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Multi-Regional

Satellite Monitoring for Forest Management

Project Implementation Summary

December 18, 2020

ENB

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[N.B. weblinks in the document are temporary and will be updated after SMFM tools have been transferred to the FAO SEPAL site]

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Abbreviations

AGB	aboveground biomass
ALOS	Advanced Land Observation Satellite
DIAS	Data and Information Access Services
DINAF	National Directorate of Forests (Mozambique)
EO	earth observation
ESA	European Space Agency
F-TEP	Forestry Thematic Exploitation Platform
FAO	United Nations Food and Agricultural Organization
FNDS	National Sustainable Development Fund (Mozambique)
FREL	Forest Reference Emissions Level
GFOI	Global Forest Observations Initiative
GIS	Geographic Information System
GPG	Good Practice Guidance
GUI	Graphical User Interface
ha	hectare
ICRAF	World Agroforestry Centre
ILUA	Integrated Land Use Assessment (Zambia)
LU/LC	Land Use / Land Cover
NRSC	National Remote Sensing Centre (Zambia)
PALSAR	Phased Array type L-band Synthetic Aperture Radar
RCMRD	Regional Centre for Mapping of Resources for Development
REDD	Reducing Emissions from Deforestation and Forest Degradation
SEPAL	System for Earth Observation Data Access, Processing and Analysis for Land Monitoring
SMFM	Satellite Monitoring for Forest Management
SSKE	South-South Knowledge Exchange
tC	metric tons of carbon
ToR	Terms of Reference
WP	Working Practice
ZFD	Forestry Department (Zambia)

EXECUTIVE SUMMARY

i. The Satellite Monitoring for Forest Management (SMFM) project, financed by the Global Environment Facility, was implemented by the World Bank between 2016 and 2020, with key earth observation (EO) data and technical assistance provided by the European Space Agency (ESA). The project development objective specifies "Improved methods for satellite monitoring of tropical dry forest landscapes and forest degradation assessment are available to countries, with technical knowledge and capacity developed for global application in sustainable forest management, including REDD+ [Reducing Emissions from Deforestation and Forest Degradation of the United Nations]." To achieve these objectives, the project was expected to develop and test new or improved methods to process and analyze new satellite EO datasets. This included, first, to develop new tools and applications and, second, to test these in three partner countries. Mozambique and Zambia were initially selected as partner countries, followed by Namibia in 2019.

ii. The project distinctly focused on tropical dry forests, which have some of the highest rates of deforestation and degradation in the world—a consequence of high demand for goods and services in support of the livelihoods of some of the world's poorest people. The project aimed to improve the monitoring of dry forests by applying the increasing plethora of open access data, cloud processing capabilities, and new satellite system performance capabilities.

iii. Four EO methods (tools) were developed to assist in the satellite monitoring of tropical dry forests. These tools primarily use radar and optical data, available from ESA's Sentinel-1 and Sentinel-2 satellites, as well as the freely available long wavelength radar from the Japan Aerospace Exploration Agency's (JAXA) Phased Array L-band Synthetic Aperture Radar (PALSAR) on the ALOS satellite. The four SMFM EO tools are as follows:

i. ***Sen1mosaic*/S*en2mosaic***: Semi-automatic preprocessing of Sentinel-1 and Sentinel-2 data to create seamless mosaics for land use/land cover classification purposes.
ii. ***Biota***: L-band radar-based tool for forest biomass and biomass change mapping, in order to provide historical information on forest cover, biomass stocks, deforestation, and degradation using ALOS-1 and ALOS-2 data.
iii. ***Deforest***: Semi-automated change detection algorithm to classify forest cover changes and to provide early warnings of deforestation events by using dense time series analyses of Sentinel-2 imagery.
iv. ***Acacia***: Classification of forest change events based on properties, such as size, shape, and intensity. The tool is compatible with outputs from SMFM tools (i), (ii), and (iii), in addition to country-specific change maps.

iv. The tools were codeveloped and tested by a select number of institutions in the partner countries. Field work campaigns were organized in Mozambique and Zambia to collect reference data of dry forest environments and recent change events for tool calibration and in order to validate the results. Work in Namibia focused on testing how the tools can be applied, using reference data that originally had been collected for other purposes.

v. Once developed, the tools were distributed as open-source code to allow customization and domestication by countries interested in dry forest monitoring. In addition, the tools were deployed to the ESA Forestry Thematic Exploitation Platform (F-TEP)[1] cloud processing platform to provide the necessary tool algorithms for direct access into the Sentinel satellite data archives, thus avoiding the download of raw data. The tools also have been applied from the System for Earth Observation Data Access, Processing and Analysis for Land Monitoring (SEPAL) platform of the Food and Agriculture Organization of the United Nations (FAO).

vi. To complement the development of methodologies and tools, the project provided comprehensive capacity-building inputs to project partner countries. Trainings took place within partner countries, as well as at the regional training facility, Regional Centre for Mapping of Resources for Development (RCMRD) in Kenya; University of Edinburgh, Scotland; and through online trainings and webinars. Trainings covered the basic skills in Linux and Python, required for tool use and testing, radar remote sensing, field data collection, specific tool trainings; and through webinars on the use of F-TEP services.

vii. Project partner countries applied selected SMFM EO tools based on their forest mapping and monitoring requirements. Examples are the production of a wall-to-wall mosaic of Sentinel-2 scenes for land use and land cover mapping and the use of the SMFM Biota tool in national forest monitoring in Mozambique. Zambia used the SMFM Biota tool to produce a nation-wide map of forest cover, forest cover change, deforestation, and degradation from 2007 to 2017. Zambia also used the SMFM Acacia methodology to identify the types of changes occurring in forest land, using an above-ground biomass (AGB) change map generated for the period 2010–16 with the Biota tool. Namibia applied the SMFM Biota to generate a forest cover map for the entire country, using forest definition parameters adjusted to the Namibian forest situation. Namibia also continues testing the application of mosaicking tools Sen1mosaic and Sen2mosaic.

viii. To address the global community of forest monitoring practitioners, project representatives attended conferences and engaged with the Global Forest Observation Initiative, the main coordination body for forest monitoring methodologies. At an SMFM side event organized at the Initiative's annual plenary in 2019, the project presented live demonstrations of the EO to representatives of other dry forest countries.

ix. A number of lessons have been learned from the project. The most important ones relate to the capacity levels required in tropical dry forest countries, the readiness of EO platforms, and the limitations to EO-based dry forest monitoring. It has become clear that potential users of the novel EO tools – including SMFM methodologies and tools – are required to have advanced remote sensing skills and some experience in script coding and the use of command-line tools. Countries wishing to make use of the SMFM tools should ensure that staff receives the necessary basic training. Another significant aspect is the capacity to generate tool calibration data from a network of plots in dry forest conditions and to establish a tool calibration model, for which external support may be required.

x. Most EO cloud processing platforms are still under development, with various important functionalities not yet in place. For example, the use of F-TEP as a cloud processing platform for the SMFM tools has provided mixed results. Another, still unresolved, issue is the cost incurred to dry forest countries for the use of these services.

[1] For further information, see https://f-tep.com.

xi. The complexity of dry forest landscapes continues to challenge the monitoring of these forests. To ensure the successful remote sensing of dry forests will require adequate biophysical information relating to the forests. Open forest types are generally difficult to monitor with EO data, as the soil moisture and grass signals unavoidably intermix with measurements of tree vegetation properties. In addition, there is no widely accepted definition for tropical dry forests and the concept of dry forest degradation remains vague, thus making the relevant assessment and monitoring a particular obstacle. Identification of the drivers of degradation and deforestation from EO data alone also remains at the experimental stage.

xii. External support could be provided to countries interested in establishing a network of dry forest plots to generate national tool calibration data. Ideally, a library of tool calibration data could be developed spanning tropical dry forest on all continents. Support also could be provided to countries interested in testing the SMFM dense time series approach, Deforest, for an extended period of time to better assess its readiness for operational use. Forestry departments and forestry law enforcement agencies could use and evaluate the early warning information provided through the SMFM Deforest tool, even without a full scale scientific validation of the results.

1. INTRODUCTION AND BACKGROUND

1.1 Project Key Rationale and Objectives

1. The Satellite Monitoring for Forest Management (SMFM) project was implemented from 2016 to 2020 to support earth observation (EO) capacities in tropical dry forest countries at national and subnational scales and to contribute to the global knowledge and capabilities for dry forest degradation assessment. New and improved methods to process and analyze satellite EO data sets were developed and tested in a select number of project partner countries. More specifically, the SMFM project's aims were to (a) improve the global knowledge and capabilities for forest degradation assessment and the monitoring of dry forest landscapes; and (b) support three select partner countries (Mozambique, Namibia, and Zambia) in developing their EO capacity and skills.

2. The immediate project development objective focused on the monitoring of tropical dry forests. This was formulated as "Improved methods for satellite monitoring of tropical dry forest landscapes and forest degradation assessment are available to countries, with technical knowledge and capacity developed for global application in sustainable forest management, including REDD+ [Reducing Emissions from Deforestation and Forest Degradation of the United Nations]."

