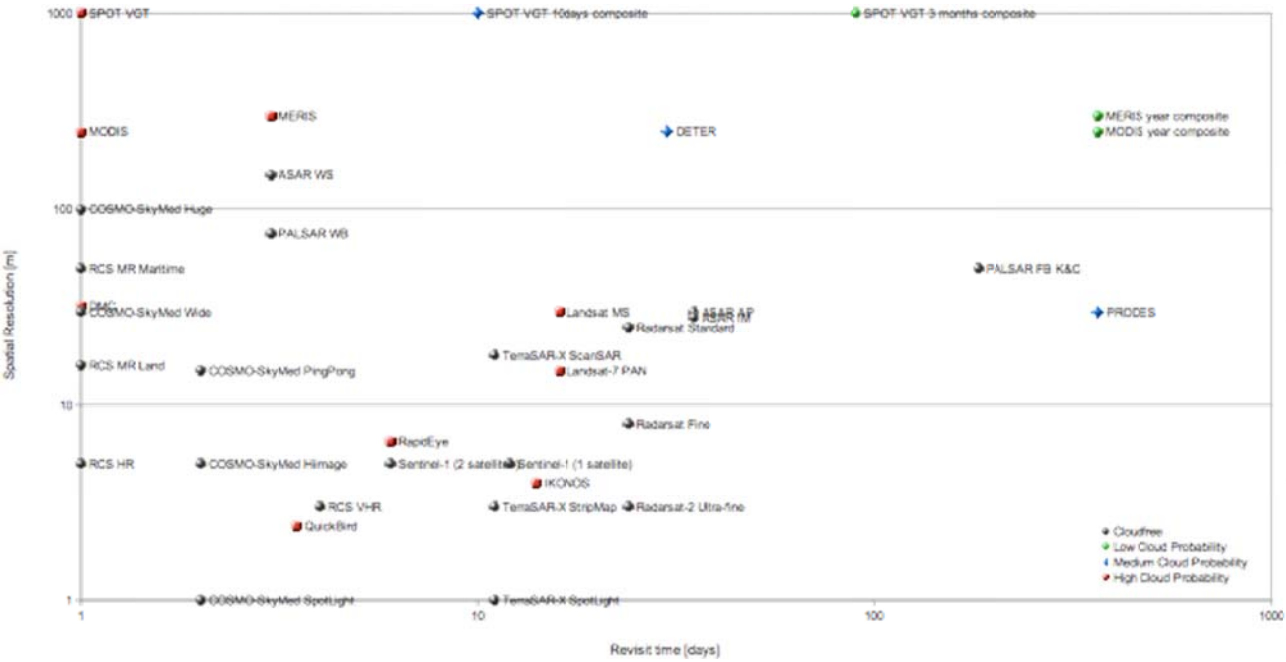

Figure 2.1 Temporal and spatial signatures for different satellites and sensors the Brazilian monitoring systems PRODES and DETER are also included in the plot. Colours represent possibility of cloud cover: grey=no cloud cover (radar data), green=no or little cloud cover (optical composites), blue=little to medium cloud cover, red=high possibility of cloud cover.

2.2 Overall objectives

The REDD-FLAME project focused on monitoring tropical and sub-tropical forest areas with high and very-high resolution earth observation satellites. The aim was to detect logging activities at an early stage and provide this information rapidly after satellite observation. The system was conceived as a high-resolution add-on for existing (semi-)operational low- to mid-resolution systems covering entire countries or regions (wall-to-wall mapping), providing hot-spot monitoring for areas at highest risk of deforestation.

The system has been designed primarily to use synthetic aperture radar (SAR) data, but as part of the project, an approach using optical remote sensing data was implemented in parallel so that the relative merits of each type of data could be assessed.

The system was implemented and evaluated in three countries to determine its potential as part of a national forest monitoring centre. The results and experiences from each of the countries involved were presented at Final Workshops, organised at the end of the project in each country to showcase the system and make recommendations for its operational implementation.

The real drivers of the REDD-FLAME project were the partners in the test site countries, who have detailed knowledge of the forest ecosystems that the system seeks to protect. In Indonesia, the Borneo Orang-utan Survival Foundation (BOSF) is dedicated to protecting endangered forest environments and developing REDD projects in Kalimantan. In Brazil, the Amazon Conservation Team (ECAM) has links to the many and diverse indigenous groups living in the Amazon Basin, with whom it is working to introduce 21st Century solutions. In Mozambique, the Faculty of Agronomy and Forestry at the Eduardo Mondlane University works very closely with the Ministry of Agriculture (Forest Service) and the Ministry of the Environment on guidelines for natural forest management and the implementation of natural forest concessions.

The system has been prototyped at test sites in established REDD project areas or GEO sites which were already well researched and characterised.

The Mawas region of Central Kalimantan in Indonesia comprises peat swamp forests, which are important carbon sinks, yet fires and drainage of the land for conversion to agriculture are resulting in large quantities of carbon being released to the atmosphere. In the Sete de Setembro Indigenous Land in Rondonia, Cacoal City and Mato Grosso, Brazil, gold mining and smuggling activities threaten vast swathes of lowland rainforest. The Mecuburi Forest Reserve, in Nampula Province, Mozambique, is at risk from agricultural conversion and harvesting of fuelwood, which result in damaging degradation of the sub-tropical Miombo forests.

The sizes of these areas (around 5,000sqkm) are typical of the regions that REDD-FLAME is intended to monitor, i.e. forest reserves, REDD project areas, threatened areas in the proximity of population centres. They are too big for frequent wall-to-wall monitoring using very high resolution satellite data, so an approach whereby high resolution monitoring and local intelligence are used to identify hotspots for investigation in greater detail is therefore essential.

The objectives of the REDD-FLAME project can be summarised as follows:

Objective
Requirements analysis: • Liaise with local actors to determine the drivers of land use change in the tropical or sub-tropical forest environment and the requirements for a national forest monitoring system. • Determine the technical requirements for a forest monitoring system using remotely sensed radar data. System development: • Design a system capable of closely monitoring areas of interest using high-resolution remotely sensed data to quickly identify changes in forested areas. Technical development: • Show how newly available high-resolution data sources can be used to improve assessment of forested areas and produce detailed and accurate change maps. System demonstration: • Implement the system at test sites on three continents. National monitoring centres: • Liaise with local contacts to establish the foundations for integration of the system within national forest monitoring centres. Impacts: • Generate data and products useful for the pursuit of the objectives of the UN-REDD Programme. International collaboration: • Promote and strengthen relations between the European remote sensing and forestry communities and their counterparts in developing countries of three continents.

3 SCIENTIFIC AND TECHNICAL RESULTS

3.1 REDD-FLAME Service Concept

3.1.1 Introduction

The REDD-FLAME system design focuses on monitoring tropical and sub-tropical forest areas with high and very-high resolution earth observation satellites. The aim of the REDD-FLAME system is to detect logging activities at an early stage and provide this information rapidly after satellite observation. The system will form a high-resolution add-on for existing (semi-)operational low- to mid-resolution systems covering entire countries or regions (*wall-to-wall* mapping), providing hot-spot monitoring for areas at highest risk of deforestation.

The system will be designed primarily to use synthetic aperture radar (SAR) data, but as part of the project, an approach using optical remote sensing data will be implemented in parallel so that the relative merits of each type of data can be assessed.

The system is being developed in collaboration with investigators from developing countries on three continents in an effort to build lasting partnerships and transfer European expertise. Sites in Southeast Asia (Indonesia), Equatorial South America (Brazil) and Southern Africa (Mozambique) have been chosen to represent a variety of forest types and deforestation issues, and thus to test the system's versatility.

3.1.2 Organisational Model

The principle of the REDD-FLAME service concept is depicted as an organisational model in Figure 3.1. It involves users (above the dotted line), the REDD-FLAME system (below the dotted line), and a number of interactions between the two.

Each box in the flow diagram represents an element of the system, with choices or options that will be determined by user requirements or previously selected options. For each dedicated implementation of REDD-FLAME, the service will be tailored through these selections.

Users

The REDD-FLAME service concept is driven by user requirements. A wide range of users has been identified, including local communities, forest managers, enforcement agencies, policy makers, monitoring and reporting agencies and logging and mining enterprises.

Broadly, these users fall into two distinct categories:

- those who need information on potential changes in the forest as soon as possible after the event to enable direct action to be taken; and
- those whose interest is in tracking deforestation and forest degradation over long time periods for reporting purposes and statistics. They require cumulative updates of deforestation extent every 3 months to 3 years (REDD).

An inventory of end user requirements and international policies concerning forest management and forest carbon stock was prepared, including existing mapping and monitoring infrastructures in the host countries, identification of high-risk areas and their specific requirements in terms of spatial resolution and update frequency of the REDD-FLAME system.

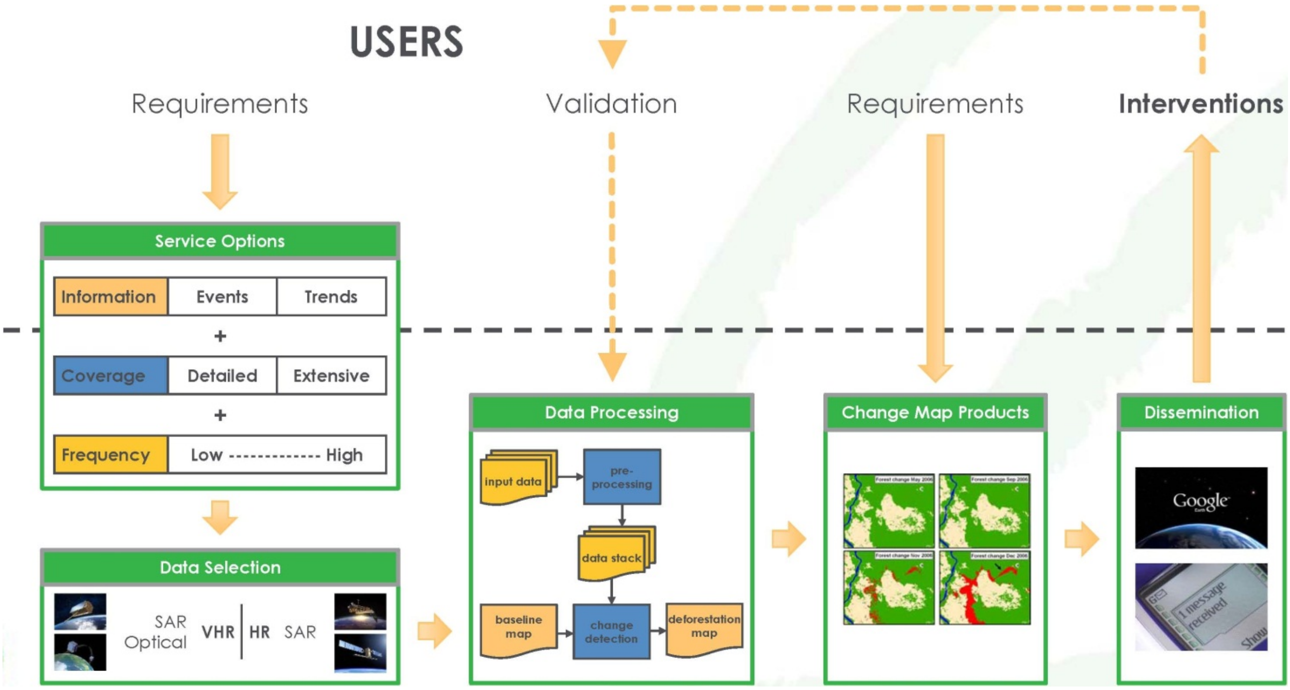

Figure 3.1 REDD-FLAME Service Concept

In general, these requirements indicate the need for monitoring at up to very high spatial resolution (1 to 3 meters) and high observation frequency (weekly to monthly), while risk is related to (selective) logging, suspected illegal logging or mining, agricultural conversion or easy access. The products most often required for forest monitoring are change maps that distinguish selective logging / forest degradation, land use conversions and other changes related to forests such as fire damage.

Users will be involved in the tailoring process for dedicated implementations of REDD-FLAME, particularly through selection of Service Options (see below) in consultation with members of the consortium. User requirements are also important for the specification of Change Map Products. Ultimately, results will be disseminated to users for use as required for intervention purposes: they may inform policy makers, provide input to monitoring programmes, facilitate law enforcement efforts or provide local communities with evidence with which to protect their lands from illegal encroachment.

Through their use of results, users will also contribute to validation of products and evaluation of the service, providing feedback to the Data Processing element.

Users will, furthermore, provide existing maps, such as land cover maps and forest / non-forest maps, for use in the system when possible.

Service Options

The REDD-FLAME monitoring regime is defined by Service Options divided into three categories. At least one option must be selected from each category to define the service(s) for a particular implementation. This selection will dictate other choices at later stages of the tailored system design. The categories of Service Options are described below.

Type of Information provided:

Events – Change Map Products that show the location of suspected deforestation phenomena which have occurred during a specific period, usually the most recent interval between acquired images. These products require fewer image data acquisitions, but results may include false alarms due to the lack of data after the change interval depicted with which to confirm change events. Satisfies the needs of forest managers and enforcement agencies, who seek to catch transgressors ‘in the act’. This is the core service offered by REDD-FLAME.

Trends – Change Map Products that show patterns of cumulative land cover change over extended periods. A longer time series with multiple datasets acquired after as well as before the period of interest allows more accurate detection, classification and quantification, and introduces the possibility for actual ground truth validation. Satisfies the needs of policy makers and monitoring authorities, who require validated results but have more relaxed time constraints. This service is possible as a consequence of repeatedly acquiring data for the Events service over a particular site and also represents a refinement of the earlier ‘preliminary’ information.

Coverage of results:

Detailed – Change Map Products that show information at very high resolution. The data required to generate such products is more expensive per square kilometre, and coverage is therefore likely to be restricted. Satisfies the needs of enforcement agencies or logging and mining enterprises, whose interests are restricted to specific sites.

Extensive – Change Map Products that show information over wide areas for a more reasonable cost. Such coverage comes at the expense of resolution, although this is still sufficient to detect many features of early tree removal. Satisfies the needs of monitoring authorities, who require a synoptic view of large forest areas.

Frequency of results:

The frequency with which new results are delivered, from weekly to monthly or longer. This choice may constrain the Data Selection. Needs vary according to the nature of the phenomena of interest or the requirements of a wider monitoring regime.

Data Selection

Choice of Service Options will restrict the Data Selection. Typically, choice of satellite data source is a trade-off between spatial resolution and spatial extent. These criteria, together with revisit frequency, likely impact of cloud cover, data cost and data availability/accessibility must be considered in making the selection.

The REDD-FLAME system will be capable of exploiting high resolution (HR) and very high resolution (VHR) synthetic aperture radar (SAR) data and very high resolution optical data. Several sensors are available as sources of each of these types of data, many of which have a further selection of operating modes to choose between. HR SAR data is suitable for Extensive coverage services, whilst VHR SAR data fits the requirements for Detailed coverage. Note that some sources of VHR SAR data have wide enough swath widths to be of interest for Extensive coverage services, although cost may be a limiting factor.

Table 2.1 summarises the characteristics of high and very high resolution data types.

