Final report of the ESA EO Science for Society project "Tropical Peat View" ESA AO/1-9101/17/I-NB

Tropical Peat View - NRT radar monitoring of peat swamp forests in Central Kalimantan and Riau

Dirk Hoekman (1), Wilbert van Rooij (2), Marcela Quiñones (2), Boris Kooij (2), Rob Luiken (2), Martin Vissers (2), Sam Vellekoop (2), Ita Carolita (3), Syarif Budhiman (3), Rahmat Arief (3) and Orbita Roswintiarti (3,4).

(1) Wageningen University, Dept. of Environmental Sciences, The Netherlands
(2) SarVision, The Netherlands
(3) LAPAN, Remote Sensing Applications Center, Indonesia
(4) LAPAN, Remote Sensing Technology and Data Center, Indonesia

Project execution period: August 2018 until October 2019
Final presentation ESA ESRIN: 6 March 2020
Final report: 30 April 2020

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Executive summary

Deposits of peat underneath tropical peat swamp forests are among the world's largest reservoirs of carbon. The largest are found in Indonesia, Peruvian Amazon and Congo, accounting for a total of ~100 GtC, equal to 25% of the carbon stock stored globally in biomass. In degraded peat swamp forests, in Indonesia, on average, ~0.4GtC per year is lost because of oxidation and fires, which is nine times more than the total carbon emission of The Netherlands. Restoration of the degraded peatlands in Indonesia and preventing degradation in the intact peat swamp forest in Indonesia, Peru and the Congo's, could contribute considerably to climate measures at relatively low costs, and support livelihoods and health of local communities. To take effective measures in these remote and difficult to access areas, satellite observation of the conditions and hydrology of the peat layers under the forest canopy is necessary. Only spaceborne radar in combination with advanced monitoring algorithms offers this possibility.

In Southeast Asia large areas of peat swamp forest have been deforested for timber and are converted into agricultural land or oil palm plantations. This increases the pressure on remaining peat swamp forests. The degradation of peat swamp forest not only leads to large carbon emissions but also to a great loss of biodiversity. Excess drainage through canals lowers ground water levels, which causes huge carbon emissions by oxidization and increased vulnerability for fire. In particular during 'El Niño' events, peat fires occur at large scale, causing huge additional emissions, forest loss and disturbance of the hydrology through subsidence.

SarVision and Wageningen University have developed an operational peat monitoring system to address this large environmental challenge. The system is based on radar imagery and is called the Tropical Peat View monitoring system (TPV). It has been developed for the provinces Central Kalimantan and Riau in Indonesia with the goal to provide support to peat conservation and restoration in Indonesia. The Indonesian government is committed to better managing peatlands and has established the Peat Restoration Agency (BRG) to coordinate its efforts. This commitment includes the rehabilitation of 3 million ha of degraded peatland.

TPV provides information to the Indonesian Space Agency LAPAN, BRG, Ministry of Environment and Forestry (KLHK) and other national and international users and stakeholders. Information is provided on deforestation, forest degradation, development of drainage canals, changes in hydrology, fire and fire damage, through innovative use and integration of multiple earth observation data sources from the European Space Agency (Sentinel-1 C-band radar, Sentinel-2 optical imagery) and other third party missions (PALSAR L-band radar, Landsat optical, MODIS thermal imagery).

The TPV system design is based on user requirements provided by the stakeholders during user requirement workshops in Indonesia. This automated system not only produces every 12 days peat forest change maps that show deforestation and degradation in peat forests (including road and canal development, open area flooding and fire scars) but provide also regular information on the hydrology of the peat forest soil under the canopy.

During the project new monitoring approaches have been developed and validated. Salient achievements include the following: (1) A historical analysis using all available L-band data of JERS-1, PALSAR-1 and PALSAR-2. This showed that the main ombrogenous peat domes in the Central Kalimantan landscape are currently much drier than in the pre-disturbance JERS-1 era which is likely caused by large subsidence events at relatively large distances. (2) An improved canal detection with Sentinel-1. This differs from canal detection with hi-res SPOT-6/7, but overall results are comparable. Sentinel-1 can detect large tracts of narrow canals very poorly visible on SPOT-6/7 images, which would otherwise have been missed in the visual analysis of optical data. (3) The use of Sentinel-1 radar for a robust, systematic and accurate detection of degradation, including gaps in the upper canopy caused by selective logging. Unlike radar, optical based systems miss a lot of degradation, mainly because of a combination of cloud cover and regrowth.

A Tropical Peat View Web GIS viewer has been built that allows users to view, combine and analyse thematic maps. Changes of the tropical forest and peat areas in Indonesia can be analysed from 2015 until the end of the project in September 2019. The main themes in this viewer are deforestation, degradation, fire and floods. With the viewer, the changes can be detected through time.

The additional value of the TPV is acknowledged by representatives of all stakeholders during the evaluation workshop (including BRG, LAPAN, BBSDLP, BBBT, KLHK and international organizations such as UNEP, FAO and WRI). The system can be used in addition to the current forest monitoring system of KLHK and will not only make it possible to provide additional information of forest change during cloud cover, but will also increase the monitoring frequency (from quarter yearly to 12 days) allowing immediate interventions, and add new themes such as peat forest degradation and changes in peat forest hydrology. The system also increases the level of detail with regards to forest degradation, which can be an important indicator for future deforestation in the neighbourhood.

The developed TPV system can easily be upscaled, not only to entire Indonesia, but also to other tropical forest areas such as the Guyana’s, Amazon basin and the Congo basin

There is a broad consensus among stakeholders to continue radar capacity building and to start full technology transfer from the Wageningen partners to the Indonesian partners LAPAN, KLHK, BRG, and possibly others, as soon as possible. An implementation plan was made by the project team and discussed with all stakeholders. Both Wageningen and LAPAN would continue to cooperate with JAXA within the Kyoto & Carbon Initiative, for which both have an agreement until 2022 for tropical peatland monitoring. Other countries with major tropical peat swamp forests, such as Peru and the Congo’s, would be supported by Indonesia through the International Tropical Peat Centre (ITPC) and the Global Peatland Initiative (GPI).

The system is cost effective because it uses free of cost radar imagery and will be a valuable addition to existing monitoring systems that are mostly based on expensive optical images. The TPV system will not replace the need for optical imagery, but can be used to reduce the cost for the purchase of optical data as hot spots can already be localized near real time.

1. Introduction and user requirements

This report provides an overview of the Tropical Peat View project and gives a summary of the main findings. SarVision and Wageningen University have developed an operational peat monitoring system to address one of the largest environmental challenges the planet faces today, i.e. better management of Indonesian peatlands. The development has been carried out in collaboration with the Indonesian government agencies LAPAN and BRG (Peat Restoration Agency).

Background

Indonesia counts around 15 million ha of peat, and a substantial part of these have been converted into plantations (in particular oil palm and acacia) or have been degraded. Both plantations and degraded peatlands are generally drained. In plantations in peat, drainage involves networks of canals, including main canals (up to 3o m wide), medium sized canals of generally 8 to 10m wide. In addition, smaller canals are established especially by local people for example for the removal of timber from peat swamp forests. All drained peatlands lead to CO_2 emissions, and the degraded and to a lesser extent planted peatlands are also prone to frequent fires, leading to further CO_2 emissions as well as smoke leading to adverse health impacts for local people. The Indonesian government is committed to better managing peatlands and has established the peat restoration agency (BRG) to coordinate its efforts. This commitment includes the rehabilitation of 3 million ha of degraded peat.

To implement its mandate, BRG is critically dependent upon up to date and accurate data on the location of existing and new canals, occurrence of flooding, drainage and occurrence of fires in Indonesian peat. Remote sensing data is needed to obtain such information in a timely manner over large areas. BRG requested the Indonesian space agency, LAPAN, to provide remote sensing data to meet this aim. The developed monitoring system demonstrates to LAPAN, BRG and other users and stakeholders a peat monitoring system providing information on drainage canals, hydrology and fires through innovative use and integration of multiple earth observation data sources from the European Space Agency (Sentinel-1, Sentinel-2) and other third party missions (PALSAR, Landsat, MODIS). The project focuses on two demonstration sites in Kalimantan and Sumatra.

After this project, it is expected that the peat monitoring system will be scaled up and implemented by LAPAN, supporting peat restoration policy analysis and monitoring in BRG for all peat areas in Indonesia.

Objectives

The main objective of the project is to demonstrate an EO-based operational system for monitoring peatlands in Indonesia for the national space agency, LAPAN, and the national peat restoration agency, BRG. Two priority areas were defined by BRG in Sumatra and Kalimantan: The provinces of Riau (Sumatra) and Central Kalimantan (Kalimantan) were selected as there was ample field data already available for ground truthing and validation. These provinces are about 87,000 and 150,000 km2 respectively, however the monitoring

systems are confined to peatlands only. In Kalimantan peat land covers about 20% of the province. The methods are scalable to the national scale.
Part of the peat monitoring system was the development of EO products addressing key requirements from BRG: the detection of drainage canals, the detection of fires, the monitoring of drainage and the monitoring of floods. The system harnesses the potential of combining multiple EO data sources: especially Sentinel-1 and Palsar-2 data, complemented with Sentinel-2, Landsat-8 and MODIS. Innovative approaches for speckle filtering and line features detection, multi-data source fires detection and multi-data sources floods monitoring have been demonstrated. EO products are delivered through a web application customized to users requirements, allowing users to perform ad-hoc times-series analysis.

User requirements

Governmental policy regarding use and restoration of peatlands
The environmental problems in peat ecosystem have drawn the attention of the government. Better plans to move towards sustainable management of peatlands are required. In 2011, a Norway-Indonesia partnership focusing on the reduction of GHG emissions was followed by a Presidential Instruction No.10/2011 about a two-year suspension of new licenses for primary natural forest and peatland clearing called moratorium. This instruction has succeeded in protection of carbon and biodiversity in 71% or 11.2 Mha of Indonesian highly threatened peatlands.

In 2014, a Government Regulation (PP) No.71/2014 about peatland protection and ecosystem management was issued to protect 30% of Indonesian hydrological unitary peatland. As a further step, a peat restoration agency (BRG) has been formed by the president of Indonesia with a target to restore approximately 2.5 Mha of degraded peatlands by 2020 (SK.05/BRG/Kpts/2016). This was followed by a Presidential Decree (Perpres) No.1/2016 about restoration priority in seven provinces (12.9 Mha of peatlands in Riau, Jambi, South Sumatera, West Kalimantan, Central Kalimantan, South Kalimantan and Papua provinces). These priority areas also include the areas most severely burned in 2015, shallow peat areas with canals (3 Mha), as well as peat domes with canals and without canals (2.8 Mha and 6.2 Mha). The demonstration sites of TPV are selected in those priority areas.

Requirements BRG
The main user of the peat monitoring system is BRG. The Peat Restoration Agency was established on January 2016 in order to accelerate restoration of the hydrology of peatlands, as a response to the massive peat fires which occurred in the extreme El Nino event of 2015. BRG has been formed by the president of Indonesia with a target to restore approximately 2.5 Mha of degraded peatlands by 2020 (SK.05/BRG/Kpts/2016). This was followed by a Presidential Decree (Perpres) No.1/2016 about restoration priority in seven provinces (12.9 Mha of peatlands in Riau, Jambi, South Sumatera, West Kalimantan, Central Kalimantan, South Kalimantan and Papua provinces). These priority areas also include the areas most severely burned in 2015, shallow peat areas with canals (3 Mha), as well as peat domes with canals and without canals (2.8 Mha and 6.2 Mha) .

The missions of BRG are to:

- Coordinate and strengthen policy in the overall peatland restoration actions;
- Develop policy, strategy and planning, provide direction and promote cooperation in peatland restoration activities;
- Carry out peatland inventory and hydrological unit mapping on seven priority provinces;
- Review and determine land use/zonation of peatland areas (based on protection and cultivation functions);
- Provide guideline, standard and supervision on the construction, operation and maintenance of rewetting infrastructure and all its accessories;
- Review permits and licenses of peatland management or concession over peatlands which fail to control peatland degradation and/or fire;
- Socialization and education on sustainable management of peatland and its restoration;
- Coordinate research and development for alternative economic activities for sustainable use of peatlands in the concession and community's cultivation areas.

Badan Restorasi Gambut

Peatland Hydrological Unit (PHU), Peatland and Peat-dome

Provinces	#PHU	PHU Area (hectares)	Peatland area (hectares)	Peat-dome area (hectares)	Non-peat area (hectares)	Restoration priority (hectares)
Riau	49	5,140,000	4,221,000	1,486,780	918,755	938,619
Jambi	10	1,040,000	751,000	298,804	288,669	136,541
South Sumatera	26	2,371,800	1,171,800	690,715	1,183,324	445,749
Sumatera Total	**85**	**8,551,800**	**6,143,800**	**2,476,299**	**2,390,747**	**1,520,909**
West Kalimantan	91	3,040,400	1,840,400	698,653	1,183,917	324,285
Central Kalimantan	32	4,633,000	3,053,000	1,770,940	1,581,809	683,024
South Kalimantan	4	340,814	160,214	93,946	180,561	68,734
Kalimantan Total	**127**	**8,014,214**	**5,053,614**	**2,563,539**	**2,946,286**	**1,076,043**
Papua	226	6,099,500	4,899,500	730,076	1,176,608	82,293
Total 7 Provinces	**438**	**22,665,514**	**16,096,914**	**5,769,914**	**6,513,641**	**2,679,245**

Figure 1.1 Peatland areas in Sumatra and Kalimantan

BRG has inventoried 438 peatland hydrological units over 7 provinces, representing 22,665,514 hectares, of which 2,679,245 have been designated as restoration priority areas. BRG's roadmap of peatland restoration is declined though 6 strategic objectives:

- Strategy 1: Controlling peatland degradation and conversion. This includes controlling and preventing forest and peatland fire (Providing early warning system, monitoring, ensuring peatland wetness index to safe level).
- Strategy 2: Assessment of peatland degradation impacts (costs/value) and determine options for future sustainable land use.

- Strategy 3: Implementing sustainable peatland management at landscape level (peatland hydrological unit/PHU). This includes phasing-out drainage based agriculture/silviculture on peatland, hydrological restoration and vegetation restoration.
- Strategy 4 : Conserving peatland as essential ecosystems (and its biodiversity) and its Surrounding Areas/PHU
- Strategy 5 : Improve social conditions and resolve conflict over resources
- Strategy 6 : Enhance Good Governance for Forest and Peatlands

BRG expressed its needs for data supporting policy analysis and monitoring.
The degradation of Indonesian peatlands occurred through drainage in order to establish plantations (oil palm, acacia) which cannot tolerate high level of water in the soils. However, excessive drainage has in turn often led to degradation, burning and land subsidence, making the land often unproductive. The core strategy to restore those peatlands relies on raising water levels, “rewetting”, through the blocking of the drainage canals and other infrastructures aimed at water loss control and prevention.

Peatland restoration follows a process in 4 steps: planning, implementing, monitoring & reporting and evaluation. The planning of restoration measures should be guided by an accurate characterization of the hydrological state of peat areas, the parameters leading to peat degradation, and the assessment of the conservation value of the peat swamp forest. Important parameters are the hydrology, the land use and status of peatland (private concession, protected areas, other land tenure), existing conflicts over land use and/or land tenure, biodiversity, habitat, species, and the degree of degradation (drainage, fire scars and historical fires).

Important monitoring and evaluation issues are the impacts of canals blocking and in-filling on the restoration of hydrology (rewetting), the monitoring of the water table, the detection of new canals, the detection of fires, the detection of new land clearing areas, and the detection of subsidence. Peatland maps for Indonesia have been published by several research institutions, including the Ministry of Agriculture and BRG. BRG has maps of the peat land areas, and priority areas for rehabilitation per province, with classification in categories (well managed, rehabilitation, moratorium, priority areas for rehabilitation). This baseline information is included in the Tropical Peat Viewer (see also chapter 3) to extract monitoring data on drainage canals, flooding regime and fires per type of area.

Another important source of spatial information is the land cover of the peatlands. KLHK is continuously (every year) producing land cover maps of Indonesia. The types of land cover (LC) are classified based on the regulation of director general of forestry planology No. P.1/VII-IPSDH/2015. These land use classes are also be included in the viewer.

Several other organizations are working on the characterisation of peatlands, including mapping of peat dome and depth, using remote sensing data and field data. Though the TPV project does not address directly this need, the data generated by the project may support these initiatives. Next to BRG other identified users of the TPV peat monitoring system are LAPAN, BBSDLP, BBBT, KLHK and international organizations UNEP, FAO and WRI. Their link with Peatland monitoring is described in brief underneath.

LAPAN (National Institute of Aeronautics and Space)
LAPAN has the mandate to provide spatial data to the governmental institutions of Indonesia to support them in achieving their goals. The objective of TPV is to support LAPAN to provide earth observation products addressing the needs of BRG. It is foreseen that LAPAN will host the TPV system after the end of the project.
LAPAN is carrying out research on peat dome and peat depth mapping using ALOS PALSAR, ALOS AVNIR and SRTM data. It has an operational system for monitoring fire hotspots, haze/smoke and map burned areas based on MODIS, VIIRS and Landsat/Spot-6/7 data.

LAPAN is regularly acquiring high and very high resolution optical data (Pleiades, Spot6/7) and high resolution SAR data (TSX), over large areas of Indonesia. These data sources are used to support the calibration and validation of TPV algorithms, in particular for drainage canals and fires detection.

LAPAN has an operational system for monitoring fire hotspots, haze/smoke and map burned areas based on MODIS, VIIRS and Landsat/Spot-6/7 data. The project will reinforce this system by bringing new products based on the integration of Sentinel-3, Sentinel-2 and Sentinel-1 data. There is no monitoring system for drainage canals detection. LAPAN is conducting ad hoc analysis with SPOT-6 satellite data, but the frequent cloud cover hinders systematic monitoring. However, this analysis can be used to support the calibration and validation of the TPV system based on Sentinel-1 data.

BBSDLP (Indonesian Centre for Agricultural Land Resources Research and Development, Agency for Agricultural Research and Development, Ministry of Agriculture)
The Indonesian Centre for Agricultural Land Resources Research and Development (BBSDLP) carries out research on the inventorization and characterization of peat, characterization of the hydrology-soil relation, cultivation of peat and evaluation and scenarios application.

BPPT (Agency for the Assessment and Application of Technology)
The Agency for the Assessment and Application of Technology is implementing an in-situ real time monitoring system of the peat water table. A network of field sensors is sending real time data on rainfall, peat moisture and water table to a centralized database. The sensors data is extrapolated to wall to wall maps using empirical models and remote sensing data (SMAP Satellite), for the estimation of carbon emissions. It is also used to estimate risks of peat forest fires (Fire Danger Rating System).

In 2018, 140 sensors had been installed, mostly in Sumatra and Kalimantan. Water table level data can be used to calibrate and validate the flood monitoring algorithms of TPV. Data produced by TPV (L-band ALOS PALSAR data) can also be integrated with water table level data through hydrological modelling to generate new products for monitoring peatland hydrology.

KLHK (Ministry of Environment and Forestry, MOEF, Indonesian abbreviation KLHK)
KLHK has the government mandate to manage all lands classified as forest land in Indonesia. This includes much of the peatlands, in particular all peatlands that have not been issues as plantation lands - in which case the ownership and mandate reside with the Ministry of Agriculture, with land leases granted to plantation companies (or sometimes land titles given

to smallholders). KLHK is strongly engaged in peat management and has played a main role in the recent establishment of the International Tropical Peatland Centre (ITPC), in which Indonesia collaborates with the governments of the Republic of the Congo and the Democratic Republic of Congo (and discussions ongoing with the government of Peru). Currently, the ITPC is still in an initial phase, and the collaboration between BRG and ITPC does not appear to be fully developed as yet. Among others, KLHK is continuously (every year) producing land cover maps of Indonesia, and involved, with LAPAN in fire monitoring and estimating CO2 emissions from peatland degradation.

UNEP The UN Environment Program
UNEP is coordinating United Nations implemented, peat related work in Indonesia. UN Environment has coordinated a range of studies on sustainable peatland management, such as on alternative crops that can be grown in peat without drainage. Recently, UNEP obtained funding from the Netherlands embassy in Jakarta to establish a program (called 'Landskap') on sustainable peat management including pilot studies in Riau and Central Kalimantan. The TPV project was presented to UNEP Jakarta in two meetings, respectively on the 12th and on 20th of February 2019. UNEP expressed great interest in the TPV viewer and it is discussed how TPV results can be made available to the UNEP peat project and to members of the Global Peatland Initiative (TPI). The tool is well in line with the goals of the TPI.

FAO Food and Agricultural Organization
FAO demonstrates a high interest in Peat monitoring and the TPV system as they organized a workshop on Peat monitoring in Rome and attended the TPV user workshop in Indonesia and the final TPV project meeting in Rome. FAO acknowledges that mapping peatlands can help countries to plan and better manage their land, water and biodiversity, mitigating climate change and adapting to it more effectively. To facilitate countries' access to RS imagery FAO developed a peatland restoration monitoring module and a simple viewing and analyses toolkit called SEPAL. The module was implemented in Indonesia by the Indonesian Peatland Restoration Agency and Ministry of Environment and Forestry. The FAO representative mentioned that the PV system would be a valuable addition to their system as it uses highly sophisticated algorithms that enable automated analysis and mapping of deforestation and degradation. SEPAL does not make use of baseline maps that are needed to detect and quantify changes in land cover classes. The TPV viewer includes analyses tools to quantify changes for selected locations trough time.

WRI (World Resources Institute)
WRI has obtained funding from the Norwegian government for the project: 'Accelerating low emissions development in Indonesia through sustainable land-use management', implemented in the period 2016–2021. Planned outcomes of the project are:
- Improved management of peatland in priority jurisdictions to reduce greenhouse gas emissions from peat degradation and fires while promoting equitable land use practices to enhance local livelihoods.
- Instilled principles of accountability, inclusivity and sustainability within land use management in priority provinces through the implementation of the One Map policy.
- Improved transparency, accuracy and usability of Indonesia's National Forest Monitoring System to better monitor and enforce sustainable land use practices in Indonesia.

The project aims to produce a better map of peatland areas including peat thickness in the country, build capacities for more sustainable peat management in Riau, South Sumatra and Papua provinces, and develop a strategy for better mapping and monitoring of deforestation.

User requirement workshop

On 18 and 19 February 2019 a workshop was organized for the assessment of the user requirements of the TPV system. An agenda of the workshop is provided in Annex I. Discussions were held about the use of the system for involved organizations who confirmed the above general description of needs.

Overall, the Tropical Peat View project targeted the following subset of the needs of BRG, which correspond to information required at both planning and monitoring & evaluation steps of the peatlands restoration process (see table below):
- Detection of drainage canals;
- Floods monitoring;
- Detection of fires.

Table 1.1. Three major topics of the Tropical Peat View monitoring system

	Planning	Monitoring & evaluation
Detection of drainage canals		Early alerts of new drainage canals and plantations development
Floods monitoring	Historical assessment of the flooding regime for characterization of the hydrological state of peatlands	Assessment of the hydrological state of peatlands and impact of the restoration measures
Fires monitoring	Historical assessment of the fires impact for characterization of the degradation state of peatlands	Early alerts of fires

Users requirements related to these 3 needs have been discussed and confirmed during the stakeholders' workshop and follow up discussions with BRG. They are described in the tables underneath.

Table 1.2. Need for information on drainage canal detection

UR1 – Detection of new drainage canals	
General objective	Early detection of new canals in Indonesian peatlands shall allow the detection of new plantations development both at industrial and smallholder scales. Industrial scale plantation development in peat is usually taking place over large areas of at least several hundred hectares, with a network of drainage canals including large canals (20-30 meters width), intermediate canals (10-20 meters width) and small canals (5-10 meters width). In these schemes, the length of the canal ranges from a few hundred meters to a few kilometres. Smallholder development is usually taking place on much smaller areas, as small as a few hectares, with intermediate to small drainage canals. However, these are often connected to existing larger drainage canals.
Minimum Mapping Unit	Minimum width: 10 meters Minimum length: 300 meters
Minimum accuracy	80%
Frequency	3 months
Delivery time	Maximum 5 days after last image acquisition

Table 1.3. Need for information on flood monitoring

UR2 – Floods monitoring	
General objective	Flood monitoring shall give users data on the floods extent and floods duration to support assessment of the hydrological state of the peatlands.
Minimum Mapping Unit	50 ha
Minimum accuracy	90%
Frequency	6 months
Delivery time	Maximum 5 days after last image acquisition

Table 1.4. Need for information on fire monitoring

UR3 – Fire monitoring	
General objective	Fire monitoring shall provide information on the extent of areas impacted by fires both in forest and open vegetation peat lands.
Minimum Mapping Unit	5 ha
Minimum accuracy	80%
Frequency	Monthly during the dry season, 3-monthly during the rainy season
Delivery time	Maximum 3 days after last image acquisition

Other feedback obtained from BRG

BRG confirmed during the meetings in February 2019 in Jakarta its interest in the system and its willingness to support development of the system by providing knowledge and feedback. BRG provided the SarVision team with some additional feedback that will be considered in the next steps of implementing the project:

1. Change the name of the viewer/monitoring system from Tropical Peat Watch to Tropical Peat Viewer. This because the name 'watch' gave the impression that people are being watched instead of being supported by providing critical information on peat.
2. BRG requested to be involved in the development of the viewer in order to ensure that its specifications align optimally with the user requirements. In this sense, BRG requested to be provided with a password of the viewer under development so that timely feedback can be provided.
3. BRG requested a 1 to 2 days training session towards the end of the project to be fully informed of the technical specifications of the monitoring system and the viewer.

All requests have been accepted and carried out by the project team.

2. Monitoring system developments

2.1 Introduction

Tropical peat swamp forests, distribution, disturbance and restoration

While peatlands cover 3% of the Earth's land mass, they contain as much carbon as all terrestrial biomass combined, twice as much as all global forest biomass, and about the same as in the atmosphere (Crump et al., 2017). Deposits of peat underneath peat swamp forests are among the world's largest reservoirs of carbon. Although tropical peatlands occupy only about 0.3% of the global land surface, they could contain as much as 20% of the global soil carbon stock, representing 63–148 Gt of carbon (Rieley and Setiadi 1997; MacDicken 2002). According a survey made in 2008 (Joosten, 2010) the following tropical countries have the largest peat carbon stocks: Indonesia with 49 Gt C and PNG, Brazil and Malaysia with each ± 5 Gt C. More recent studies reveal previously unknown large tropical peat carbon stocks such as in the Peruvian Amazon with ± 20 Gt C (Lähteenoja et al., 2011) and the Cuvette Centrale swamp forest in the Congo Basin with ± 30 Gt C (Dargie et al., 2017).