3. The Terms of Reference (ToR) of the SMFM project implementation team emphasize the importance of developing EO methodologies to assist in national and global assessments of tropical dry forests, which generally lack reliable figures on (a) the extent and (b) condition of these forests. In addition, available and established EO methodologies generally focus on the humid and evergreen types of tropical forests instead of dry forests and woodlands. As a result, dry forests often fail to appear in national forest cover statistics and forest management objectives. Project deliverables are further exacerbated by the dearth of intense studies of tropical dry forests in comparison to humid and evergreen forests, thus leading to scarce background information, research data, and forest inventories. One particular explanation for this is that dry forests have insufficient economic potential and value, except for forest industry. Furthermore, at the local level, dry forest ecosystems in tropical areas can provide essential ecological services and livelihoods to the local populace, such as energy in the form of fuel wood or charcoal, nutrition, construction material, traditional medicine, and pasture for livestock. While this is an important factor and, in some cases, is a critical means for survival, the economic value, however, may not be recognized (e.g., national accounting).

4. As such, the SMFM project aims to take into account the potential economic relevance of tropical dry forests by undertaking an assessment at a national and global level. It also will focus on monitoring the efforts to fill this void with its EO methodologies.

5. Another key element of the SMFM project was the gap between the vast and increasing quantity of satellite EO data being generated and made available through open access arrangements and their actual use in forest monitoring, especially with regard to tropical dry forests. To address this, the project explored and developed ways to make better use of the large, daily accessible quantities of EO data. Particular focus was set on the imagery and data generated by the Sentinel satellites of the European Space Agency (ESA), which provide a wide range of EO data from the Copernicus satellite constellation. Focus was placed primarily on Sentinel-1 satellite constellation (C-band radar imagery) and Sentinel-2 satellite constellation (multispectral imagery in the visual and near-infrared spectrum).

6. The availability of freely accessible EO data in the way of global coverage represents a huge potential for forest assessment and forest monitoring—yet to be garnered by countries with dry forests. The almost daily availability of new imagery would, in theory, allow for near real-time monitoring of changes in dry forest environments. Since such EO data is not widely used for dry forest assessment as yet, however, it may be due to technical limitations. Dry forest environments are often sparse and can stretch over large areas. Consequently, the amount of imagery required for a single area may be a challenge for some countries, especially with regard to accessing, downloading, and processing large sets of imagery every couple of days.

7. To address these limitations, the SMFM project investigated potential emerging technologies, such as cloud processing platforms that are specifically tailored to the process and analyses of EO data. The aim was to eliminate the need to download, store, and process large volumes of EO data at the local level, and replace it by a particular algorithm on the EO cloud platform where the data are stored. The SMFM project thus developed algorithms to allow deployment onto such platforms. To do so, the project assessed two cloud processing platforms and infrastructures, the (a) System for Earth Observation Data Access, Processing and Analysis for Land Monitoring (SEPAL) of the Food and Agriculture Organization (FAO) of the United Nations and (b) the Forestry Thematic Exploitation Platform (F-TEP) under the Data and Information Access Services (DIAS) platform of ESA.

8. A further key aspect of the project rationale was the need to address the lack of capacities and skills in tropical dry forest countries, in particular the selected partner countries. In the absence of adequate knowledge, capacity, and skills at the country level, existing and emerging high-frequency EO data—potentially combined with the power of EO cloud processing platforms—are likely to remain underexploited.

9. Since there is no globally accepted approach to the satellite-based assessment and monitoring of tropical dry forests, a further aim of the project was to contribute to global knowledge by disseminating and sharing the methodologies and algorithms, once tested and developed, through various forums such as the Global Forest Observation Initiative (GFOI). The project also was to consider the requirement for national monitoring systems to be developed under the REDD+ mechanism.

10. Based on the above, the project rationale highlighted that there are unresolved challenges in terms of assessing tropical dry forests. The inherent technical challenges to reliably detect and identify tropical dry forest ecosystems with EO data are a result of seasonal or soil humidity variations on remote sensing signals. As such, the project ToR did not include the delivery of clearly predefined products, other than to examine and test novel approaches. The project team, in partnership with the select countries, was to develop manuals of best practice and concrete working practices so that countries with tropical dry forests can independently make use of the new approaches.

11. The SMFM project was developed, on the one hand, based on the need for (a) data on the extent and condition of tropical dry forests in national and global statistics, (b) technical capacity at the country level, and (c) globally accepted approaches to enable the assessment of dry forests; and on the other hand, (d) to exploit the potential of modern EO data and EO processing platforms. The ability to assess the national economic value of tropical dry forests and their role in sustainable resource management and the protection of natural capital is of significant concern to the World Bank and especially to that of its clients.

12. The project was financed by a medium-size grant from the Global Environment Facility. It also received the support and technical advice of the ESA. Field work in Mozambique, Namibia, and Zambia (the select countries) was mainly done in connection with other World Bank operations in these countries.

13. This *Project Activity Summary Report* summarizes how the project was developed and implemented. It also provides guidance to project teams on how future comparable projects can be designed. While the report does discuss various technical elements in relation to the tools developed during the project, it is by no means an indepth technical account of the work effected. The main technical findings and recommendations are available from other documents prepared during the project, such as the following:

i. *Good Practice Guidance (GPG) Note.* Presents key issues in dry forest management and monitoring, with new tools to address those issues.
ii. *Summary for Senior Forestry Administration Officials, Forest Managers, and Donor Representatives.* Presents a brief summary of the tools developed for nonspecialist senior staff and management.
iii. *Working Practice (WP) Documents.* Provide detailed technical guidance on the use of each of the five tools developed.
iv. *Validation Summary* for the tools developed.
v. Several briefing notes and other communications material.

1.2 Deforestation and Degradation in Dry Forests

14. The SMFM project design was based on two main concerns in terms of tropical dry forests: deforestation and degradation. Tropical dry forests occur in different forms, compositions, and densities, ranging from rather dense, multistorey, semideciduous forests to sparse woodlands and savannas. Given this wide spectrum of appearance, it is no surprise that definitions vary widely from country to country. Given that it is already uncertain "what actually counts as dry forest," identifying and quantifying when and where dry forest was lost is rather difficult. This highlights the need to identify where dry forests are subject to degradation. The degradation of tropical dry forests is particularly difficult to define and capture. Common approaches include the reduction of aboveground biomass (AGB) or the reduction of canopy cover. Other definitions might focus on the loss of certain environmental or livelihood services. Different actors or countries having various perceptions of (a) dry forest, (b) deforestation and (c) degradation results in potentially differing outputs from remote sensing methodologies. This fact represented the core challenge that the SMFM project attempted to address.

15. For the purpose of planning and implementing the SMFM project, the global distribution of tropical dry forest, as per the FAO global forest ecosystem zones, has served as a starting point. For the testing and application of SMFM methodologies and algorithms, the definitions used by partner countries have been used. These were generally described in structural terms, using a combination of crown cover and tree height. For practical application, the structural definitions have been converted into AGB estimates (in metric ton carbon/hectare (tC/ha)) to define the equivalent threshold to distinguish between forest and nonforest in the EO data.

16. While it was a task of the project to agree with project partner countries on a working definition of tropical dry forest, it was not within the scope of the SMFM project to engage in a scientific discussion on developing a globally applicable definition for tropical dry forest. Rather, the project aimed to contribute to the development of practical approaches to make better use of available EO data and platforms for dry forest assessment and monitoring. Work was largely based on existing national definitions and forest and land cover categories.

17. Whereas deforestation of dry forest (i.e., removal of woody biomass to below the agreed AGB threshold) is relatively straightforward to capture with remote sensing data, the concept of degradation (i.e., partial removal of biomass or the degradation of certain ecological functions of dry forest) presents a different challenge. Forest degradation is generally understood as the process of reducing the "quality" of forested land without the loss of the biophysical properties that define it as a forest. In more practical terms, this can be the result of a reduction of forest biomass but not reaching a level below the threshold of a particular forest definition. Perceptions of forest degradation often depend on the main features of interest or concern. Different users of a forest may apply varying criteria or measurements for forest degradation, such as the loss of biodiversity, wood production, soil conservation, or carbon storage. For the purpose of the SMFM project, the assumption was made that degradation is best captured by loss of AGB, which makes it also detectable by EO methodologies.

18. Tropical dry forest ecosystems are often considered as fragile. They can be relatively resilient, however, and can withstand the impacts of repeated bush fires or droughts as well as recover from them. These may temporarily result in a considerable loss of AGB; however, the ecosystem itself generally survives and fully recovers over time. As a consequence, any methodology that can capture a reduction or partial loss in AGB may not immediately be able to identify whether such a loss will result in lasting degradation or even deforestation. Here, the SMFM project explored ways to analyze dense time series of remote sensing data to better understand how a monitoring approach could respond to such phenomena. Another crucial aspect in dry forest monitoring is the distinction between natural cycles and anthropogenic impacts. Being able to detect forest degradation with a remote sensing approach is an important step; however, to identify the driver of degradation and distinguishing whether the underlying cause is natural or anthropogenic is a different challenge. The SMFM project explored ways in which to use EO data to provide indications of the actual drivers behind changes in dry forest biomass.