REDD-FLAME will typically implement time series monitoring using high resolution SAR data, to be complemented by mapping at very high resolution, using SAR and/or optical data, where required at sites of particular interest. The Trends service is addressed by regular acquisitions of high resolution data, whilst Events service products could be produced from high or very high resolution data.

Data delivery arrangements and times vary by source and will have a significant impact on the speed of Events service product generation.

	High Resolution	Very High Resolution
Scale	1:10,000 - 1:50,000	1:5,000 - 1:10,000
SAR data sources	Envisat ASAR IM or AP, RADARSAT-2 Standard / Fine Beam	COSMO-SkyMed, TerraSAR-X, RADARSAT-2 Ultra-fine Beam
Optical data sources		RapidEye, GeoEye, SPOT-5, IKONOS, QuickBird, FORMOSAT MS, WorldView-2
Revisit	Monthly	Daily to weekly
Features visible	Roads, Camps, Logging decks, Fire scars	Small forest tracks, Small scale tree removal
Typical use for REDD-FLAME	Long time series monitoring, Detection of new deforestation activities, Trends service, Events service	Detailed investigation of hotspots, Land use change analysis at hotspots, Events service

Table 3.1 REDD-FLAME data and services at different geometric levels

Data Processing

At the heart of the REDD-FLAME system are algorithms for processing satellite imagery of forest areas and detecting and characterising changes. The processing chain will vary according to the choice of Service Options, but will always include pre-processing steps and change detection algorithms.

Satellite data cannot directly be implemented in the system: they first require radiometric and geometric calibration and registration to a map grid. For change detection, calibrated data sets are absolutely necessary, otherwise radiometric variations and geometric mis-registrations will be detected as changes. The data pre-processing steps in the Data Processing element will perform the calibration steps needed, accurately co-register satellite time series and integrate these with other geographic data sets.

Once the input data is properly calibrated and co-registered, the change detection processing can take place. This will be done at two levels:

1. Events service processing, providing the latest changes as quickly as possible after image acquisition (within 24 hours once the data is received);
2. Trends service processing, providing high-accuracy maps of cumulative change over longer time intervals, enhanced through the addition of subsequent images to reduce false alarms. When field data is available, validation will improve accuracy further.

So-called hot spots, to be monitored in detail, will be selected in the following ways:

- Using intelligence or circumstantial evidence acquired in cooperation with local partners and other users;
- Detection of indicators (such as camps, new roads) through routine high resolution monitoring or lower resolution national or regional wall-to-wall monitoring systems.

Change Map Products

The end products of the REDD-FLAME data processing chain are, in general, forest change maps. However, the nature of such maps can be tailored according to user requirements, or information can be extracted from the maps for dissemination by non-graphic means (e.g. coordinates of change features as text files).

The following aspects of Change Map Products can be tailored:

- Map legends will depend on the user's requirements, but as a minimum will always discriminate between deforestation/forest degradation and unchanged forest. Other land cover categories may be included.
- Annotations on map products could include the coordinates of change features, their estimated area or extent, etc.
- Map overlays and image backdrops at the discretion of the user, where applicable.

Dissemination

The last element of the REDD-FLAME system concerns results Dissemination. The mode of dissemination will depend on the user's preferences and the nature of the Change Map Products required. Data may be provided at different resolutions or in different formats to suit different dissemination modes.

Maps may be disseminated in raster form (as derived from the original satellite image data) as relatively large files, or converted into vector data. Such conversion might reduce file size, but will require filtering operations in order to "smooth" pixelated raster features.

File format should be compatible with the user's viewing capabilities. The most widely supported raster formats are GeoTIFF (NASA JPL, public domain) and KML/KMZ (Google Earth); for vector, ESRI shapefiles (shp) and KML (Google Earth) are most commonly used. These file formats can be converted with the GDAL software to other common formats used by remote sensing image processing and GIS software. Simple image formats such as JPEG and PDF may also be used.

Map files could be sent by email, on physical media by post or distributed as downloads from the REDD-FLAME website (or from an FTP site). Information in short text form representing the coordinates of change features could be sent to a mobile phone by SMS.

3.2 System

3.2.1 SAR system

The processing chain shown in Figure 3.2 is based on SAR imaging modes covering large areas with spatial resolutions in the order of 10 to 25 meters with monthly updates. Regular updates are necessary for improving accuracy and reducing false alarms. The system was designed to work with Envisat ASAR or RADARSAT-2 data, but can easily be adapted to work with data from Sentinel-1 or other sources.

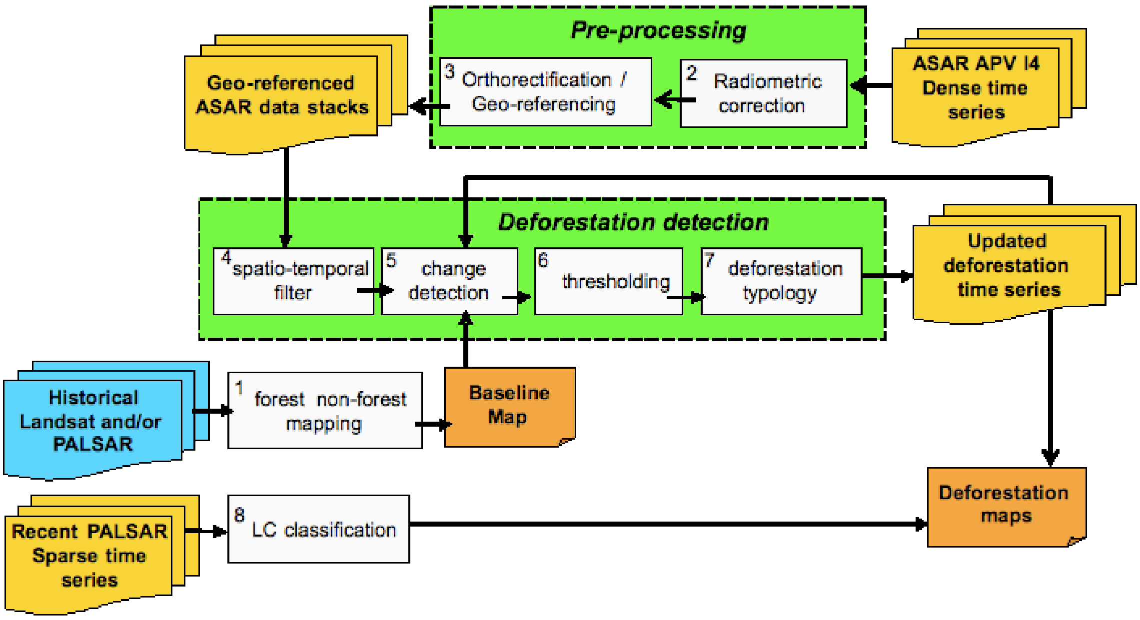

Figure 3.2 SAR data processing chain based on Envisat ASAR Alternating Polarisation data

Figure 3.2 shows the system processing chain based on Envisat ASAR Alternation Polarisation (APV) data. The main input is a time series of SAR images, which will be continuously updated as new images are added. Other inputs are reference data sets to be used for forest / non-forest masking and co-registration. The pre-processing takes care of basic image calibration and geocoding. Output data will be co-registered and radiometrically levelled to a multi-temporal stack of SAR data. Speckle reduction is needed; otherwise speckle noise will be interpreted as forest change by the change detection algorithm.

Multi-temporal filtering of radar images can decrease the effect of speckle significantly (Quegan and Yu, 2001 [6]). Best results are obtained with adaptive filters like the modified Lee filter (Lopes et al., 1990 [3]). This technique is included in step 4, Spatio-Temporal Filtering, of Figure 3.2, using a Structured Lee algorithm.

The change detection itself is based on a forest / non-forest baseline map. This may be a pre-existing product provided by the user, or one derived on an *ad hoc* basis from satellite data. It has been shown (at the GEO-FCT demonstrator site SUM-2, Harapan) that reasonable results can be derived without a baseline, but in areas where surface changes relating to other causes are significant, a mask is preferable as a starting point.

Both polarisation changes and backscatter intensity changes will be analysed and classified as the most likely forest change class. Determining the sensitivity and accuracy with which degradation /

deforestation changes can be identified in different forest environments is key to successful classification.

The same change detection techniques will be applicable to VHR data.

3.2.2 Optical system

Standardised pre-processed scenes are the input for a forest disturbance monitoring system as demonstrated in Figure 3.3. This monitoring framework consists of raw inputs (raw image data), processes (image processing steps), intermediate inputs (pre-processed and ancillary data) and outputs. An important component of this monitoring system is a very accurate forest benchmark map as intermediate input that represents the forest area for the monitoring starting point (t0). There are two options to derive such forest benchmark map, either through a land cover classification by the use of bi-temporal data (two images are most likely needed for filling data gaps resulting from cloud cover), or from other sources that provide an already existing forest benchmark map (e.g. from national authorities). If such existing maps are up-to-date, have a sufficient accuracy and a similar spatial scale as the image data used in the monitoring system, this option is preferable (option 1 in Figure 3.3). The forest benchmark map is subsequently used as the basis to indicate forest disturbance (deforestation and forest degradation) by repeated monitoring.

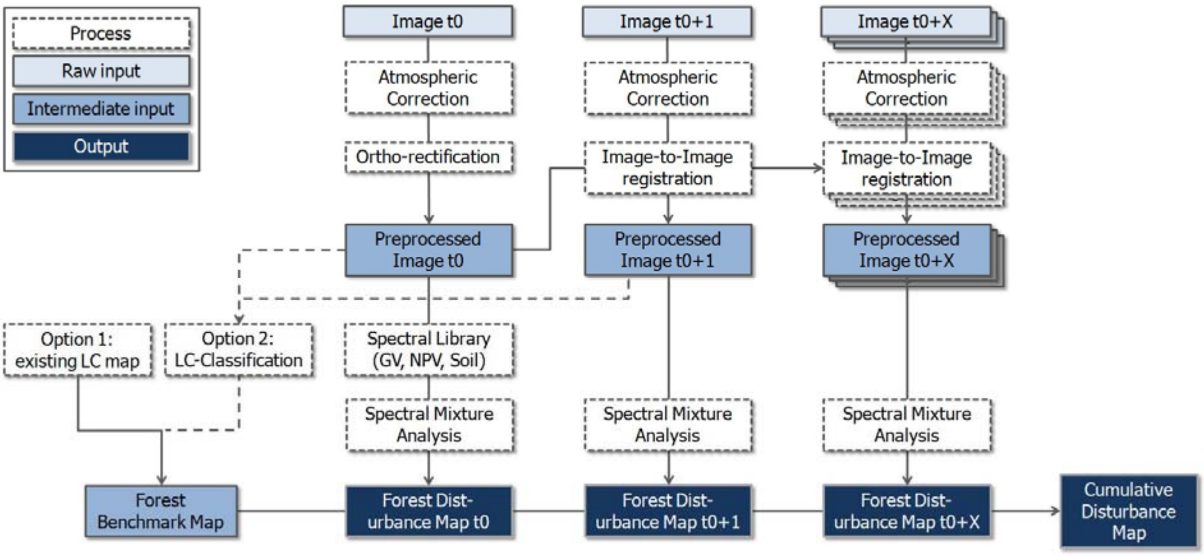

Figure 3.3 Example of a forest change detection system based on optical data
Dashed lines represent optional processes.

Since areas with degraded forests cause a mixed pixel problem due to the presence of different land cover types within a single pixel (e.g. photosynthetic active vegetation (GV), non-photosynthetic vegetation (NPV), soil, shade etc.), SMA analyses have a high potential to derive forest parameters from remote sensing data (Souza Jr. et al. 2005 [7]; Asner et al. 2009 [2]). A linear SMA assumes that each pixel spectrum is a linear combination of a finite number of end members (Adams et al. 1986 [1]). Ideally, the end member represents the signature of a pure component. These end members can be directly derived from the image t0 (spectral library) and subsequently used for the spectral mixture analyses of all subsequent images (if consistently pre-processed).

Based on the forest benchmark map and the end member fractions derived from the spectral mixture analysis, the final classification of forest disturbance can be conducted for each scene by thresholding the GV, NPV and soil fractions. The result is a forest disturbance map (within the forest area given by the forest benchmark map) for each observation date. By the use of these maps, a cumulative forest disturbance map can be iteratively generated during the monitoring period.

3.3 Dataset overview

Table 3.2 gives an overview of the data available for mapping and monitoring during the REDD-FLAME project. All data were supplied as part of the Earth Observation Data Access Portfolio (DAP), part of the GMES Space Component (GSC) (otherwise known as the GMES Data Warehouse), and the consortium acknowledges this arrangement and its contribution to the overall success of the project.

The SAR change detection algorithm requires a stack of SAR images as input. Real changes need to be discriminated from radar speckle noise and slow trends of degradation must be detected as well. The algorithm works better with substantial time series of at least 5-6 acquisitions: shorter time series will yield more false alarms since noise cannot be properly calibrated.

The RADARSAT-2 HR SAR time series include almost every viewing opportunity at intervals of 24 days. Since acquisition only began after the failure of the ESA Envisat mission, HR SAR change detection was limited to July 2012 onwards.

	RADARSAT-2 S3 VV/VH	TerraSAR-X StripMap HH	RapidEye MSI
			26/07/2010
			02/11/2010
			21/10/2011
		07/02/2012	
		29/02/2012	
		22/03/2012	
		07/06/2012	
			09/06/2012
		10/07/2012	
	20/07/2012		
Mozambique		12/08/2012	
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	06/09/2012		
		14/09/2012	
	30/09/2012		
	24/10/2012		
		28/10/2012	
	17/11/2012		
	11/12/2012		
	28/01/2013		
	21/02/2013		
		09/08/2008	
		01/02/2009	
			22/05/2009
			10/02/2010
			21/06/2010
		06/02/2012	
		28/02/2012	
		21/03/2012	
		06/06/2012	
Indonesia	22/07/2012		
			29/07/2012
		31/07/2012	
	15/08/2012		
		02/09/2012	
	08/09/2012		
	02/10/2012		
	26/10/2012		
	19/11/2012		
	13/12/2012		
			09/07/2009
			14/05/2010
			24/05/2011
		12/03/2012	
		03/04/2012	
		25/04/2012	
			01/06/2012
		08/06/2012	
	09/07/2012		
	02/08/2012		
		13/08/2012	
Brazil	26/08/2012		
		04/09/2012	
		15/09/2012	
	19/09/2012		
		07/10/2012	
	13/10/2012		
	06/11/2012		
	30/11/2012		
	24/12/2012		
	17/01/2013		
		05/02/2013	
	10/02/2013		
	06/03/2013		

Table 3.2
REDD-FLAME dataset overview
All data provided by the GMES Data Warehouse
TerraSAR-X data in Brazil were divided between two stacks

3.4 Results

Some examples of REDD-FLAME system outputs are presented below.

3.4.1 Benchmark mapping

Using a spectral mixture analysis methodology applied to optical data (RapidEye or Landsat), forest / non-forest maps representing the forest extent at some moment in time were created by RSS. A minimum mapping unit of 0.5ha was applied to the forest area (according to the FAO forest definition). These “Benchmark Maps” were the basis for both optical and SAR change detection systems (see Figure 3.4).