Peat swamp forests are among the world's most threatened and least known ecosystems. In Southeast Asia large areas of peat swamp forest have been deforested (for timber), converted for agricultural projects (even though the soil is too acid), or are converted into plantations (such as oil palm, acacia and Borneo rubber), even though peat systems are fragile and sensitive to hydrological disturbance (e.g. Hoekman 2007). Drainage through canalisation has frequently severely disrupted water table level dynamics, causing the peat layers to dry out and trees to collapse over large areas. Besides resulting in CO_2 emissions due to oxidisation

(Harris et al. 2012; Zarin 2012) this process makes them particularly vulnerable to fire, especially during 'El Niño' years (Van der Werf et al. 2009). Emissions from the fires in Indonesia during 1997-1998 for example, have been estimated at 0.8-2.5 gigatonnes (Gt) of carbon (Page et al. 2002; Kool et al. 2006).

Only 15% of the world's peatlands are drained (Crump et al., 2017). Global emissions from drained peatlands through oxidisation account, for ± 0.5 Gt C emission per year, which is ± 5% of the total global emission. With ± 0.2 Gt C per year Indonesia is the largest contributor in this category. Besides oxidisation, peatland fires, mainly from Russia and Indonesia, cause huge additional emissions. In Indonesia in the El Niño year 2015, 900,000 ha or 3.5% of the peatland area was on fire. The extent of peatland fires in Indonesia changes from year to year, peaking in El Niño years. On average, Indonesia emits an additional ± 0.2 Gt C per year because of peat fires (Crump et al., 2017).

Water management is essential in addressing these disturbances. However, the relationship between spatial and temporal dynamics of peat swamp forest hydrology, carbon content and forest health would need further study. Such understanding would not only support the conservation of peat swamp forest, but also the rehabilitation of degraded tropical peatlands, which may significantly reduce carbon emission and fire risk.

Indonesia makes efforts to restore degraded peatlands by "re-wetting", blocking canals and promoting paludiculture (sustainable wet agriculture and forestry on peatlands). This will decrease global emissions caused by oxidation and fire.

Tropical peat swamp forests and remote sensing

In the humid tropical regions, optical remote sensing systems largely fail because of persistent cloud cover. LANDSAT is most commonly used but fails to provide useful data every year (e.g. Gastellu-Etchegorry 1988). A recent study using the optical RapidEye data showed a good potential for peat swamp forest inventory and disturbance mapping (Franke et al. 2012). Spaceborne radar observation is not hindered by adverse atmospheric conditions (such as clouds, smoke and haze) and can be made frequently and repetitively but is still not widely used and relatively unknown. The advantages are considerable, however. Observations can be made frequently, also in the wet season, and because of a certain level of penetration of the radar waves, also observation below the canopy is possible. Particularly the L-band sensors on board the former JERS-1 and ALOS-1 satellites (Rosenqvist et al. 2007, Hoekman 2007, 2016) are superior to all other spaceborne sensors for assessment of flooding and drought conditions and, thus, hydrological cycles. Moreover, radar signals are sensitive to forest structure and biomass level (Hoekman and Quinones 2002; Hoekman et al. 2010; Englhart et al. 2012; Schlund et al. 2014). This offers unique opportunities for applications such as peat swamp forest health and fire susceptibility monitoring as well as fast illegal logging response monitoring.

Rationale for Tropical Peatland View project

Until 20 years ago Indonesia's peatlands were used for selective logging. This was followed by large scale drainage and deforestation. Restoration relies on raising water levels.

The Indonesian government is committed to improve peatland management and has established the peatland restoration agency (BRG) to coordinate its efforts. This commitment includes the rehabilitation of 3 million ha of degraded peatlands, blocking 10,000 km of canals and construction of 10,000 dams in the next few years. Nine peat restoration areas are identified which are located in Sumatra, Kalimantan and Papua (7 provinces). In these 7 provinces there is 16.1 Mha peatland, of which 5.8 Mha ombrogenous peat (domes) and 2.7 Mha assigned as priority for peat restoration (Fig.2-1).

South-south cooperation between Indonesia and the other countries with large areas of tropical peat resulted in the establishment of the International Tropical Peatland Center (ITPC). The ITPC was opened in Jakarta on 30/10/2018 by the Governments of Indonesia, Democratic Republic of the Congo, the Republic of Congo and Peru.

To implement its mandate, BRG is critically dependent upon up-to-date and accurate data on the location of existing and new canals, occurrence of flooding, drainage and occurrence of fires in Indonesian peat. Remote sensing data is needed to obtain such information in a timely manner over large areas. In this project C- and L-band data are used. L-band radar is uniquely suitable (a) to monitor flooding under vegetation canopies, such as tropical peat swamp forests, (b) to assess variations in peat soil moisture and (c) to detect excess drainage along canals. Sentinel-1 radar can deliver timely and accurate information on deforestation, fire damage and road/canal development, even in periods of persistent cloud cover. It also has great potential for degradation detection and quantitative estimation, outperforming optical data. It may be possible to monitor ground water level under a closed peat swamp forest canopy, but this is still under investigation

The main objective of this project is to develop and demonstrate a prototype peatland monitoring system (mainly based on PALSAR-1/2, JERS-1 and Sentinel-1) to potential users and stakeholders in Indonesia and internationally, such as through the Global Peatland Initiative (GPI) and the International Tropical Peatland Center (ITPC).

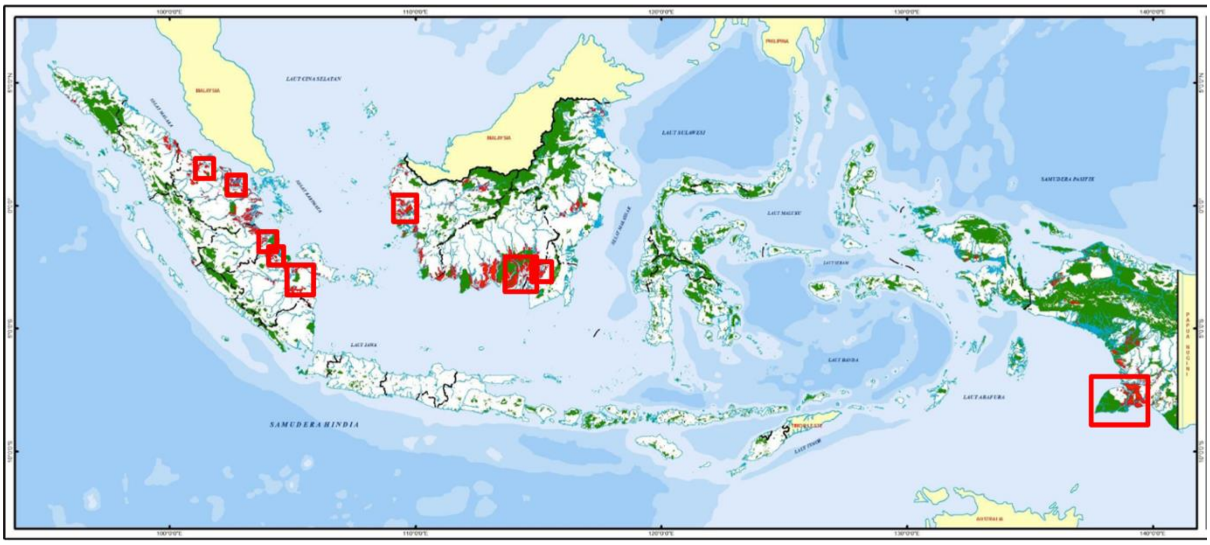


Fig 2-1. Nine peat restoration areas located in Sumatra, Kalimantan and Papua (7 provinces). In these 7 provinces there is 16.1 Mha peatland, of which 5.8 Mha ombrogenous peat (domes) and 2.7 Mha assigned as priority for peat restoration.

Overview EO data availability and baselines

For this project all available ascending Sentinel-1A/B data covering the test sites have been used and pre-processed interferometrically. Since the system is scalable and easy to expand large parts of Sumatra and Borneo were already processed at the end of this project (see Fig 2-2). Large areas have been divided in stacks of varying size for a fixed number of burst (typically 30-50) for efficient processing.

Ample L-band data have been made available by JAXA in the framework of the Kyoto & Carbon Initiative. For the current post-K&C phase 5 (2019-2022) both LAPAN and WU focus have an agreement with JAXA, and both focus on tropical peat monitoring. For all major tropical peat areas all JERS-1 and PALSAR-1/2 ScanSAR data are available (Fig 2-3). These include the Pastaza-Marañón foreland basin in Peru (16 tiles), the Cuvette Centrale wetlands in Congo (90 tiles) and Indonesia: Sumatra (61 tiles), Borneo (89 tiles) and Papua (58 tiles).

Table 2-1. Overview radar satellites used

L-band, 24 cm wavelength	
JERS-1	1992 - 1998
PALSAR-1	2006 - 2011
PALSAR-2	2014 – present
PALSAR-3 and others	Continued future service
C-band, 5.6 cm wavelength	
ERS-1/2	1991-2000/1995-2011 (not used in this project)
ASAR	2002-2012 (not used in this project)
Sentinel 1A	2014 – present
Sentinel 1B	2016 – present (identical)
Sentinel 1C etc.	Continued service for two decades

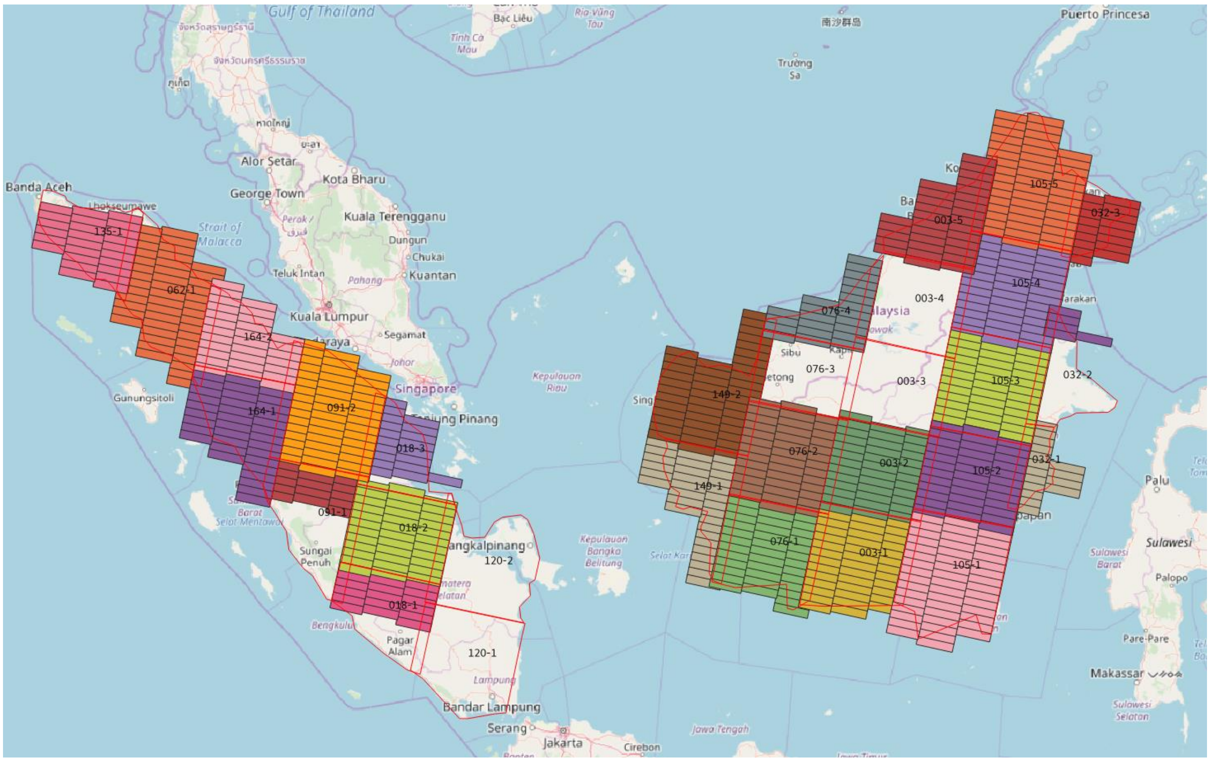


Fig 2-2. C-band, Sentinel-1, Processing status August 2019

Fig 2-3. L-band data availability: JERS-1, PALSAR-1/2 ScanSAR. *PALSAR data courtesy: ALOS K&C © JAXA/METI. (a)* Pastaza-Marañón foreland basin, Peru (lat-long 3S-7S/77W-73W, 16 tiles); (b) Cuvette Centrale wetlands, Congo lat-long 4N-5S/15E-25E, 90 tiles); (c) Indonesia: Sumatra (61 tiles), Borneo (89 tiles) and Papua (58 tiles).

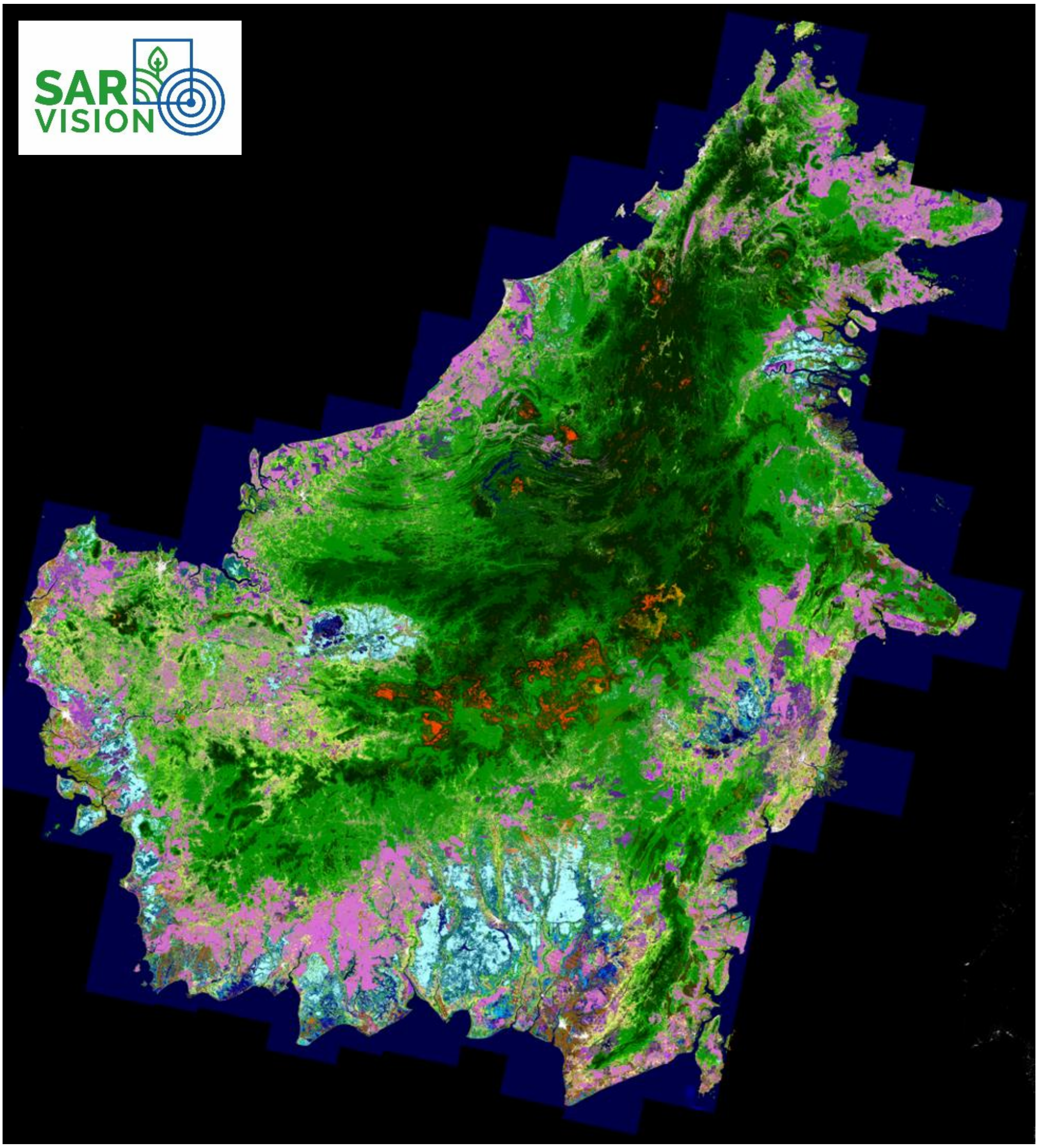


Fig 2-4. Borneo baseline 2019 based on PALSAR-2, Sentinel-1 and Landsat-8; 25 m pixel size.

Fully automated deforestation and degradation monitoring is done using very accurate land cover and forest type baselines (several years), preferably with several additional information layers such as re-growth (decadal change) and flooding, at 25 m pixel size. An example, based on PALSAR-2, Sentinel-1 and Landsat-8, is given in Fig 2-4. The classes relate to ecological characterisation and biomass levels and are conform the FAO Land Cover Classification System (LCCS). Such maps have been made for Borneo and Sumatra, and were used in this project, but are also already available for Papua (Indonesia) and Peru. An overview of the Indonesian baseline maps are shown in Fig 2-5. This Fig 2-5 also shows the location of this project's test areas, i.e. the provinces Riau and Central Kalimantan (white boxes), as well as the location of the Mawas research area and field station (yellow box).

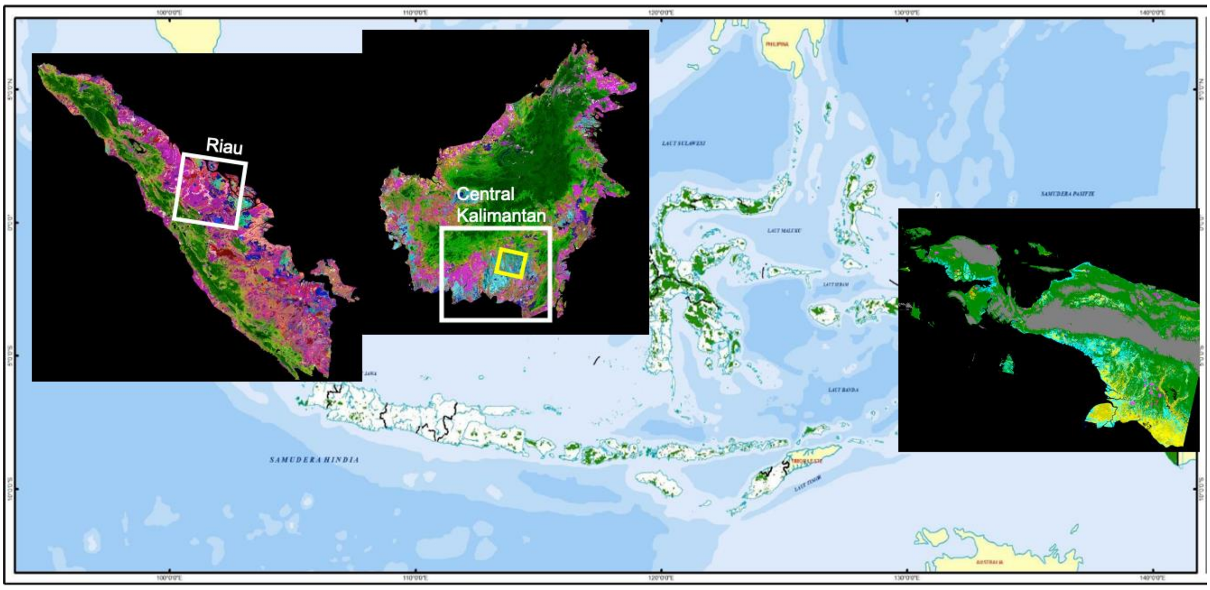


Fig.2-5. Baseline overview and project areas. LC baseline maps based on PALSAR-2, Landsat-8 and Sentinel-1.

Overview Sentinel-1 NRT forest monitoring system components

A fully automated and scalable interferometric pre-processing and thematic processing chain was developed, which has the following components.

Radar data pre-processing chain: Free Sentinel-1 radar data in SLC format are automatically downloaded from data portals (including ESA and ASF portals) as soon as available. When available, interferometric processing is started to achieve radiometric calibration and geometric correction. State-of-the-art slope correction algorithms and multi-temporal speckle reduction algorithms (developed by Wageningen University and SarVision) are applied to improve the quality and usefulness of the data. The result is an (updated) time-series of dual-polarization (VV- and HV-) intensity images at a 15-meter pixel size and interferometric coherence data. Updates are available within two days of satellite overpass.

Thematic processing chain: State-of-the-art time-series analysis algorithms (developed by Wageningen University and SarVision) are applied to monitor changes in forest cover in terms of deforestation and degradation. Salient features are the use of object-based changes and the use of feedback loops to increase sensitivity while at the same time reducing noise. New models have been developed and validated to quantify the intensity of the degradation.

Near real-time and historical processing chains: The thematic processing chain is divided in an historical part (for all already available Sentinel- 1 images) and a near real-time part (for all newly available Sentinel-1 images). The historical analysis gives good insights in the nature and location of recent changes.

Forest baseline: Baseline maps are based on available radar and optical images around the start of the Sentinel-1 data acquisition period. Radar images used usually are the Sentinel-1 (C-band) and PALSAR-2 (L-band); optical images used include Sentinel-2 (when available) and Landsat-8. The baseline shows land cover using the systematics of FAO Land Cover Classification System (LCCS). For Indonesia it shows all main forest types over some degradation and regrowth classes and hydrological features such as flood frequency (also under the canopy). The pixel size of 15-meter matches the pixel size used for the forest monitoring.

Change mapping: The system maps change by comparing recent Sentinel-1 radar images with historical Sentinel-1 images, using a baseline land cover map. The baseline is defined for a certain date, for example the date when the first Sentinel-1 images have become available at a regular basis, or later. For most places in the world a January 2017 baseline can be adopted, however, for the prototype system developed for Borneo a mid-2015 baseline was used.

The system can map change in several fundamentally different ways, resulting in a number of half-products, which can be combined and post-processed to generate several NRT mapping products. These products include deforestation maps, forest degradation maps and maps of road and canal development in peat swamp forest. Other NRT products, still in development, include forest regeneration maps and maps showing ground water level in peat swamp forest.

Examples of several NRT mapping product types are (1) the change detection of deforestation and degradation (Fig 2-6a); (2) canal/road mapping on peat (Fig 2-6b); (3) Quantitative estimation of degradation (Fig 2-6c). A wide area example is shown in Fig 2-7.

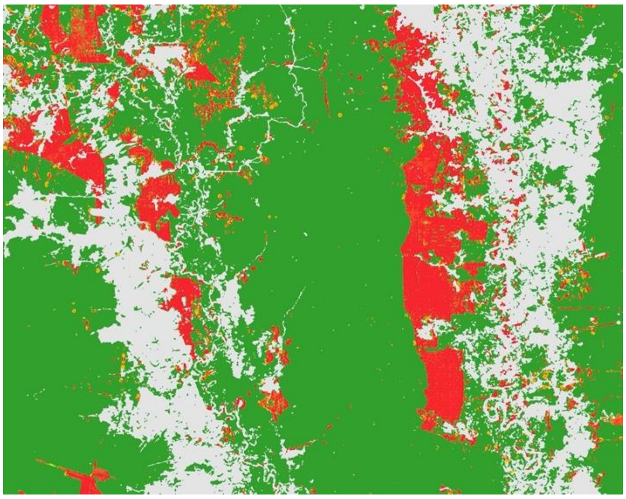


Fig 2-6a. Change detection of deforestation and degradation. Forest: green, non-forest: black; deforestation: shades of red; degradation: shades of yellow and orange. For details see section 2.3.

Fig 2-6b. Canal/road mapping on peat. Forest: green, non-forest: white; canal gaps: yellow; For details see section 2.3.

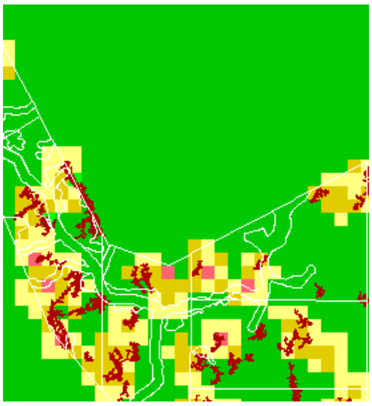


Fig 2-6c. Quantitative estimation of degradation. Forest: green, non-forest: black; deforestation: shades of red; degradation: blocks of 150mx150m in 4 colours. For details see section 2.3.