1.3 Project Implementation Arrangements

19. The SMFM project was implemented by the World Bank, with day-to-day management of the project provided by the World Bank task team based in Washington, D.C. Within selected partner countries, project implementation was channeled through the respective World Bank country office or regional representations.

20. The immediate partner to the World Bank was ESA, which provided the project with EO data, access to cloud processing infrastructure, and technical assistance. Besides its role in supporting the World Bank in orienting the project, the ESA was instrumental in providing the project with early access to the F-TEP cloud processing infrastructure, services, and data repositories via its contractor, the Technical Research Centre in Finland, VT. ESA had identified the F-TEP as the suitable cloud processing service for the SMFM project and was instrumental in including the project into the group of preferred users and application developers.

21. A consultant consortium composed of LTS International and The University of Edinburgh, both from Scotland, provided direct technical support to the World Bank through project planning and reporting. The main task of the consortium was the design, development, and testing of new EO methodologies and approaches in direct collaboration with and support to select government institutions in the project partner countries.

22. Mozambique and Zambia were preselected by the World Bank as project partner countries for country-level implementation and validation of the satellite EO methods. Toward the end of the project, Namibia was selected as a third partner country with the role of independently testing the applicability of the developed methodologies and approaches. Government authorities in the countries were identified based on their official mandates for forest assessment and monitoring. In Zambia, the implementation was shared between its Forestry Department (ZFD) under the Ministry of Lands and Natural Resources; and its National Remote Sensing Centre (NRSC) under the Ministry of Higher Education. In Mozambique, implementation was assigned to the National Sustainable Development Fund (FNDS), with the Forestry Department (DINAF), under the Ministry of Land and Environment, playing a role in field data collection. In Namibia, a specialized unit within the Namibia Directorate of Forestry, under the Ministry of Agriculture, Water and Forestry, was charged with testing and applying the SMFM EO methods and algorithms.

23. Table 1.1 summarizes the main roles of the various SMFM project partners.

Table 1.1 Main Project Partners and Their Roles

Project Partner	Role in the Project
World Bank task team in Washington, D.C.	• Overall oversight and responsibility for project execution
World Bank Country Office task teams	• Organization of in-country workshops, meetings, and trainings • Main communication link to partner countries
European Space Agency	• Advice to World Bank task team • Provision of earth observation data • Access to earth observation processing infrastructure and data repositories
Consultant consortium (LTS International; The University of Edinburgh)	• Project work plan • Earth observation methodology/algorithm development and documentation • Training and capacity development • Reporting
Country working groups	• Codevelopment and testing of Satellite Monitoring for Forest Management earth observation tools • Field data collection for calibration/validation (Mozambique and Zambia) • Coordination and communication among country stakeholders
	• Long-term hosting of Satellite Monitoring for Forest Management tools on the System for Earth Observation Data Access, Processing and Analysis for Land Monitoring (SEPAL) platform

24. During the project, other institutions also played a role. One was the Regional Centre for Mapping of Resources for Development (RCMRD) in Kenya, which provided venues and experts for regional SMFM trainings. Another was the F-TEP team, which helped the SMFM project to set up the EO tools on the F-TEP platform by implementing adjustments to the platform. The F-TEP team also provided online trainings and webinars to the SMFM partner country specialists. Toward the end of the project, it was agreed that FAO's SEPAL platform will host the tools and make them available for the global community of practitioners. FAO also provided expert advice during tool development.

1.4 Global Knowledge Context

25. Data on tropical dry forests are sparse and incomplete. The available knowledge on assessment and monitoring of dry forests is equally sketchy. As stated above, there is no commonly accepted or adopted definition and there also are no standard EO methodologies and approaches that specifically apply to tropical dry forest. There are, however, various initiatives that produce global data sets that include some information of tropical dry forests. The main ones are FAO with its global Forest Resource Assessment; the Global Forest Watch initiative (Hansen et al. 2013) that tracks the global distribution of forests as well as loss and gain; and Global Forest Ecoregions (Olson 2001). There also has been research on tropical dry forests by the Center for International Forest Research (CIFOR 2014).

26. Regarding the remote sensing of forests GFOI, launched in 2013, has provided guidance in its second edition Methods and Guidance Handbook (GFOI 2016), available at the onset of the SMFM project. The 2016 document lays out the general principles of remote sensing of vegetation and forest cover; however, it does not provide any methodologies or approaches that are specifically tailored to the assessment of tropical dry forest. It states that global and national forest assessments have so far largely been based on medium-resolution optical imagery (e.g., Landsat), but acknowledges that future assessments will be mostly based on radar and high-resolution optical imagery (e.g., Sentinel-2[2]). The third edition (GFOI 2020) became available soon after the technical work by the project was completed and it has reference to SMFM tools.

[2] The Sentinel-2 satellites were still being launched when the second edition was being prepared.

2. PROJECT PLANNING AND INCEPTION PHASE

2.1 Project Work Plan

27. The scope of work of the SMFM project, as described in the ToR, cover four main phases or tasks, as follows:

i. Project planning and analysis
ii. Satellite EO methods design
iii. Support to implementation and validation of satellite EO methods at the country level
iv. Global knowledge exchange and capacity building.

28. Project planning and analyses were ongoing tasks throughout the project. They began with a project kick-off meeting in December 2016,[3] followed by the inception phase that included the in-country analysis and stock-taking of existing EO capacity, skills and data, national policies, legislation, and definitions relating to dry forests. This phase also included the evaluation of existing national forest monitoring activities. An overall SMFM project work plan was prepared for the period December 2016 to June 2019. This work plan was repeatedly updated and adjusted based on actual project progress.

29. In January 2019 at a joint video conference with the World Bank, the work plan was extended from June to December 2019 to accommodate additional work with the third partner country, Namibia. By end-2019, a further extension to April 2020 was made in a separate period work plan. This plan no longer included any implementation activities—only timelines for completion of key deliverables.

30. In February 2018, separate work plans were prepared for the implementation of project activities in the partner countries, Mozambique and Zambia. The plans initially covered the period April 2018 to April 2019 and included detailed implementation activities and budgets. Key activities covered by country work plans were:

- preparing interim working definitions for dry forests (deforestation and degradation);
- collecting data for calibration and validation;
- installing and testing EO tools;
- preparing biomass, forest cover change, and degradation data sets; and
- participating in exchange visits and South-South Knowledge Exchange (SSKE) activities.

31. When the decision on Namibia as the third project partner country was made in April 2019, a list of activities was agreed upon between the World Bank regional representation and Namibia Forestry Department representatives. A separate country work plan for Namibia was prepared by June 2019.

32. The project inception phase lasted from January to October 2017. During this phase, several activities were carried out. In particular, the inception period served to agree with the World Bank and ESA on the types of methodologies to be developed and on the class of EO data to be used. By the time the inception report was approved and adopted, the following activities had been carried out by the consulting consortium:

[3] There was a number of administrative delays at the early stage of the project, causing a relatively slow start for the project.

- **Requirement assessment**: Included the review of the needs for geospatial information relating to Sustainable Forest Management in tropical dry forests and for forest degradation assessment and monitoring at the global and national levels (partner countries). It also analyzed the availability of knowledge and information.
- **Technical gap analysis**: Examination, in particular, of the capabilities of partner countries in relation to the satellite EO for the monitoring of tropical dry forests and for forest degradation assessment. It also included an assessment of available infrastructure and skill sets within the two countries, Mozambique and Zambia.
- **Review of methods and tools**: Covered the available approaches for monitoring tropical dry forests and for degradation assessment.
- **Capacity building plan**: Initial capacity building was prepared in order to respond to the needs that were identified with respect to the satellite EO monitoring of tropical dry forest landscapes and forest.
- **Work planning**: Review of country capabilities during the inception phase helped in preparing the SMFM project work plan for the subsequent implementation phase. The first full work plan was presented together with a project Inception Report in October 2017.

33. The detailed results of the above activities were presented in the SMFM project Inception Report in October 2017. Main deliverables of the project are presented in Table 2.1.