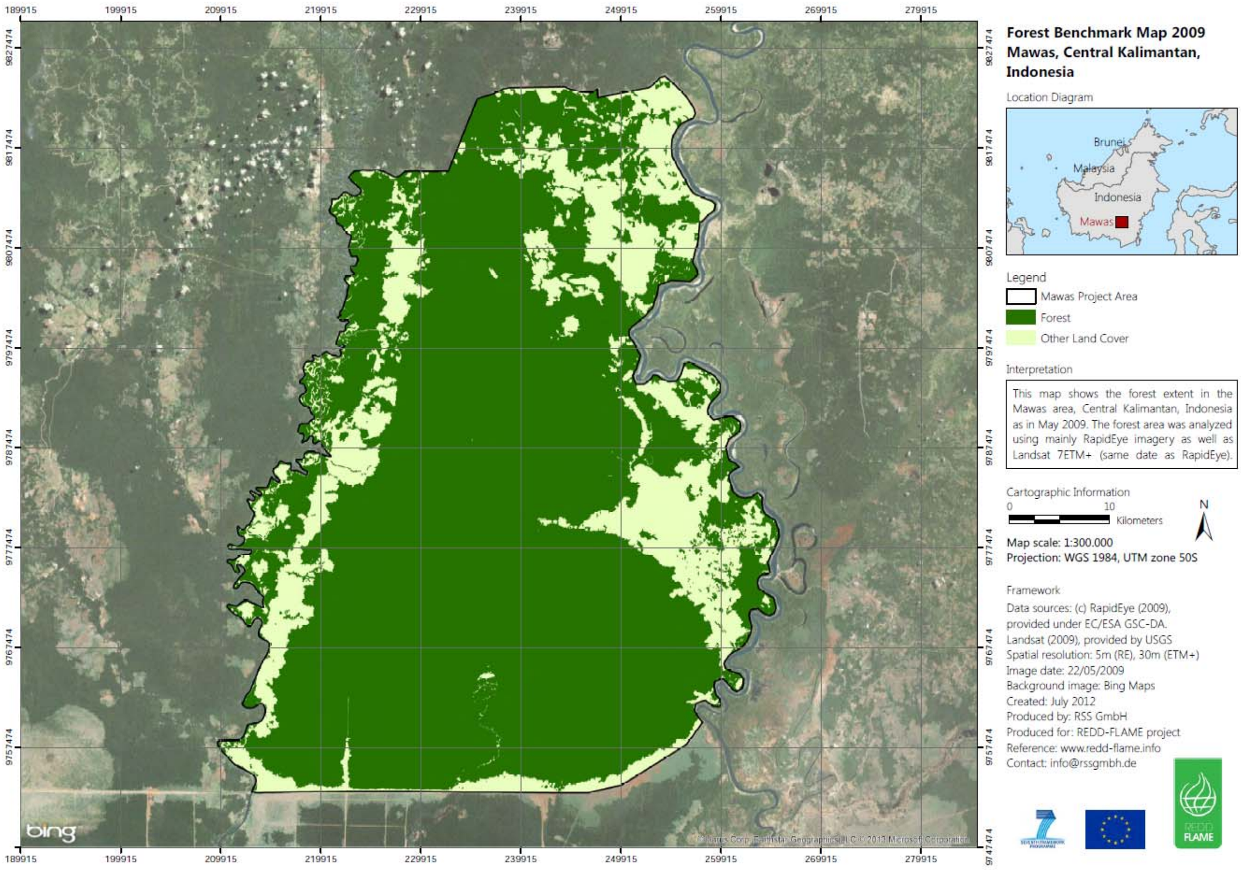

Figure 3.4 Forest Benchmark Map of Mawas, Indonesia
showing forest (green) and non-forest (light yellow) classes
The Forest Beanchmark Map is created using RapidEye and Landsat images, acquired on 22 May 2009

The distinction between forest and non-forest in the Mecuburi Forest Reserve of Mozambique is not clear, and some subjectivity is involved in setting thresholds at appropriate levels to achieve the most suitable output (Figure 3.6). Whilst wetlands are certainly non-forest, it is difficult to draw a line in the continuum between single-tier ‘open’ forest (including seasonal wetlands containing some woody biomass) and high, or ‘closed’, Miombo forest; for the purposes of REDD-FLAME, the forest class tends towards underestimation to eliminate open forest and minimise insignificant fringe areas considered in the subsequent change detection (Figure 3.5). The application of a minimum mapping unit also contributes to this effect. The benchmark map was evaluated during the field campaign later in the project; whilst a few errors were identified, the map was found to be good for the project’s purposes overall.

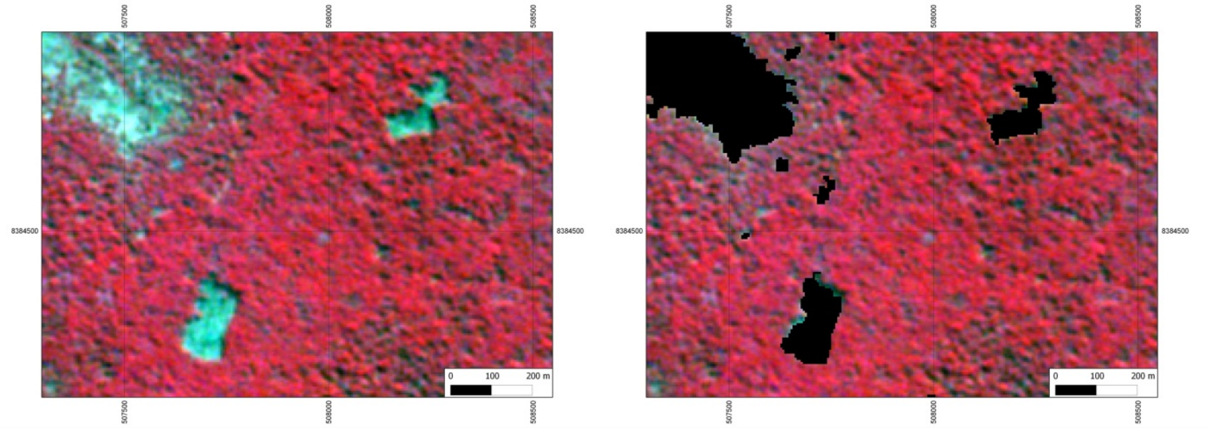

Figure 3.5 Derivation of the forest/non-forest benchmark using RapidEye imagery acquired on 9 June 2012, thresholds were set to mask out open single-tier forest, as well as wetlands, machambas and other non-forest classes in Mecuburi Forest Reserve, Mozambique

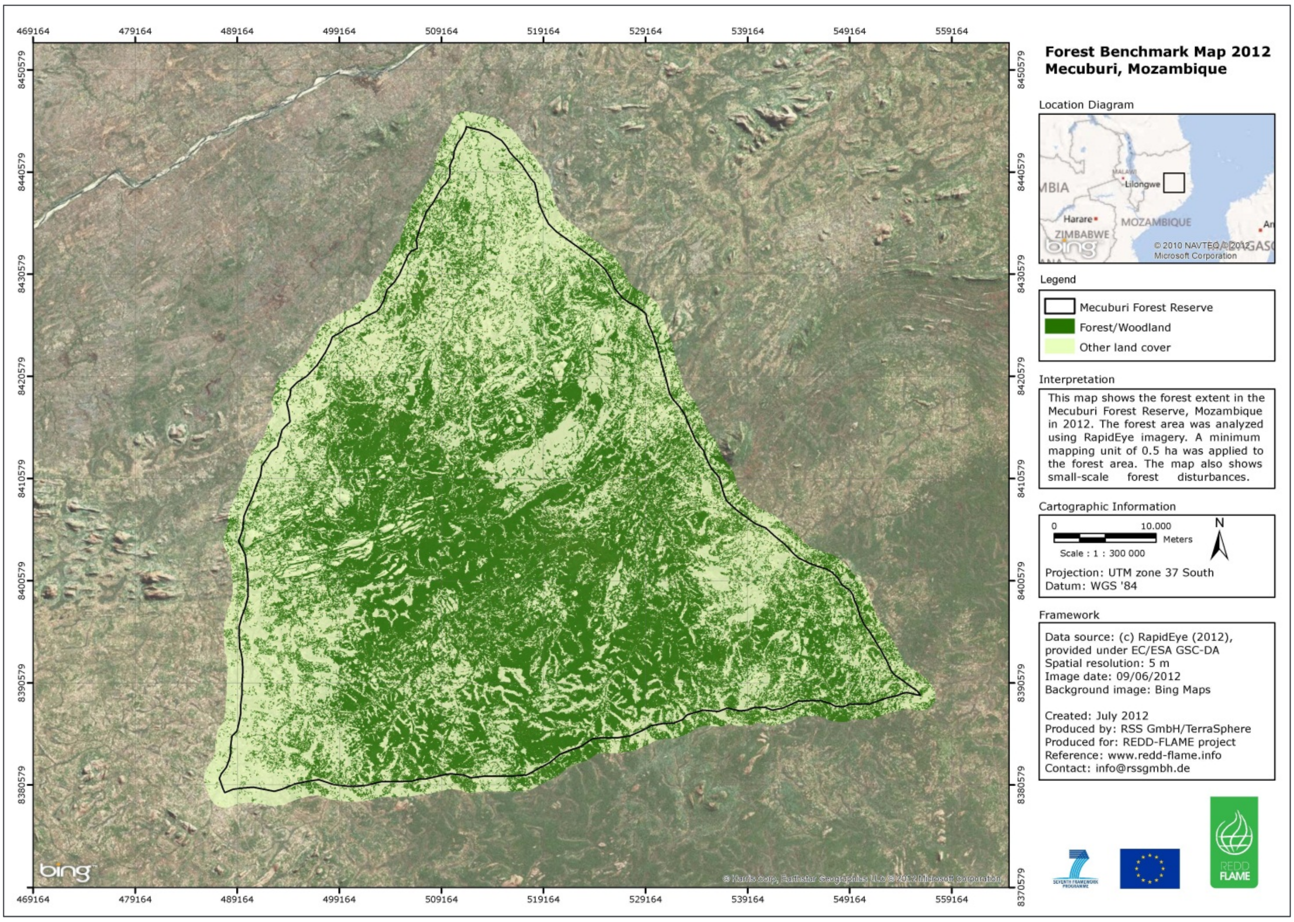

Figure 3.6 Forest Benchmark Map of Mecuburi Forest Reserve, Mozambique created from RapidEye image acquired on 9 June 2012

An independent statistical accuracy assessment and verification of results with reference data is an essential component of any classification. The accuracy assessment can be done via *in-situ* observations or with additional remote sensing data, preferably with higher spatial resolution than the originally classified data. The accuracy analysis should provide an accuracy matrix considering errors of commission and omission, the overall accuracy and the kappa index.

The accuracy of the RapidEye-based forest benchmark map for Mecuburi was evaluated by comparing it with the very high resolution image from Worldview-2. Since the forest benchmark map was created through an object-based image classification approach, the accuracy assessment must also be performed with an object-based approach. Within the area covered by the Worldview-2 image, 264 polygons that were segmented during the RapidEye-based forest benchmark classification were randomly selected and classified as forest or non-forest via visual interpretation using the 0.5m spatial resolution evaluation dataset (Figure 3.7). These reference data were subsequently compared with the classification and an error matrix was generated (Table 3.3). The achieved overall accuracy of the forest benchmark map is 83.3% with a Kappa coefficient of 0.61. Since there is a temporal gap between the acquisitions of the RapidEye and Worldview-2 images, an even higher classification accuracy is expected since some changes occurred in this period.

		WV-2 Reference class			
		Forest/ Woodland	**Other Land Cover**	**TOT**	***Users accuracy***
LC Class	**Forest/ Woodland**	**161**	35	**196**	*82,1*
	Other Land Cover	9	**59**	**68**	*86,8*
	TOT	**170**	**94**	***Total Correct = 220***	
	Producers Accuracy	*94,7*	*62,8*	***Total Samples = 264***	

Overall Accuracy	**83,3**
Kappa	**0,61**

Table 3.3 Confusion matrix for the Mecuburi forest benchmark map

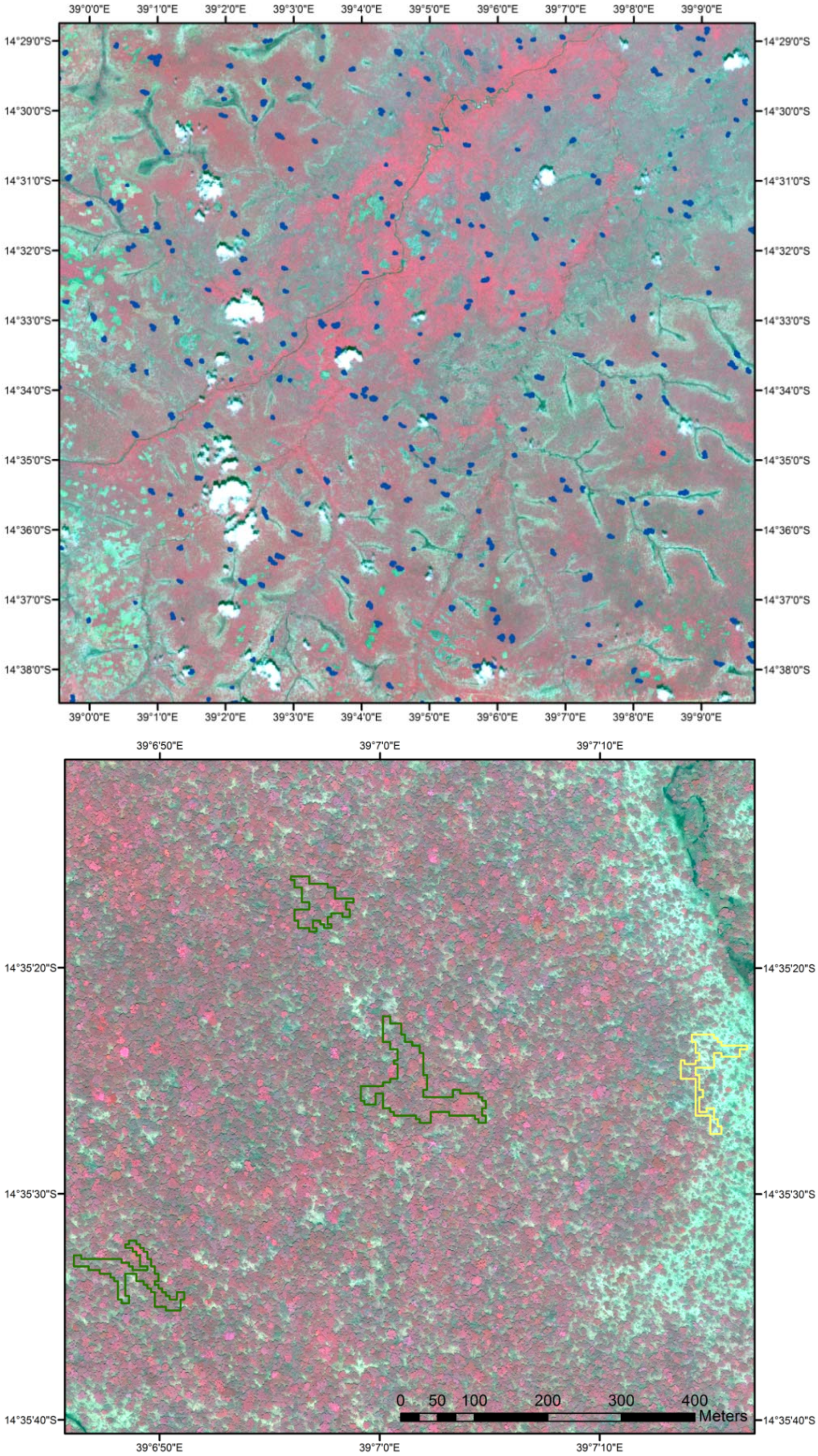

Figure 3.7 Independent statistical accuracy assessment of the Mecuburi forest benchmark map (top) 264 random polygons (blue) from the forest benchmark classification on which the accuracy assessment is based; (bottom) detailed example of some polygons categorised as forest (green) and non-forest (yellow) using the Worldview-2 image.