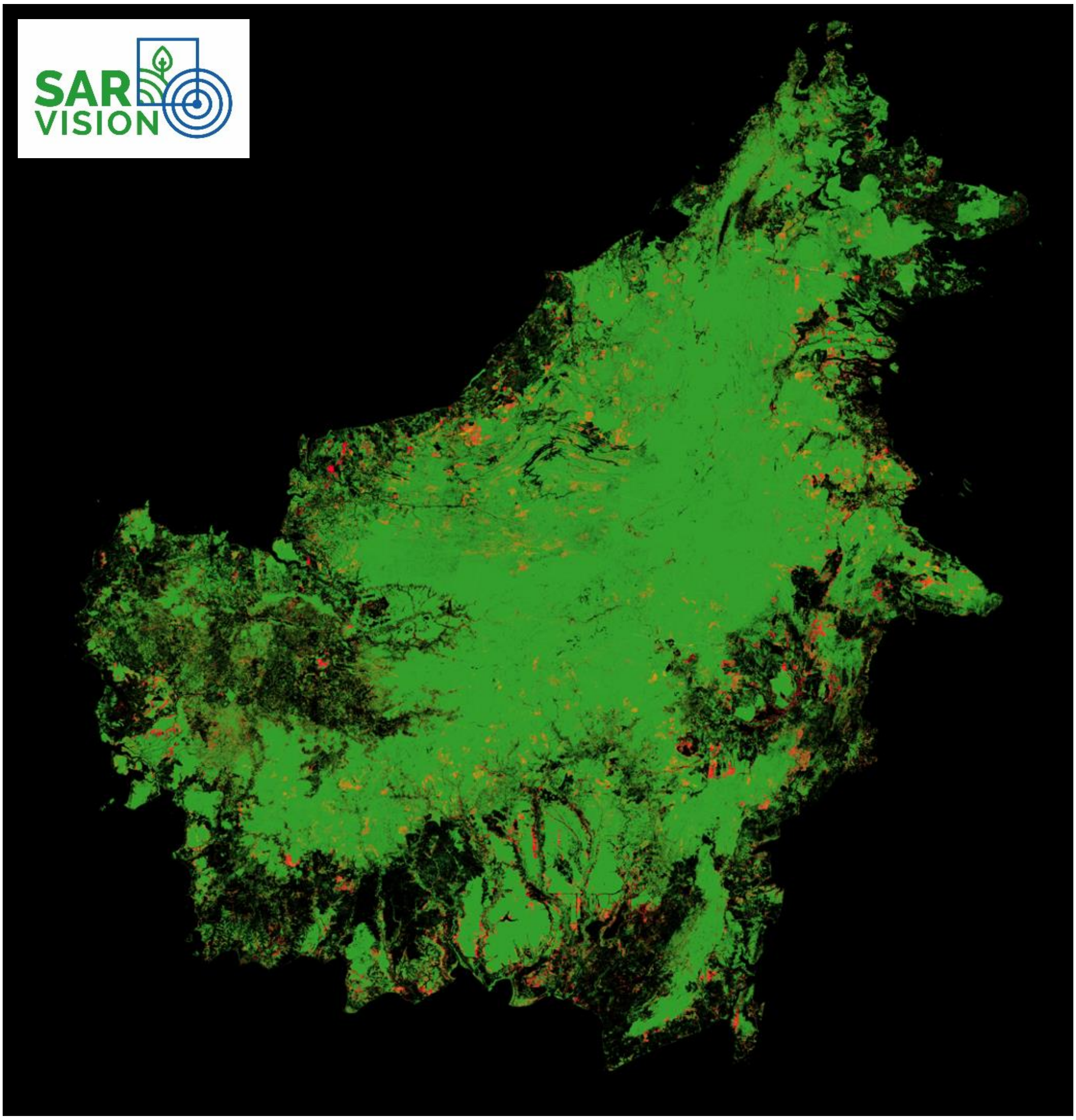


Fig 2-7. Sentinel-1 product over entire Borneo for end 2019 showing cumulative deforestation (launch-present) and current degradation status. Forest: green, non-forest: black; deforestation: shades of red; degradation: shades of yellow and orange.

Overview L-band monitoring system components

PALSAR makes systematic acquisition in the ScanSAR mode, covering all main wetlands of the World frequently. For Indonesia, the interval between consecutive acquisitions for PALSAR-2 is usually 28 or 42 days and for PALSAR-1 every 46 days. It is noted that the overlap of the PALSAR-1 swath is more than 50% at the Equator, which means that often observations are available every 23 days. Two data formats of ScanSAR have been used. The first is the tile product, which is a pre-processed image covering an area of 1 degree by 1 degree. These data are available for participants of the K&C Initiative (such as WU, SarVision and LAPAN) allowing study of all major tropical peatlands (see Fig 2-3). A higher quality can be achieved using ScanSAR standard data in SLC format. These have been obtained systematically for the test sites of this project, the provinces Riau and Central Kalimantan, but also for all other provinces in Indonesia with ongoing peat restoration activities. Both types of time-series have been processed to data stacks covering the JERS-1, PALSAR-1 and PALSAR-2 eras (see section 2.2).

Using these stacks two types of products were made. The first is a flood detection time series, resulting in flood frequency maps. The thematic processing is based on incidence angle and forest structural type dependent thresholding (see also Hidayat *et.al.,* 2012, 2017). An example is given in Fig 2-8a where three types of flood frequency are shown. More detail is given in section 3. The second product is a drought map (Fig 2-8b). Drought is expressed as ground water level. Thematic processing relies on empirical relationships based on field work near the Mawas research station (Hoekman, 2007). This approach is described in section 2.2.

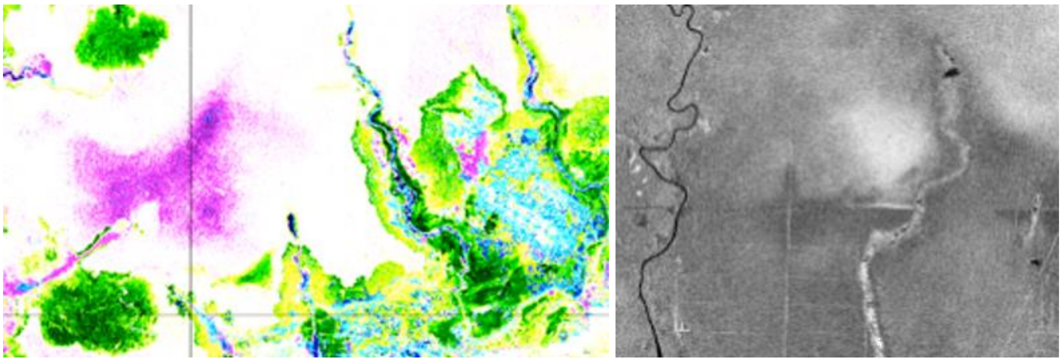


Fig 2-8. (a) Detail of flood frequency map, showing flood frequency in open areas (blue colours), under the vegetation (green colours) and under the vegetation for intact peat domes (purple colours). type – frequency; **(b)** Detail of a L-band HH-pol radar image showing peat soil moisture under the canopy (in this case qualitatively). Bright areas are wet and dry areas are dark. For details of (a) and (b) see, respectively, sections 3 and 2.2.

2.2 L-band

Data availability and basic interpretation

For the Central Kalimantan test site, a historical analysis of all JERS-1, PALSAR-1 and PALSAR-2 data was done. These data cover three eras and each era captures a major El Niño event. These are summarised in Table 2-2.

Table 2-2. Summary JERS-1 and PALSAR eras and events for Central Kalimantan.

Sensor	*Number of observations*	*Period*	*Major events*
JERS-1	15	1994-1998	1997 El Niño event
PALSAR-1	22	2006-2010	2006 El Niño event
PALSAR-2	39	2014-2019	2015 El Niño event

Though the quality of the JERS-1 data is somewhat limited in terms of radiometry and geometry, the importance of these data for understanding the present hydrological conditions is very large. In the JERS-1 era, especially the oldest data, very often show the ombrogenous peat domes of Sumatra and Borneo in a “pre-disturbance” situation. Even though in many areas selective logging already had taken place, the disturbance of the hydrology is still minor, especially compared to the large-scale disturbance of the last two decades, when large canals were made to drain the area, to make these areas suitable for conversion to plantations. The PALSAR-1 data are generally of very good (radiometric and geometric) quality and are available, like JERS-1, in HH-pol only. PALSAR-2ScanSAR has HH- and HV-polarizations. The quality of the PALSAR-2 data is comparable with PALSAR-1, however, suffers from disturbances from Faraday rotation. This is related to larger sunspot activity in this period. Approaches to correct for Faraday rotation disturbance are still under study. When uncorrected, the effect is a radiometric striping (in range direction), which is often distinctive over the large homogeneous peat forest areas. This phenomenon is visible, for example, in Fig 2-9c.

Nevertheless, even though the quality of the L-band data varies over time, phenomenological analyses of this time-series can be made, and important conclusions can be drawn. Such conclusions are partly based on knowledge of the physical and ecological characteristics of the terrain and knowledge of the history of recent processes that have caused disturbances. They are also partly based on knowledge of the L-band radar interaction mechanisms with peat swamp forests (Hoekman, 2007). L-band waves partly penetrate the forest canopy, even when fully closed and, therefore, part of the signal relates to conditions at the soil surface. When the soil is wet or flooded the signal component from the forest floor is strong, mainly because of increased double-bounce scattering with tree trunks. When the soil is dry, the signal component from the soil is very low, even lower than for a dryland forest, because of low scattering and absorption by the rough and dry peat soil surface. The overall result is a wide range of backscatter variation related to soil moisture or ground water level. For this project, a limited effort was made to quantify this relationship empirically on the basis of PALSAR-1 data and GWL data collected near the Mawas research station. This will be presented later on. First the general observations will be discussed.

Qualitative evaluation of temporal changes in hydrology and landscape

Ground water levels in peat domes increase during the wet season and decrease in the dry season. In the pre-disturbance area this is clearly visible. An illustration is given in Fig 2-9a, where areas in the blue ellipses represent several large domes which fill up during the wet season (high backscatter) and dry out (low backscatter). This happens every year in the JERS-1 era until the 1997 El Niño. The JERS-1 lifetime ended in 1998 and L-band observations were resumed in 2006 by PALSAR-1 at the time of another large El Niño event. The 1997 and 2006 El Niño events, in combination with the construction of large drainage systems, resulted locally in extremely low ground water levels, which in turn made the soil vulnerable for (underground) fires. Large forest areas were lost, thick layers of peat were burned and compacted, resulting in a severely disturbed hydrology. Some areas remain very dry even in the wet season, causing further damage by oxidization and fire. Fig 2-9b shows the permanent effect of this disturbance as well as the possible causes. The permanent effect is most easily visible on the peat domes (blue ellipses) which do not flood during the wet season to the same extent as before. For the two most Northern peat domes the extent of the flooding is far less (yellow ellipses), while the most Southern peat dome never floods again. The possible causes for each of these three peat domes is indicated by the red arrows. These are the bright linear features. These were once drainage canals, which drained ground water level to a large

depth. Underground fires burned the dry layers, causing deep linear shaped concave depressions (or soil subsidence), which fill up with water in the wet season. Note they are bright because of the double-bounce scattering with remaining (burned) trees, tree remnants and/or secondary vegetation. These deep depressions severely drain the higher peat domes nearby constantly. The first PALSAR-2 images of 2014 still shows very similar peat dome flooding as in Fig 2-9b. The current situation after the last strong El Niño event of 2015 is even more alarming. As shown in Fig 2-9c, all three major peat domes (in the ellipses) were never flooded again. The only wet areas in this image are depressions, filled up with water, which are the deep fire scars of previous strong fire events.
The photo (Fig 2-10) is an illustration of the onset of underground peat fires along a canal in Sebangau National Park during the 2006 El Niño. The forest is still standing but will collapse after the roots are burned. When the fires are intense, thick layers of dried out peat will burn and cause soil surface subsidence. In the next two paragraphs quantitative methods to assess peat soil subsidence will be discussed.

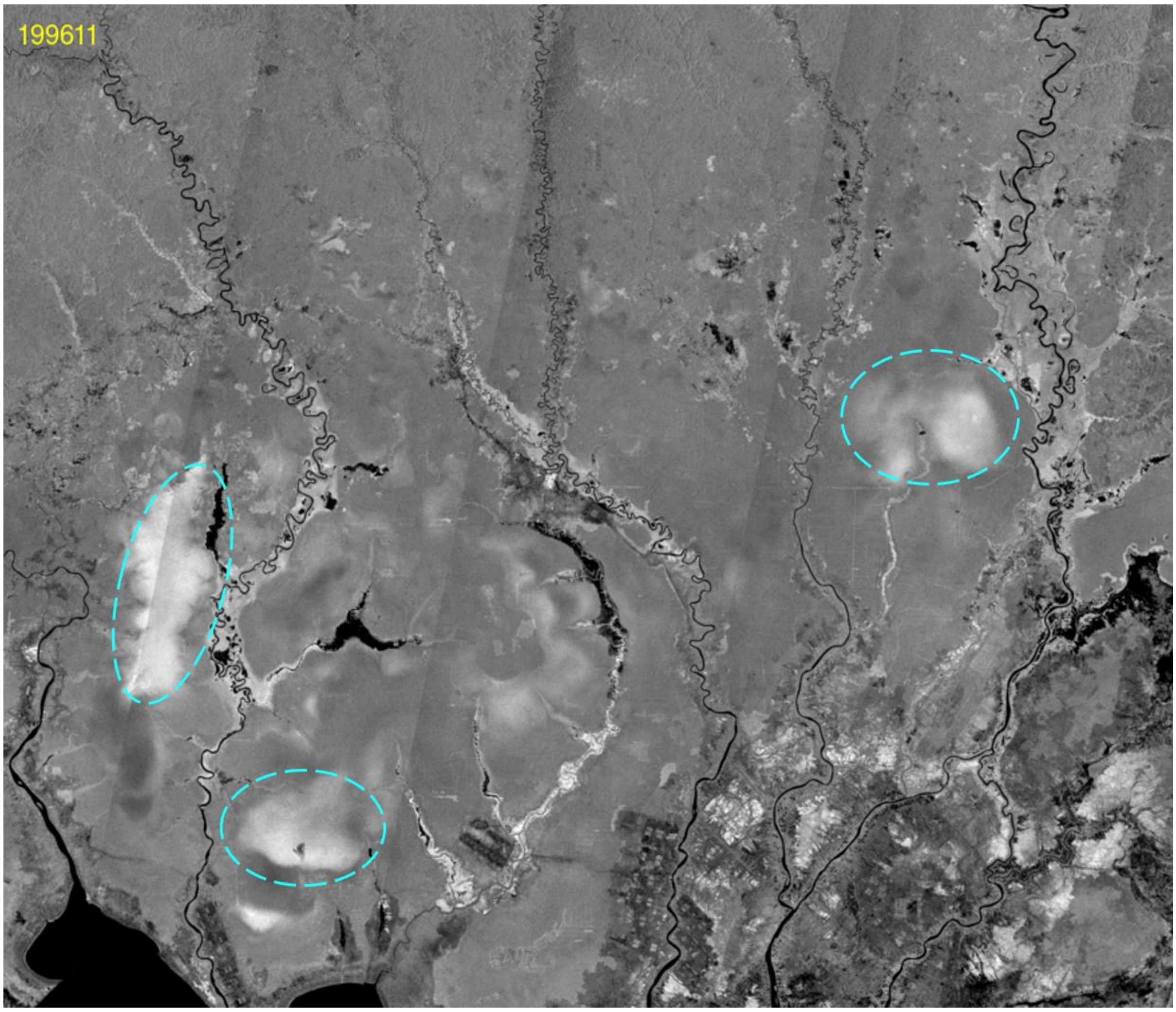


Fig 2-9a. Peat in the pre-disturbance era are often locally very wet, which can be noted from the high backscatter in the blue ellipses. JERS-1, November 1996. *JERS-1 data courtesy: ALOS K&C © JAXA/METI.*

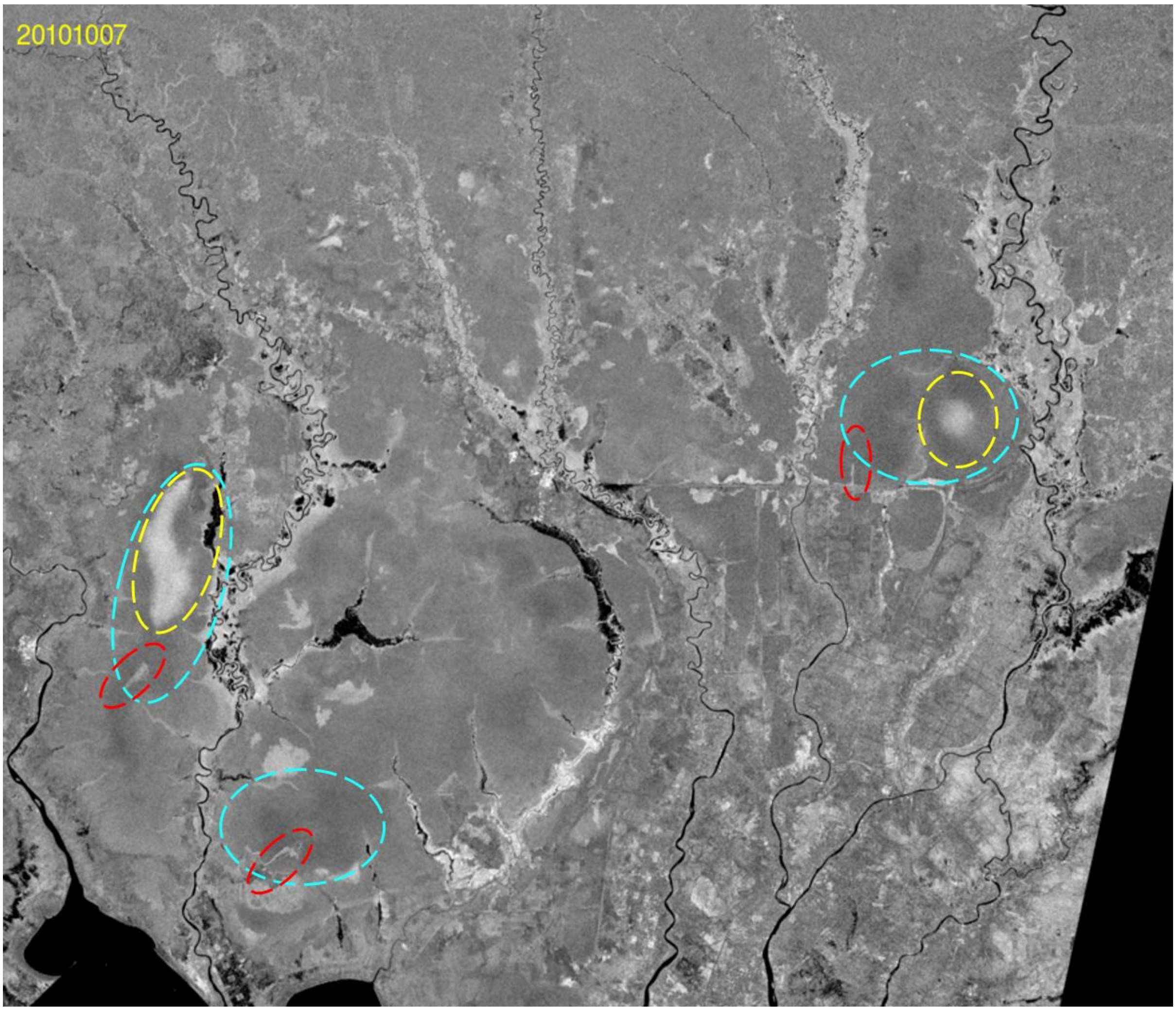


Fig 2-9b. After the 1997 and 2006 El Niño's these areas are permanently smaller (yellow ellipses) or absent. This may be attributed to major disturbances indicated by the red arrows. PALSAR-1, 7 October 2010, *PALSAR-1 data courtesy: ALOS K&C © JAXA/METI.*

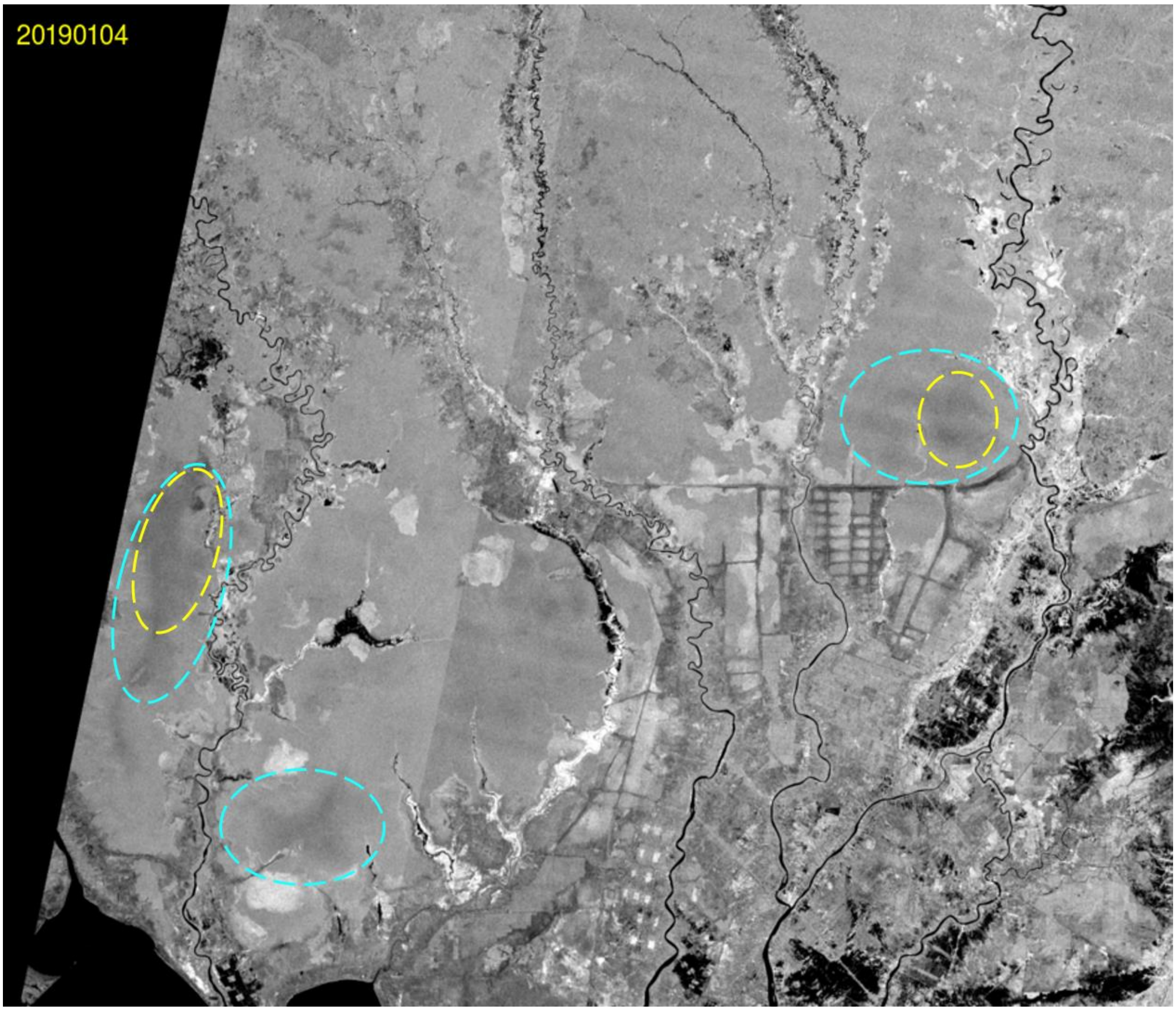


Fig.2-9c. After the 2015 El Niño these areas have never been wet again. Note that the effect of Faraday rotation is locally visible as a dark-bright striping pattern oriented in range direction, such as in the peat dome in the upper-right. PALSAR-2, 4 January 2019, *PALSAR-2 data courtesy: ALOS K&C © JAXA/METI.*

Fig 2-10. Excess drainage and underground fire in peat swamp: Sebangau National Park, Central Kalimantan, 2006 El Niño.

Field observations and empirical relations between GWL and L-band backscatter

To study peat swamp hydrology, ecology and radar wave interaction in a systematic way a dedicated research station was established in the Mawas peat swamp forest conservation area, which is located some 80 km east of Palangkaraya, in the province of Central Kalimantan. The main feature is a research bridge, 23 km in length, crossing an entire peat dome (Fig 2-11). Instruments placed along this bridge automatically measured rainfall and water level every hour. Field surveys were made to characterize the variation in vegetation structure along this bridge. Moreover, in December 2004, an airborne radar survey (the ESA INDREX-2 campaign) was carried out along the bridge to test a variety of advanced imaging radar techniques (Hajnsek et al., 2005; Hoekman, 2007).

Field observations in the Mawas peat swamp area commenced early 2004 to prepare for the 2004 ESA INDREX-2 campaign in Kalimantan. Ground water level data were used to support the interpretation of the INDREX-2 airborne data. However, the instruments remained in the field, continued to function until the memory of the data loggers were filled completely, and retrieved later to allow any future analysis. This analysis was finally done in the framework of this project, using GWL data recordings coinciding with PALSAR-1 observations. Out of the original 15 instruments, 7 could be used for this purpose.

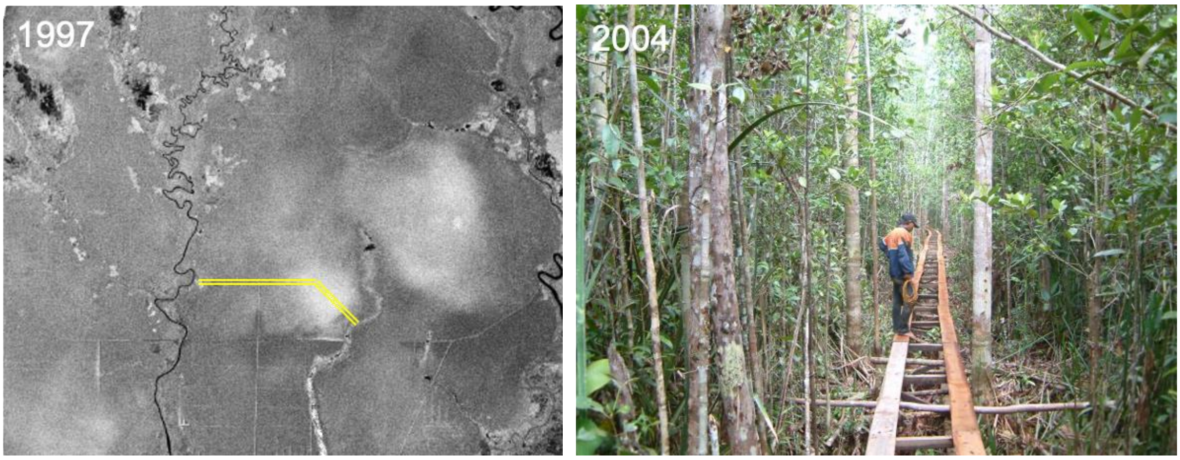


Fig 2-11. (a) Location of the 23 km long research bridge in the Mawas peat swamp forest research area on a JERS 1997 backdrop image. (b) Photo of the bridge.

GWL data were recorded every hour in the period 9 October 2005 until 2 July 2008. In this period 14 PALSAR-1 ScanSAR observations are available. Three of these observations were made in path RSP091 observing the GWL recording instruments at an incidence angle range of 35.5^{o} – 36.7^{o} and 11 observations were made from path RSP094 at an incidence angle range of 22.9^{o} – 24.4^{o}. An overview of the PALSAR-1 observations dates is given in Table 2-3. An example of GWL variation over the entire data recording interval is shown in Fig 2-12. It illustrates how the peat domes slowly fill up with water during the wet season and slowly drain in the dry season. Fig 2-12 also indicates the dates of PALSAR-1 observation. Fig 2-13 shows the relationship between the elative GWL measured in the field and the L-band HH-pol radar backscatter. The three RSP091 observations are indicated with an Asterix, while the 11 RSP094 observations are indicated with a triangle symbol. In general, a fairly strong positive relationship is found with correlations ranging from 0.63 until 0.84. The influence of the difference in incidence angle seems very small and may be ignored. The influence of other environmental factors is large. The latter is summarized in Fig 2-14. The five tubes under the canopy on intact deep peat (i.e. > 10m) all gave a very similar result. The single tube under the canopy but on shallow peat (i.e. < 2m) gives a significantly less steep backscatter response, while for the single tube in a more open area (such as disturbed or burned areas) the backscatter values are higher.