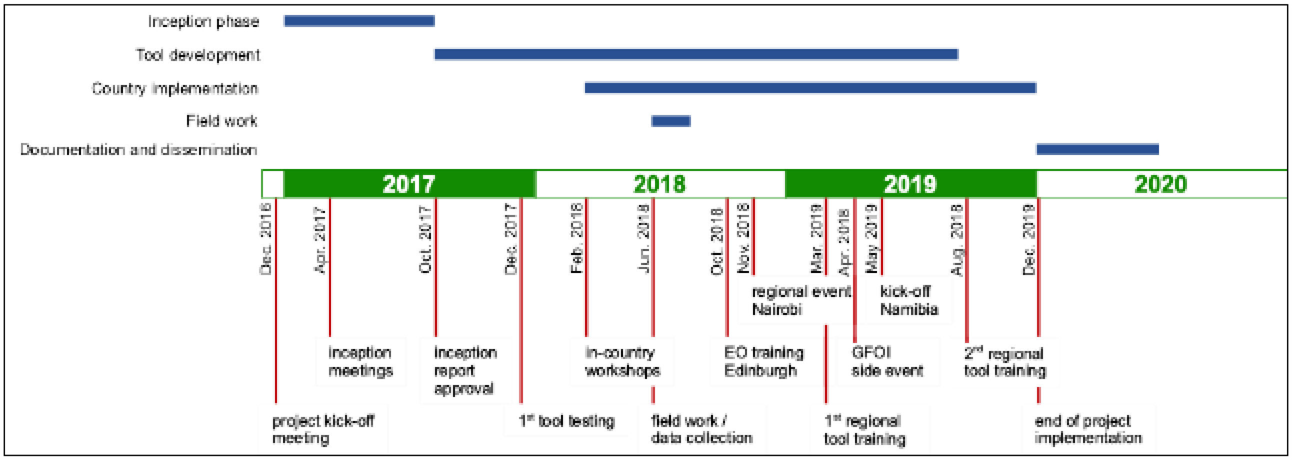
Table 2.1 Satellite Monitoring for Forest Management: Deliverables

No.	Deliverable	Submission*
D1	Detailed Work Plan	12/2016
D2	Inception Report	10/2017
D3.1	Satellite Earth Observation Methods Design Report	03/2018
D3.2	Validation Plan	Combined with D3.3/D4
D3.3	Terms of Reference for country work (Mozambique and Zambia)	05/2018
D4	Validation Compliance Report	03/2020
D5.1	Good Practice Guidance for Satellite Monitoring of Tropical Dry Forests	04/2020
D5.2	Good Practice Guidance for Satellite Assessment of Forest Degradation	combined with D5.1
D5.3	Working Practices for Application of New Methods in Satellite Monitoring of Tropical Dry Forests	04/2020
D5.4	Working Practices for Application of New Methods in Satellite Assessment of Forest Degradation	04/2020
D5.5	Awareness Raising Materials and Action Plan	06/2020
D6	Training materials and training courses	06/2020
D7	South-South Knowledge Exchange Activity Report	combined with D8
D8	Project Activity Summary Report	04/2020

* Final delivery dates

34. Figure 2.1 2.1 provides an overview of the main phases and key events of the SMFM project.

Figure 2.1 Project Timeline and Key Events



35. An SMFM project website (www.smfm-project.com) was launched in June 2018. It provides essential information on project objectives and activities as well as links to key documents and presentations.[4]

36. The project was steered through agreements reached at periodic video conferences with the three project partners; World Bank task and country teams, ESA representatives, and the Consultant team. During these meetings, progress was discussed and assessed, and major decisions on the orientation of methodology and tool development were taken. Many additional video conferences were held between the Consultant team and the World Bank task team to address urgent issues, as well as with partner country institutions, in particular, to prepare for field work and in-country training events.

37. Monthly progress summaries were produced by the Consultant team until the end of 2019, coinciding with the end phase of country implementation. Monthly reporting was discontinued during the final extension of the project between January and the end of July 2020, when implementation activities had ceased and tool development was completed.

2.2 Partner Country Assessments

38. During the inception phase, the policies and legal frameworks for forestry were assessed in the initial project partner countries, Mozambique and Zambia. This included rather detailed analyses of policy objectives, key strategies, action plans, and linkages to global conventions and treaties. Country-specific definitions of forest and forest degradation were collected and analyzed. Both countries have only an official forest definition, with Zambia having no clear one for forest degradation, and with Mozambique having nothing specifically adapted to tropical dry forest other than a general definition for forest degradation. In lieu of an adequate definition for dry forest degradation, the occurrence and appearance of degradation in dry forests now has been described for both partner countries, including the land uses that were generally considered as the main drivers of dry forest degradation.

[4] The website will be active until June 2021.

39. Inception phase assessments include a review of existing national forest monitoring systems or activities. In Zambia, for instance, the Integrated Land Use Assessment (ILUA) II program is a joint program between FAO and Zambia's Forestry Department and its National Forest Monitoring System, the latter of which was established with support from the United Nations REDD. In Mozambique, forest monitoring activities were fundamentally based on ground observations and field work.

40. The SMFM consulting consortium organized inception missions to Lusaka, Zambia, in April 2017 and to Maputo, Mozambique, on April 8–13, 2017. During these missions, inception meetings were held with government stakeholders, potential implementation partner institutions, academia, and World Bank country teams. Table 2.2 provides a list of the partner country institutions consulted during stakeholder meetings in April 2017.

Table 2.2 Institutions Consulted during Inception Phase, April 2017

Country	Institutions and Stakeholders
Zambia	Forestry Department Zambia Environmental Management Agency National Remote Sensing Centre Survey Department Ministry of Fishery and Livestock Ministry of Land and Natural Resources Centre for Energy, Environment and Engineering University of Zambia
Mozambique	National Development Fund/Reducing Emissions from Deforestation and Forest Degradation of the United Nations (UN-REDD+) Technical Unit National Directorate of Forests and Wildlife National Directorate of Environment) National Center of Cartography and Remote Sensing National Directorate of Lands and Forest Mozambique Institute of Agricultural Research Directorate for Territorial Planning and Resettlement Eduardo Mondlane University

Note: REDD = Reducing Emissions from Deforestation and Forest Degradation.

41. Capacity and skills assessments were carried out during inception phase missions to the first two project partner countries. These assessments examined the skills that were available for EO data processing and analyses at various government institutions, so as to identify the most suitable institution to implement country-level activities. General geographic information system mapping (GIS) and remote sensing (RS) software skills were assessed, as were practical experience in analyzing satellite imagery and general skills in using programming software for geospatial applications. Particular attention was given to skills relating to the assessment and monitoring of forest cover or forest types. In addition, technical capacity was assessed; that is, the availability of computer and server capacity that could be mobilized for SMFM project activities and existing infrastructure for forest monitoring at the national level.

42. Assessments confirmed good levels of skills in both partner countries in terms of processing and analyzing optical satellite imagery for general vegetation mapping. Nevertheless, significantly limited experience was revealed in terms of radar remote sensing for forest biomass mapping and EO cloud processing applications. These outcomes guided the immediate training inputs provided during inception missions.

43. In terms of data, the assessment explored existing and accessible EO data sets at the national level that could serve as reference or baseline data for dry forest monitoring or as calibration data for the EO tools. Zambia's assessment confirmed the availability of land use and land cover (LU/LC) maps for the years 2000, 2010, and 2014, based on Landsat satellite imagery, as well as a forest change map for the same period. In Mozambique, LU/LC maps produced from Landsat and Advanced Land Observation Satellite (ALOS) optical imagery were available for the years 2002, 2005, 2008, 2010, and 2013. A LU/LC map generated from Sentinel-2 optical imagery was available for 2016.

44. Following the inception phase, the SMFM team—jointly with the World Bank country teams—organized in-country workshops in Zambia and Mozambique in February 2018. The workshops were held in Maputo and Lusaka in February 2018 to screen the institutional capacity and identify the main implementation partners (Figure 2.). The working group lead in Mozambique was assigned to the FNDS, while the lead in Zambia was shared between ZFD and NRSC. These workshops were conducted to gauge the readiness of stakeholder institutions to implement country activities and to jointly agree with stakeholders on:

- a working group composition and its lead;
- country implementation ToRs and work plan; and
- a tentative field data collection program.

Figure 2.2 Planning Workshop in Zambia, 2018

Photo credit: SMFM project team

3. METHOD DESIGN AND TOOL DEVELOPMENT

3.1 Approach and Principles

45. The general approach to developing EO methodologies and applications for the mapping and monitoring of tropical dry forests already had been laid out in the SMFM project ToR. These included the use of:

- open source software;
- free and open access satellite data (e.g., ESA Sentinels); and
- cloud processing services.

46. All software tools produced under the SMFM project were developed in Python for the Linux command line. This combination was considered the best possible solution to make use of the open source operation system, Linux, and the openly accessible Python programming environment.[5] The resultant SMFM tools and developments are equally open source, can freely be accessed and downloaded from online repositories, and are fully documented. During the project completion phase, the final tool versions were packaged as self-contained docker files for easy installation by nonspecialist users.

47. Furthermore, SMFM methodologies and tools rely on access to and use of open data, in particular open access satellite imagery from the ESA Sentinel satellites and the Japan Aerospace Exploration Agency's Phased Array L-band Synthetic Aperture Radar (PALSAR) on the ALOS satellite. ESA Sentinel-1 and -2 satellites had been selected for their global coverage of optical and radar imagery and short revisiting interval, making these data ideal for dense time series analyses. The ALOS PALSAR data were selected for the specific suitability of the L-band radar data for biomass assessments in dry forest environments. The Japan Aerospace Exploration Agency–JAXA annually publishes a free mosaic of PALSAR L-band scenes that is well suited to year-on-year biomass change mapping.