3.4.2 Optical change mapping

The results of the optical monitoring system, developed by RSS, are detailed forest disturbance maps (within the forest area given by the forest benchmark map) for each observation date. By the use of these maps, a cumulative forest disturbance map of Mawas, Indonesia, was generated during the monitoring period between 2009 and 2012. The high resolution of the RapidEye sensor of 5m allows for a detailed detection of small-scale logging activities. Figures 3.8 and 3.9 show examples of the optical change mapping results. The changes are colour-coded (see legend) to indicate the year of their detection by the system.

Figure 3.8 shows an example with different detected phenomena. Along the Kapuas River at the western edge of the Mawas area, the dominant forest type is riparian forest which is in some parts intensively used for agroforestry. The forest cover changes between 2009 and 2012 due to agroforestry were clearly detected by the monitoring system. Further east of the Kapuas River, the dominant forest type is peat swamp forest, where various human-induced changes were detected such as deforestation (mainly patches of deforestation along the forest edge) as well as selective logging (mainly small-scale illegal logging). Some non-human induced changes were detected in the peat swamp forest, which are likely to be “natural changes” due to dead trees, regenerating areas or flooding of the swamp area.

Figure 3.9 shows a change map result of a forest area which was intensively logged through small-scale illegal logging.

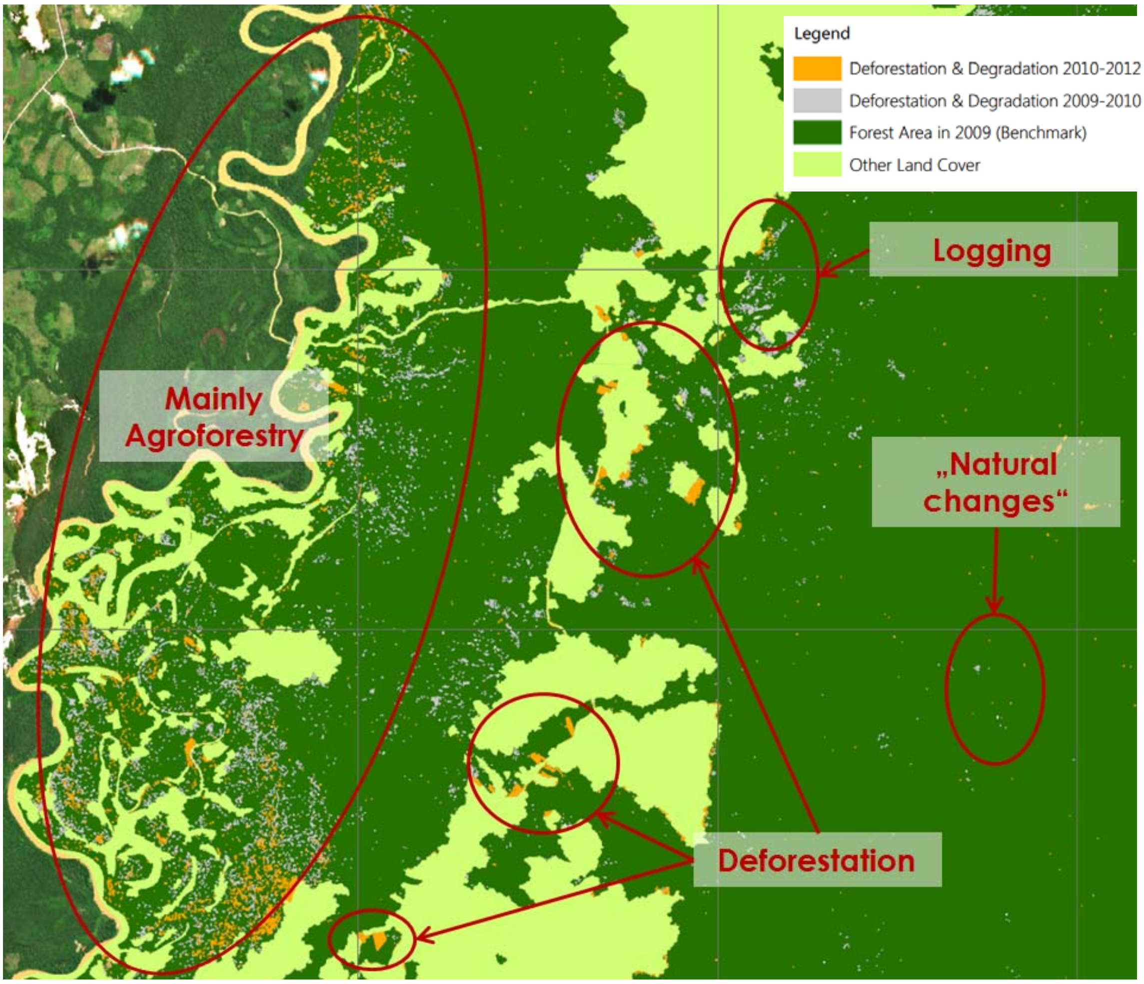

Figure 3.8 Example of the forest cover change mapping using RapidEye in the Mawas area (1)

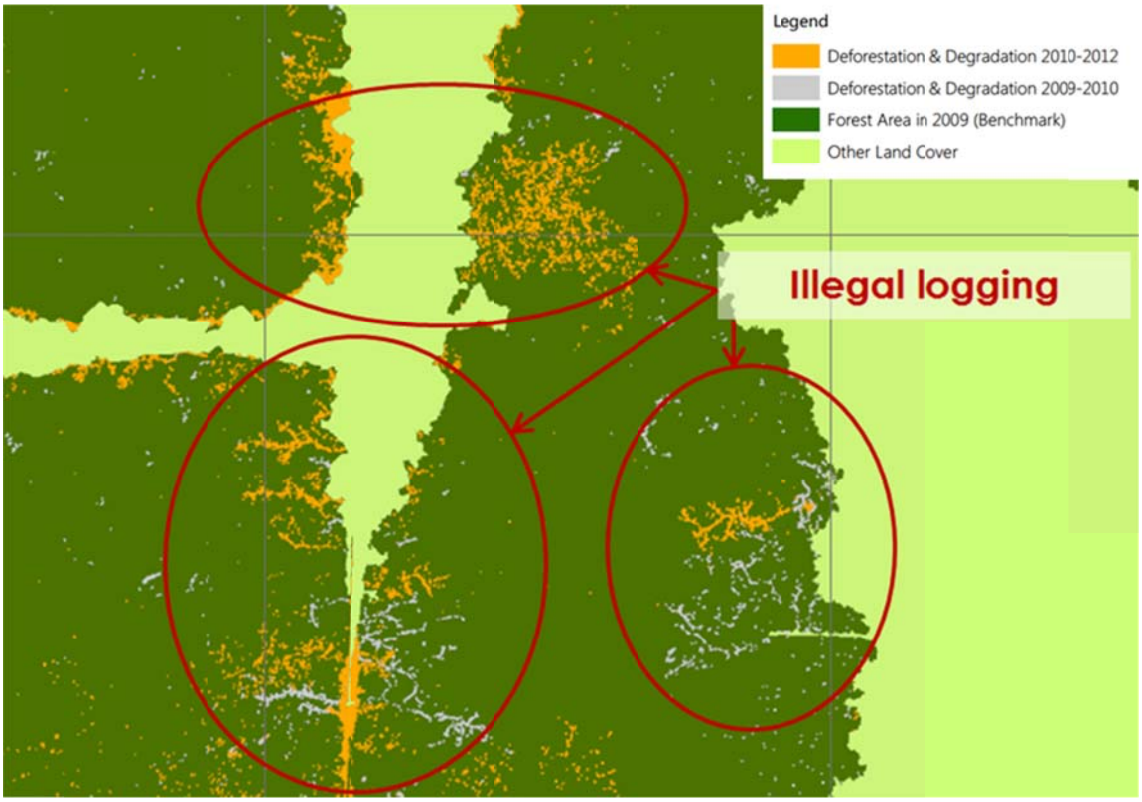

Figure 3.9 Example of the forest cover change mapping using RapidEye in the Mawas area (2)

Reporting the accuracy of image analysis results is an essential component of a monitoring system, whereby accuracies can be assessed by the use of in-situ observations or the analysis of very high resolution aerial or satellite data. Whereas the conducted field work provided qualitative information about the characteristics of existent forest disturbances, in-situ mapping of illegal logging was not feasible due to security reasons. Therefore, a GPS-coded video recorded during a flight campaign in 2010 that was conducted by RSS GmbH for a quantitative assessment of illegal logging was used. An example can be found in Figure 3.11 which displays aerial images of narrow logging trails in a peat swamp forest that demonstrates the suitability of very high resolution aerial imagery for a reliable identification of logging activities. Based on the GPS-coded video frames, 246 stratified reference sample points representing non-forest, forest and logging trails were set (Figure 3.10). These sample points were subsequently used for the accuracy assessment of the cumulative forest disturbance map.

Table 3.4 shows the result of the accuracy assessment of the cumulative forest disturbance map. An overall accuracy of 91.5% was achieved with a mean class accuracy of 90.3% and a Kappa coefficient of 0.87. The classes non-forest, forest and logging trails had an accuracy of 90.6%, 98.0% and 82.3% respectively. The highest confusion occurred between logging trails and forest, which is characterised by a lower producer accuracy of the degraded forest class of 82.3% and a lower user accuracy of the forest class of 83.6%. This is likely caused by the two-month time lag between the 2010 classification date and the date when the reference data was collected. Logging which occurred in these two months is included in the reference data but not in the classification. The achieved accuracies demonstrate that the monitoring approach is suitable to provide reliable activity data on logging and fire.

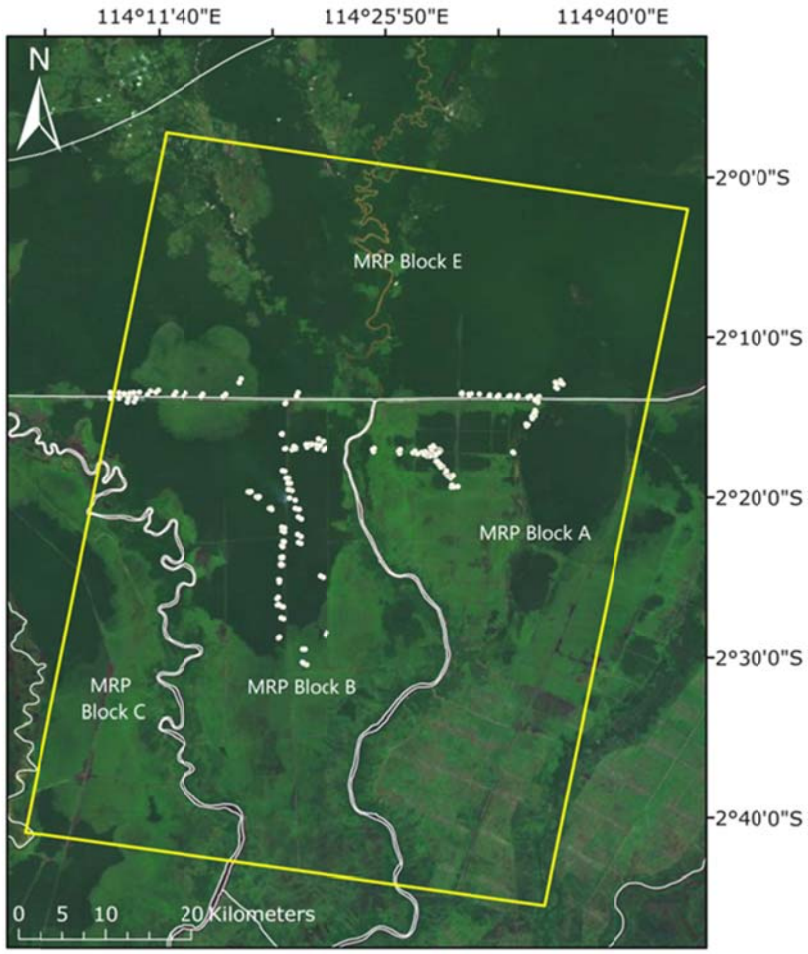

Figure 3.10 Overview of the Mawas flight campaign conducted by RSS in 2010 with the outlines of the former MRP blocks and the 246 reference sample points. Background: ESRI World Imagery.