Table 2-3. Overview of path and dates of PALSAR-1 observations used for GWL study.

Path	*Date*
RSP094	20061111
RSP094	20061227
RSP094	20070211
RSP094	20070329
RSP094	20070514
RSP091	20061106
RSP091	20061222
RSP094	20070814
RSP094	20070929
RSP094	20071114
RSP094	20071230
RSP094	20080331
RSP094	20080516
RSP091	20080626

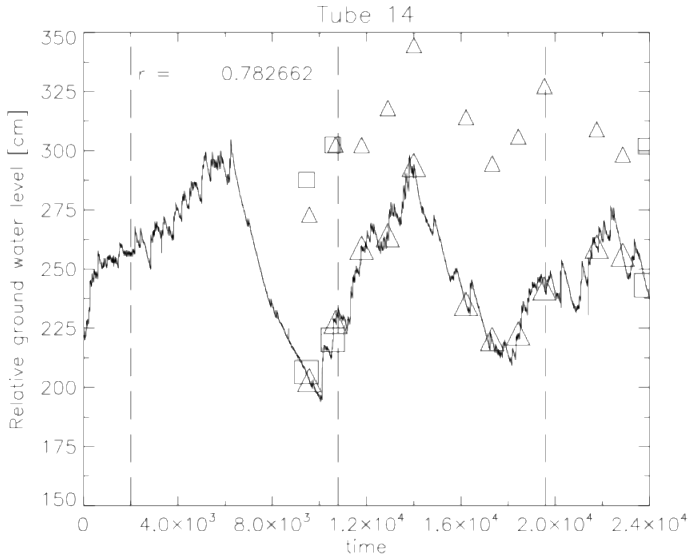


Fig 2-12. Ground water level variation over the period 9 October 2005 until 2 July 2008 for tube number 14 (solid line). The vertical dashed lines mark the first GWL observations in 2006, 2007 and 2008. The horizontal scale is in hours after the first GWL recording. Squares correspond to the time of RSP091 PALSAR-1 observations and triangles the times of the RSP094 observations. The large symbols mark the GWL while the small symbols above show the backscatter level. The relationship between the large and small symbols is the relationship between GWL and backscatter as shown in Fig 2-13.

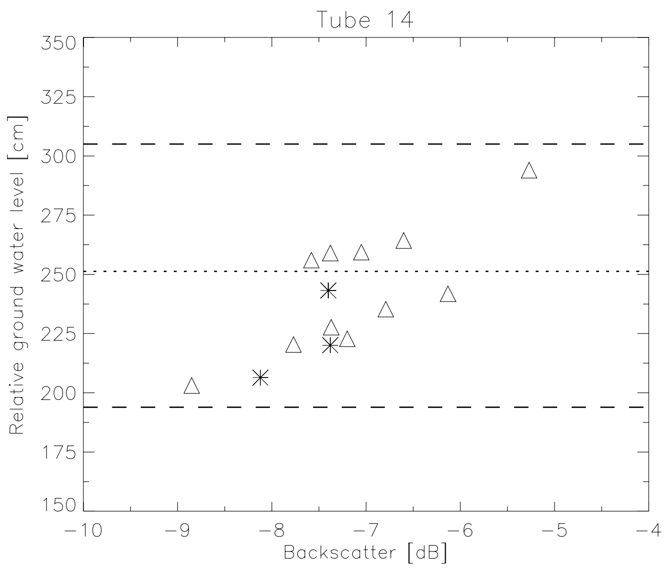


Fig 2-13. The relationship between relative GWL and L-band HH-pol backscatter for 14 PALSAR-1 observations of tube 14. The three RSP091 observations are indicated with an Asterix, while the 11 RSP094 observations are indicated with a triangle symbol.

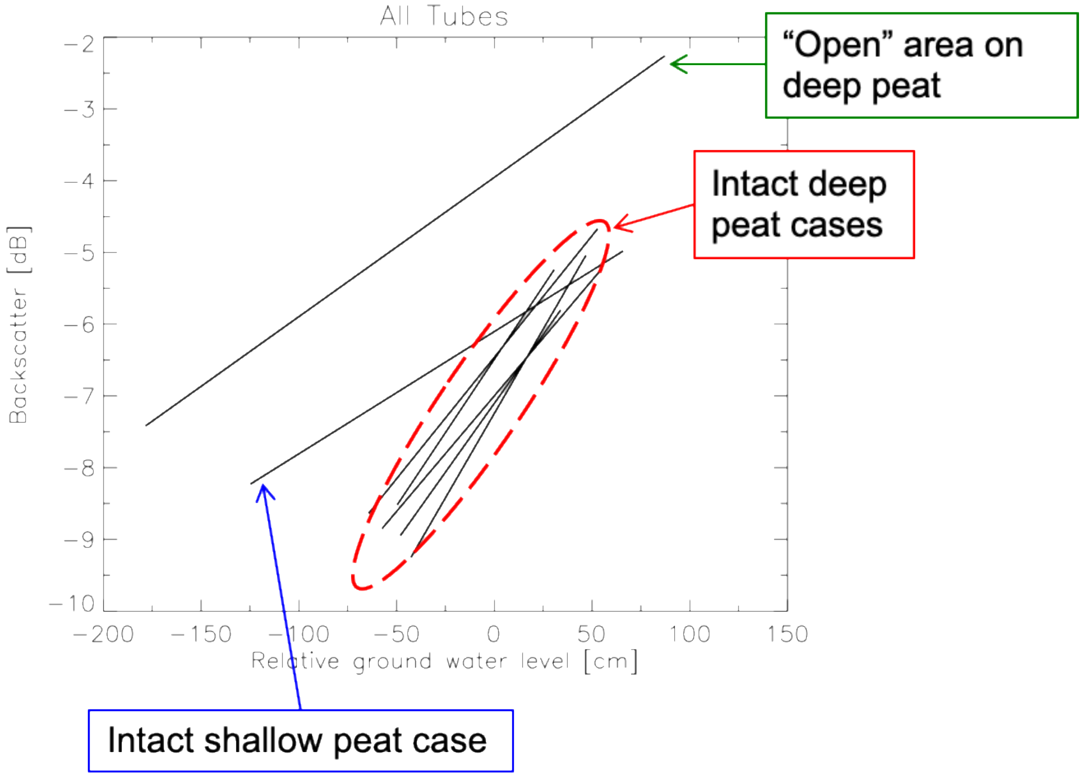


Fig 2-14. Overview of new results. Relationship between (L-band HH) backscatter and relative water levels for a range of conditions.

A quantitative analysis in Sebangau

To illustrate application of empirical relationships with GWL and the combined use of L-band and Sentinel-1 monitoring for applications in peat swamp forest an example will be given next. One of the disturbed peat domes in Sebangau National park near Palangkaraya is a suitable case for demonstration (Fig 2-15). The initial damage was done during the 1997 El Niño. In the JERS-1 radar image of January 1998, taken in the wet season shortly after this El Niño, the subsided part of a peat dome is visible and is indicated by the yellow border in Fig 2-16. The subsidence is caused by burning of peat layers and compaction of the remaining peat layer. In the wet season the depression fills with surface water which results in high backscatter caused by double bounce. In the PALSAR-2 radar image of 8 January 2016 o, taken in the wet season shortly after the 2015 El Niño this bright area has expanded in the North-East direction (Fig 2-16b). A series of maps generated by the Sentinel-1 NRT monitoring system (see section 3) shows the development of fire damage during the 2015 El Niño. These fires start at the edge of the area subsided in 1997 and extends in the subsequent months. It is not surprising that fires start at this location because the area just outside the subsided area is relatively high and the GWL, because of the high hydraulic conductivity is at the same absolute height. However, relative to the soil surface the GWL is high in the subsided area and low in the adjacent area which did not subside. The same is true for the events in 2015 leading to the extended subsided area. Consequently, it follows, that the subsidence can be quantified through the differences in estimated GWL. This is illustrated in Fig 2-16d leading to an estimated subsidence of ± 1 m, through application of the appropriate empirical relationship, as is illustrated in Fig 2-17. From this subsidence estimation, in combination with the aerial extent of this particular fire event, it can be concluded that more than one megaton of carbon was emitted.

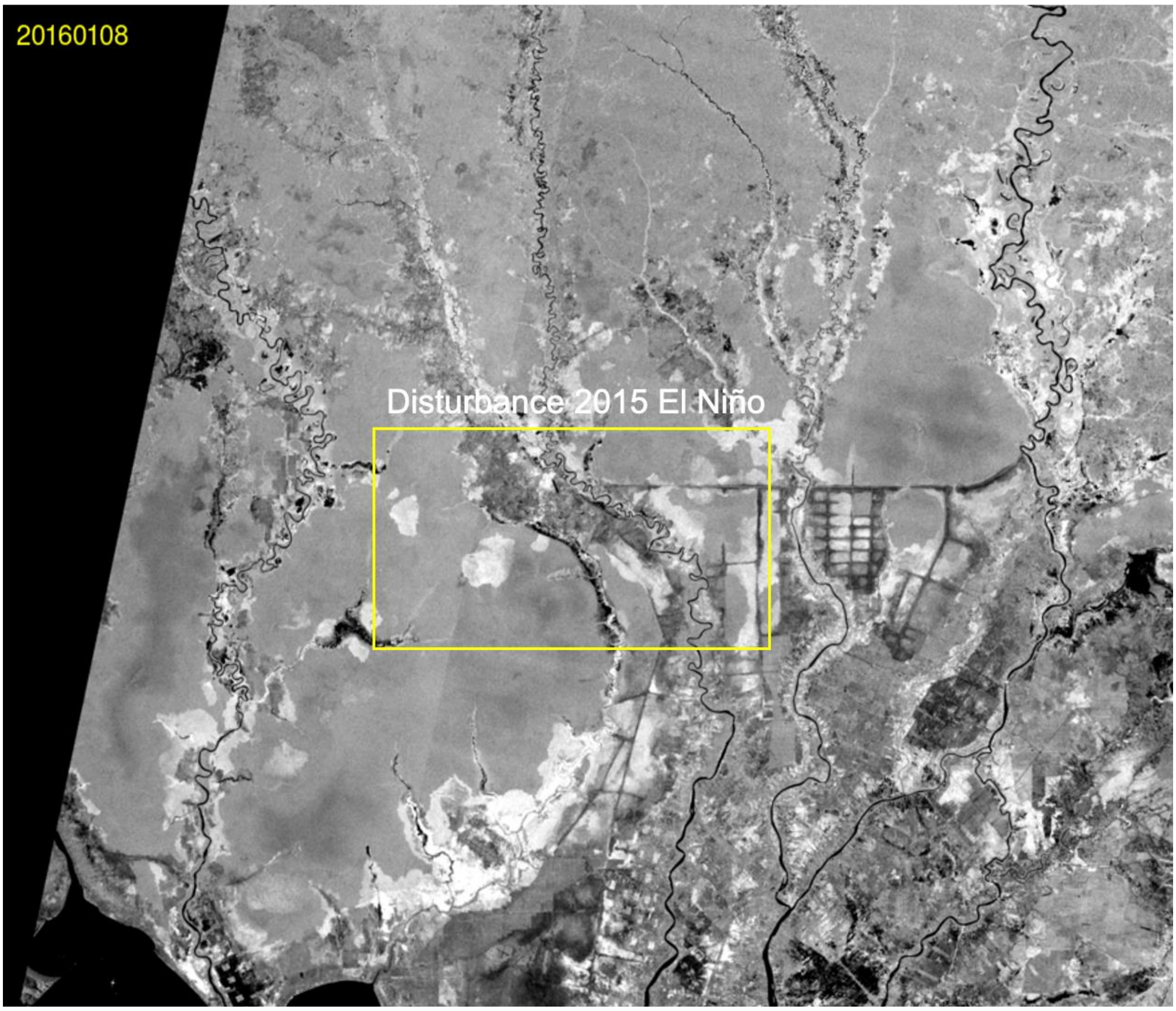


Fig.2-15. Location of the area selected for a more quantitative analysis. It covers the city of Palangkaraya (top center) and a part of the Sebangau National park (left side).

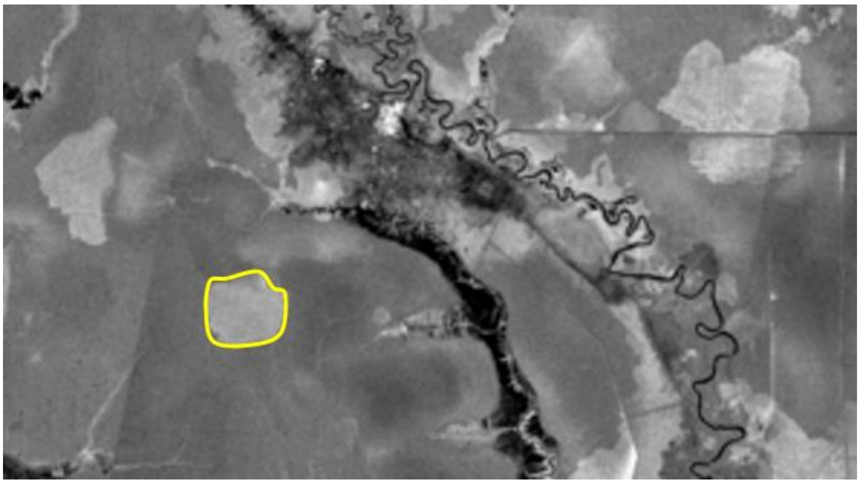


Fig 2-16a. JERS-1, January 1998, shortly after the 1997 El Niño. The area indicated by the yellow border is the subsided part of a peat dome. The subsidence is caused by burning of

peat layers and compaction of the remaining peat layer. In the wet season the depression fills with surface water which results in high backscatter caused by double bounce

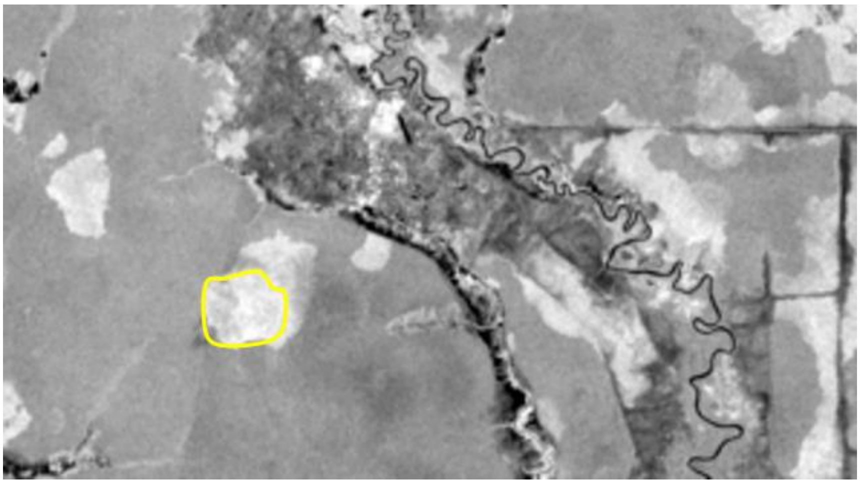


Fig 2-16b. PALSAR-2, 8 January 2016 observation, shortly after the 2015 El Niño. The bright area shown in Fig 2-16a is expanded in the North-East direction.

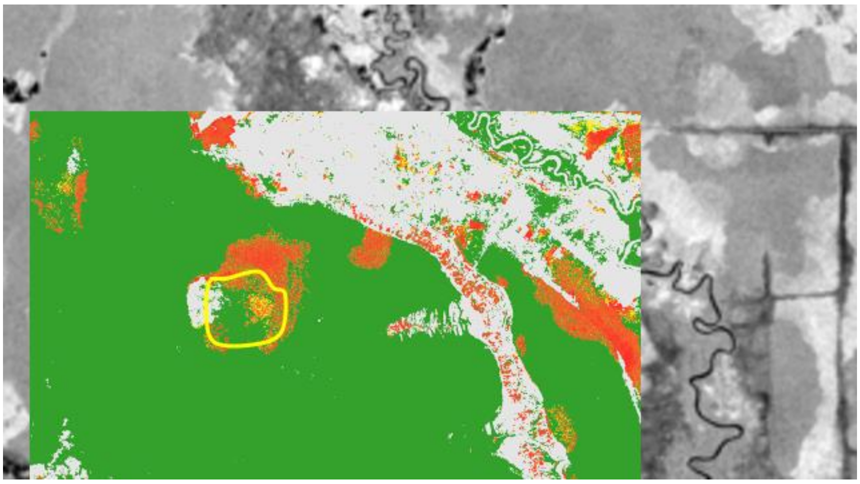


Fig 2-16c. Fire damage during the 2015 El Niño is mapped by the Sentinel-1 NRT monitoring system and is shown in shades of red.

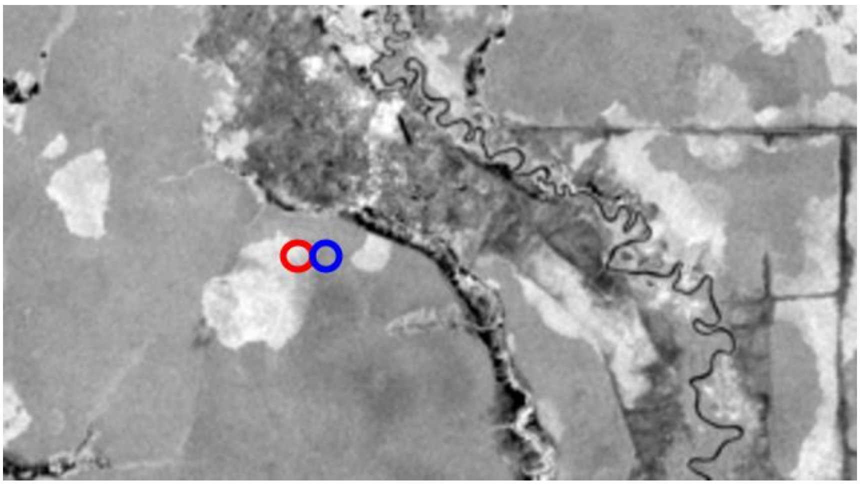


Fig 2-16d. Locations used to estimate relative ground water levels using the empirical relationships between GWL and L-band H-pol backscatter. The location indicated by the red

circle is on disturbed/burned/subsided deep peat, while the nearby location indicated by the blue circle is located in a forested area on intact deep peat.

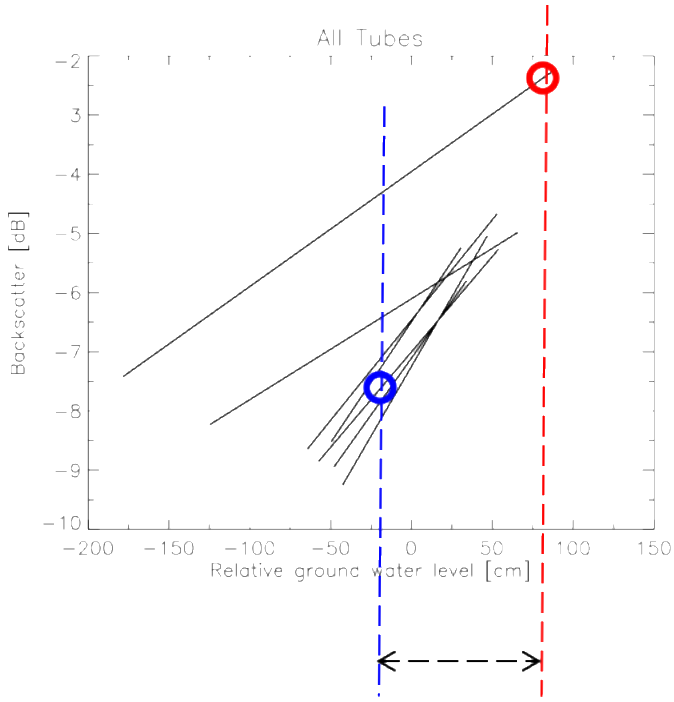


Fig 2-17. Subsidence estimation for the area indicated by the red circle in Fig 2-16d by application of the appropriate empirical relationships. The dashed horizontal arrow relates to a subsidence of ± 1m.

2.3 C-band

Notes on methodologies and validation approaches

Section 2.1 provided an overview of the Sentinel-1 NRT forest monitoring system components. In section 3 and 4 the use of these products will be discussed. This section 2.3 will focus on the methodologies used and the approaches adapted for validation.

This section starts with a discussion on the theoretical background of the radar imaging of canopy gaps caused by canal construction and selective logging. It will be shown that a physical model of radar imaging at high-resolution accurately explains both the way canal gaps show up in a radar image as well as the potential detection capability. Small gaps caused by selective logging are too small to be detected individually, however, the same theoretical model (that describes canal gaps) can be used to quantify the canopy disturbance in a statistical sense. Consequently, in simple words, forest degradation is monitored by a change in texture and deforestation by a decrease in radar backscatter.

After discussing the theory (1), this section continues by discussing (2) validation results for canal gap detection, (3) validation approach for deforestation monitoring, (4) validation results for degradation monitoring, (5) validation approach and results for degradation monitoring and (6) an overview of the main results and considerations.

Theoretical background of canal gap mapping and forest degradation quantification

Models of the physical interaction, the forest structure and the canal gap geometry can be used to simulate radar imaging of canal gaps. The canal gap geometry was derived from SPOT-6/7 data and is expressed as canal width and orientation. The description of forest structure is based on field observations from previous studies (Hoekman and Varekamp, 2001; Schlund et.al., 2015; De Grandi et.al., 2016; Ferraz et.al., 2018). Relevant parameters include forest height and canopy roughness. The physical interaction is modelled at high resolution, accounting for the three-dimensional structure of canopy roughness and incidence angle, as described in (Varekamp and Hoekman, 2002) and canal gap geometry.

Radar profiles of canal gaps in East-West direction were derived by re-sampling and averaging over straight canal sections of approximately 45 radar image rows, which strongly reduces the variation caused by speckle. Fig 2-18 shows a comparison between an observed profile and a simulated profile. The observation differs from the simulation because of remaining speckle and texture effects. However, across the canal profile the fit is very good with a standard error of estimate of only 0.5 dB. Since realistic simulations can be made, the radar backscatter model can be used as a theoretical tool to support further quantitative analysis. In following sections this is done (a) to study limiting factors related to canal gap detection and (b) to study possibilities to quantify small forest gap dimensions in relation to forest degradation.

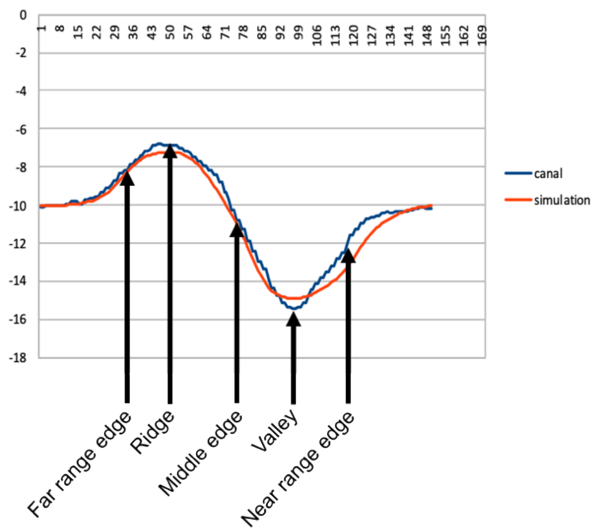


Fig 2-18. Comparison between simulated radar backscatter profile across a canal gap (red) and an observed profile (blue).

Since the radar data are acquired near the equator in descending orbit, the azimuth direction is -168.0° with respect to North and the radar look direction, which is towards the right, is -78.0°, i.e. almost West. For descending data, as shown in Fig 2-18, the radar profile of the canal gap, shows a ridge positioned left of a valley. The valley results from radar shadowing and the ridge from radar overlay. The widths and heights of the ridges and valleys vary as function of canal gap width and orientation. The characteristic shape of the radar gap profile suggests several alternative approaches for linear feature detection. For descending data in the direction from East to West (or right to left) the profile shows a negative edge (or sharp decrease) followed by a valley, a sharp increase, a ridge and a second negative edge. It suggests that several classes of operators are suitable to detect the canal gaps, such as edge detectors, ridge-valley (or line) detectors and matching filters (for the characteristic valley-ridge pattern in descending data). The application of these operators is the first step in the process of generating canal gap maps. Subsequent steps include thresholding of the detections, applying spatial shifts (because the operators act on different parts of the canals gaps), linking small segments into larger segment (by evaluating canal gap directions), and time-series analysis (to reduce false alarms). The operators used for detection will be briefly described first.

The Sobel operator was used for edge detection. It uses two 3×3 kernels which are convolved with the original image to calculate approximate edge gradients in the horizontal and vertical direction. In subsequent steps, for computational efficiency, the edge gradients in only eight discrete directions (at 45 deg intervals) are used. Therefore, in the initial step, eight 3x3 kernels are applied as shown in Fig 2-19 (top). The same approach was used for the ridge and valley detection (see Fig 2-19 middle) and the matched filter detection (Fig 2-19 bottom). Therefore, in this approach, in total, 24 types of detection per pixel can be made. Since these detections are not independent, a selection of a sub-set of these detections would be sufficient. A careful evaluation showed that 10 types suffice without decreasing performance and that the main value of the matched filter is the improvement of the detection of small canals. The latter also explains the shape of the matched filter, which works well on small canals and is less efficient for wider canals.

-1	0	1
-2	0	2
-1	0	1

0	1	2
-1	0	1
-2	-1	0

Horizontal Sobel grad
& 45 deg Sobel grad

-1	-2	-1
2	4	2
-1	-2	-1

-2	-1	2
-1	4	-1
2	-1	-2

Horizontal ridge
& 45 deg ridge

0	0	0	0	0
0	0	0	0	0
0	1	2	-2	-1
0	0	0	0	0
0	0	0	0	0

0	0	0	0	-1
0	0	0	-2	0
0	0	2	0	0
0	1	0	0	0
0	0	0	0	0

Matched filter in E-W direction
& +45 and -45 direction

Fig 2-19. Filters used for canal gap detection.