48. Another principle applied to the development of SMFM methodologies and tools was to use, as much as possible, online data sources by (a) direct access to satellite imagery in provider repositories or (b) making use of EO cloud processing platforms and services. In the first scenario, the EO methodologies and tools, when executed locally, would access and use data stored on provider servers instead of using previously downloaded and locally stored data. In the second scenario, the algorithms would be deployed into the data provider's platform or similar data processing platforms to avoid data download altogether.

49. The actual development of the methodologies and tools was to be undertaken jointly with partner countries. This involved, where possible, early testing of tool prototypes or parts of tools by specialists in the partner institutions. The project ToR outlined the requirement to address specific dry forest methodological challenges, such as vegetation seasonality, vegetation density with regard to class boundaries, and mixed land cover/use classes. The ToR also identified forest degradation challenges to be addressed, in particular the discrimination of various disturbance events relating to forest management from those events resulting in real forest degradation. In addition, it was suggested to identify proxies to estimate forest degradation.

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[5] Originally, SMFM EO tools were written in Python 2. Between April and May 2019, tool scripts were rewritten in the upgrade, Python 3, to ensure that the tools were future-proof beyond the duration of the SMFM project.

50. During the inception phase, it was agreed to develop three main methodologies for the assessment and monitoring of deforestation and degradation in dry forests, as well as one methodology for the preprocessing of ESA Sentinel data. Contrary to early discussions, it was agreed not to attempt to develop a methodology for the prediction of where future deforestation is likely to occur but, rather, to explore ways in which to detect early signs of degradation and deforestation for near real time monitoring of deforestation.

51. Another principle applied to the development of methodologies and tools was the use of relatively generic types of dry forest categories. In the absence of clear definitions in project partner countries and considering that differences in national definitions would make tool development even more challenging, the following broad dry forest categories were applied:[6]

- Dry forest = closed canopy of mostly deciduous trees without grass with AGB > 100 t/ha.
- Woodland = woody savanna with a continuous grass layer and a discontinuous tree canopy with AGB 20–100 t/ha
- Savanna = as woodland but with very sparse trees with AGB < 20 t/ha

3.2 Sen1mosaic/Sen2mosaic

52. The preprocessing of satellite imagery was necessary to remove artificial effects caused by atmospheric conditions at the time the imagery was captured. These generally relate to atmospheric humidity, aerosol content, and sun angle inclination, mostly affecting optical and multispectral imagery through the scattering of incoming light and radiation at different wavelengths. Another effect commonly addressed during preprocessing was the masking of clouds and cloud shadows. These effects are not relevant for radar imagery. The preprocessing methodology developed by the SMFM project applies atmospheric correction and mosaicking of adjacent scenes for Sentinel-2 imagery and filtering and mosaicking for Sentinel-1 imagery. Consequently, two different EO tools were developed as follows:

- Sen1mosaic for Sentinel-1 radar imagery
- Sen2mosaic for Sentinel 2 multispectral imagery.

53. Outputs from both tools can be used as inputs to other SMFM methodologies and tools. Due to different requirements and data specifications, the tools were already separated during the early stages of methodology development.

[6] With globally diverse dry tropics, this generic distinction may not be applicable to all vegetation situations. Some countries may need to adjust existing tool calibration or develop individual calibration data.

54. The Sen1mosaic methodology and tool was mostly developed and tested during 2018. With the final selected approach for the main biomass mapping Biota tool, ultimately based on ALOS PALSAR data alone, there was no longer a need to ingest Sen1mosaic outputs into other SMFM developments. The Sen1mosaic methodology and tool have been developed, however, to offer a wide range of useful improvements to Sentinel-1 scenes, including noise removal, backscatter calibration and filtering, geometric terrain correction and, finally, seamless mosaicking. Outputs are produced in standard GeoTIFF format, providing users with the option of further using and analyzing the data in standard GIS or image processing applications. Sen1mosaic has been applied by partner country specialists during various training workshops.

55. The Sen2moaic methodology and tool went through several development stages that resulted in essential improvements and additional capabilities. From its early versions at the beginning of 2018, when it basically performed only mosaicking and color-balancing while borrowing on existing algorithms such as the ESA Sen2cor toolset, it was constantly improved to include algorithms specifically developed by the SMFM team. This included a superior cloud masking algorithm and a color-balancing approach that selects, inserts, and balances cloud-free pixels from other scenes into areas covered by clouds and cloud shadows during the mosaicking process. This was an important achievement, as the enhanced Sentinel-2 image mosaics offer not only a valuable starting point for countries to carry out their land cover/use mapping, but also as these improved and corrected mosaics served as input data to other SMFM algorithms. To meet user requirements better, the option of performing quick mosaics from unprocessed level-1C Sentinel scenes was included. When ESA announced its intention to make preprocessed level-2A data available, the SMFM team updated Sen2mosaic accordingly.

56. Sen2mosaic and its outputs were successfully tested by Mozambique and Zamia during 2018 and later by Namibia in 2019. A number of users outside the SMFM project also downloaded and tested the tool on their own initiative. The most relevant examples are listed in Section 4.5.4.

57. Early prototype versions of Sen1mosaic and Sen2mosaic were completed by April 2018 and subsequently tested. Advanced versions were available by mid-2018 and deployed onto the ESA F-TEP platform by September 2018 for testing. A fully functioning version of Sen2mosaic was available on F-TEP in December 2018. In June 2019, the Sen2mosaic tool was updated to maintain compatibility with the latest changes in Sentinel-2 data formats.

58. Various types of documentation have been produced for both tools. Final document versions are available online from the project website, which include latest updates and modifications. A set of WP documents has been produced in PDF format, which reflects the document status as of early 2020. More information on the documentation of the Sen1mosaic and Sen2mosaic tools is presented in Section 5.2.

3.3 Biota

59. The SMFM methodology for the annual mapping of forest biomass change and degradation monitoring tool, Biota, is central to the SMFM project approach, and has been developed to a fully operational tool for users in tropical dry forest countries. It has been designed to ingest free ALOS PALSAR mosaic data, and it provides users with the required stages to carry out annual forest biomass change mapping. These stages are:

- accessing and downloading ALOS mosaic tiles;
- preprocessing the ALOS data;
- mapping aboveground biomass and forest cover for different years; and

- detecting forest biomass changes.

60. It is an important outcome that the Biota tool also can be used to process Sentinel-1 radar data. This has been tested during the early stages of tool development. Due to limitations of the Sentinel-1 C-band radar data, with a backscatter signal saturation at around 50 t/ha and therefore not suitable for the types of dry forest vegetation encountered in the SMFM project partner countries, this option was discontinued in later tool versions. The use of Sentinel-1 C-band data in Biota still has a clear potential in other types of environments and may prove useful for mapping purposes outside typical dry forests.

61. Early in the development stage, it had been decided to build the tool around a generic definition of tropical dry forest. Given the geographic distribution of SMFM project partner countries, this definition was aligned to forest types occurring throughout the southern Africa region. For global applicability, the SMFM team has developed the option of using available national forest plot data, if available, to calibrate the tool with a country-specific, backscatter-AGB relationship.

62. Four main forms of deployment of the Biota tool have been developed, as follows:

- Basic Linux command-line tool
- Python module
- Graphical User Interface (GUI)
- A version for the F-TEP platform.

63. The Linux command line and the Python module both address the advanced user, while the GUI version has been developed with an entry-level user in mind. This version allows a simple setting of parameters from dropdown menus, familiar to most users. The F-TEP version of Biota has been developed as a proof-of-concept rather than a fully operational application, as the F-TEP platform was still lacking some functionalities required for Biota to run efficiently.

64. Development of the Biota tool continued throughout most of 2018 and 2019, and included the following major steps:

- Early version developed as a Python library and tested using biomass-backscatter calibrations and biomass mapping from Mexico, Mozambique, and Tanzania. This version was designed around the requirements identified by the Mozambique and Zambia country teams.
- Further development stages included the use of the ESA Climate Change Initiative land cover map to mask out areas of water inundation.
- The first operational prototype version was available for testing in March–April 2018. Draft documentation was also developed at that time.
- An advanced version was available by October 2018 and tested by the Mozambique country team in Gilé District prior to national-scale application. The fully operational version of Biota in Python and Linux was available in December 2018.
- First F-TEP tests of Biota began in September 2018. A basic Biota version was then deployed into F-TEP in January 2019. A fully functioning version followed in February 2019 in preparation for the regional SMFM training event at RCMRD in Kenya in March 2019.
- In April 2019, an advanced version was presented at a GFOI plenary and a first GUI was developed for Biota and subsequently refined.

65. The SMFM project produced various types of documentation for the Biota tool, including the WP document and a dedicated section in the SMFM GPG document. More information on the tool documentation is presented in Section 5.2.

3.4 Deforest

66. Following the Biota tool for annual forest biomass change and degradation monitoring, the second most important output of the SMFM project is the methodology for dense time series analyses. This methodology and the relevant developed series tool, **DE**nse **FORES**t **T**ime (Deforest) are innovative, still at an experimental stage, and not yet ready for mainstream operation.