Overall Accuracy = (225/246) 91.5 %
Mean Class Accuracy= 90.3 %
Kappa Coefficient= 0.87

	Reference sample class				
Class	**Non Forest** (n=85)	**Forest** (n=99)	**Logging trail** (n=62)	Producer Accuracy	User Accuracy
Non	**90.6 %**	1.0 %	0.0 %	90.6 %	98.7 %
	9.4 %	**98.0 %**	17.7 %	98.0 %	83.6 %
Logging trail	0.00 %	1.0 %	**82.3 %**	82.3 %	98.1 %
Total	100.0 %	100.0 %	100.0 %		

Table 3.4 Classification accuracies for optical change detection in the Mawas area giving the overall accuracy, the mean class accuracy, the Kappa coefficient, the class confusion matrix and the producer and user accuracy

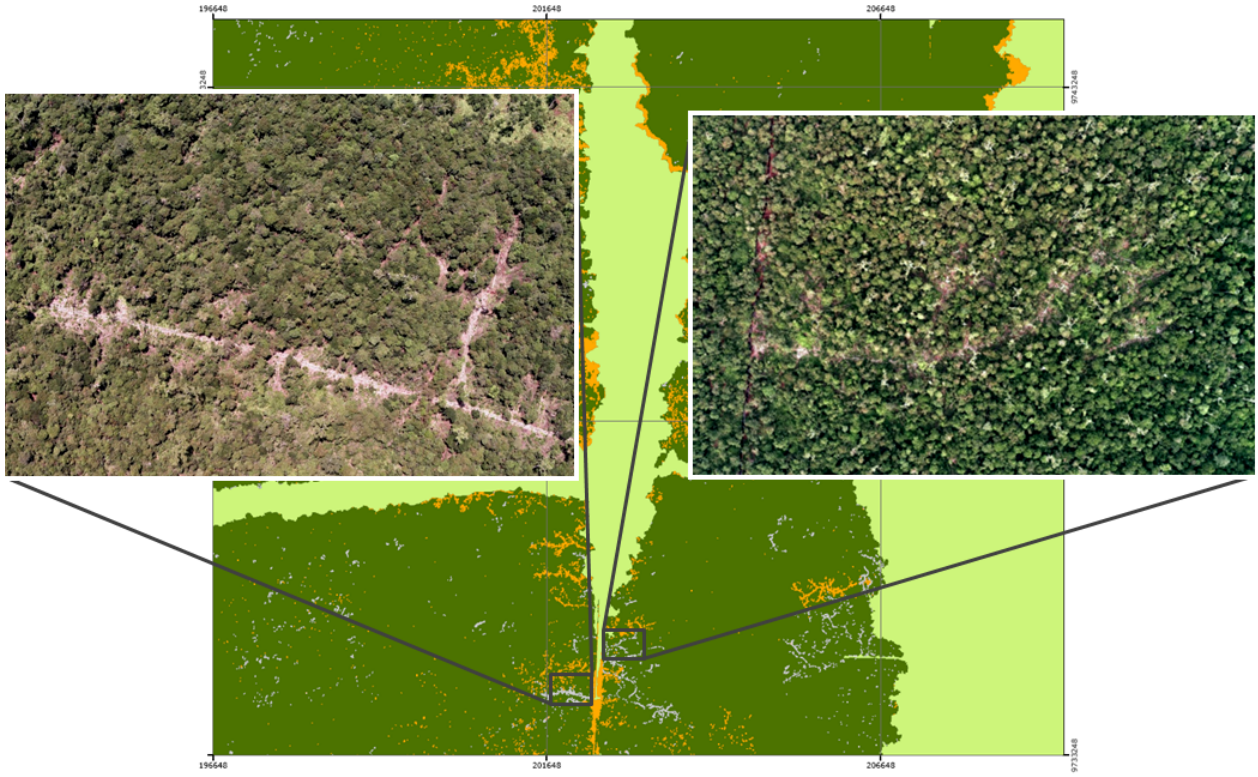

Figure 3.11 Examples of aerial images taken over the Mawas study area with indication of locality in the change map product

3.4.3 SAR change mapping

SAR Change Map Products are produced by SarVision. Output from the change detection algorithm is a series of change maps for intervals between consecutive SAR image acquisitions, which are aggregated into a thematic map.

In all cases, maps show undisturbed forest (green) and areas where land cover change is detected (various blues and oranges). Change is classified according to the date on which deforestation occurred. An additional class for ‘prior deforestation’ highlights any areas not masked as non-forest by the benchmark map where the SAR data suggest deforestation occurred before the first SAR image of the time series, or that reforestation is occurring.

The legend of standard classes is shown in Figure 3.12. Shades of blue and orange correspond to date ranges between consecutive data acquisitions in time series when changes were first detected at a particular location. The same colour schemes are used for SAR change map products throughout this report.

	non-forest (as defined in the Forest Benchmark Map)
	Undisturbed forest
	Prior deforestation / reforestation

Figure 3.12 Legend of standard classes in Change Map Products

Regardless of the frequency of product delivery, all maps show a cumulative history of change over an extended period. This is effectively Trends Information; Events Information showing changes pertaining to just one interval in the time series – the most recent – can be inferred by considering a single class of the change date legend.

A change map of the Sete de Setembro Indigenous Land in Brazil derived from RADARSAT-2 data shows a number of recent changes, mostly along the west border of the area (Figure 3.13). Also major changes were found at the east side of the area, probably due to fires. A field mission by ECAM took place between 26 November and 6 December 2012. This date range is covered by the Radarsat time series, so these changes were able to be verified.

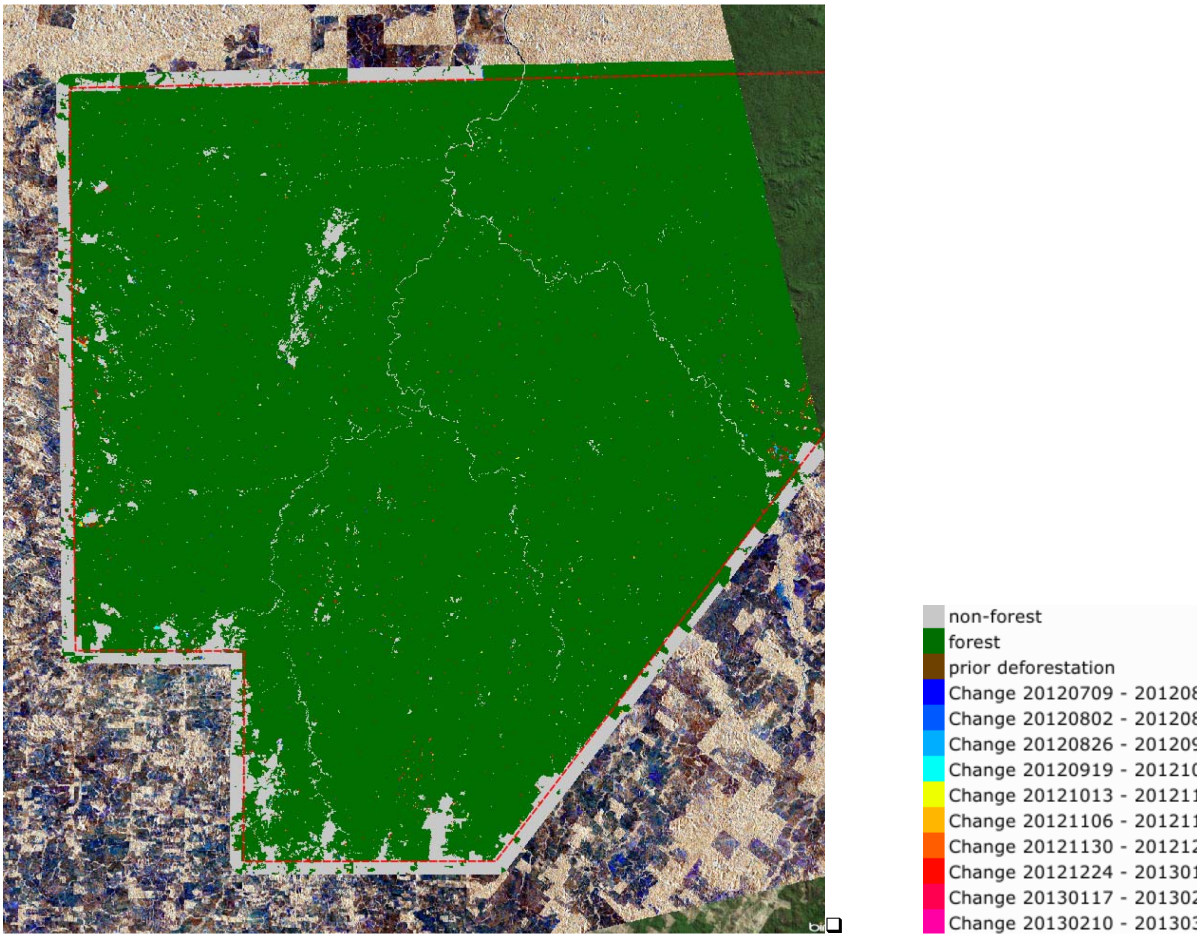

Figure 3.13 Radarsat-2 change map of the Sete de Setembro Indigenous Land, Brazil

VHR SAR change mapping of the Mecuburi Forest Reserve, Mozambique, uses TerraSAR-X StripMap data. The data stack covers only the western part of the Reserve (Figure 3.14). HR SAR change mapping uses a stack of RADARSAT-2 Standard Beam mode 3 data, which fully covers the Reserve (Figure 3.15).

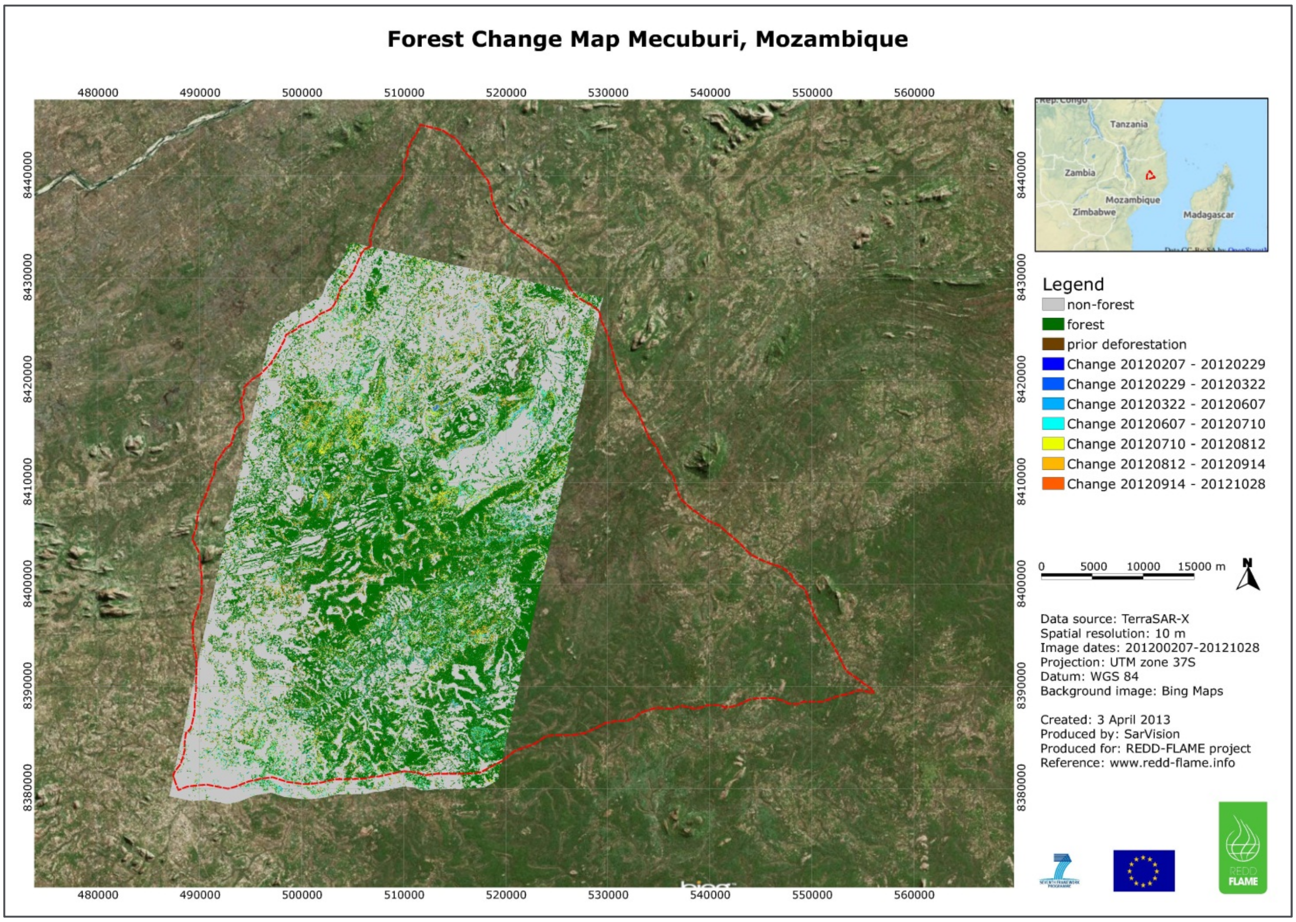

Figure 3.14 Change Map Product of Mecuburi Forest Reserve derived from TerraSAR-X data

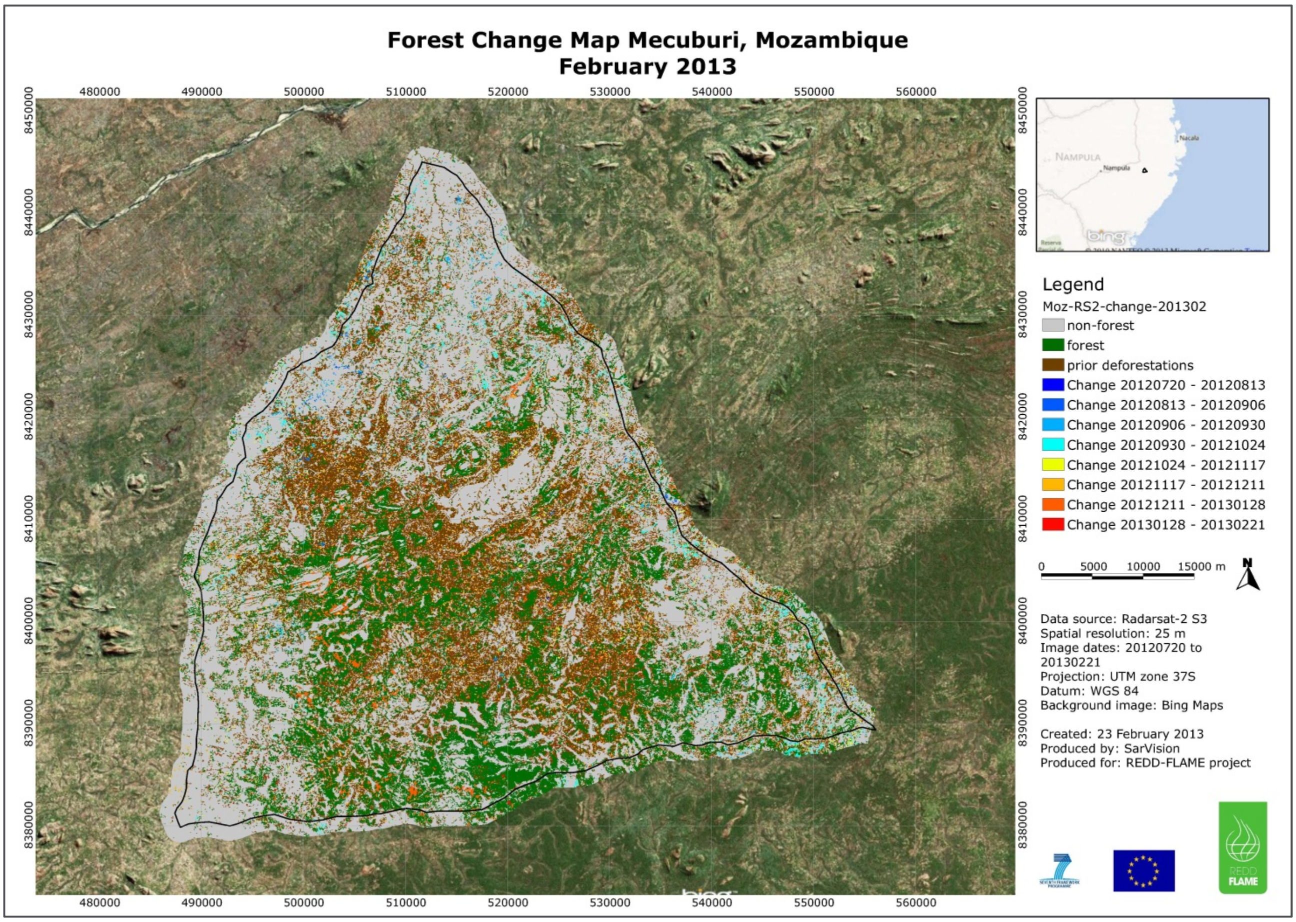

Figure 3.15 Change Map Product of Mecuburi Forest Reserve derived from RADARSAT-2 data

Field evaluation was performed during the week of 12 November 2012, when RSAC staff visited the Mecuburi Forest Reserve in the company of Sosdito Mananze of UEM and Aly Awasse, Community Forest & Wildlife Management Unit Co-ordinator in the Provincial Forest & Wildlife Service, Nampula (Figure 3.16).