Before discussing experimental results of canal gap mapping, the utility of the theoretical model introduced above should be discussed in more detail. Canal gaps in peat swamp forest show up more prominently in radar images when they are oriented more closely in azimuth direction and when they are wider. The theoretical model can be used to quantify these relationships, moreover, it can be used to predict the effect of forest structural parameters and incidence angle on these relationships.

This can be done by introducing the parameter “contrast”, which simply is the sum of the absolute radar backscatter change (in dB) of the disturbance in the forest canopy caused by the canal gap, as shown in Fig 2-18. This sum is taken over pixels of a single row (i.e. East-West direction) matching the canal disturbance section. Higher contrast values can be related to higher visibility of canals gaps in the radar image. Higher contrast values are found for canals gaps wider than 10 m in combination with a canal orientation smaller than 75 degrees from azimuth direction (see Fig 2-20).

Since the contrast parameter is independent from canal length, it also applies for gaps of very short canals, which resemble gaps caused by selective logging. These small canopy gaps, or forest degradation gaps, are usually not elongated. Therefore, it may be assumed that contrast values for small orientation angles apply. Furthermore, it can be noted that for small angles the ratio between contrast and gap width is almost constant when the gap width is above 20 m. The latter relation can be computed using the same model and depends on incidence angle and forest structure. In Fig 2-21 the relation between contrast and degradation gap width for a peat swamp forest at three incidence angles is shown. This example shows that lower incidence angles give higher contrast. Simulations also show that higher forest in general give higher contrast. Therefore, when the right model is applied and contrast is not computed over a single gap section but over a certain fixed area (e.g. 10x10 pixels), then the averaged contrast can be related to the fraction of the forest canopy lost because of degradation. Examples for quantification of degradation are discussed in Section 2.4.

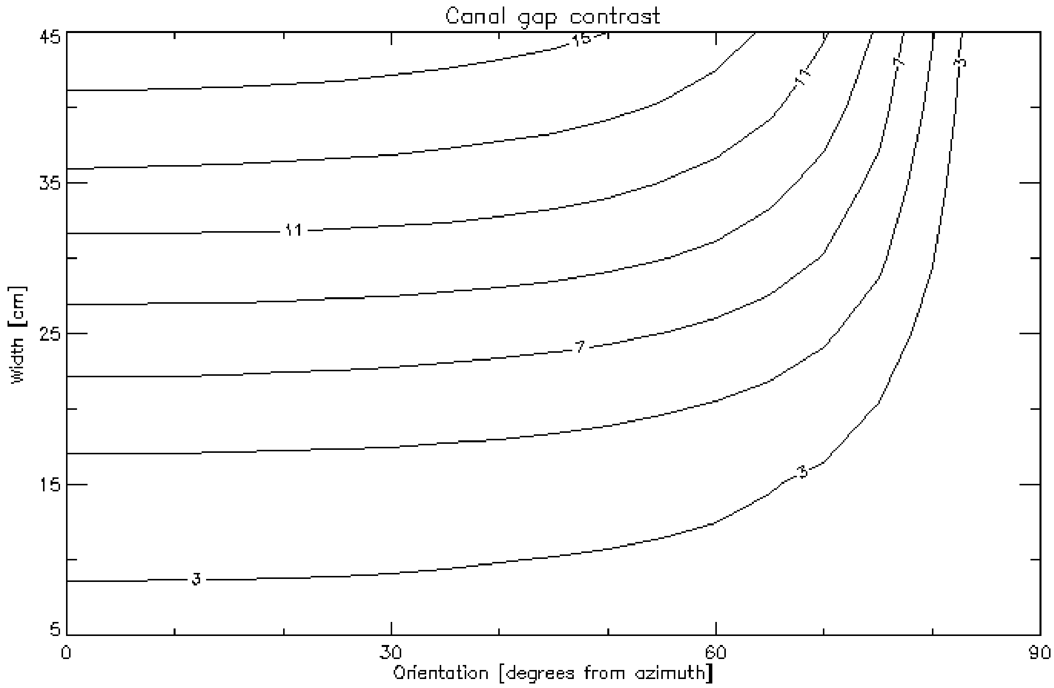


Fig 2-20. Contour plot of contrast as function of orientation (x-axis) and width (y-axis).

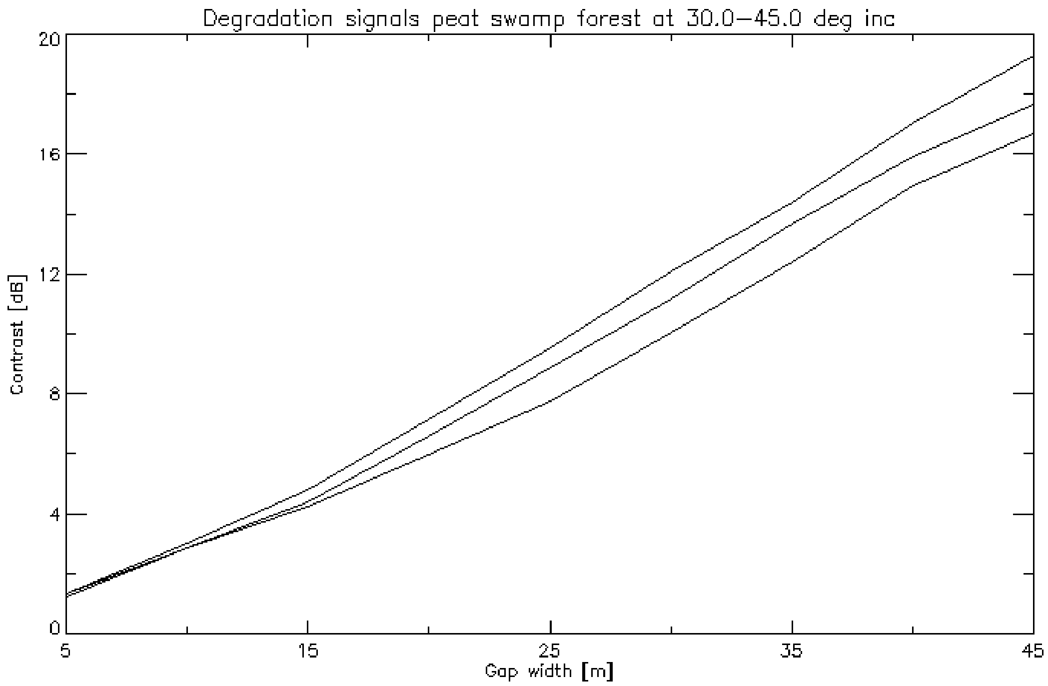


Fig 2-21. 30.0 degrees (top); 37.6 degrees (middle); 45.0 degrees (bottom). Steep incidence angles have higher contrast.

Results for canal gap detection

The Sentinel-1 NRT canal maps were validated using results of visual interpretation of SPOT-6/7 images as reference. For each canal visible, the length, width and orientation were determined. The detection rate was studied by comparing the lengths of these canals with the corresponding lengths in the Sentinel-1 map. This was done as function of canal width and orientation. The false alarm rate was studied by evaluating Sentinel-1 canal detections not present in the initial reference data set. A large fraction of the initial reference map for 8 August 2017 is shown in Fig 2-22a, while in Fig2-22b the corresponding Sentinel-1 NRT canal map for 7 August 2017 is shown.

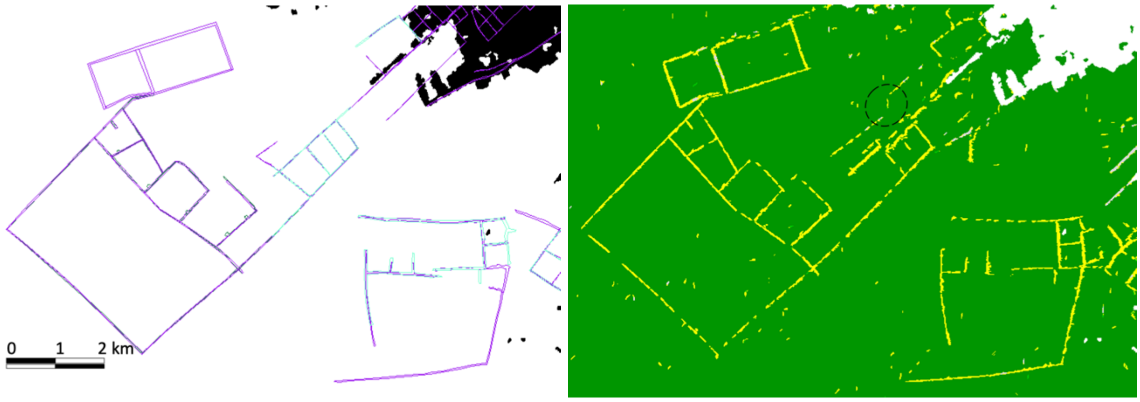


Fig 2-22. (a) Reference data from SPOT-6/7 20170908 and **(b)** S1 NRT canal map 20170907

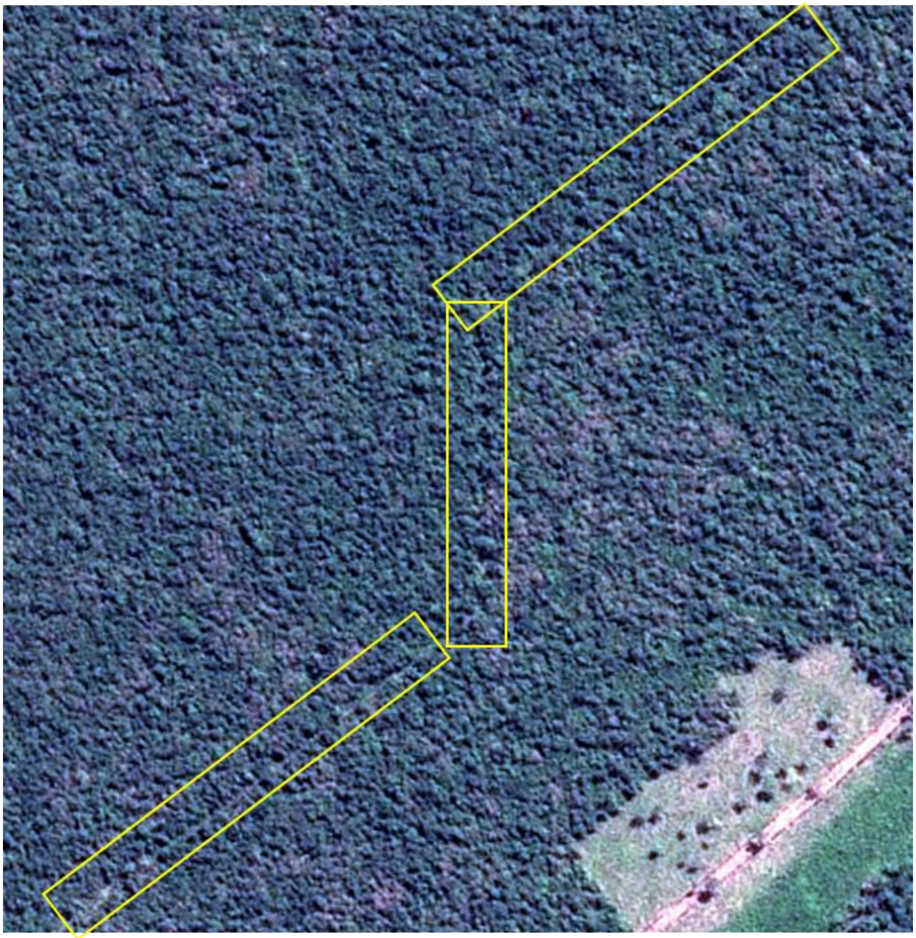


Fig 2-23. Location of canals hardly visible in SPOT-6/7 corresponding with the detections by Sentinel-1 in the black ellipse of Fig 2-22.

The overall detection rate is 85.5%, i.e. 9.3 km of canal length is missed out of a total 64.2 km. Table 24-a,b and c divide this result over several width and orientation classes. Only for the smallest width class (5-10 m range, Table 2-4a) and the orientation two classes closest to range direction (more than 80 degrees from azimuth direction, Table 2-4b) the accuracy drops below 50%. Table 2-4c combines these 2 classes showing that for small canals (smaller than 20 m) in radar look direction (within ± 15 degrees from range direction) the accuracy drops to 27.3%. In all other cases the accuracy is much higher, which is in agreement with the simulated result presented in Fig 2-20.

Sentinel-1 canal detections not present in the initial reference set could be divided in two different categories. The first category consists of true canal gap segments very poorly visible in the SPOT images. These canal gaps are often narrow and often show regrowth. An example is given in Fig 2-23. Once these canals are recognized in SPOT images, aided by the Sentinel-1 maps, additional visual interpretation is possible. In this study 7.3 km of additional canal gaps could be found in the SPOT data, of which 4.6 km (or 62.7%) was actually already mapped by Sentinel-1. This includes 3 canals smaller than 10 m, all oriented at 55 degrees from azimuth direction: (1) 9.7 m width, 114 m length, 100.0% detected; (2) 8.1 m width, 340 m length, 100.0% detected; (3) 6.5 m width, 348 m length, 48.3% detected. The second category consists of small canal gap segments in the NRT map which are not visible in the SPOT images, even after careful re-evaluation. While a part of these false alarm detections may constitute true false alarms, another part may be true detections (or "false false" alarms) not visible in the SPOT image, for example related to small canopy gaps caused by illegal selective logging. This notion is based on an evaluation of a time-series of canal gap maps. For example, in the 7 August 2017 NRT[1] canal gap map the false alarm rate is 9.5%. However, in subsequent maps an increasing number of these false alarms disappear. Therefore, these false alarms may be related to noise effects and could be regarded as true false alarms. After approximately two months persistent false alarm detections remain. These persistent false alarm detections, unlike the non-persistent false alarm detections, are not located at random, but are located near canals and rivers or forest edges. These places are much more accessible and prone to illegal logging activities. Thus, the false alarm rate of 9.5%, after approximately two months, may be divided in a non-persistent false alarm rate of 3.9% and a non-verifiable false alarm rate of 5.6%, which may relate to a large extent to true disturbances such as illegal logging.

Table 2-4a. Detection rate based on canal width

Width (m)	*Length (m)*	*Correct (%)*
5-10	1559	47.4
10-15	15634	77.8
15-20	13462	91.3
20-25	7938	84.1
25-30	9351	99.9
30-35	3859	70.7
35-40	5838	84.4
40-45	2511	92.4
45-50	2861	87.8
>50	1186	100.0
Total	**64197**	**85.5**

[1] Here NRT is NRT(N=0), for definition see next section

Table 2-4b. Detection rate based on look direction

Azimuth	*Length (m)*	*Correct (%)*
0-5	2283	97.8
5-10	152	100.0
10-15	720	100.0
15-20	3555	99.7
20-25	1511	99.3
25-30	1119	98.7
30-35	12283	95.0
35-40	4470	83.2
40-45	3255	94.8
45-50	2562	83.2
50-55	2827	95.6
55-60	6883	79.3
60-65	7317	81.4
65-70	903	84.5
70-75	6048	81.1
75-80	6610	68.4
80-85	1422	45.2
85-90	275	27.3
Total	**64197**	**85.5**

Table 2-4c. Detection rate for wide and narrow canal, oriented in look direction or other direction. Here wide means >20m; In look direction means within ±15 degrees from range direction.

Combination classes	*Length (m)*	*Correct (%)*
Wide, not in look direction	25510	96.2
Wide, in look direction	8032	64.3
Narrow, not in look direction	30379	82.7
Narrow, in look direction	275	27.3
Total	**64197**	**85.5**

User defined settings and QC

The performance of the system can be tuned to specific needs of the user. Basically, the user has to make two important choices. The first relates to the interchangeability of the two types of detection error, i.e. the false alarm (FA) rate and the missed detection (MD) rate, also known as false positive and false negative. When algorithm settings are selected to decrease the FA rate, then the MD rate increases, and vice versa. Of course, multiple maps using different settings can be made. The second choice relates to the interchangeability of overall accuracy and timeliness. The timeliness of NRT maps is defined on the basis of the dates of the available radar image time-series. When the first radar image has the time stamp t_0 (t zero), the second t_1, etc, and the last t_p (t present), then the second to last image has time stamp t_{p-1}. An NRT map can be based on a t_p radar image, a t_{p-1} radar image or, in general, a t_{p-n} radar image. Larger values for n cause larger delays in map availability, however, in general, result in larger overall accuracy. Of course, again, multiple maps using different values of n can be made. To make a distinction between different types of NRT maps these will be denoted as NRT(N=0), NRT(N=1), etc. Within an NRT(N=1) system the most recent radar image is only used as confirmation, which, for example can be used to avoid false alarms caused by heavy rain cells. The default NRT system is an NRT(N=1) system with a low FA rate.

Several validation procedures have been developed to evaluate the accuracy of the NRT radar mapping products. Reference data used include maps based on visual interpretation of optical data, such as SPOT-6/7, Google Earth and time-series of Sentinel-2, and other radar data such as time-series of high-resolution TerraSAR-X data. For comparison of asynchronous map series, such as comparison between NRT (radar-based) maps and Sentinel-2 (optical-based reference) maps, an automated quality control (QC) procedure was developed. Results for the default NRT system are presented next.

Results NRT deforestation monitoring

Sentinel-1 NRT deforestation maps have been validated in Borneo and Brazil using all available Sentinel-2 images and Google Earth. Results of QC can be shown in charts such as shown in Fig 2-24. This example is the aggregated result for three representative landscapes in Central Kalimantan with a total area of 194,235 ha, and with major deforestation events in the Sentinel-1 observation period. The legend is explained in Table 2-5. In the chart (Fig 2-24) the transition in time from forest to non-forest is visible in terms of QC classes. Only the classes MD (orange) and FA (red) represent errors. In the vertical direction the relative strength of the errors is visible and in the horizontal direction the duration of the errors.

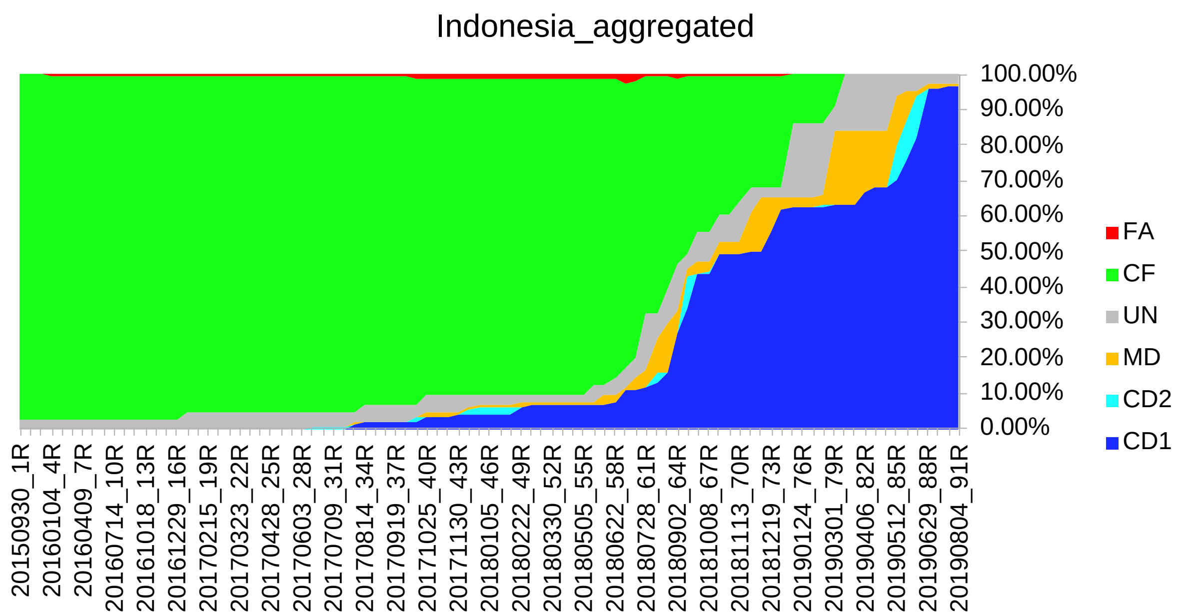


Fig 2-24. Aggregated results of QC for three representative landscapes in Central Kalimantan for the period September 2015 until August 2019.

Table 2-5. Quality control classes and colour coding used for validation of deforestation.

(blue)	CD1	Correct deforestation detection
(cyan)	CD2	Correct deforestation detection, prior to next optical reference date
(orange)	MD	Missed non-forest detection
(grey)	UN	Unknown
(green)	CF	Correct forest classification
(red)	FA	False alarm

The false alarm rate (FAR) and missed detection rate (MDR) are calculated using the following equations:

$$FAR = FA/(FA+CF) \quad (1)$$

$$MDR = MD/(MD+CD1+CD2) \quad (2)$$

The FAR, in this example, is very low. The MDR is sometimes substantial and varies over time. For example, on 30 April 2019, at a 90% confidence level, the MDR has a value of 18.6% ± 1.0% while on 17 June 2019 the MDR is 1.9% ±1.1%. This variation can be explained partly in methodological terms and partly in physical terms. The presented result relates to an NRT(N=1) system (see above). This means detected deforestation is only (or mostly, depending on system settings) mapped when it can be confirmed by the next radar image. This is often not the case as is illustrated by the time series of radar images in Fig 2-25. This series of eight consecutive radar images, covering an oil palm plantation development area on shallow peat, clearly demonstrates the backscatter contrast between forest and new clear-cut can go up and down. This may be explained, physically, by the relatively large soil roughness in combination with changes in soil moisture. The same phenomenon is illustrated in segment averaged temporal backscatter signals for VH, VV and VH-VV ratio for the same area in Fig 2-26 (left). The VH and VV signals jointly go up and down and deforestation is detected at the first moment it stays down. However, the VH-VV ratio stays low from the moment the VH and VV signals go down for the first time. The lowered VH-VV ratio is a sign of vegetation loss and the fluctuation of the VV and VH are signs of soil moisture fluctuations. High levels of soil moisture and large soil roughness in combination with the NRT(N=1) methodological rules explain the delay in deforestation detection in this shallow peat landscape. It could also be noted that on average the delays are larger in the deep peat landscape and absent in the dry forest landscape. This may be related to other soil roughness and/or soil drainage conditions.

In summary, it can be concluded that the FA rate is very low (because of selected user settings) and the MD rate can be significant and varies because of delays in detection, however the MD error is not permanent. The detection delay is a typical feature of the NRT(N=1) system. Such delays are absent in the NRT(N=0) system at the expense of a higher FA rate (for example caused by heavy rain cells). In an NRT(N≥2) system the delays are much shorter at the expense of having less timely maps. This may illustrate the importance of proper user settings or adopting a more complex systems with multiple sets of user settings.

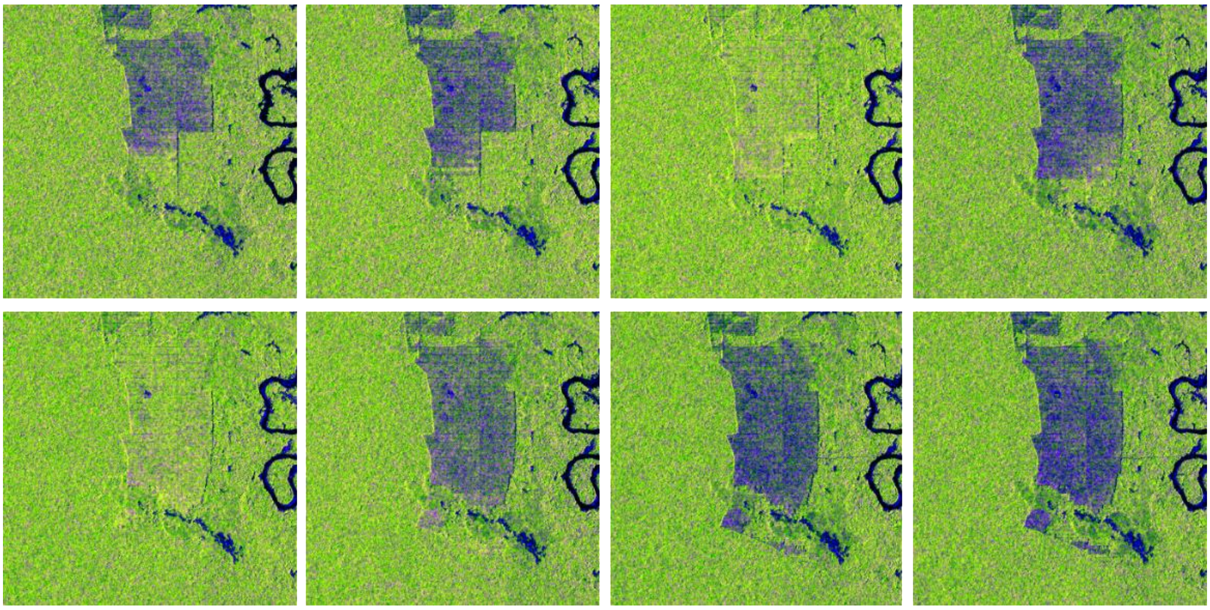


Fig 2-25. Eight successive radar observations at a 12-day interval for the period 20180704-21080926 (from top left to bottom right).

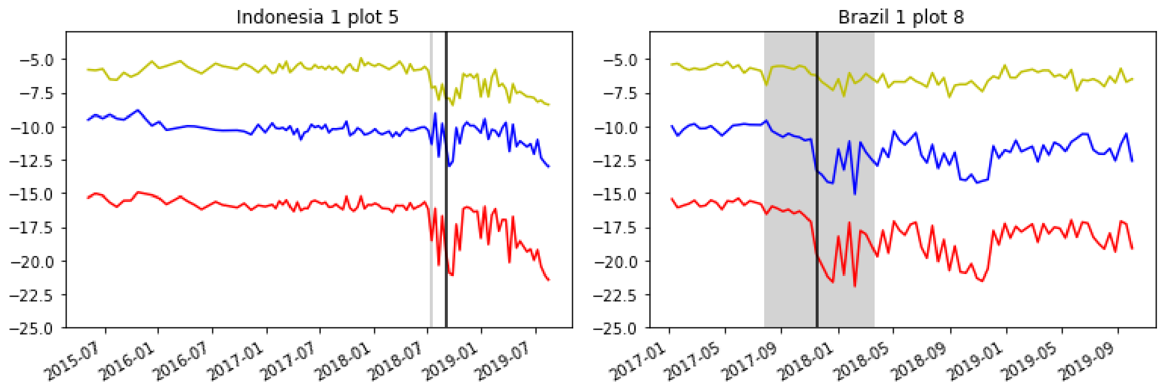


Fig 2-26. (left) Temporal radar signature for an area located in Fig 2-25. VH-polarization (red), VV- (blue), VH/VV-polarization (red). The black line shows the time of detection for the NRT(N=1) system and the grey line is the reference time following from visual interpretation of Sentinel-2. (right) Temporal radar signature for an area in Brazil with much more cloud cover. In this case Sentinel-2 data can only show that deforestation is at some time in the grey interval.