67. The Deforest tool makes use of ESA Sentinel-2 data and exploits the high frequency of new imagery available every couple of days. The key concept behind the development of this tool was to provide forest managers with a tool to detect the early stages of degradation and deforestation in dry forests. In addition, the dense time series methodology allows for the detection of historical forest change at a very fine temporal resolution and, therefore, potentially "closes the gap" between annual forest biomass assessments through shorter assessment intervals. The methodology and tool, therefore, should be considered a complement to the SMFM Biota tool.

68. In theory, the Deforest methodology should allow forest managers to implement a near real-time monitoring of forest change for forest management purposes. It responds to the SMFM ToR requirement of assessing and quantifying forest disturbance events over time. Initially, it was planned also to use Sentinel-1 radar data in the dense time series approach. While this was tested and is technically possible, it was not further pursued as there was no immediate added value from adding Sentinel-1 data due to the prevailing limitations of the C-band radar data in detecting dry forest environments.

69. Due to the relative novelty of this approach, the SMFM team explored various avenues in developing the methodology and tool, from the initial testing of the existing Breaks for Additive Season and Trend (BFAST) approach to the Bayesian online changepoint detection algorithm and to the final version that uses the Random Forest Classifier and various vegetation indices and spatial or textural pattern analyses alongside temporal and seasonality aspects.

70. To make full use of the dense time series approach, it was essential to have direct access to a cloud-based data repository, as otherwise data volumes to download would prove prohibitive. The SMFM team therefore deployed and tested a version on the ESA F-TEP platform. In theory, the execution of the Deforest algorithm on F-TEP would allow the processing of large amounts of data by directly accessing the repositories and using the cloud processing infrastructure. Despite repeated exchanges and discussions with the F-TEP team, a crucial functionality could not be made available on F-TEP. The Deforest tool requires temporary storage between different runs of the algorithm to allow keeping the scenes preprocessed with Sen2mosaic for further processing within Deforest. As this functionality was not implemented by F-TEP, the tool only could use single scene stacks that were preprocessed and permanently stored by F-TEP operators. For the purpose of testing under the SMFM project, the F-TEP team preprocessed four full stacks of scenes over selected locations in Mozambique and Zambia. While this enabled the development and testing of the tool, it did not allow for fully independent use by partner countries over their select areas of interest.

71. Major development stages of Deforest involved the following:

- Early versions were prepared when sen1mosaic and Sen2mosaic tools were fully operational to allow integration of mosaic outputs into the Deforest algorithm. A first operational version of Deforest was ready by the end of 2018. Considerable time was spent in 2018 on iteratively addressing seasonality aspects in the time series data.
- Testing with field work calibration data pointed at better chances of success with the information-rich Sentinel-2 data. Consequently, the use of Sentinel-1 data was dropped from tool development in August 2018. The resulting development version already supported the multiresolution data structure of Sentinel-2 scenes. Random Forest Classifier and various new model features (e.g., vegetation indices, burn scar indices, texture analysis, timestamp) were integrated into the development version. An updated version allowed for training pixels to be extracted from existing land cover data to compensate for insufficient levels of field calibration data.
- A first functioning prototype was developed by December 2018, which produced initial outputs, although further development was required at this stage.
- A prototype version of the Deforest tool was showcased at the SMFM side event during the GFOI plenary in April 2019 as well as during a presentation at World Bank offices in May 2019.
- A fully functioning version was available for the second regional SMFM training event in August 2019 and was made publicly available in the tool code repositories. This version also was made available on F-TEP, using time stacks of scenes preprocessed by the F-TEP team, since the crucial temporary storage capability had yet to be implemented.
- The final tool produced by August 2019 is available as a Linux command-line version, providing the four main processing steps. The F-TEP implementation has to be considered a proof-of-concept rather than a fully operational version.

72. The documentation produced for the Deforest tool consists of a detailed manual in the form of a WP document, with a dedicated section in the SMFM GPG document. More information on available documentation is presented in Section 5.2.

3.5 Acacia

73. The ToR of the SMFM project laid out several methodological challenges to address. These included the challenge to discriminate individual disturbance events that may be the result of planned sustainable forest management activities from other events relating to unauthorized resource use. To address this challenge, the SMFM team developed an analytical approach to identify and classify specific forest change properties. This approach makes use of forest change detection, using the Biota methodology and, in a second step, examines the parameters that could possibly relate to a specific type of activity or driver of deforestation. The main properties or attributes used in this analysis were the size, shape, and intensity of the change event. Other parameters proved less conclusive and were finally dropped from the analysis.

74. Development of this methodology and the tool, referred to as Acacia, commenced only in late 2018 and continued well into 2019, since it built upon outputs from other tools. Development therefore only began once fully functioning prototypes of these were available. The resulting methodology responds to the ToR requirements; however, it is still experimental and, at best, can be seen as proof of concept and it definitely requires further research testing and refinement.

75. Approaches pursued in the development of the Acacia methodology and tool involved the following steps:

- The Acacia tool was developed as a set of Python scripts.
- Early versions used Google Earth high-resolution imagery to calibrate the tool and validate initial test results. Later versions also included data from SMFM field work for validation.
- Various development versions explored the use of supervised and unsupervised hierarchical clustering of change event types. Attempts to have results identified and labeled automatically through machine learning procedures had to be abandoned in favor of user-based labeling.
- A GUI was developed between June and August 2019, outputting the results in standard GIS format for further analyses by users.

76. The development of Acacia methodology explored different avenues by testing a number of physical attributes of identified and confirmed change events, as well as various image-related properties such as roundness, rectangularity, fractal dimension index, and parameters relating to shape complexity. Additional external data sources (e.g., Global Forest Watch data (Hansen et al. 2013)) or country-specific data sets also were analyzed and tested for their potential value in helping to identify types of activities and drivers.

77. Various supervised and unsupervised clustering and classification approaches were tested and compared for their suitability and classification success. After initial testing, a hierarchical, unsupervised classification method was finally selected and implemented in the tool code. While this helped to address the first part of the analytical problem (i.e., to group and classify forest change events correctly by their key characteristics), it did not yet allow for automatic identification and labeling of the type of activity causing the change event. In its final stage of development, the Acacia tool still requires intervention by the user to assign the presumed type of driver to a specific class of change events. Further research and testing may lead to a higher degree of automatization in this approach, although experience so far has shown that drivers of land cover and forest change, in reality, often overlap spatially as well as temporally. As a consequence, degradation of forest can result from several activities, such as selective cutting of trees combined with charcoal producing, leading to a complete removal of forest for small-scale agriculture. This considerably limits the possibility of identifying the causes and activities with EO data analysis alone.

78. Another still unresolved aspect of this methodology is the practicability of collecting and using validation data, since field data collection represents a significant effort; an approach based on remote sensing (e.g., using Collect Earth) would depend on the availability of high-resolution imagery for the same date. Testing has shown that it was neither always possible to determine the cause of forest changes nor to reliably identify degradation from high-resolution imagery. Forest degradation caused by unauthorized resource-use activities is seldom static or likely to evolve, and is therefore prone to change. By the time validation data can be collected, the situation on the ground already may have changed. The SMFM team relied on the field data collected during the partner country field work to test the tool calibration and validation. This, however, limited the applicability of this methodology for countries that do not have plot-level data. It still does provide useful additional information, however, to direct field monitoring and environmental supervision.

79. The Acacia methodology and tool were tested by SMFM partner countries during the training workshop at RCMRD in Nairobi in August 2019. Feedback from workshop participants confirmed that there is general interest in making such methodology operational; it was emphasized, however, that deploying such methodology is not yet a key priority for the countries.

80. The SMFM project has produced different types of documentation for the Acacia tool, which include a manual-like WP document, with a specific section for the SMFM GPG document. More information on available documentation is presented in Section 5.2.

4. COUNTRY IMPLEMENTATION PHASE

81. Mozambique and Zambia are dominated by different varieties of dry woodlands, with the *miombo* woodland and the *mopane* woodland being the principal ones. There are some areas of seasonally dry forest, particularly in the Zambezia and Manica Provinces of central Mozambique, and in northwestern Zambia, although these are more limited in extent. Savannas are widely distributed and occur in heterogeneous landscapes. Southern Mozambique is much dryer and has little forest. The dry forest situation in Namibia generally differs from that of Mozambique and Zambia, with the exception of the Zambezi region in northern Namibia, where dry forest types are more similar to Mozambique and Zambia. The rest of the country is much dryer and is dominated by savannas and shrublands, with an interannual variation more pronounced than in Mozambique and Zambia.

82. Inception phase activities reviewed the data situation in the initial partner countries of Mozambique and Zambia. Aside from already available satellite imagery, the assessments mainly examined available data sets on current land cover and plot data, with forest-related parameters as reference data for tool calibration. Both countries had land use and land cover change maps available. At the onset of the project, plot-level forest inventory data were partly available in Mozambique. The plot size was too small, however, to serve as reference data for forest degradation. In Zambia, data were available and accessible from the ILUA-I and ILUA-II projects. Namibia had some data, although these were not consistent and not collected over a sufficiently large area. Regional plot-level data were available from the Socio-Ecological Observatory for Southern African Woodlands initiative that maintains a series of large-scale forest plots across southern Africa.