Figure 3.16 Field evaluation campaign in Mecuburi Forest Reserve, November 2012

Sites were selected for field evaluation based on visual analysis of the change map products available, together with an assessment of accessibility.

Given that the first versions of the change map products, especially those derived from TerraSAR-X data, were quite noisy, manual filtering was necessary to identify those features most likely to represent real deforestation features. The following criteria were used:

- homogenous areas of change with consistent or consecutive change time periods;
- agreement between TerraSAR-X and RADARSAT-2 change maps;
- unbroken tree cover in earlier optical satellite images;
- evidence of disturbance in latest optical satellite image;
- evidence of access route.

The evaluation approach adopted involved confirming the occurrence of deforestation where this had been mapped. Once in the vicinity of a selected site, other mapped change features were also checked for veracity, whilst any evidence of deforestation or degradation found on the ground was compared with the maps to determine whether it had been included.

A further evaluation activity involved confirming the benchmark map classification at random locations. Throughout the field campaign, the change map products were evaluated in terms of utility and usability.

Change map products, plus optical satellite images and source SAR data, were stored on a GPS-enabled tablet PC. The location of the field party on any of the data layers was able to be displayed in real time, thus allowing accurate and reliable navigation and data verification (Figure 3.17).

Figure 3.17 Use of tablet PC for navigation in the field

One of the selected evaluation sites appeared on the June 2012 RapidEye image as a clearing of 1.4ha and was duly masked out in the forest/non-forest benchmark map. Since the July 2010 RapidEye image showed no evidence of the clearing, it was inferred that the area was cleared in late 2010 or 2011. Both the RADASAT-2 and TerraSAR-X change map products show change dated at October 2012 in an area to the west of the original clearing. A multi-temporal composite of TerraSAR-X images and the September 2012 RapidEye image both show larger homogenous areas than the originally masked clearing (Figure 3.20).

On visiting the site, it was found that the whole area has been recently cleared of all but the largest standing trees and burnt ready for cultivation (Figure 3.18). There was no visible distinction between the ‘older’ (masked) clearing and the new mapped area of change; the evidence suggests that clearing activity was actually on-going at the time of the June 2012 RapidEye acquisition and has been completed in the weeks before the field visit. This hypothesis is supported by temporal profiles of radar intensity in each part of the clearing (Figure 3.19). The burning is very recent indeed: on the day of the field visit (14 November 2012), larger logs were found still smouldering.

The total area of the enlarged clearing is about 4.4ha. The deforestation is clearly detected by the radar data in this case of homogenous large-scale clearance.

Figure 3.18 Evidence of recent forest clearance and burning in Mecuburi Forest Reserve

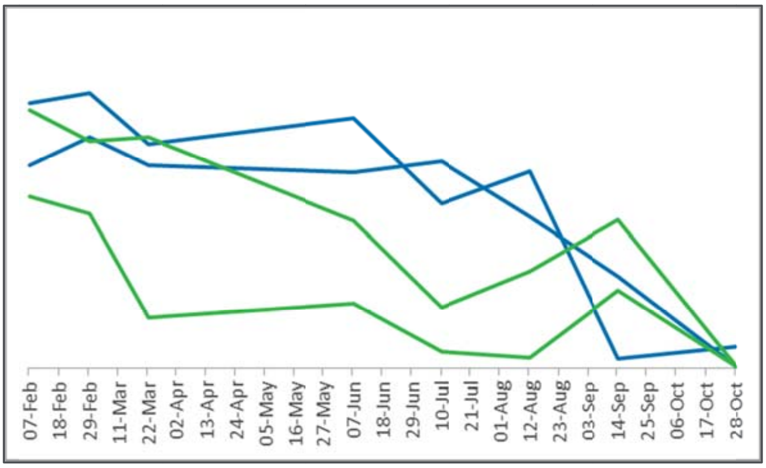

Figure 3.19 TerraSAR-X temporal profiles for a clearing in Mecuburi Forest Reserve
(green) 'older' (masked) clearing showing drop-off in intensity between February and June (continuing into July)
(blue) area of new change showing later drop-off in intensity

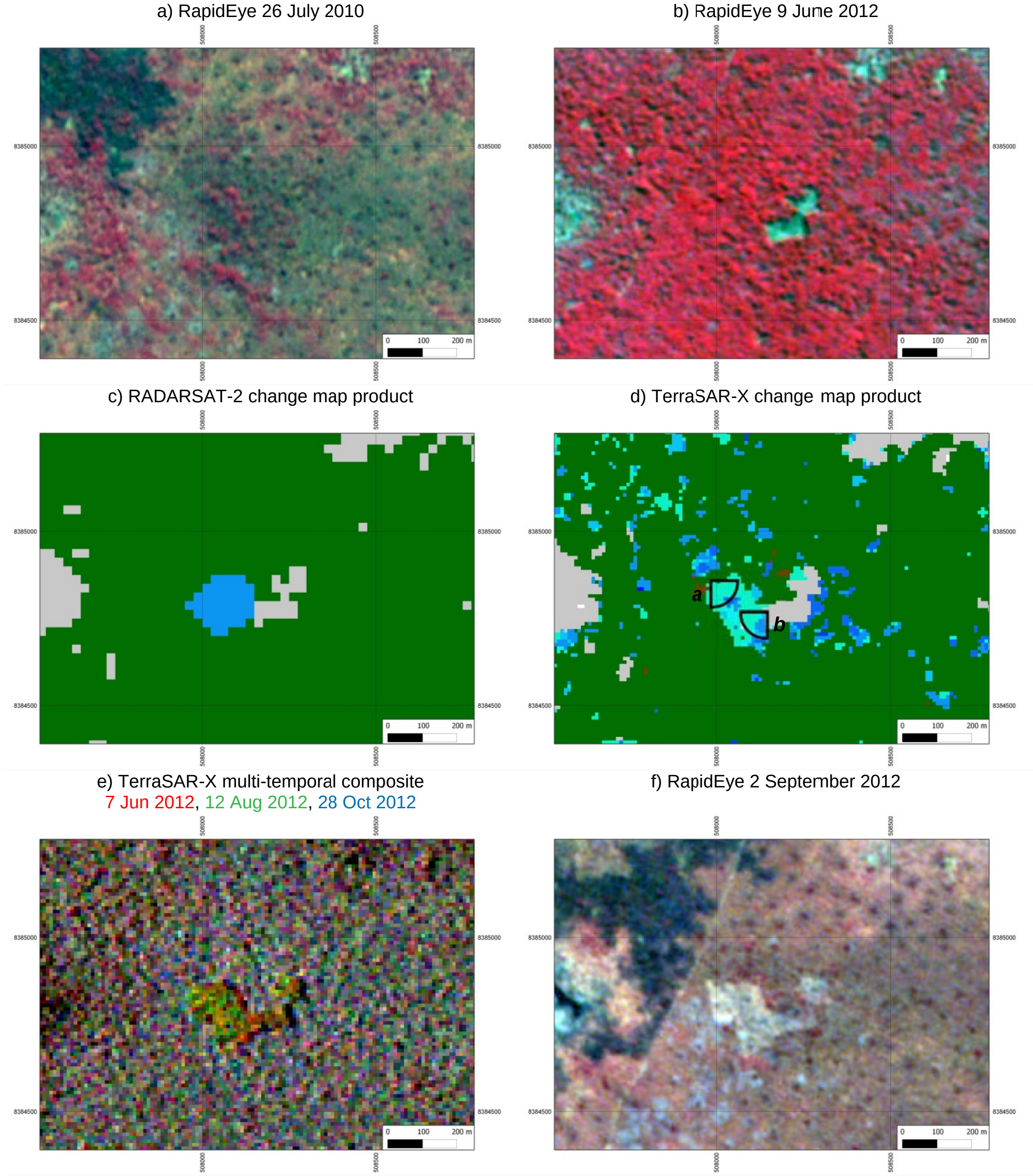

Figure 3.20 Maps and images of a very large clearing in Mecuburi Forest Reserve

Validation points were collected from optical imagery available over the Mawas area to statistically analyse the SAR change maps. RapidEye (5m) and Landsat (30m) images were selected as reference data for validation. The selection of sample locations was carried out randomly and independently from the TerraSAR-X and RADARSAT-2 data sets and change maps. The RapidEye image was acquired on 29 July 2012, the Landsat images chosen to correspond with the SAR changes. The Landsat images were not useful for validation, as too many clouds and artifacts reduce the set of validation points drastically to be statistically irrelevant. Table 3.5 shows the SAR and optical data sets, and their acquisition dates.

TerraSAR-X	Radarsat-2	RapidEye	Landsat
20080809			20081010
20090201			20090207
20120206 20120228 20120321 20120606			
20120731	20120722	20120729	
	20120815		
20120902	20120908		
	20121002 20121026		
	20121119		20121106
	20121213		

Table 3.5 SAR and validation data for Mawas, with acquisition dates (yyyymmdd)
Blue- highlighted scenes cover both SAR stacks and an optical validation set (in casu RapidEye). Landsat appeared to be less useful for validation due to SLC-off artefacts and cloud cover

Figure 3.21 shows graphically the validation approach. By visual interpretation, polygons were digitised in each optical image for forest and non-forest classes, and labelled accordingly. A sufficient distance (more than 2 pixels) from the edges between different land cover classes was taken into account. This was done in order to reduce the influence of mixed pixels.

In practice, only the RapidEye image from 29 July 2012 appeared to be useful for validation. The Landsat scenes did not provide enough useful validation samples due to sensor artefacts and cloud cover. Figure 3.22 shows the RapidEye image and the validation polygons (yellow).

The TerraSAR forest / non-forest map was derived from the Forest Benchmark map and the changes detected in the TerraSAR-X time series between August 2008 and July 2012 (later changes were ignored). For RADARSAT-2, only deforestations until 22 July 2012 were taken into account for validation. These forest / non-forest maps were compared with the samples taken from the RapidEye image and put into a confusion matrix (Table 3.6).

The tests were done with and without the information from the Forest Benchmark Map, the latter representing forest / non-forest at 22 May 2009. The validation accuracy without the Forest Benchmark map is much worse, because all pixels were assumed to be forest at the start of the time series. This explains the large percentage of points being wrongly set to forest. Having a forest/non-forest mask in advance, accuracies are much better, above 90%. Of course this validation only represents one moment in a series of changes. For proper validation of the entire time series, good validation data should be available for all moments.

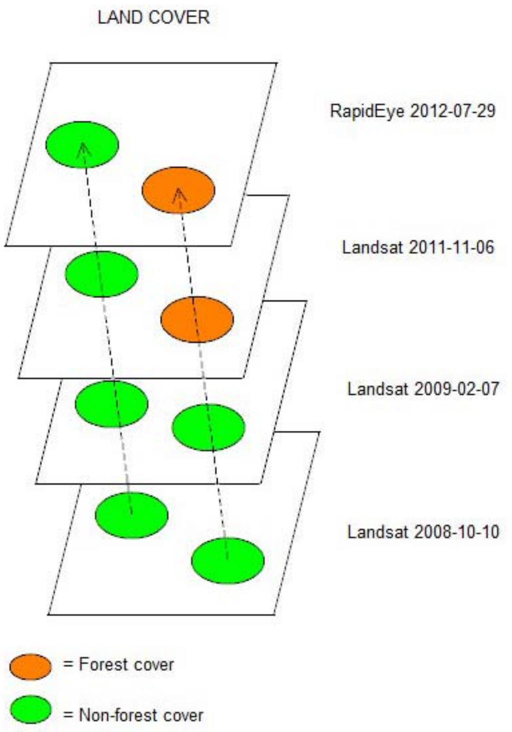

Figure 3.21 Sampling of the validation polygons having forest or non-forest label for each of the dates: in the example shown, only the RapidEye image from 29 July was used, Landsat scenes contained too many clouds.

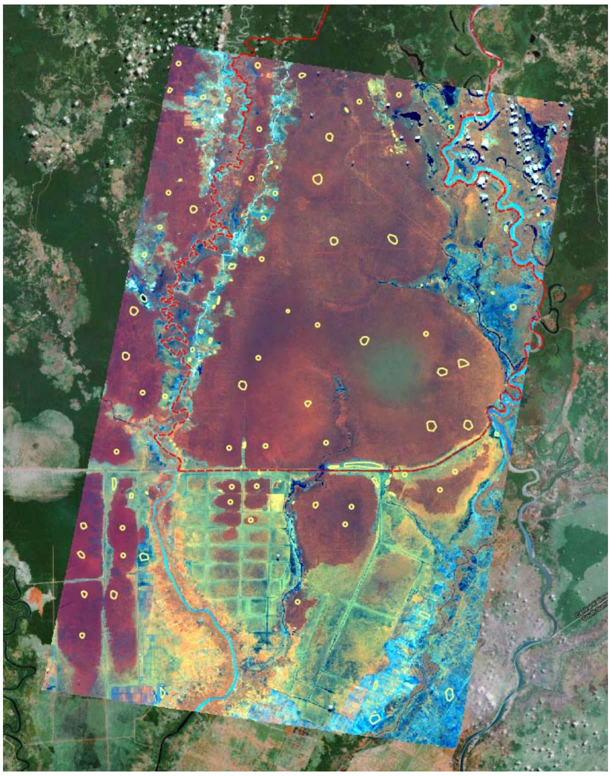

Figure 3.22 Location of sample polygons (yellow) over the Mawas area, overlaid on the RapidEye image from July 2012. Forest appears in red-brown colours.

		Reference data set: RapidEye 29 July 2012			
		Without mask		With mask	
SAR data set	**class**	**Forest**	**Non-Forest**	**Forest**	**Non-Forest**
TSX 2008-2012	Forest	61%	25%	63%	1%
	Non-Forest	0%	13%	0%	35%
	Over-all accuracy	74%		98%	
	Kappa	0.3838		0.9587	
TSX June-Sept 2012	Forest	62%	38%	63%	3%
	Non-Forest	0%	0%	0%	34%
	Over-all accuracy	62%		97%	
	Kappa	0.0131		0.9369	
Radarsat-2 July-Dec 2012	Forest	60%	28%	68%	3%
	Non-Forest	0%	12%	0%	30%
	Over-all accuracy	72%		97%	
	Kappa	0.3429		0.9341	

Table 3.6 Confusion matrix of forest and non-forest classes in SAR Change maps of Mawas compared to forest and non-forest classes found in the RapidEye image from 29 July 2012. Also overall accuracy and Kappa is calculated. This is done with and without using information from the Forest Benchmark Map (forest/non-forest mask).

3.5 Conclusions

Large clear-cuts could be easily detected by the REDD-FLAME system. Small scale deforestations, old and new, were also successfully detected in both HR and VHR optical and SAR time series. Removal of individual small trees is not detected by the REDD-FLAME change detection systems when larger trees are nearby.