Opposed to detection delays in radar data, there are also detection delays in optical data. In the QC the class CD2 shows radar detection prior to the first available next optical image. However, there are many more cases where radar detection precedes optical detection. In the QC these cases are present in the class unknown (UN), but these cases cannot be validated, by definition, by optical data. An example is given in Fig 2-26 (right). Because of cloud cover the optical data can only be used to show the deforestation occurs in the period August 2017 until April 2018. The radar detection is in the middle of this period, where a significant drop in the radar backscatter occurs. In cases where validation could be done, a drop of such a magnitude leads to a correct deforestation detection. An evaluation of the radar signatures of all test areas reveals that for the Brazilian landscape more than 20% of the cases the radar detection precedes the optical detection by at least two months and up to 11 months. For the Indonesian landscapes, all relatively close to the coast, where there is less cloud cover, the radar detection precedes the optical detection in approximately 10% of the cases by at least two months and up to 8 months.

Results NRT degradation monitoring

Canal gaps in peat swamp forest show up more prominently in radar images when they are oriented more closely in azimuth direction and when they are wider (see canal gap section above). The theoretical model (see theory section above) can be used to quantify these relationships, moreover, it can be used to predict the effect of forest structural parameters and incidence angle on these relationships. Since the model applies equally well for gaps of very short canals, which resemble gaps caused by selective logging, it can be used to quantify degradation. In Fig 2-21 the relation between the radar ("disturbance") signal and degradation gap width for a peat swamp forest at three incidence angles was shown. This example shows that lower incidence angles give a stronger signal (or "contrast"). Simulations also show that higher forest in general give higher contrast. Therefore, when the right model is applied and contrast is not computed over a single gap section but over a certain fixed area (e.g. 10x10 pixels), then the averaged contrast can be related to the fraction of the forest canopy lost because of degradation.

Radar is a suitable instrument to quantify degradation. Unlike optical data, which detects degradation mainly by the signal fraction from the bare soil, the radar detects degradation by signals from gaps in the canopy, even when the understory still covers the soil. Therefore, the radar signal is very persistent (gaps in the upper canopy do not fill up fast), while the optical signal is visible for a short time window only (secondary re-growth on bare soil appears fast). The latter is even more troublesome when cloud cover is frequent. This is illustrated well by the example given in Fig 2-27. Here, for a selective logging concession area in Brazil a comparison is made between the Sentinel-1 radar and Sentinel-2 optical results. The solid line shows the total forest canopy fraction loss for each radar observation as a function of time. For optical data such is a result is not feasible because of cloud cover. Instead the accumulated detections can be shown (dotted line with diamonds). This accumulated result sums all detections, even when they are not visible anymore because of regrowth or cloud cover. It can also be noted that in this period where 81 radar observations were made only 12 partly cloud free optical images (diamonds) are available. From the comparison it is clear that most degradation in the wet season (December-May) is not detected by the optical system. Obviously, optical data have severe limitations to detect degradation and, thus, are less suitable for the validation of radar degradation maps. An alternative is the use of high-resolution radar data such as TerraSAR-X, which is used to map selective logging at the level of individual trees. Results for the wet season, in January-February 2018, show a clear correspondence in time and location of degradation. The 85 trees logged in this period (mapped by TerraSAR-X) compare with an effective forest canopy fraction loss of 4.5 ha (mapped by Sentinel-1). This relates to an average loss of ±500 m^2 per logged tree.

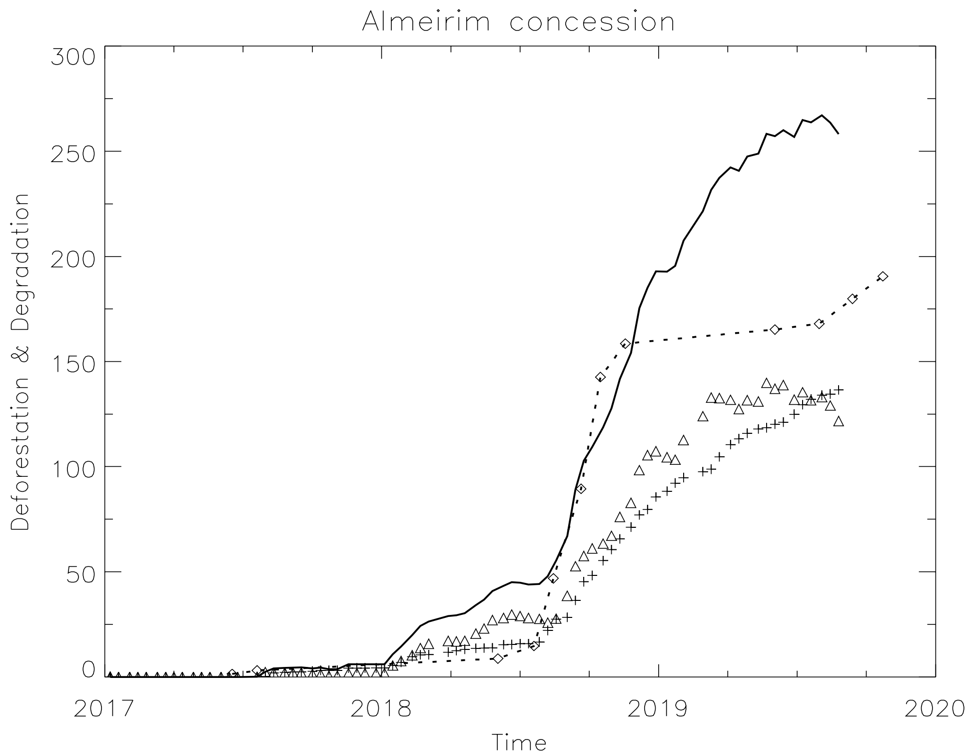


Fig 2-27. Results of degradation mapping for a selective logging timber concession in Brazil. Total forest canopy fraction loss as a function of time for radar (solid line), optical (dotted line with diamonds), the radar fraction related to canopy gaps (triangles) and the radar fraction related to timber trails (plusses). The symbols indicate he time of observation.

2.4 Synthesis and main conclusions for Sentinel-1 NRT system

The Sentinel-1 NRT radar monitoring system presented here maps change in three fundamentally different ways. Deforestation is detected using segment-based time-series analysis and uses a decrease of backscatter as an indicator of deforestation. Canal gap detection is based on time-series analysis of linear features using edge, line and matched filters. Degradation is quantified using a time-series analysis of textural change based on a physical model. These three approaches are not completely independent, not from a data processing point-of-view nor from a forest change interpretation point-of-view.

Several examples of interdependency can be given. For deforestation mapping in peat swamp forests an MMU of 15 pixels (0.3 ha) applies. This means that wide canal gaps are often mapped as (a row of individual) segments. The same canal gaps show up in the canal gap maps as linear features. Of course, the dedicated canal gap product shows more canals, including some very narrow ones which are hardly visible in SPOT-6/7 data. Very small deforestation segments or very short canal gap detections are often part of degradation areas. At the Brazil test sites some areas of deforestation, the ones that gradually change from forest to low secondary forest without going through a bare soil stage, are not detected with the deforestation mapping approach. However, the near range edges of such areas are still visible as elongated segments and parts of these areas are detected as degraded. Using such interdependencies explicitly may contribute to a better interpretation of ongoing forest change processes.

Deforestation.

Deforestation detection success is evaluated using results of a careful visual interpretation of Sentinel-2 time series as a reference. These results are independent of any issues related to baseline class definitions and timing. In summary, for the Central Kalimantan landscapes, it is shown that the false alarm rate (FAR) is very low (less then 1%) and the missed detection rate (MDR) varies between 18.6% ± 1.0% and 1.9% ±1.1% (90% confidence level). However, results also depend on user settings. FAR and MDR are interchangeable. Settings were selected to favour a low FAR at the expense of a slightly higher MDR. Another compromise to be made is between overall accuracy and timeliness. In other words, the faster the maps should be made available after radar observation, the lower the accuracy. Settings were selected to favour a relatively fast system, which results in significant detection delays in the map time series. It was found that peatlands are a typical case where detection delays up to two months occur which are caused by the combination of rough soil surface and high soil moisture. This is causing the high MDR, but these missed detections are only temporary, not permanent. Other settings could decrease such delays to a few weeks. These delays were not found outside the peat areas or in the Amazon. Because of cloud cover radar can be much faster than optical systems, but this cannot be validated by optical systems. It was found that radar very often detects deforestation two months and up to 10 months faster than optical systems.

Canal detection.

Results of visual interpretation of SPOT-6/7 images were used as reference. The overall detection rate is 85.5%, however results strongly depend on canal gap orientation and to a lesser extent to canal gap width. Only for the smallest width class (5-10 m range) or for orientations of more than 80 degrees from azimuth direction, the accuracy drops below 50%. In total 9.3 km of canal length was missed out of a total 64.2 km. Sentinel-1 canal detections not present in the initial reference set could be divided in two different categories. The first category consists of true canal gap segments very poorly visible in the SPOT images. These canal gaps are often narrow and often show regrowth. Once these canals are recognized in SPOT images, aided by the Sentinel-1 maps, additional visual interpretation is possible. In this study 7.3 km of additional canal gaps could be found in the SPOT data. The second category consists of small canal gap segments in the NRT map which are not visible in the SPOT images, even after careful re-evaluation. A part of these false alarms is persistent while others disappear within two months. These persistent false alarm detections, unlike the non-persistent false alarm detections, are not located at random, but are located near canals and rivers or forest edges. These places are much more accessible and prone to illegal logging activities. Therefore, the false alarm rate of 9.5%, after approximately two months, could be divided in a non-persistent false alarm rate of 3.9% and a non-verifiable false alarm rate of 5.6%, which may relate to a large extent to true disturbances such as illegal logging.

Degradation.

Like for deforestation, degradation detection success is evaluated using results of a careful visual interpretation of Sentinel-2 time series as a reference. Radar is a suitable instrument to quantify degradation. Unlike optical data, which detects degradation mainly by the signal fraction from the bare soil, the radar detects degradation by signals from gaps in the canopy, even when the understory still covers the soil. Therefore, the radar signal is very persistent (gaps in the upper canopy do not fill up fast), while the optical signal is visible for a short time window only (secondary re-growth on bare soil appears fast). The latter is even more troublesome when cloud cover is frequent. Validation is difficult using optical data since degradation is detected in a fundamentally different way and a lot of degradation is missed. Nevertheless, results are spatio-temporally consistent. It may be much better to use TerraSAR-X for validation of degradation, notably for quantitative validation. The result presented here, for Brazil, is based on limited data only but provides high spatio-temporal as well as quantitative agreement.

3. Tropical Peat Viewer

In order to visualize and analyse the results a Web GIS viewer has been built. Viewing, combining and analysing the data is possible with this Tropical Peat Viewer.

The Tropical Peat Viewer shows the change of the tropical forest and the peat areas in Indonesia from 2015 until the current situation. The viewer is updated frequently with the latest data until the end of the project in September 2019. The main themes in this viewer are deforestation, degradation, fire and floods. These themes are mainly based on processed radar images from the Sentinel 1 and PALSAR satellites. With every orbit from the radar satellites, an image is calculated which shows deforestation, degradation, flooding, canal and road development, but also regrowth of the vegetation. In forests, the radar will detect degradation. Other thermal satellites pick up signals of fires. The fire data is translated into an image showing the centre and spread of the fires.
Flooding is detected by two radar satellites. The shortwave Sentinel-1 satellite perfectly shows open water, whereas the PALSAR satellite that uses a longer wavelength can even show flooding underneath the canopy.
With the viewer, the forest change, fires and floods can be detected trough time. The time selector at the bottom of figure 3.1 shows the dates and time interval.

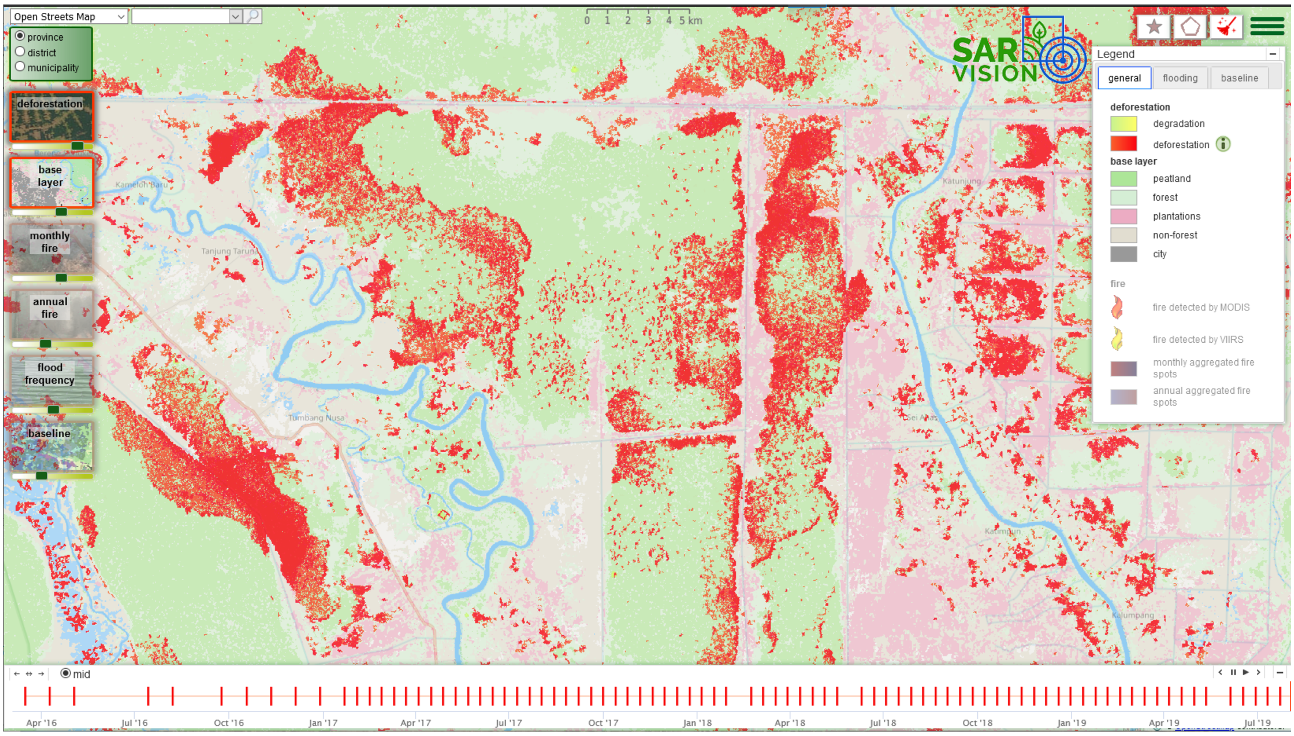


Figure 3.1: Lay out of the Tropical Peat Viewer. Deforestation is visible in red colours.

3.1 Using the viewer

The viewer helps to visualize and analyse the results. Several tools will help doing analysis (Figure 3.2). Underneath the different tools are described separately.

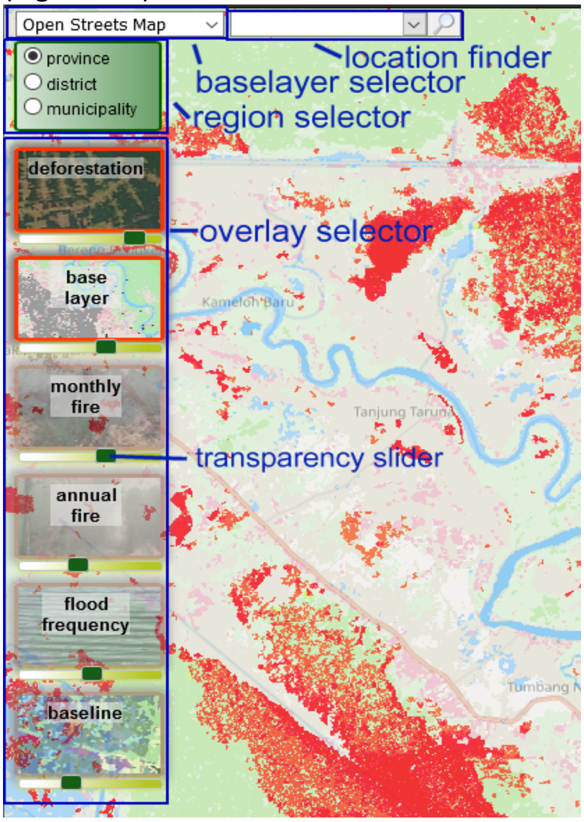


Figure 3.2: Layer tools

3.2 Layer tools

3.2.1. Base layer map selector

The viewer enables the user to choose different background layers. The default background layer is the OpenStreets Map. This layer shows the geographical names of cities, villages and rivers but is generally neutral in appearance and serves well as an all-purpose background. When more detail is required it is helpful to select an optical imagery base layer. The viewer supplies 2 satellite layers from Here WeGo, with or without geographical names, and 2 Bing aerial layers with a higher resolution. The Stamen layers offers either a terrain layer or a dual-tone layer. Keep in mind that the imagery can be old and of different ages than the theme layers.

3.2.2 Overlay sector

At the left of the screen several different themes can be selected by clicking on the corresponding icon. Once selected, a red line will show up around the icon. The selected theme will be displayed in the main screen. By clicking again on a selected theme icon, it will be switched off.

Six different themes can be selected; The deforestation layer, base layer, monthly aggregated fire spots, yearly aggregated fire spots, flood frequency map and the baseline layer. These will be described further down. By default, the simplified base layer and the deforestation layer are enabled.

3.2.3. Transparency slider

Sometimes it is necessary to display more than one theme at the same time. This is possible by using the transparency slider at the bottom of each theme icon. By increasing the opacity of one overlay and lowering the other, the first layer will become more visible (Figure 3.3). The layer that is selected latest will be on top of the other selected layer.

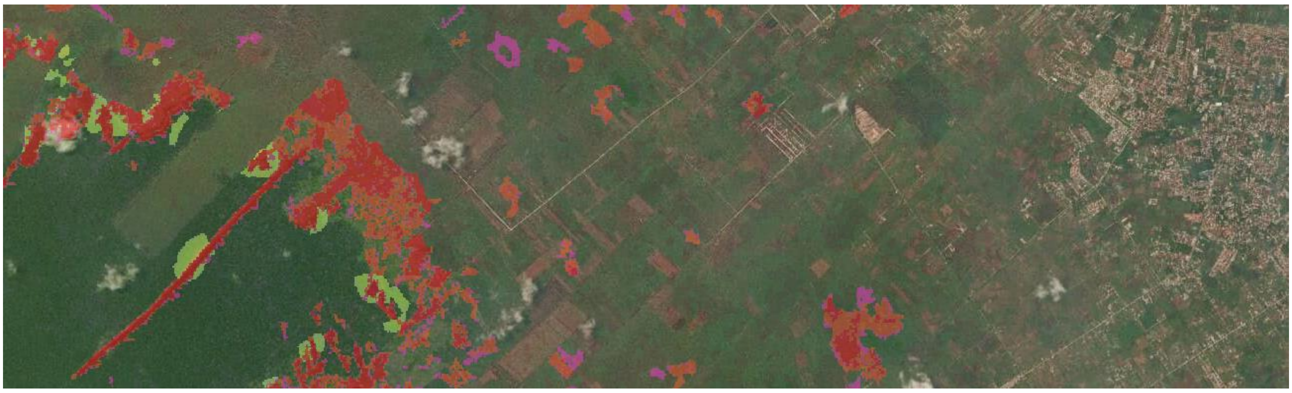


Figure 3.3: Changing opacity to combine the optical background image with the deforestation layer

3.2.4. Region selector and search field

The region selector is displayed at the top left of the screen just above the theme icons. One can select between three administrative boundaries to be displayed on the screen; province, district and municipality (or *desa*). The search field helps to find locations or other topological entities. If a topological name occurs more than once, which often is the case in Indonesia, several options are given in the dropdown box.

3.2.5. Time selector

A time bar is located at the bottom of the screen. By clicking on a specific date, the theme layer (deforestation, fire, flooding) will be displayed for that particular date. The time bar runs from January 2016 until August 2019. The red vertical dashes represent the date of a Sentinel1 radar image recording. From 2017 onwards Sentinel1 images are available every 12 days.

By default, the whole period is visible. The **year switcher** can change that behaviour. By clicking on the right, the timelines leap to the next or last year. By clicking on the left the timelines will leap to the previous year, the middle one will again show the complete period.

3.2.6. Player button

On the right side of the time bar a video play function is visible

By clicking on the black arrow, the viewer will show an animation of the theme changes through time. It will start running from the date that was selected. It automatically loops back to the start once it reached the end. By running the play mode, you can observe the changes through time.

3.2.7. Legend box

The legend is displayed at the right side of the screen. You can select three different legends: General, Flooding and Baseline. In the legend the used colours or symbols are described for each of the selected themes. Please note that you will have to select the legend by yourself, it will not change if you select another theme. The legend categories will be described underneath in more detail per theme.

3.3 Map themes

3.3.1. Deforestation layer

The deforestation layer shows the forest degradation and deforestation through time. The deforestation layer is currently only shown for the central part of Central Kalimantan. Deforestation is shown in red colour.

The degradation is divided into different degradation classes and the colours vary from medium to light green and yellow. The degradation cannot be observed with optical sensors, but the radar shows it clearly. Additional verification is needed to quantify the different degradation classes.

3.3.2. Baseline map and Base layer

The baseline map shows the land use situation in 2015 and is used as a reference or "starting point" for detecting the theme changes in time. The baseline map categories can be found in the Baseline legend under the baseline tag or are visible after clicking on the map (Figure 3.4).

This map contains a lot of information and may be too diverting for visual interpretation in combination with other overlays.
For this reason, a simplified version of the baseline map has been created, the so called "base layer", where categories have been grouped and colours are less intense.

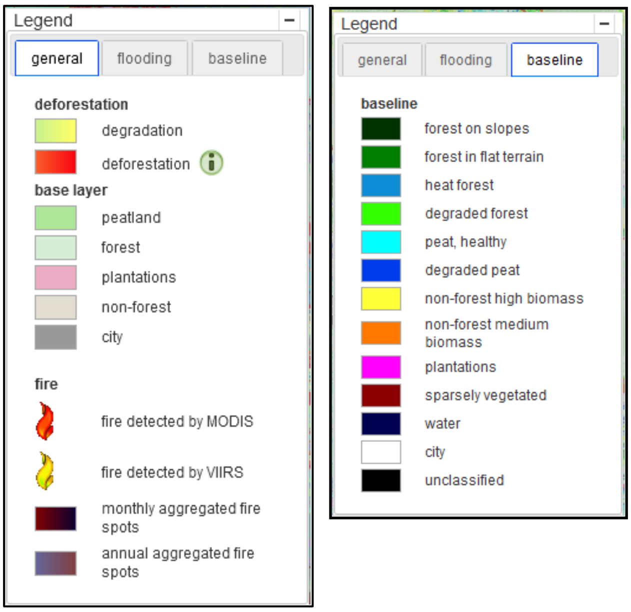


Figure 3.4: Base layer map and baseline legend

In contrary with the "baseline map" the "base layer" is by default switched on and combined with the deforestation map. The base layer map shows the area of peatlands, forest, forest plantations, non-forest and cities at the initial timestep (2015).

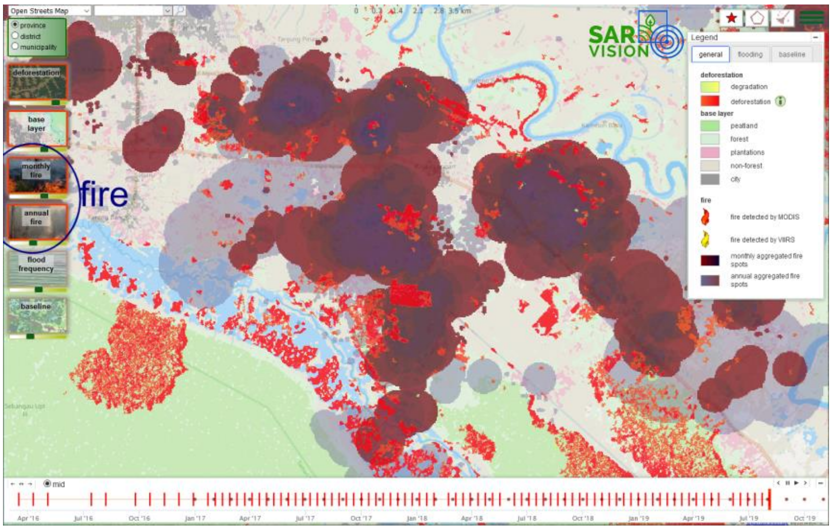
3.3.3. Fire overlay

Thermal satellites will pick up signals of fires. These signals are converted into an image showing the centre and spread (intensity) of the fires, showing as brown buffer zones around a fire centre that gives the highest fire signal.

Starting from the 1st of the month a daily image is composed of the encountered fires. For every day a new fire overlay is calculated, leading to one aggregated image per complete month. The more fires per month are detected, the darker (blue-ish brown) the buffer areas will be.

If zoomed into more detail, the individual fire spots for this month will show up. The yellow flame identifies a fire detected by the thermal VIIRS satellite, and the red flame identifies a fire detected by the thermal MODIS satellite using surface differences in temperature. The VIIRS data are in a higher resolution than the MODIS data. MODIS is available starting from 1st of January 2017 and VIIRS data is available from 1st of July 2018. *(Please note that not all signals detected by these thermal satellites are actual fires and the location is sometimes also not very accurate, whilst the deforestation locations are accurate.)*

The monthly aggregates are used to create an annual aggregate, starting from January till the end of the year or either the latest available month.