83. Mozambique, particularly FNDS, applies an open data policy, so data are generally accessible. In Zambia, data collected with public funding have to be made public within one year from collection. The quantity and quality of the available plot data, however, was not sufficient or suitable as reference for tool calibration or validation of results.

84. General access to and download of ALOS and ESA Sentinel data proved no particular obstacle in partner countries. Actual conditions, however, varied among the different partner country working group institutions.

4.1 Field Work

85. The SMFM team organized field work for reference data collection in both initial project partner countries. The main purpose of the field work campaign was to produce subnational datasets on forest cover, forest cover change, biomass, and forest degradation. The project assisted partner institutions in preparing the field work through site selection, elaboration of a data protocol, and specific training. The scope of the field work campaign covered preselected areas in Mozambique (provinces of Manica, Zambezia, Gaza, and Maputo) and in Zambia (Lusaka, Central and Copperbelt provinces). Main activities included:

- compiling a catalogue of drivers of deforestation;
- preparing a data collection protocol;
- developing a working definition of deforestation and degradation; and
- preparing and carrying out field data collection.

86. Field data collection was organized only in original partner countries for calibration of the tools and, later, for validation of results. There was no field work planned in Namibia, as the third partner country served as a test case for independently applying the developed tools. As a consequence, Namibia applied the tools with a calibration based on Mozambique and Zambia data.

87. Field work in Mozambique began on July 23, 2018, with a three-day practical training event provided by the SMFM Consultant team, and ended on August 2, 2018. The data collection protocol was jointly established during initial field work training. The Mozambique country team then shared the data collection protocol with the Zambia country team.

88. Mozambique working group lead FNDS, with support from DINAF, deployed teams to two regions, the provinces of Gaza and Manica. The originally planned third area in Zambezia was not covered due to logistical and administrative difficulties relating to interinstitutional issues. After several postponements, it was agreed to discontinue the field work in Zambezia Province. Altogether, data were collected on a total of 126 field plots (Gaza, 50 plots; Manica, 76 plots) for seven different types of drivers of degradation and deforestation. After completion of the field work, data sets were compiled and checked for inconsistencies.

89. Field work in Zambia began on June 20, 2018, with a three-day training workshop in Chongwe attended by participants from all working group institutions. Field data collection commenced in the vicinity of Lusaka Province, then moved to Central Province and Copperbelt Province, and was completed by July 18, 2018 (Figure 4.1).

Figure 4.1 Field Work on a Charcoal Production Site, Zambia

Photo credit: *SMFM project team*

4.2 Earth Observation Platforms

90. The project inception report continued to suggest exploration and use of SEPAL in parallel to DIAS platforms. A decision was taken in August 2018 to fully orient the SMFM EO tool development toward emerging DIAS platforms, in particular the CREODIAS platform, in combination with the F-TEP platform as a front-end.[7] Subsequently, the SMFM team established contact with the CREODIAS team and later with the F-TEP developer, Finland's Technical Research Centre VTT, and agreed on direct collaboration. Although designed as a pay-for-use service, F-TEP provided the SMFM project with unlimited access during the development phase. Initially, the SMFM team started testing access to the data repositories on the CREODIAS infrastructure. At this stage, production of time stacks of images, essential for dense time series analyses, was not yet implemented. Early testing of F-TEP capabilities revealed limitations of available processing power for dense time series analyses over large scales. From October 2018, the SMFM team modified sen1mosaic and sen2mosaic to run on the F-TEP environment with initial outputs generated at low resolution. The fact that both platforms (i.e., CREODIAS and F-TEP) were, themselves, still under development until October of 2019, frequent adjustments were necessary for the otherwise functioning EO tools in order to keep them operating on the evolving platform environment.

91. A video conference was held between the SMFM Consultant team and the F-TEP team in November 2018 on the requirements for hosting the SMFM tools in the F-TEP platform. In particular, the assignment of processing power to large-volume data processing applications, such as the dense time series analysis, was addressed. At the same meeting, the SMFM project obtained priority status on F-TEP, with development access to parts of the platform's services. Other aspects discussed concerned the continuing restricted data accessibility prior to CREODIAS repository integration. At that time, not all Sentinel scenes and no ALOS PALSAR data were available on F-TEP. This was partly addressed following another video conference in January 2019, when F-TEP announced the successful integration of the CREODIAS platforms into the F-TEP platform and services.

92. It became clear from a very early stage that the operational cost of using cloud processing services risked being substantial. The SMFM team, at that point, enquired into planned cost schemes at CREODIAS and later with the F-TEP team. Only at the end of August 2019 did the F-TEP team share tentative pricing information. Until the end of the SMFM project (July 2020), the F-TEP team had not yet made public any definitive pricing scheme for the use of its platform services.

93. Other EO platforms were originally considered, in particular the SEPAL platform operated by FAO. Subsequent to the decision having been taken in August 2018 regarding the use of F-TEP services for the SMFM project, no further effort was made to develop specific tool versions for SEPAL. Discussions with FAO continued throughout the project, however, and in particular during and after the GFOI plenary in 2019. It subsequently has been decided that SEPAL will be the main long-term depository of SMFM tools. The tools, furthermore, are platform agnostic and can be run on other systems as well.

94. At the end of the project, partner countries stressed the need to have access to affordable EO cloud processing services. There were initial reservations by partner countries against the use of online platforms or cloud processing infrastructure. Nevertheless, these changed in the course of the project, mainly due to their first-hand experience in processing large volumes of EO data, such as the dense time series.

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[7] CREODIAS and F-TEP became fully integrated in January 2019.

95. On several occasions, the F-TEP team was invited to provide webinars to SMFM partner country participants at training events (Figure 4.2). In turn, the SMFM project team participated in ESA evaluations of the F-TEP and SMFM projects to produce a user case for the F-TEP team. The SMFM team also contributed toward an F-TEP journal article and various symposiums.

Figure 4.2 Live F-TEP Webinar at Regional Training in Nairobi, Kenya

Photo credit: SMFM project team

4.3 Capacity Building

96. The project provided capacity building in various forms. Formal training workshops were followed up by online collaboration and video sessions. Training locations varied between partner countries, other countries in the region, and Edinburgh, Scotland. The trainings covered not only basic EO skills, especially relating to radar remote sensing and those required for Python and Linux, but also those specifically necessary to calibrate and use SMFM EO tools. Other training inputs prepared the field teams for reference data collection or provided users with the necessary basics to operate the tools on the F-TEP cloud processing platform.

97. Initial trainings were carried out in both partner countries during inception phase missions. The training in Lusaka, Zambia, was provided on April 6–7, 2017, at the World Bank country office. It was attended by 18 participants from the Forestry Department, including regional offices, NRSC, Survey Department, University of Zambia, and the Center for International Forestry Research office in Lusaka. The training covered the key concepts of EO applications for forest monitoring (QGIS and ESA's Sentinel Application Platform) and included group work on the actual forest monitoring needs of Zambia. Training materials on basic geospatial data concepts, the practical use of radar imagery for mapping of forest environments, and more advanced radar data preprocessing techniques were provided.

98. The training in Maputo, Mozambique, was held on April 11–12, 2017. It was attended by five participants from the FNDS REDD+ team and one participant from University Eduardo Mondlane. The training program covered an overview of forest monitoring methods with EO optical and radar data, using QGIS, ESA's Sentinel Application Platoform, and Python; an update on the status of Mozambique's permanent sample plot network; and a group discussion on defining degradation in the context of Mozambique. Training tutorials on the use of radar imagery and on the introduction to geospatial Python were provided.

99. The following list summarizes the sequence of training inputs provided during project implementation (Table 4.1 provides additional details for each training session, such as the main contents, participating institutions, and the dates).

- **Field work trainings:** Two workshops of three days each were delivered in Zambia (June 2018) and Mozambique (July 2018) to prepare the field teams for data collection. These were hands-on trainings that also served to develop a data collection protocol.
- **Radar remote sensing training:** A specific one-week radar remote sensing training workshop was organized in October 2018 at The University of Edinburgh, Scotland, with the participation of working group members from Mozambique and Zambia. Following the training, the SMFM team began the interactive development of Biota with FNDS in Mozambique.
- **First SMFM tool training:** The first regional SMFM tool training was organized in March 2019 at RCMRD in Kenya with the participation of Mozambique and Zambia representatives. Focus was on the use of the SMFM tools Sen1mosaic, Sen2mosaic, and Biota.
- **Introductory training in Namibia:** The Namibia country team received basic training in May 2019 after it joined the project as the third partner country. The training covered the basics in Python and Linux and the functioning of the sen1mosaic, Sen2mosaic, and Biota tools.
- **Second SMFM tool training:** The second SMFM tool training was again organized at RCMRD in August 2019 with the participation of Mozambique, Zambia, and Namibia working group members. The focus of the training was on the use of the Deforest and Acacia tools. The training also included tool calibration and validation strategies. Participants had the opportunity to carry out concrete work, using the SMFM EO tools.
- **Online trainings and webinars:** A total of six online training inputs have been provided to the Namibia country team via video link (June to December 2019). Two specific webinars on using the SMFM tools on the F-TEP platform were provided to all partner countries. In addition, there were one-on-one calls on many occasions during the tool development and testing phases.