Logging trails are visible in VHR data sets, but were not detected by the VHR SAR change detection system. Automatic detection of linear features has been demonstrated but is not yet implemented in the change detection algorithm.

Accuracy assessment of a change detection system using independent optical reference data sets was hampered by cloud cover and artefacts such as Landsat ETM SLC-off. Validation of the SAR change maps was done using single optical images. Though accuracy is good, this validation covers only one moment in a long time series. Validation of optical data was based on aerial photos, and also yielded good accuracies.

Preliminary results of extensive research at the GEO-FCT test site at Harapan on Indonesian Sumatra indicate that the system is sufficiently accurate for official reporting, as the accuracy is higher than 85%. The false alarm error was quantified as 3.2% ± 2.2% (at the 95% confidence level) and the missed classification error as 10.0% ± 2.1% (at the 95% confidence level).

4 EXPLOITATION OF RESULTS

4.1 Dissemination activities

4.1.1 Logo

A project logo was professionally designed for use as an eye-catcher on all publications, the project website, brochure and newsletters (Figure 4.1). The logo is designed to be simple and direct, easy to remember and reflect the nature of the work that the REDD-FLAME project is engaged in.

Figure 4.1 The REDD-FLAME project logo

4.1.2 Website

A website has been established where the project, the consortium and REDD are explained:

http://redd-flame.info

A smartphone (mobile) version of the website is also available (see Figure 4.2).

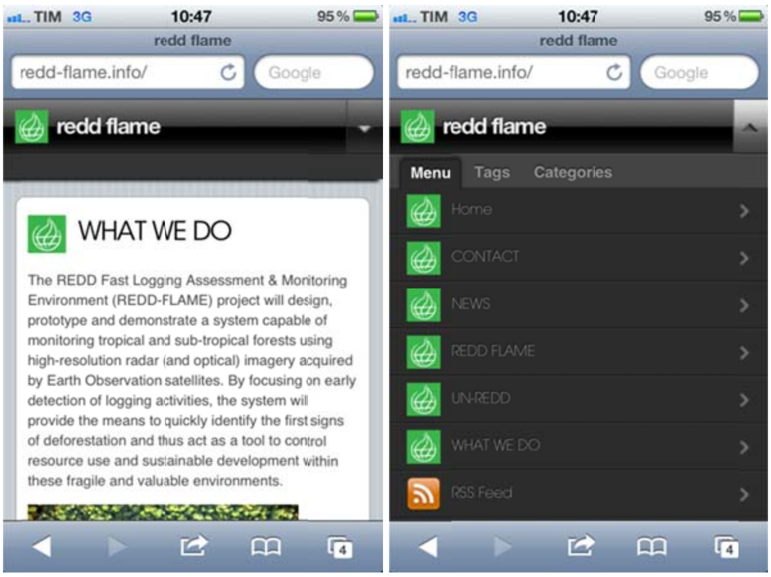

Figure 4.2 Mobile version of the project website

News on the project, new publications (including newsletters, project brochure, promotional video and scientific publications), announcements, and all mapping results can be viewed on the website. All maps and publications are viewable and downloadable as PDF files.

4.1.3 Newsletters

Newsletters have been produced on a 6-monthly basis (or otherwise appropriate based on project status) to describe the progress of the project and give information on related developments and plans for the future. The newsletters were distributed as a PDF by email, and are available to download from the project website (under the Publications tab).

4.1.4 Workshops

The REDD-FLAME project successfully organised an international series of workshops in early 2013, held on 31 January in Bogor Indonesia, 27 February in Maputo, Mozambique and on 20 March in Brasilia, Brazil. The 1-day workshops showcased the main results of the project and made recommendations for operational implementation.

With the participation of representatives from government, NGOs, local stakeholders and experts in the field of sustainable development of tropical forest ecosystems, the workshops gave an ideal opportunity to exchange knowledge and ideas, strengthen links between these groups, and build on the capacity for forest monitoring and management in each of the host countries.

Figure 4.3 Photos of the Final Workshops
top: Maputo, Mozambique; bottom: Bogor, Indonesia

The objectives of the Workshops were to:

- present the results of the system evaluation and other findings of the project;
- provide guidance on the interpretation of REDD-FLAME outputs;
- demonstrate how the system could be integrated into national forest monitoring systems;
- discuss the future of UN-REDD and REDD-FLAME.

An aggregate total of approximately 120 people attended the workshops in the three countries. A short impression of the workshops can be viewed on the project website (under the About > News tab), including some photos (see also Figure 4.3).

Proceedings from the three Final Workshops are published on the project website for viewing and downloading (under the Publications tab).

4.1.5 International conferences

Dirk Hoekman (WU), Mike Wooding and Richard Metcalfe (RSAC) attended the Third Science and Data Summit (SDS) of GEO-FCT in Arusha, Tanzania, from 6-10 February 2012. Dr Hoekman included slides on the REDD-FLAME project during some of his presentations.

The REDD FLAME project was also presented by Eric van Valkengoed (TerraSphere) at a conference on deforestation called "REDD het bos" (Save the Forest) in Amsterdam on 27 March 2012. The project was presented as an objective tool to monitor deforestation and forest degradation in relation to the implementation of REDD.

In November 2012, Mike Wooding (RSAC) presented REDD-FLAME at the FP7 Space Conference in Larnaca, Cyprus. Dirk Hoekman (WU) attended the Fourth Science and Data Summit (SDS) of GEO-FCT in Sydney, Australia, from 4-6 February 2013 and included slides on the REDD-FLAME project during some of his presentations.

The project will also be presented at the 2013 European Space Agency Living Planet Symposium, to be held in Edinburgh, United Kingdom from 9 to 13 September 2013.

4.1.6 Scientific papers

A scientific publication prepared by Jonas Franke (RSS), featuring work undertaken within the scope of the REDD FLAME project, was accepted for publication by IEEE in 2012:

> Franke J., Navratil P., Keuck V., Peterson K. & Siegert F. (2012). Monitoring Fire and Selective Logging Activities in Tropical Peat Swamp Forests. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, early access article, Vol. PP, no.99, pp.1-10, doi: 10.1109/JSTARS.2012.2202638.

This publication can be downloaded from the project website (under the Publications tab).

Dirk Hoekman (WU) will also be publishing the results of algorithm validation work performed for a GEO site at Harapan (Sumatra), Indonesia.

4.1.7 Brochure

A brochure promoting the REDD-FLAME project has been produced to distribute at meetings, conferences and other public events (Figure 4.4). The brochure contains general information on REDD and specific examples from the project team, as produced during the course of the project. The brochure is printed on thick 100% recycled paper and was distributed to all workshop participants in Indonesia, Mozambique and Brazil. The brochure can be downloaded from the project website (under the Publications tab).

4.1.8 Video

A promotional documentary (video) on the REDD-FLAME project has been produced and can be viewed on the project website (under the Publications tab). The video was shown during the Final Workshops held in Indonesia, Mozambique and Brazil. Filming took place in Mawas, Kalimantan, Indonesia in November 2012, where the results of the Indonesian test site were validated in the field.

4.1.9 Other

A REDD FLAME notebook has been produced, consisting of a small 100% recycled paper notebook with the green REDD-FLAME logo on the cover (Figure 4.4). The notebook was distributed to all workshop participants in Indonesia, Mozambique and Brazil.

Figure 4.4 REDD-FLAME promotional material
left: notebook; right: brochure

4.2 Potential impact

4.2.1 System effectiveness

The UN-REDD Programme seeks to reduce emissions of carbon dioxide from both deforestation and forest degradation.

The FAO definition of deforestation is “the conversion of forest to another land use or the long-term reduction of the tree canopy cover below the minimum 10 per cent threshold.” REDD-FLAME does not prove conversion to another land use but it does successfully identify tree canopy reduction, which is a good indicator of deforestation. In practice, all of the canopy reduction identified in Mecuburi Forest Reserve was a change of land use to agriculture and therefore deforestation, but this is certainly not the case in all forest areas, including Mawas and the Sete de Setembro Indigenous Land. In all probability, loss of tree canopy, whether long term (i.e. deforestation) or not, *will* be counted as carbon emissions for REDD performance payments.

As others have found, forest degradation is more problematic. FAO states that “most globally established definitions allude to the basic notion of a human-induced, long-term, negative change in the forest's structure, function and capacity to provide goods and services in general. Degradation has thus the clearly negative connotation of a long-term impairment of a forest... Such a long-term impairment, however, can realistically only be assessed after a given observation period. This violates one criterion for a set of useful definitions listed above, in that degradation in this sense is not measurable during a short assessment period". Thus, with the exception perhaps of Trends Information over an extended period, the REDD-FLAME service cannot claim to detect what could be considered to be forest degradation by the above definition; it can, however, detect changes relating to loss of biomass in areas where the criteria for classification as forest are still met: a different definition of forest degradation.

REDD-FLAME was able to locate new forest clearings that were previously unknown to the local authorities. Using images and change map products on a GPS-enabled mobile device, field teams navigated directly to these sites, proving the usability of the system outputs. Clearings were detected in SAR data time series and are also visible in optical imagery acquired at annual intervals; the latter, however, is unsuitable for fast change detection at intervals of less than a year or six months.

Clearly, to be most effective, change map products must minimise false alarms and maximise detection of real deforestation: fine-tuning of parameters to achieve the optimal balance between false alarms and missed detections is critical to the success of the service. Further work and longer time series are still necessary to improve accuracy by better discriminating between changes due to tree removal and those related to other activities such as burning, which do not reduce the tree canopy. However, above an acceptable threshold, it is important to balance marginal improvements in accuracy against the cost and timeliness of results. Preliminary results seem to show that, in some environments, the high resolution change maps derived from RADARSAT-2 data are as clean or cleaner, and less prone to false alarms or over-detection, than the VHR TerraSAR-X products: this augurs well for the introduction of Sentinel-1 data.

From our experience, clearances of 2-3ha for unauthorised agricultural conversion in Miombo forest can take 3-6 months to be developed. It is therefore highly plausible that, in Mozambique at least, timely intervention could reduce the extent of forest clearances in any year.

It is also plausible that successful enforcement coupled to publicity surrounding monitoring by remote sensing can have a deterrent effect: even if only a few areas are monitored, knowledge of such monitoring will make deforestation actors wonder whether their area of activity is one of those being watched. Success of this nature is demonstrated in the EU, where agricultural subsidy fraud is contained because of selective monitoring under the Remote Sensing Control programme. In Harapan, Indonesia, it is known that illegal loggers have moved away because of monitoring by remote sensing.[3]

To determine the overall effectiveness of REDD-FLAME, the following question must be addressed: can intervention following detection (supply of information) of a small scale clearance prevent the clearance of further forest by the deforestation actors? In other words, are systems in place to act on the information available from remote sensing to complete the process illustrated in Figure 4.5? If not, then implementation of REDD-FLAME is a futile exercise. From the discussions at the Final Workshops, it is apparent that there are significant concerns about the current capability for such intervention in all countries.

[3] This example was recounted by conservation organisation, BirdLife Indonesia Association (Burung Indonesia) during the REDD-FLAME Final Workshop held in Bogor, Indonesia.

4.2.2 Cost benefit analysis

Having considered the accuracy of REDD-FLAME products and the effectiveness of the approach, it is necessary to weigh these and other potential benefits against the cost of the solution on offer.

REDD-FLAME is conceived to operate as a service delivered from providers located in Europe. Products can be transmitted digitally in formats appropriate to the needs of various users, and feedback can easily be returned by similar modes of telecommunication.

The cost of operating REDD-FLAME is driven by the choice of service options (Figure 3.1). These dictate the type of satellite data required, the frequency of observations and the number of information products delivered, each of which has a bearing on price. Costs are essentially split between data and processing. All the following prices are indicative and will of course vary in time. Table 4.1 shows indicative costs for a variety of service scenarios.

Coverage (example sensor)	AOI km^2	Observation Frequency	Trends Information cost per km^2 per year (delivery frequency)	Events Information cost per km^2 per year (delivery frequency)
Detailed (TerraSAR-X)	1,500 (30×50)	medium (33 days)	~€30 (6 months) min €45,000	~€40 (33 days) min €60,000
Extensive (RADARSAT-2)	10,000 (100×100)	medium (24 days)	~€4.50 (6 months) min €45,000	~€6 (24 days) min €60,000
Extensive (Sentinel-1)	10,000 (100×100)	medium (24 days)	~€1 (6 months) min €10,000	~€2 (24 days) min €20,000
Detailed (TerraSAR-X)	1,500 (30×50)	high (11 days)	~€88 (6 months)	~€100 (11 days)
Extensive (Sentinel-1)	10,000 (100×100)	high (12 days)	~€2 (6 months)	~€4 (12 days)
Extensive (RapidEye)	2,500 (50×50)	low (annual)**	~€6 (annual)*	-
Extensive (RapidEye)	2,500 (50×50)	low (6 months)**	~€12 (6 months)	-
Extensive (Sentinel-2)	2,500 (50×50)	low (6 months)**	~€4 (6 months)	-

Table 4.1 Indicative REDD-FLAME service costs
**equivalent to the cost for a benchmark map, if one is not already available*
***The optical monitoring system using either RapidEye or Sentinel-2 data can also technically be applied with a medium observation frequency (due to very short repetition cycles), but this scenario was not considered in the framework of REDD-FLAME*

Minimum costs derive from the necessity to purchase whole data scenes from image providers.

All other variables remaining equal, service costs are approximately scalable for larger areas of interest. Note that, for very large areas of interest and detailed coverage with high observation frequency, Events mapping becomes impractical because of the necessary mixture of acquisition dates in the required image mosaic. Such an approach does not form part of the REDD-FLAME concept, and for economic as well as practical reasons, a maximum delivery frequency of monthly Trends Information would be proposed on this spatial scale.

REDD carbon payments are usually quoted in sums per tonne of carbon 'saved'. The saving is based on an improvement of the business-as-usual projection for deforestation rates. Such figures can be converted to sums per km^2 saved forest, if the carbon content and biomass density of a forest ecosystem are known. For Mozambican Miombo forest, the carbon content is approximately 50t/ha or 5,000t/km^2. With carbon emissions reduction prices currently in the region of €4 to €7 per tonne, this means that payments of €20,000 to €35,000 can be expected for every 1km^2 of saved forest. In a highly simplified cost benefit model, this is the figure against which the cost of the REDD-FLAME service should be assessed.

The cost of monitoring 1km^2 of forest is not the same as the cost of *saving* 1km^2 of forest: it is anticipated that rather larger areas of forest must be monitored in order to make a detection that permits a successful intervention leading to a small reduction in deforestation. Just how large an area is important in determining the cost-effectiveness of the service.

In Mozambique, the annual rate of deforestation between 1990 and 2004 was quantified as 0.58%[4]. Under REDD, a target of 0.21% has been set for 2025[5]. To achieve a reduction of annual deforestation from 0.58% to 0.21%, 0.37ha of forest must be saved in every 1km^2, i.e. 1km^2 must be saved in every ~270km^2 of forest. To put it another way, when monitoring 270km^2 of forest, changes totalling 1.57km^2 could be expected in the business-as-usual scenario, but only 0.57km^2 of changes are acceptable to achieve the REDD target. REDD-FLAME seeks to detect some of this 'permitted' (or sacrificial) tree removal – as an indicator of more widespread clearance to come – in order to prevent up to 0.37ha of further deforestation per km^2.