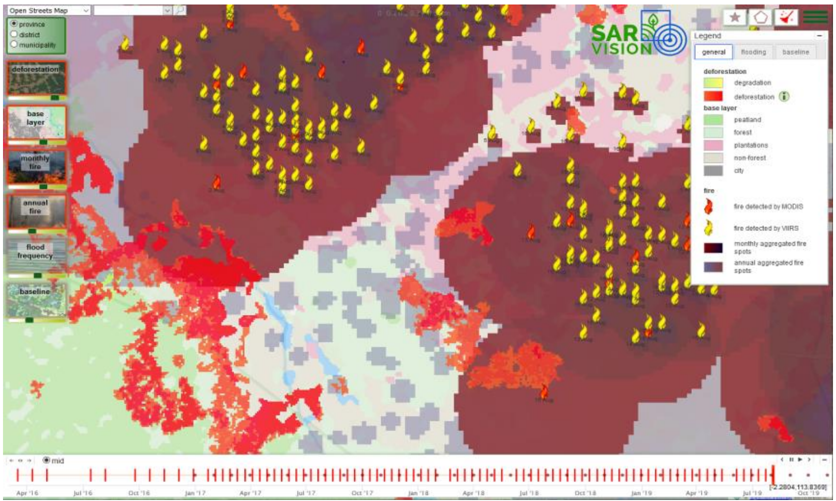


Figure 3.5: Fire overlay added to viewer. In the second image individual firespots show up when zoomed in.

3.3.4. Flood Frequency

Flooding is detected both by Sentinel1 and PALSAR. The Sentinel-1 satellite perfectly detects open water, whereas the PALSAR satellite can even show flooding underneath the tree canopy.

It is of interest to see where floods occur frequently throughout the years. For this reason, a cumulative flood frequency map is created by analysing the flooding status over a large period.

PALSAR flooding is categorized in the following flooding categories:

- flooding in open terrain or under canopy
- waterlogged peat

For the flood frequency map shown in this viewer 37 PALSAR images are used, starting from 13 August 2014 and ending on 26 December 2018 to create one aggregated image.

Thus, next to where, and how often open water is spotted, it also shows how often the peatland and forests are flooded under the canopy. The static map can be used as background map and does not change when a new timestep is selected.

The colour changes with the flooding intensity. The more intense the colouring is, the more frequent a flooding occurs.

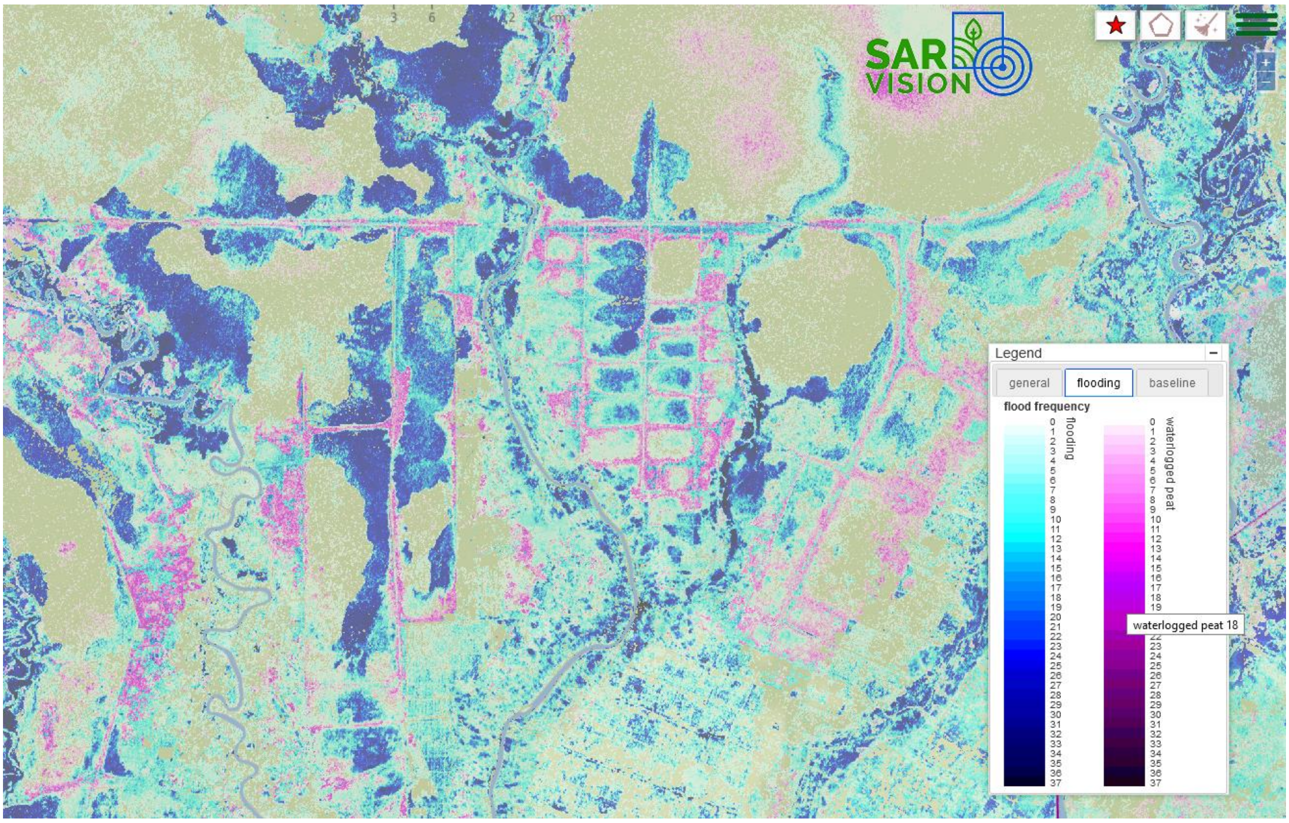


Figure 3.6: Example of the flood frequency map with the corresponding legend

3.4 Toolbox

A special toolbox allows the user to identify the layers for a specific location and makes it possible to draw a polygon to get information for the area within that polygon.

On the top right of the screen there are a few toolbox options.

Figure 3.7: Toolbox options: Star, Polygon and Broom.

Star: By clicking on the map the active layer values will show for that location
Polygon: Calculate area and analyse deforestation and degradation in a drawn polygon
Broom: Remove the selected point/polygon

3.4.1. Star option

In the default modus the coordinate-click-modus is enabled. Clicking on the map will result in a list with the enabled overlays and their values. In the example in figure 7, the click shows that the value of the base layer for this coordinate is “heath forest”. The deforestation overlay shows that a first detection of deforestation is detected. The coordinate click is quite useful to find out what values the selected layers have. Please note that at the bottom right of the viewer window, just below the time bar the coordinates of the cursor location can be read.

3.4.2. Polygon option

When selecting the polygon button in the toolbox, the viewer is in “polygon drawing modus”. A polygon can be drawn by left-clicking in the map and double-click when ready. The viewer will calculate the area of the polygon and create a chart of the changes in time. The chart shows the degraded area and the deforested area over time.

Figure 3.8 shows the chart after drawing a rectangle polygon on the map. As is visible, this area was not deforested at the start of the measurements in 2016. Shortly after, deforestation started. The tooltip shows a sharp increase at 18 October 2016 where almost half of the total area was deforested. At the end of the period even 768.8 hectare was deforested. Calculation example: Total area = 1253 hectare, deforested area at 4 August 2019 = 768.8 hectare. (768.8/1253 = 0.6135) 61% is deforested.

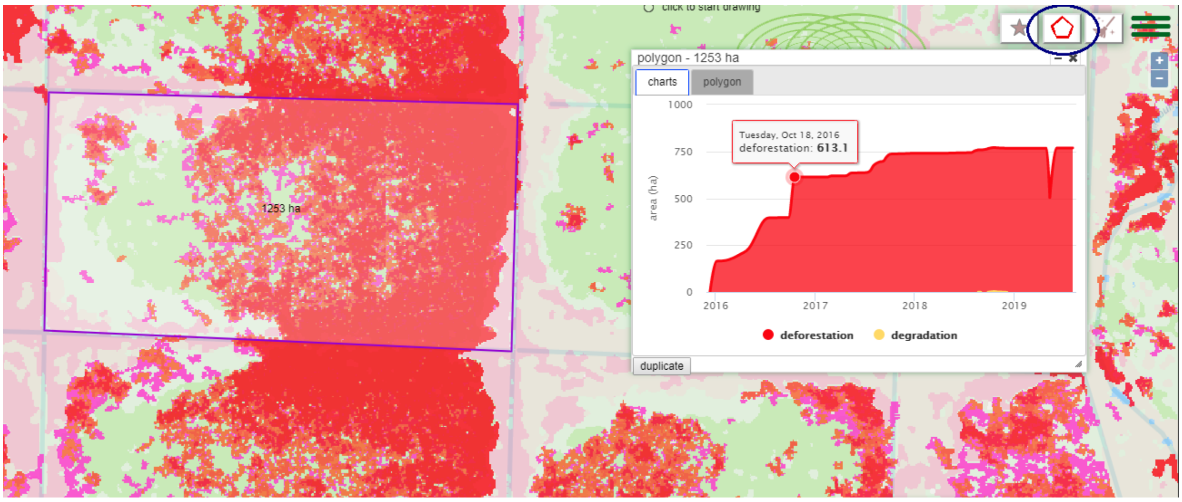


Figure 3.8: Calculate area and deforested and degraded area

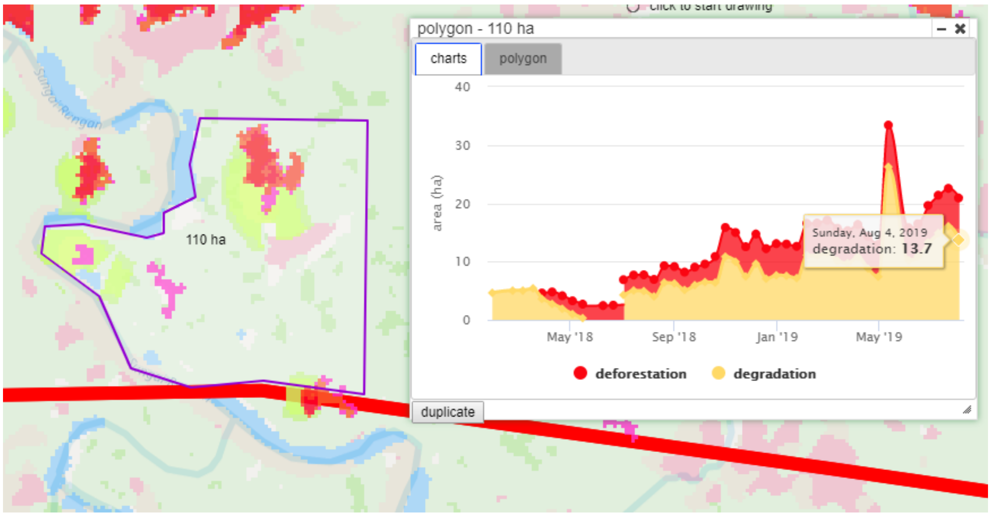
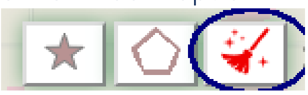


Figure 3.9: Using the tooltips for getting the individual values.

Figure 3.9 shows a more complex example, showing both degradation and deforestation. Using the polygon option, you can calculate both deforested area and the degradation area over time. In this figure it shows that at the 4th of August 2019 the degraded area is 13.7 hectare and the deforested area is 7.2 hectare, adding up to 20.9 hectare of affected land. To be able to compare the chart information for two polygons, one can select the duplicate option at the bottom of the chart window.

3.4.3. Broom option



When this modus is selected all point information will be cleared. The polygons can be removed individually by clicking them.

3.4.4. Options menu

On the right top side of the viewer there is a symbol with three horizontal lines.

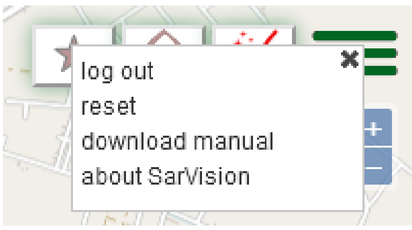


Figure 3.10: Option menu

By clicking on this symbol, a selection can be made between the following options:

- Log out: Closes the viewing session and shows the login screen
- Reset: Return to the default values. The focus will be reset to the initial overview of central Kalimantan.
- Download manual: To download this manual in a separate tab
- About SarVision: Pops up a screen with additional information about the SarVision company

4. Result Service Demonstration Workshop

A final service demonstration workshop was held in Jakarta on 8-9 October 2019 and hosted by LAPAN. Annex 2 provides the ToR and agenda for both days.

During the first 1 day high level workshop SarVision provided a general overview of applied method and results. Representatives of the following organizations were present:

- Meteorology, Climatology and Geophysical Agency (BMKG)
- Geospatial Information Agency (BIG)
- Assessment and Application of Technology (BPPT)
- Disaster Risk Management Agency (BNPB)
- Ministry of Forestry and Environment (KLHK)
- Bilateral and multilateral donor Agencies: Norway, Bank Dunia, UNEP
- Conservation International Indonesia (CI-Ind)
- Sinar Mas (pulp and paper company)
- Dutch embassy (economic counsellor)
- FAO forest
- Green Economy UNDP
- Global Forest Watch, WRI
- Peat Restoration Agency (BRG)
- Indonesian Space Agency (LAPAN)

Virtually all participants were enthusiastic about the results and indicated that they would like to have the system implemented in Indonesia as soon as possible. LAPAN indicated to implement the radar based monitoring system at their institute. KLHK mentioned to have an operational monitoring system based on optical imagery but acknowledged that their system had limitations due to cloud coverage. Also the representative of FAO mentioned that the radar based monitoring system would be complementary to their own system.

The workshop on the 2nd day was more technical oriented and meant for users of the monitoring system.
Technical staff of all involved ministries were present and representatives of WRI, SinarMas, BCG_Indo, FAO. The participants received training about the use of the viewer and how to interpret the results for their own implementation. The training exercises are included in Annex 3.

The participants provided feedback during the workshops and filled in an evaluation form regarding technical aspects of the drainage detection, flood monitoring and fire monitoring. In addition they filled in a qualitative review form with respect to uses and benefits, user friendliness and functionality of the Tropical Peat Viewer. The outcome of this questionnaire is provided below.

4.1. Assessment of the utility of the service

The utility of the service has been assessed both quantitatively and qualitatively. In the quantitative assessment achievements of EO products are compared with the targets set in the users' requirements document. The qualitative assessment has been carried out through a questionnaire filled in by the participants of the workshop and by discussions with and between participants. The participants were selected based on their potential use of the monitoring system output for their own organization.

Review summary of users requirements achievements

Achievements of the EO products in terms of minimum mapping unit, accuracy, frequency and delivery time are compared to the targets set in the users requirements document. We have asked the participants to fill in a form with technical questions per monitoring aspect (drainage canals detection, flood and fire monitoring) add observations from their own perception.

The participants found it difficult to comment on the technical requirements as they had no proper understanding of what requirements had to be met. Even if the target is met, users could find out that a higher target would in fact be required for the service to be useful, or on the contrary, if the target is not met, users mentioned that the service would still be useful.

The findings of this technical evaluation are included in the tables 4.1, 4.2 and 4.3, describing the general objective of the information need, targets, achievements and user observations for each of the monitoring aspects.

In addition, a more qualitative review was held. A questionnaire was distributed and filled in by the participants at the end of the workshop. In a final conclusion session, the results were discussed and used for the final closing follow up session. The questions and results of this questionnaire are provided in Table 4-4.

Table 4.1. Technical user needs, set targets, achievements and user observations for detection of drainage canals

UR1 – Detection of new drainage canals			
General objective	Early detection of new canals in Indonesian peatlands shall allow the detection of new plantations development both at industrial and smallholder scales. Industrial scale plantation development in peat is usually taking place over large areas of at least several hundred hectares, with a network of drainage canals including large canals (20-30 meters width), intermediate canals (10-20 meters width) and small canals (5-10 meters width). In these schemes, the length of the canal ranges from a few hundred meters to a few kilometres. Smallholder development is usually taking place on much smaller areas, as small as a few hectares, with intermediate to small drainage canals. However, these are often connected to existing larger drainage canals.		
	Targets	Achievements	Users observations
Minimum Mapping Unit	Minimum width : 10 meters Minimum length : 300 meters	Achieved	Ok

Minimum accuracy	80%	Achieved	Ok
Frequency	3 months	Achieved	Ok
Delivery time	Maximum 5 days after last image acquisition	Achieved	Ok

Table 4.2. Technical user needs, set targets, achievements and user observations for flood monitoring

UR2 – Floods monitoring			
General objective	Flood monitoring shall give users data on the floods extent and floods duration to support assessment of the hydrological state of the peatlands.		
	Targets	Achievements	Users observations
Minimum Mapping Unit	50 ha	Achieved	Ok Although some users mention that Palsar would be better to use for flood monitoring than Sentinel
Minimum accuracy	90%	Achieved	Ok
Frequency	6 months	Achieved	Ok
Delivery time	Maximum 5 days after last image acquisition	Achieved	Ok

Table 4.3. Technical user needs, set targets, achievements and user observations for fire monitoring

UR3 – Fire monitoring			
General objective	Fire monitoring shall provide information on the extent of areas impacted by fires both in forest and open vegetation peat lands.		
	Targets	Achievements	Users observations
Minimum Mapping Unit	5 ha	Achieved	Ok
Minimum accuracy	80%	Achieved	Ok

Frequency	Monthly during the dry season, 3-monthly during the rainy season	Achieved	Ok Would be useful if system could provide daily fire data in dry season
Delivery time	Maximum 3 days after last image acquisition	Achieved	Ok Maximum 2 days would be great

Qualitative review

The service utility is assessed through a questionnaire answered by users of the service during face to face meetings with users. Table 4.4 presents an outline of the questionnaire with the main findings. In total 18 questionnaires were returned.

Table 4.4. Qualitative review questionnaire with answers by the participants (→)

Uses and benefits	What are the uses and benefits of the Tropical Peat Watch service for your organisation? → Useful for forest and land cover monitoring → Useful for detection of deforestation, degradation and fire scars in near real time (also in or near concessions) → Complements current (optical) monitoring system and makes it more complete and up to date → Can be used to classify peatland floods and to get info on fire hotspots (+ wetness of peat) → Providing info on peatland activities → Useful for restoration of peatlands in Indonesia → Additional information for specific project sites → Useful as it shows changes through time → TPV can be integrated with own platform → Can help strengthening BRG's Prims platform to monitor their restoration area. Especially for detecting new canal openings Does the Tropical Peat View service provide new information that was previously not available? → Yes, at field level (majority) → Especially in remote areas → radar product is superior to FAO's SEPAL → (More) Information of flooding

	→ Flood frequency is new for most users → Level of detail and frequency → Not really but easier to view all in one place → Better data quality → Specific model to use historic data Does the Tropical Peat View service complete already available but insufficient information (more exhaustive, quicker, more accurate)? → Enough → More time is needed to investigate this → More areas needed (incl entire Sumatra) → It appears to be unique → Should provide a tool to upload own maps and display these in the viewer → Provide administration information → Combining all layers makes the system unreadable → More detailed data about where and when change detection for flood or fire occurs, not in web service but for extracted data What are the barriers to the use of the information provided by the Tropical Peat View service? → Currently no possibility of typing in a coordinate to where viewer will automatically scroll to → Star info is not updated if time changes → linking with other platforms / monitoring systems → viewer needs stable internet connection that is not everywhere available in Indonesia → Data should be downloadable → information needed on soil moisture and peat depth → To be recognized as an appropriate tool by Gov of Indonesia → No info related to village name, city and provinces → Barrier by my own organization (Peat Hydrological Unit) Which changes/improvements to the Tropical Peat View service could make it more useful? → Provide details about used satellite and which bands / polarization(s) is used → More than 1 star pointing for multiple info

	→ Export information feature → Degradation measure does not always seems to be reliable as regrowth can not happen as quickly as it sometimes shows → Link between soil type and land cover classes → Add terrain data → Download data and link it with concession area or other field data → How to identify between natural flooding and rewetting by peatland activity → Showing fire scars → Showing deforestation in HTI area → Combining it with Google Earth viewer → More segmentation, not only land cover but also land use → Pull the service to other platforms → Improvement on search function
User friendliness	Is the Tropical Peat View viewer user friendly? → Yes, relatively easy (majority) → Baring the issue of baseline time → Yes, but it is difficult to carry out an analysis in a short time. More info is needed on the field information. Is the navigation self-explanatory? → Yes (majority) . → Depends on background viewer → More improvement needed Is it easy to find all features? → Yes (majority) → Easy but not all. You need to input “Search” for coordinate Is the content of the viewer well described? → Yes (majority) → Information needed on some definitions, e.g. on ‘1st deforestation’ and ‘2nd deforestation’ Is the viewer documentation complete and understandable? → Yes, maybe some more detail (majority) → Some legend classes need more information, e.g. description of non-forest medium biomass and non-forest high biomass

	Is the speed of the viewer satisfactory? → Yes (majority) → Can be improved → Should be, with a better internet present → enough if not too many maps are displayed at the same time → Medium speed
Functionalities	Does the Tropical Peat View viewer include all required functionalities for viewing and analysing the data? → Yes (majority) If no, what is missing? → Similar charts as for degradation for fire and flooding → Peat soil type should be available in baseline and base layer → Provide special tools to download data in various formats → Provide special tools to input coordinates → Display radar image (Sentinel-1) as background layer → Need info on soil moisture, high water level and precipitation level → Search location feature → More explicit on rewetting → Ground wetness as an early warning indicator at the surface and at 20 and 40cm → need for measuring tools for line segment; ruler feature (only polygon now) → How to find a road that has been built 20 years ago → Extract data for Area of Interest

5. Summary and recommendations

5.1 Workshops

A series of dedicated workshops were held in Jakarta, focusing on different aspects of the development, demonstration and implementation of satellite monitoring tools for tropical peatland management and restoration. The kick-off of the project was done during the Users & Stakeholders Workshop (29 October 2018), which was followed by the User Requirements Workshop (18-19 February 2019). This resulted in the introduction of new radar technology to a wide range of stakeholders and consolidation of user requirements for the main radar monitoring system components related to new canal detection, fire damage and flooding assessment (see section 1). During the Validation Workshop (17-20 June 2010), first results and validation protocols were discussed, mainly with dedicated staff of LAPAN (section 2). During the final Service Demonstration Workshop (8-9 October 2019), results for the main system components (i.e. canal, fire, flooding) were shown, together with other results such as automated wide-area NRT monitoring of deforestation and forest degradation (section 2). The Tropical Peat View web portal was demonstrated and tested by participants (section 3) and important feedback was generated (section 4). The project team also presented the system at a dedicated Global Peatland Initiative meeting at FAO, Rome (22-23 May 2019), the JAXA Kyoto & Carbon Initiative meeting in Tokyo (K&C-26, 21 January 2020) and at the Final Presentation at ESA-ESRIN, Frascati (6 March 2020).

5.2 Main achievements

Stakeholders and user requirements
The main objective of the Tropical Peat View (TPV) project is to demonstrate an EO-based operational system for monitoring peatlands in the provinces of Riau (Sumatra) and Central Kalimantan (Kalimantan) for the Indonesian space agency, **LAPAN**, and the national peat restoration agency, **BRG**. Other potential users also expressed their interest in the system during the above described workshops:

- **BBSDLP** (Indonesian Centre for Agricultural Land Resources Research and Development, Agency for Agricultural Research and Development, Ministry of Agriculture)
- **BPPT** (Agency for the Assessment and Application of Technology)
- **KLHK** (Ministry of Environment and Forestry, MOEF, Indonesian abbreviation KLHK)
- **UNEP** (The UN Environment Program)
- **WRI** (World Resources Institute)

The Tropical Peat View project targeted the following subset of the needs of BRG, which correspond to information required at both planning and monitoring & evaluation steps of the peatlands restoration process:

- Detection of drainage canals;
- Early alerts of new drainage canals and plantations development;
- Floods monitoring;

- Assessment of the hydrological state of peatlands and impact of the restoration measures;
- Detection of fires;
- Early alerts of fires

Sets of user requirements per subset were defined and confirmed during the User Requirements Workshop (18 and 19 February 2019). It was further decided to change the original name of the Tropical Peat Watch viewer into Tropical Peat View viewer. Another outcome of the workshop was that BRG staff would be involved in the development of the viewer and would receive training in October 2019.

L-band

For the Central Kalimantan test site, a historical analysis using all available L-band data of JERS-1, PALSAR-1 and PALSAR-2 was made. These data cover three eras and each era captures a major El Niño event. A phenomenological analysis of this time-series could be made based on knowledge of the terrain and L-band physical interaction mechanisms, revealing permanent disturbance phenomena as well as the possible causes. One major conclusion is that the main ombrogenous peat domes in this landscape are currently much drier than in the pre-disturbance JERS-1 era which is likely caused by large subsidence events at relatively large distances.

The physical relationship between L-band backscatter and ground water level was quantified empirically based on PALSAR-1 data and GWL data collected near the Mawas research station along a 23 km research bridge, which crosses an entire ombrogenous peat dome. Though this relation was found to depend on other environmental factors as well, such as forest canopy characteristics, simple quantitative analyses can already be made as was demonstrated for an intense localised fire event in 2015 in the Sebangau National Park area. Peat surface subsidence was estimated at ± 1 m, which could be related to an estimated emission in the order of 1-2 megaton C.

Sentinel-1

The Sentinel-1 NRT radar monitoring system is an automated system based on interferometric pre-processing and time-series analysis of small image segments, linear features and small-scale disturbances. This results in a system that can accurately map different phenomena simultaneously such as deforestation (clear-cut, fire scars), degradation (e.g. selective logging) and new narrow canals in peat swamp forest. Radar imaging of canal gaps and the canal gap detection mapping results were shown to be in agreement with a physical interaction model. This model was used for model-based statistical quantification of similar, but smaller, gaps resulting from degradation, such as selective logging. Deforestation and degradation detection success was evaluated using results of careful visual interpretation of Sentinel-2 time series. For canal gap detection this was done with SPOT-6/7 data. For deforestation mapping low false alarm and missed detection rates were found. However, deforestation detection on peat is sometimes delayed, which may be caused by a combination of rough bare soil surface and high (peat) soil moisture. For canal detection mapping results are good but drop below 50% for canals narrower than 10 meter and for canals oriented within 10 degrees from the radar look direction. However, Sentinel-1 can also detect large tracts of narrow canals very poorly visible on SPOT-6/7 images, which would otherwise have been missed in the visual analysis of optical data. Degradation is easier to detect on radar data than on Sentinel-2 data. Analysis showed that spatio-temporal patterns of degradation are in agreement but that large parts (roughly 50%) are missed by Sentinel-2, mainly because of cloud cover. Comparison with TerraSAR-X radar, however, shows a very high degree of agreement, which suggest that TerraSAR-X radar may be more suitable for validation of Sentinel-1 radar degradation mapping.