Therefore, on average, the cost of saving 1km^2 of forest in Mozambique is equivalent to the cost of monitoring an area of 270km^2. This is a maximum cost, since REDD-FLAME focusses on hot spots where deforestation is likely to be higher than average and the service is hence more cost effective. In a forest reserve, deforestation should be zero, meaning that all forest is saveable and again the cost effectiveness improves.

The service costs in Table 4.1 can thus be converted into an annual cost per km^2 of saveable forest, for direct comparison with potential REDD payments. Table 4.2 shows these figures in a summary of the above costs by data type.

Other costs to add in for the total monitoring outlay include procurement of a benchmark forest/non-forest map (or regular updates to this) and integration and interpretation of REDD-FLAME products within a local GIS system, as well as other start-up costs.

Savings may be made on the cost of data where agreements can be reached with commercial data providers and/or with governments. Other than Sentinel data from the Copernicus (GMES) missions, there is a real possibility that free data can be secured through other channels. Even with free data, there is still a requirement for processing, and the cost of this can be inferred from the Sentinel examples.

Other organisations have their own arrangements for free access to data, and even software licenses. Thanks to such arrangements, the capacity for data handling is also growing.

Data	Resolution	Cost per km^2 per year	Cost per km^2 saveable Miombo forest per year
RapidEye (optical)	Very High	€6 - €12	€1,622 - €3,243
Sentinel-2 (optical)	High	€2 - €4	€541 - €1,081
TerraSAR-X	Very High	€30 - €100	€8,108 - €27,027
RADARSAT-2	High	€4.50 - €6	€1,216 - €1,622
Sentinel-1	High	€1 - €4	€270 - €1,081

Table 4.2 Summary of indicative REDD-FLAME service costs by data type for Mozambique

[4] This figure is of questionable accuracy, but will continue to be used for the purposes of the present illustration

[5] Ministério para Coordenação da Acção Ambiental, Estratégia de Redução de Emissões por Desmatamento e Degradação Florestal, 2011

Against these costs, the benefits of implementing REDD-FLAME must be weighed: not only REDD carbon payments, but also more intangible and indirect benefits.

It is important to consider costs and benefits in the context of an integrated campaign, targeting not only deforestation and forest degradation but also biodiversity protection and local population welfare. In Indonesia, conservation of orang-utan habitats is one of the main drivers for the prevention of deforestation. It is difficult to quantify the cost of herbal remedies lost as a result of deforestation, but it is important to raise awareness of this and other hidden impacts and add them into the equation. Then, the outlay does not seem so great and can be much more easily justified.

In reality, the web of costs and benefits associated with reducing deforestation and forest degradation is much more complex than presented here, and the analysis above sits within a much wider-reaching consideration of the overall costs and benefits of forest conservation, to which the mechanisms of REDD are ultimately addressed. Nevertheless, these figures provide a good starting point for a full market analysis to evaluate opportunities for the exploitation of the foreground developed herein.

Of course, in assessing costs, it is important to consider the price of alternative monitoring systems: it is questionable whether complete areas can be covered by other means for a comparable price. However, it will be difficult to justify investment in REDD-FLAME or any other similar initiatives whilst so much uncertainty remains around the implementation of REDD.

4.2.3 REDD-FLAME in the context of REDD

Figure 4.5 shows how REDD-FLAME would fit into REDD activities on a national scale.

In an operational REDD implementation, governments, civil society and local inhabitants will be motivated by the incentives offered through REDD to reduce carbon emissions from forests. Reducing the rates of deforestation and forest degradation can be achieved by various stakeholders, for example, by adjusting governance, improving conservation practices and making lifestyle changes. Through user consultation, the requirements necessary to progress towards these objectives, and to measure such progress, have been determined; among such requirements, the need for early detection of deforestation and forest degradation is seen as important, both to facilitate control of carbon stocks and also as a means to assess risk of deforestation in a particular area for carbon investors. Thus, delivery to stakeholders of timely, usable information on new forest disturbances forms the central REDD-FLAME service objective.

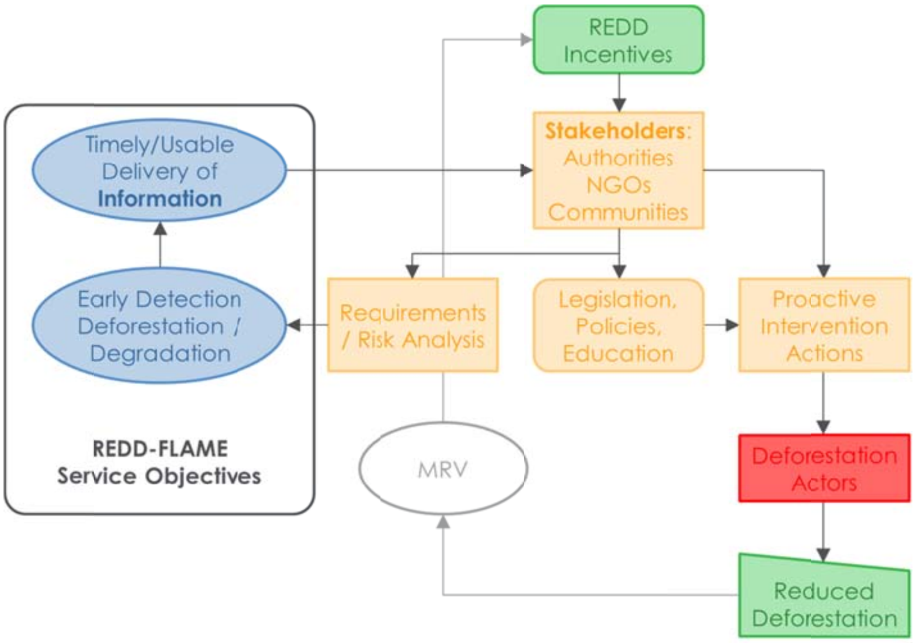

Figure 4.5 REDD-FLAME in context

The REDD Programme necessitates formulation of policies for emissions reduction and enactment of subsequent legislation to enforce them. REDD-FLAME products can inform this process and contribute to education on deforestation matters, as well as facilitating proactive actions to reduce deforestation by enabling intervention directly at the site of encroachments that violate such new or other existing laws. Hence, the deforestation actors – loggers, farmers, charcoal producers – are reached and their activities interrupted so that deforestation and forest degradation, and consequently carbon emissions, can be reduced.

Traditionally, REDD remote sensing projects focus on MRV: Measurement, Reporting and Verification (Figure 4.6). This provides a means to periodically monitor progress towards reduced rates of carbon emission, providing the feedback loop to authorise the release of REDD incentives. In Mozambique, this will be conducted biennially. However, a complete REDD approach also requires proactive measures to actively contribute to the reduction of deforestation on a continuous basis; REDD-FLAME has demonstrated how remote sensing can also make an important contribution to this aspect of the programme.

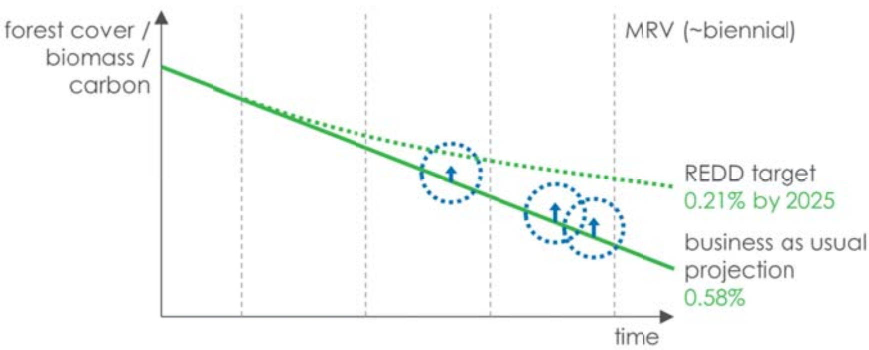

Figure 4.6 Mozambique's REDD objective to reduce deforestation blue arrows indicate potential contributions from REDD-FLAME

Table 4.3 contrasts the characteristics of REDD-FLAME and MRV. The REDD-FLAME approach is an important tool to support REDD actions and is *complementary* to MRV: it is the combination of periodic wall-to-wall monitoring and focussed fast detection, plus effective intervention strategies responding to both, that will ultimately lead to successful reduction of deforestation rates.

REDD-FLAME	MRV
Operational reporting	International reporting requirement
Proactive	Reactive
Risk-based time interval	e.g. Biennial
Risk-based geography	National wall-to-wall

Table 4.3 Comparison of REDD-FLAME and MRV

4.3 Exploitation

The REDD-FLAME project has successfully demonstrated a pre-operational system for the detection of logging activities at an early stage using Earth Observation data. Furthermore, the project has fostered the potential for the system to be developed further for sustainable provision of services in the host countries. The prospects for future exploitation of the generated foreground are good.

It is expected that results and algorithm developments from the project will in future be documented in peer-reviewed scientific publications, lending greater authority to the work, raising the profile of the project and partners, and increasing the likely impact of the project overall.

The simplified cost benefit analysis presents a compelling argument for implementation of REDD-FLAME, and the consortium believes that more time and resources could be fruitfully invested to consolidate the concept and establish an operational system. One area requiring particular focus in any future work is the detection of forest degradation; however, this also relies to an extent on the establishment of agreed definitions within the REDD community.

It is anticipated that the system or some if its components will become operational in future, and all partners must benefit from such developments. European partners will also be able to make use of the new contacts that the project has introduced, and stakeholders who participated during the project and at the workshops could be valuable allies in support of further system development and establishment of operational services. There is also the possibility for partners to provide consulting services to these stakeholders relating to the implementation of REDD.

REDD-FLAME can potentially also be of use in the process associated with the EU Forest Law Enforcement, Governance and Trade (FLEGT) Action Plan, and this opportunity should be explored further by the consortium.

Members of the consortium will continue to stay in touch professionally; indeed, some partners are collaborating on other projects following their successful partnership in REDD-FLAME. Links to partners and stakeholders in host countries will be maintained and further cultivated in the pursuit of future REDD-related or forest monitoring work. Where requests for services linked to REDD-FLAME foreground are received by any consortium member, they will be shared with the rest of the group so that any benefits are fairly distributed.

There are plenty of on-going government activities in **Indonesia**, but they do not (yet) relate to REDD-FLAME. In Indonesia the focus is entirely on wall-to-wall annual mapping at 25m resolution. Since the Indonesian government is more interested in capacity building than buying foreign services, private sector companies and NGOs are more likely to represent realistic potential customers.

REDD implementation in **Mozambique** is not as advanced as it is in Indonesia and Brazil. It is proposed that a brief should be produced based on the findings of this project, to help Mozambican policy makers identify the steps required to utilise REDD-FLAME information products within their REDD strategy. This also needs to emphasise the consequences of doing nothing, and should set out persuasive cost benefit arguments for implementing REDD-FLAME in Mozambique.

The APPS4GMES project (http://www.apps4gmes.de) – partly funded by the Bavarian Ministry of Economy, Infrastructure, Transportation and Technology – will generate operational services using Sentinel data and additional GMES products. The challenges therein are the enormous amount of data, the complex data flows, the information extraction and the quality assessment. During the project, RSS will develop prototypes based on standardised products and demonstrate operational product generation. The specific applications are in the context of agriculture, water quality and quantity, environment and climate protection. The services are all based on consolidated user requirements. The APPS4GMES project consists of specific applications in the context of agriculture, water quality and quantity, environment and climate protection. The services are all based on consolidated user requirements.

Planned services in the context of environment and climate protection mainly aim at "Measuring, Reporting and Verification (MRV)" applications in the framework of REDD+ using the latest earth observation techniques. Successful measures for forest protection require near real time information on deforestation and forest degradation processes, such as logging and fire damage. Therefore, remote sensing based services will be developed in APPS4GMES to address MRV requirements. These methods aim at providing quantitative information on forest area change and the corresponding carbon losses and gains in REDD+ project areas. For the developed services, a high level of automation will be reached, so that near real time and cost-saving services can be supplied. All three test sites of REDD-FLAME will continue to be monitored in the framework of APPS4GMES, as a follow-up of the project. Results can be provided to users until 2014.

4.3.1 Recommendations

It has been demonstrated how recent small clearings in tropical and sub-tropical forests can be detected both in optical imagery, given good weather conditions and data acquired at the correct time of year, and in SAR data time series. Resultant change map products readily improve knowledge of recent forest disturbances and allow quick location of these features on the ground. They can also provide information about the age of changes.

Detected changes appear to predominantly represent deforestation. Some forest degradation may also be detected, but cases of individual tree removal can easily be missed. Burning, which does not necessarily pose a long-term threat to the forest and is not necessarily of interest for carbon accounting, causes confusion in the change detection, but high resolution SAR data seem less prone to this. More work is required to better understand the contribution of burning to the change signal, and to filtering out this confusion where appropriate. By improving and better quantifying the accuracy and overall reliability of the system, REDD-FLAME will become a more appealing proposition for stakeholders looking to implement REDD.

Interpretation of the change maps can be improved with local knowledge and some contextual information. For example, considering change features in relation to terrain and elevation would allow false alarms associated with wetlands in Miombo forest to be eliminated. Other clues to the authenticity of a change feature could be its proximity to forest tracks (for access) and homogeneity in terms of change date: mixed date features are more likely to represent false alarms associated with burning events. Local users need to understand how to effectively interpret change map products to make best use of REDD-FLAME outputs.

The uncertainties inherent in current wall-to-wall forest mapping methodologies and the difficulties of consistently classifying forest and non-forest mean that this approach to MRV cannot alone reliably measure the small incremental advances towards target reduced rates of deforestation that are to be expected during the implementation of REDD. Thus, REDD-FLAME can provide complementary information on the detailed changes occurring in specific areas and during the periods between MRV exercises, shining a spotlight on the effect of localised emissions reduction actions, as well as facilitating proactive interventions.

The costs of the system as presented above might be a concern in a country like Mozambique, although instruments and funds are available internationally to support the implementation of REDD. The low cost of manual labour makes arguments for the adoption of high-tech solutions difficult to win when large numbers of field operatives could be deployed for the same price; nevertheless, some areas of interest are very remote and difficult or dangerous to access, so supporters of the status quo should be persuaded that long-term investment in technology would be ultimately beneficial. The Sentinel programme, starting with the launch of Sentinel 1a in December 2013, will provide free data and reduce costs to a minimum, thereby maximising potential benefits. It is recommended that preparations continue to be made to exploit this opportunity as soon as it becomes available.

As this project has found to its cost, data continuity is critical for the provision of operational change detection services, and it is therefore vital that the long-term future of the Sentinel programme – and its provision of free data – is assured.

Of course, there is little sense in implementing a fast detection system if the capacity to respond with fast interventions is not also established. Current national systems may need to be modified so that new information can be acted upon quickly enough for it to be effective. There also needs to be a change in the approach to logging law enforcement, which often aims at intercepting illegal timber at ports rather than seeking to catch loggers in the act of clearing trees in the forest. REDD-FLAME would help to focus limited intervention resources at sites most likely to represent on-going illegal forest clearances, thereby raising efficiency.

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