Web viewer and user feedback

The Tropical Peat View Web GIS viewer has been built to visualize and analyse the results. With the viewer it is possible to view, combine and analyse data on deforestation, degradation, fire and floods (incl. flood frequency). Changes of the tropical forest and the peat areas in Indonesia can be viewed from 2015 until the current situation in time steps of approximately 12 days. The different themes are mainly based on processed radar images from the Sentinel -1 and PALSAR satellites. With every orbit from the radar satellites, an image is calculated which shows deforestation, degradation, flooding, canal and road development, but also regrowth of the vegetation. In forests, the radar will detect degradation. Other satellites with thermal sensors pick up signals of fires. The fire data is translated into an image showing the centre and spread of the fires. Flooding is detected by two radar satellites. The shortwave Sentinel-1 satellite shows open water, whereas the PALSAR satellite that uses a longer wavelength shows also flooding underneath the canopy. In the viewer several GIS background layers can be switched on and displayed on top of each other. A time selector lets you select a theme for a specific date, and it is possible to show a video-like presentation of the changes through time with help of a play function. A special toolbox allows the user to identify the layers for a specific location and makes it possible to draw a polygon to get information for the area within that polygon.

During the final Service Demonstration Workshop that was held from 8 to 9 October 2019 at LAPAN a general overview of applied method and results was shown to a large number of national and international organizations that showed great interest in the TPV system. The second day of the workshop was more technical oriented and meant for users of the monitoring system. Technical staff of all involved ministries were present. In addition, there were representatives of WRI, SinarMas, BCG Indo and FAO. The participants received training about the use of the viewer and how to interpret the results for their own implementation.

KLHK mentioned to have an operational monitoring system based on optical imagery but acknowledged that their system had limitations due to cloud coverage. Also, the representative of FAO mentioned that the radar-based monitoring system would be complementary to their own system.

During the Service Demonstration Workshop participants gave feedback that confirmed the fulfilment of the technical user needs and set targets per monitoring theme (drainage canals detection, flood and fire monitoring). In addition, a qualitative review was carried. Participants provided their feedback on a series of questions related to the use of the TPV system for their own organization and if and how the system could be improved.

5.3 Implementation plan

There is a broad consensus among stakeholders, as discussed during the final Service Demonstration Workshop, to continue radar capacity building and to start full technology transfer from the Wageningen partners to the Indonesian partners LAPAN, KLHK, BRG, and possibly others, as soon as possible. An implementation plan was made by the project team and discussed with all stakeholders. This technology transfer would include near-real time fully automated processing, primarily for Sentinel-1 and PALSAR-2, for peat swamp forest in particular, and forests in general. This technology is easy to use, robust, very cheap and gives important basic information in a reliable, spatio-temporal complete and fast way. Sentinel-1 radar would be used to monitor deforestation, degradation, fire damage and road/canal development in Kalimantan, Sumatra and Papua, wall-to-wall and in near real-time. PALSAR-2 would be used to develop hydrology monitoring in peat swamp forest and prepare for operational L-band NRT implementation (NISAR, PALSAR-3). Both Wageningen and LAPAN would continue to cooperate with JAXA within the Kyoto & Carbon Initiative, for which both have an agreement until 2022 for tropical peatland monitoring. Other countries with major tropical peat swamp forests, such as Peru and the Congo's, would be supported by Indonesia through the International Tropical Peat Centre (ITPC) and the Global Peatland Initiative (GPI).

5.4 Recommendations

Recommendations for follow-up can be made.

- A full transfer of Sentinel- 1 radar technology to LAPAN should be made as quickly as possible to allow use by BRG and KLHK for all peatland areas in Sumatra, Kalimantan and Papua.
- TerraSAR-X radar time-series should be used for calibration and validation of quantitative degradation mapping by Sentinel-1 radar.
- It is very useful to extend the demonstrated L-band phenomenological historical analysis to all tropical peat swamp forest areas, also in Peru and the Congo Basin. For a good understanding of the current threats in all these areas, a historical analysis of recent vegetation changes and canal development using Sentinel-1 should be done in addition. These should be done in cooperation with GPI and FAO.
- More ground water level (GWL) data should be recorded, including recordings in remote locations on ombrogenous peat domes, to refine the empirical relationships with L-band backscatter.
- Experimental findings from this project suggest innovative methods could be developed and tested for GWL estimation under the forest canopy by Sentinel-1

Possible follow up projects:

- Expansion to other peat and forest zones (Papua, Congo basin, Peruvian Amazon). Duration: 1 year.
- Technology transfer to Indonesia. Duration: 3 year.
- Large scale demonstration for FAO or GPI. Duration: 2-3 years, which include expansion to other tropical peat areas as Congo Basin, Peruvian amazon and Papua and as well workshops, capacity building and extended training.

- More Fieldwork related to ground water measurements in the peat domes. Duration: 2 year. Pilot area: Sebangau National Park, Indonesia.
- Investigate novel approach to monitor ground water level under the peat forest canopy with Sentinel 1. Duration: 4 months. Pilot area: Sebangau National Park.
- Quantification degradation with S1 calibration with TerraSar-X Duration: 1 year. Pilot area: Brazilian Amazon (TreeSar proposal; Brazil). Estimated cost: 150K Euro

Acknowledgements

Work on tropical peatland monitoring is supported through the ESA EO Science for Society project "Tropical Peat View" (**ESA AO/1-9101/17/I-N**B; Sep 2018 – March 2020). This work has been undertaken in part within the framework of the ALOS Kyoto & Carbon Initiative. ALOS PALSAR data have been provided by JAXA EORC. The development of NRT Sentinel-1 monitoring technology is partly developed within the international EWS system of WWF Netherlands. The Borneo Orang-utan Survival Foundation facilitated field work in the Mawas peat swamp forest.

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Annex 1: Workshop agenda User requirements 18-19 February 2019

Time	Agenda	Facilitators
Session 1: Opening		
09.00-09.30 9.50	Opening Remark: 1. WUR / Sarvision 2. LAPAN (Deputi Penginderaan Jauh) 3. BRG (Deputy of Research and Development BRG, and officially opening the workshop)	MC: BRG
09.30-09.45 09.45-10.00	Presentation: 1. Introducing SV and WU Proposals including detection of new drainage canals, monitoring of hydrology, and detection of fires, by Dr. Dirk Hoekman 2. Introducing of peatland projects of WUR in Indonesia by Prof. ~~Lars Hein~~ DH ?	
10.00-10.15	Presentation: Introducing of BRG and research needs by Dr. Haris Gunawan	
10.15-10.30	*Coffee Break*	
Session 2: The Research needs of BRG Session		
10.30-10.45	What research have been done and how further research needed? by Ir. C Nugroho S Priyono (15 minutes)	Moderator: Dr. Rohis (LAPAN)
10.45-11.00	What data and monitoring system has been done and how further research or development needed? by A. Karim Mukharomah, SE, ME & Dr. Awaluddin (15 minutes)	
11.00-11.15	Work has been done by BIG (Information and Geospatial Agency) (15 minutes)	
11.15 - 11.30	Work has been done by BBSDLP, Ministry of Agriculture (15 minutes)	
11.30 - 12.00	Work has been done by LAPAN (30 minutes)	
12.00 - 12.30	General Discussion	
12.00 13.30	Lunch	
Session 3: Collaborating [illegible]		
13.30-14.40	iscussion 1. Integrating Research Needs of BRG 2. Specific Research Areas in Kalimantan and Sumatra *Aim: to elaborate MoU based on the research needs and requirement of BRG and supports provided by WUR/SV. The elaboration will include connecting research-puzzle into the research has been done by BRG and partners as well as the research offered by WUR/SV. Specific areas are selected based on the availability of data and requirement of BRG.*	Moderator: Ir. C Nugroho S Priyono, MSc
14.40-15.30	Discussion: Intellectual Property Right *Aim: to elaborate MoU-specifically in terms of intellectual property right based on the understanding that Intellectual Property Right will have mutual benefit for parties*	Moderator: A. Karim Mukharomah, SE, ME
Session 4: Closing		
15.30-16.00	Wrap up Discussion and closing	
16.00-16.30	Coffee Break	

Annex 2 ToR and agenda Service Demonstration Workshop LAPAN 8-9 October 2020

Terms of Reference: Tropical Peat View

Cooperation : LAPAN - Wageningen University- SAR Vision

Service Demonstration workshop and Technical user workshop
Proposed Dates: 8 and 9 October 2019

Objectives of the Tropical Peat View Service demonstration workshop (8 October):

1. Inform stakeholders about results of Tropical Peat View and review service utility & roll out

Tropical Peat View is of interest for many different stakeholders involved in the sustainable management and restoration of peatland such as public institutions, donors, NGOs, technical and research organizations and the private sector. With this workshop we would like to inform the main stakeholders about the services developed as part of the Tropical Peat View and show the results that have been achieved so far. We would also like to discuss how the services will help BRG, LAPAN and the government of Indonesia in relation to their needs. In addition we would like to discuss the next steps, including how the technology can be transferred to LAPAN and how it can be upscaled to entire Indonesia.

List of identified stakeholders:

- LAPAN
- BRG
- BMKG
- BIG
- BPPT
- BNPB
- Government and other public authorities: Min. of Environment and Forestry
- Bilateral and multilateral donors: Norway, WB, UNEP
- Local NGOs: Kemitraan, WWF_Indo
- International NGOs: GGGI, Wetlands International, Conservation International
- Private sector: SinarMas, BCG_Indo
- FAO working with BRG for peatland monitoring system
- WRI working with BRG for peatland monitoring system

Objectives of the Tropical Peat View Technical user workshop (9 October):

2. Inform technical users of the achievements and use of the Tropical Peat View Portal

In this workshop the main users of the service will get a short training how to use the Tropical Peat View Portal in order to view the output data of the developed monitoring system. Afterwards the results and the portal viewer will be reviewed and validated by the participants. They will be also asked which elements are considered to be the most useful and how these could be transferred to BRG and LAPAN.

List of identified stakeholders for the technical workshop: Technical staff of:

- LAPAN
- BRG
- Government and other public authorities: Min. of Environment and Forestry
- Private sector: SinarMas, BCG_Indo
- FAO working with BRG for peatland monitoring system
- WRI working with BRG for peatland monitoring system

3. Review and validate service utility:

User requirements have been analysed by SV and WU based on previous exchanges with BRG, LAPAN and other potential users. One objective of the workshop is to review and validate the service utility by the (potential) users. In the table underneath the different services are listed. In both workshops participants will be asked if and how these services could help their organization in terms of the information requirements of their organizations. Participants will be asked if the services should be improved and if so, what is needed to realize this.

Information service	Drainage canals monitoring	Hydrology monitoring	Fire monitoring
Data sources	Sentinel-1	Sentinel-1 Palsar-2	Sentinel-1 Sentinel-2 Landsat-8 MODIS
Period	2015-2018	2015-2018	2015-2018
Thematic information	Drainage canals (Line features)	Floods duration Floods frequency (pixel based classification)	Burnt areas (pixel-based classification)
Pixel size	15 m	15-70 m	15 m
Minimum Mapping Unit	Minimum width: 10 m. Minimum length: 300 m.	50 ha	1 ha
Update frequency	3 monthly	2 times/year	Monthly
Thematic accuracy	80%	90%	80%
Delivery time	<5days after last image acquisition	<5days after last image acquisition	<3days after last image acquisition

In the technical workshop participants will be asked to answer the same questions with respect to the use of the Tropical Peat View portal.

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4. Next steps, roll out

Now the services have been developed it needs to be investigated how the technology can best be transferred to LAPAN and other organizations that would like to use it. What will be the conditions between the collaborating organizations for future use. Based on the feedback a technology transfer plan will be drafted.

The services have been developed for Central Kalimantan and Riau. But how can they be extended to the whole of Indonesia? What is needed, not only organizational and in terms of data, but also in terms of support by Wageningen and SarVision to adjust the services so that they can be applied to areas with deviating ecosystems. Will financial support be necessary for extending the monitoring area and what potential donors could be interested in this?

Tentative Agenda Tuesday 8 October 2019

Final Workshop of ESA Tropical Peat View project : (Part 1) Results

08.30-09.00	Registration	Secretariat
09.00-09.30	Opening Remarks	LAPAN : Dr. Orbita R WUR:Dr.Dirk Hoekman BRG:Dr.Haris Gunawan
09.30-10.30	Presentation and discussion of main project results of SV and WU, including detection of new drainage canals, monitoring of hydrology, deforestation, degradation and fire scars	Dr. Dirk Hoekman
10.30-11.00	Discussion	Moderator : Mr. Syarif Budhiman
11.00-11.15	Coffee Break	
11.15-12.15	What research has been done and what further research is needed? (30 minutes)	BRG
	What is the status of the monitoring system at BRG and which development is still needed? (30 minutes)	BRG
12.15-12.30	Work done by LAPAN (15 minutes)	Dr.M.Rokhis K
12.30-13.30	Lunch	
13.30-13.45	Work done by WRI	WRI
13.45-14.00	Work done by BPPT (15 minutes)	BPPT
14.00-14.15	Work done by WWF-ID	WWF
14.15-14.30	Work done by MEOF	
14.30-15.30	Integrating discussion for research and technology transfer needs of BRG and LAPAN.	Moderator : Mr. Syarif Budhiman
15.30-15.45	Coffee Break	
15.45-16.30	Wrap up discussion, pointing out: - What are the needs of BRG and Gov. of	Moderator : Mr. Syarif Budhiman

	Indonesia - How to facilitate the technology transfer from Wageningen to LAPAN - Up-scaling to entire Indonesia - Next steps	
16.30-17.00	Closing	BRG

Tentative Agenda — Wednesday 9 October 2019

Final workshop of ESA Tropical Peat View project : (Part 2) Technical Demonstration & training

09.00-09.30	Opening Remark s	LAPAN, WU, BRG
09.30-10.00	Summary of main project results of SV and WU, including detection of new drainage canals, monitoring of hydrology, deforestation, degradation and fire scars	Dr. Dirk Hoekman
10.00-10:30	Demonstration of the Tropical Peat View portal	Wilbert van Rooij
10.30-10.45	Coffee Break	
10.45-12:30	Hands-on exercises:	Wilbert van Rooij
12.30-13.30	Lunch	
13.30-14:00	Draft implementation plan for technology transfer to LAPAN	Dr. Dirk Hoekman
14:00-15.00	Discussion next steps: - Which elements are the most useful? Why? - Which elements o the TPV system should be transferred to BRG and/or LAPAN? - How to do this technology transfer? - Next steps	Moderator: Dr. Rahmat Arif
15.00-15.30	Coffee Break	
15.30-16.30	Wrap up discussion:	Moderator: Dr. Rahmat Arif
16.30-17.00	Closing	LAPAN

Annex 3 Training session Tropical Peat Viewer

Hands on exercises
Open an internet browser and use the following address:
http://forest.sarvision.nl/tropicalpeatviewer/
Log in with username: **tpvtraining** and password: **lapan**
If you do not have a print out of the viewer manual, download it from the menu (3 horizontal green stripes at the right top of the viewer). Read the manual before you do the exercises.

1. Familiarize with the viewer
Zoom out so that you can see the entire island of Borneo.
Make only the deforestation layer active and put the date on 4 August 2019. Now you can see the extent of the current deforestation map.

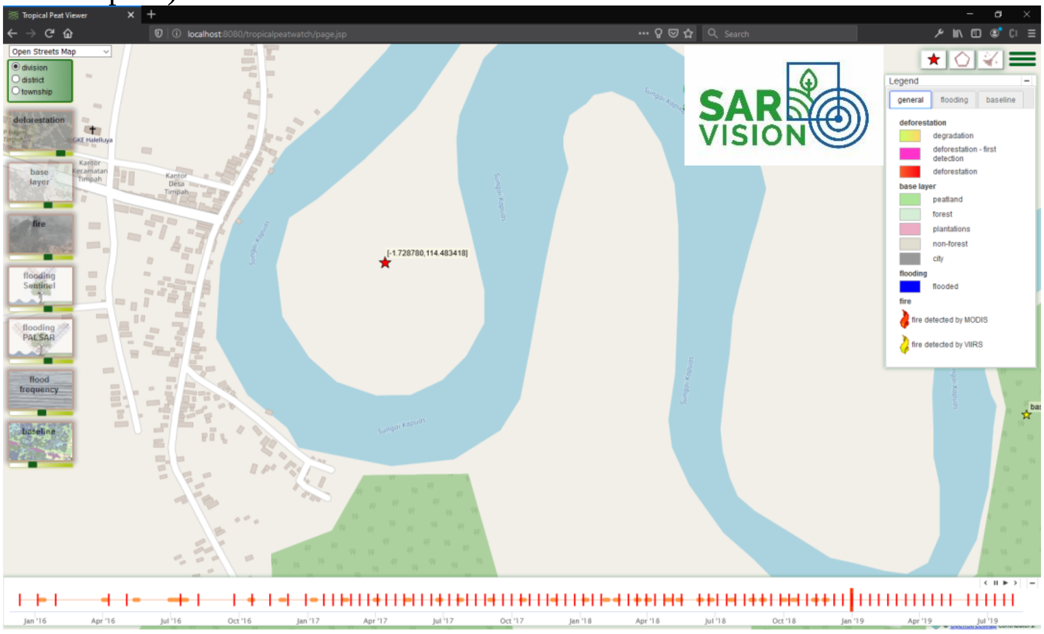
Check also the extent of all the other layer themes. You can keep the base layer always active, but it is better to deselect the other layers first before you select another layer.
For the flooding maps select a late October date, as flooding occurs normally during this time of the year.
1a. Can you find out the similarity between the base layer and the baseline layer?
Which categories are grouped together?
Answer:
Peatland: Peatland healthy, degraded peat
Forest: Forest on slopes, forest in flat terrain, heath forest, degraded forest
Plantations: Plantations
Non-forest: Non-forest high biomass, non-forest medium biomass, sparsely vegetated, unclassified
City: City (Water: Water)
Switch on the different background layers. The Open Street Map is switched on as default.

1b. Do you see differences between the Here we Go Satellite map and the Bing areal map?
Hint: Zoom far in. Notice that the images change for different zoom levels.
Answer: Bing map has a higher resolution
Zoom in to the southern part of Central Kalimantan.
Switch of all layers, then switch on the baseline map first and then the deforestation layer.

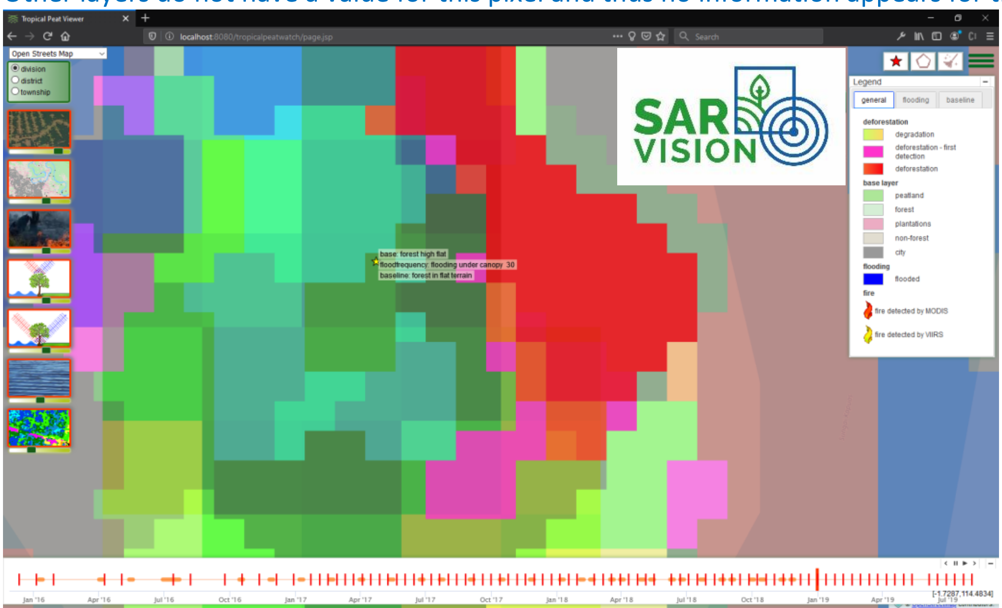
1c. Can you see along which of the base layer categories the deforestation is the largest?
Answer: Along degraded forest, degraded peat, non forest medium biomass and along plantations

2. Use the player function
Switch of all the layers except the baseline layer and the deforestation layer. If you switch on first the base layer and then the deforestation layer the deforestation will be visible more clearly. You can also do this by changing the transparency of the different layers with the transparency slide underneath each layer icon.
Go to the play function and look how the deforestation develops trough time.
Why appear the forest changes quicker in 2016 than after 2017?
Answer: Because there are less Sentinel1 images available in 2016 and the viewer does not adjust its speed according to time.

3a. Localization and inquiry map layer information for a certain date.
What pixel values are detected for all layers on the opposite shore of Timpah at coordinate [-1.7287, 114.4834] for all layers at Monday 31 December 2018? (Centre of peninsula of river Kapuas)

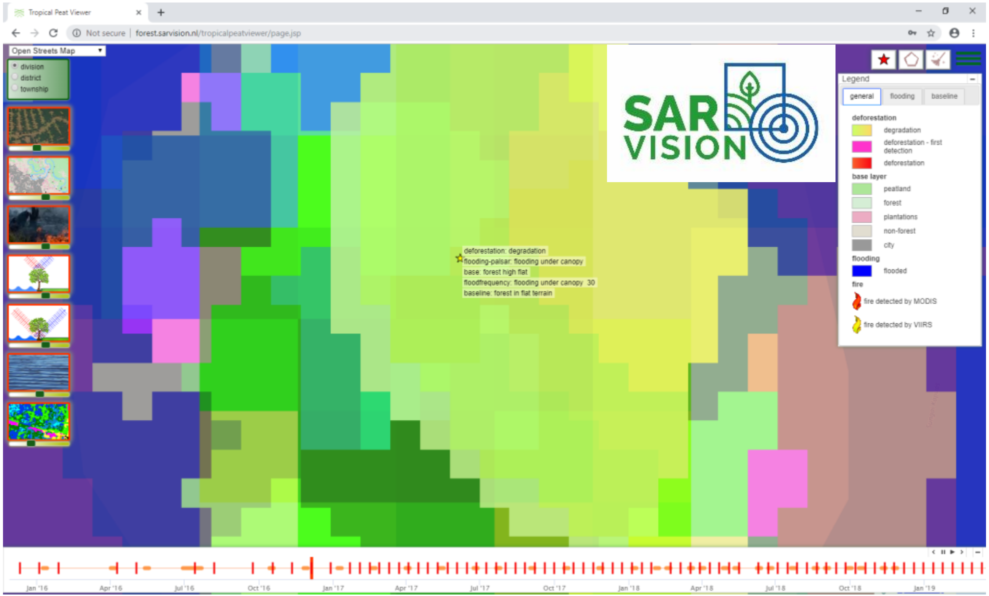


Answer:
Find Timpah and zoom in at the center of the island. Only if zoomed in at a detailed level it is possible to find the coordinate with enough accuracy. (coordinate values can be seen at the bottom right of the screen, just below the time bar)
Select the correct time on the time selector.
Switch on all layers and click on the right coordinate.
Base: forest high flat
Floodfrequency: flooding under canopy 30
Baseline: forest in flat terrain
But it can differ somewhat if clicked a pixel further away
Other layers do not have a value for this pixel and thus no information appears for these layers



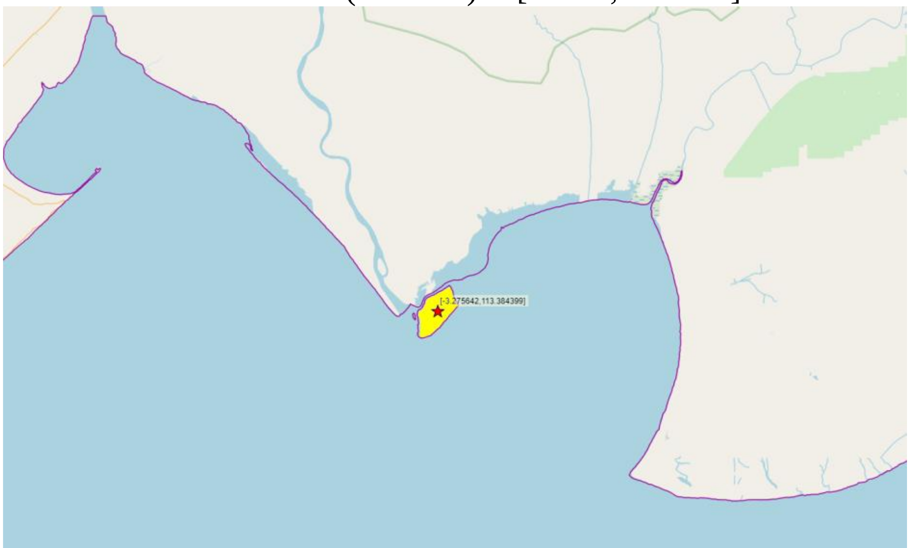
3b: And what values at 5 December 2016?

Answer:
Switch the time selector to 5 December 2016 and click again on the same position
Base layer: forest high flat
Flood frequency: flooding under canopy 30
Baseline: forest in flat terrain
Deforestation: degradation
Flooding-palsar: flooding under canopy



3c. What overlays have the same value for all timestamps and why?
Answer:
Base layer, Baseline and Flood Frequency. These are static maps and are not depending on the timestep

4.a Calculate area and quantify forest change within certain timespan
Calculate the area of the island of Pulau Damar, situated where the river Sungai Katingan flushes into the Laut Jawa (Java Sea) at [-3.276, 113.384].



Answer:
With the calculate area tool you can draw a polygon which tells you it is about 1583 hectare.

4b How much hectare of this island is deforested between 4 January 2016 and 4 August 2019 ?
Answer: Use the polygon drawing option in the chart to find out that the deforested area at 4 August 2019 is 38.1 ha and at 4 January 2016 is 6.6 ha. The deforested area is 38.1 – 6.6 = 31.5 hectare