Figure 4.3 Training at The University of Edinburgh, Scotland

Photo credit: SMFM project team

100. The original intention to include a third project partner country was to have an independent user apply the SMFM EO tools in the absence of having received the same level of training inputs from the project. Namibia did receive some training, especially with regard to Linux, Python, and in concrete tool use; otherwise, the team would not have been in a position to run the tools autonomously. This suggests that future users of SMFM tools beyond the project may not be able to use the tools without some targeted training. This cannot be generalized, however, as the actual capacity and skill situation is likely to vary considerably between counties. As a matter of fact, the project became aware of a number of outside users testing and applying the tools without any training whatsoever (see Section 4.5.4).

Table 4.1 Overview of Training and Capacity-Building Inputs

No.	Title, Contents	Location	Date/Duration	Participants
1	Inception phase training • Radar remote sensing • QGIS, Python	Lusaka, Zambia	6-7 Apr 2017 2 days	ZFD, NRSC, UNZA
2	Inception phase training • Radar remote sensing • QGIS, Python	Maputo, Mozambique	11-12 Apr 2017 2 days	FNDS, DINAF, CENACARTA, UEM
3	Field work training	Chongwe, Zambia	20-22 Jun 2018 3 days	ZFD
4	Field work training	Ndozu Camp, Mozambique	23-25 Jul 2018 3 days	FNDS, DINAF
5	Radar remote sensing for dry forests	The University of Edinburgh, Scotland	8-12 Oct 2018 5 days	ZFD, NRSC, FNDS
6	SMFM EO tools 1 and 2	RCMRD Nairobi, Kenya	11-15 Mar 2019 5 days	ZFD, NRSC, FNDS, RCMRD
7	F-TEP webinar	RCMRD Nairobi, Kenya	14 Mar 2019 0.5 days	ZFD, NRSC, FNDS, RCMRD
8	SMFM tools 1 & 2; Linux basics	Windhoek, Namibia	23-24 May 2019 2 days	NDoF
9	F-TEP webinar	Windhoek, Namibia	24 May 2019 0.5 days	NDoF
10	SMFM EO 3 and 4	RCMRD Nairobi, Kenya	19-23 Aug 2019 5 days	ZFD, NRSC, FNDS, NDoF

Notes: ZFD = Forestry Department (Zambia); NRSC = National Remote Sensing Centre (Zambia); UNZA = University of Zambia; FNDS = National Development Fund (Mozambique); DINAF = ; CENACARTA = National Center of Cartography and Remote Sensing (Mozambique); UEM = University Eduardo Mondlane (Mozambique); SMFM = Satellite Monitoring for Forest Management ; RCMRD = Regional Centre for Mapping of Resources for Development; NDoF = Namibia Directorate of Forestry; F-TEP = Forestry Thematic Exploitation Platform.

101. Two types of training materials have been produced. The first is an introductory training in the basics of radar remote sensing, Linux, and Python. As prerequisites to working with SMFM tools, stand-alone training documents have been made available. The second training material is tool-specific training, integrated into the SMFM WP documents, including worked examples, which allow for independent use of the tools.

102. The following training materials were produced:

i. Introductory trainings:

- Introduction to Geospatial Linux
- Introduction to Geospatial Python
- Introduction to Radar Remote Sensing

ii. Tool-specific trainings:

- Sen1mosaic /Sen2mosaic Working Practice
- Biota Working Practice
- Deforest Working Practice
- Acacia Working Practice

103. Aside from the above, various presentations that were used during the training courses are available from www.smfm-project.com.

104. While it had no official role as a partner in the project, RCMRD in Nairobi, Kenya, became the *de facto* regional capacity building hub for the SMFM project. RCMRD provides member states with technology support and support in natural resource and environment management on a demand basis. All three project partner countries are member states of RCMRD,[8] and the center has proved to be a suitable location and hub for SMFM regional trainings.

Figure 4.4 Training during Namibia Kick-Off Mission (May 2019)

Photo credit: *SMFM project team*

4.4 Codevelopment

105. The original intention of the codevelopment approach was to work on developing the code for SMFM EO tools together with partner country teams via platforms, such as GitHub, and through video links. Specialists from partner country institutions contributed significantly by testing these and providing feedback on early versions and tool prototypes.

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[8] Namibia and Zambia are contracting member states, while Mozambique is a noncontracting member state.

106. When updating the Biota command-line interface in January 2019, the SMFM team included code that was produced by the Mozambique country team during their testing phase and use of the tool for annual deforestation mapping. This is a concrete example of not only codevelopment that functions, but also an example of active sharing of developed knowledge from one project partner country to current and future users of SMFM EO tools. Equally, in January 2019, Mozambique and Zambia named their codevelopers for direct exchange with the SMFM Consultant team, and an online collaboration on tool development was formed.

107. By February 2019, the SMFM team had set up a dedicated user and developer group on F-TEP, consisting of the partner country codevelopers and key developers of the Consultant team in Edinburgh. First results of successful testing were subsequently shared among project partner countries. The feedback and contributions by partner country developers and testers included important inputs to the overall development of functionalities in the SMFM tools. Tool prototypes were used at SMFM training events to allow for an early feedback loop from participants. This user perspective was then built into the final tool versions.

4.5 Tool Application by Partner Country

108. SMFM project partner countries were able to test the tools during the two major regional training events. The project, however, did not require partner countries to test and apply all SMFM EO tools systematically. Rather, project partner countries chose to use selected EO tools for concrete forest mapping and monitoring purposes according to their current information and reporting needs. The following sections present key examples of the countries using the tools.

4.5.1 Mozambique

109. Mozambique has generated an LU/LC map from Sentinel-2 imagery as the basis for Mozambique's Forest Reference Emissions Level (FREL) submission to the United Nations Framework Convention on Climate Change. The Sen2mosiac tool was used to produce wall-to-wall mosaics for the dry and wet seasons as an alternative input method to previously applied approaches. The resulting composite mosaic was judged an improvement over previous datasets. Mozambique also made use of the SMFM Biota tool to implement its own methodology and improve previously used methods for forest cover change monitoring in the context of FREL reporting. FNDS used Biota to produce a forest stratification, upon which a stratified sampling system was built to reduce sampling effort and uncertainties for continuous forest change monitoring. This approach used a systematic set of ground control points and FAO's Collect Earth tool. The results of the deforestation assessment have been successfully validated by the country team.[9]

110. Mozambique also used the SMFM Deforest tool in a structurally diverse area of central Mozambique, mainly to identify locations where this approach works well and to understand in which context the tool might be useful for Mozambique. In this case, Mozambique operated Deforest over one of the SMFM field work locations and calibrated the tool using data from known locations of stable forest and nonforest. The time series used Sentinel-2 images for the period of 2015 to 2019. The results were assessed against available field data and visually against other high-resolution remote sensing data.

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[9] See *Satellite Monitoring for Forest Management: Validation Compliance Report*.

111. Despite the relatively short time series period, the Deforest methodology produced good results in denser forest types and in relatively homogeneous woodland structures. It also managed to identify recent forest loss, resulting from flooding in the wake of Cyclone Idai in March 2019. Other area results, however, were influenced by terrain conditions or agricultural cycles, leading to less reliability of results and revealing the limitations of this approach in complex or heterogenous landscapes. In direct comparison with SMFM field data, however, the high probability of a real deforestation event being identified was confirmed. Overall, Mozambique found the Deforest methodology to be an interesting and potentially powerful EO approach, although it concluded that there was not yet operational need for this approach under current domestic and international reporting requirements (e.g. REDD+).

4.5.2 Zambia

112. Zambia used the SMFM Biota tool to produce a nation-wide map of forest cover and forest cover change, as well as a national deforestation and degradation map, for the period 2007–17. This work made use of calibration parameters derived from available plot data in neighboring Mozambique, but applied Zambia's own forest definition. Zambia compared the outputs from Biota to other available data sets, such as Global Forest Watch data (Hansen et al. 2013) and found the results to correctly represent the known distribution of forest and nonforest areas in Zambia. Detected forest changes also corresponded to known areas of recent deforestation in Zambia. Overall, the results were judged a substantial improvement over existing data sets of remote sensing of forest cover and forest loss thus far utilized in Zambia's FREL.

113. The SMFM Acacia methodology was applied in Zambia to identify the types of changes occurring in forest land. It made use of an AGB change map for the period 2010–16, generated with the SMFM Biota tool. The SMFM field work data collected in 2018 were used to identify and label the types of clusters generated by the tool. Results of this case study are experimental only and were not meant for operational use in Zambia. They revealed some level of spatial mismatch between the change type polygons generated by the Acacia tool and the ground data. It also was concluded that AGB change alone as a parameter prevents the classification of the different drivers of deforestation, and that a larger set of ground data for calibration might enhance performance and improve results.

114. Zambia's NRSC, as the national remote sensing institution in charge of processing EO data, was particularly interested in the mosaicking tools, Sen1mosaic and Sen2mosaic, and there was substantial engagement during and following training events.

4.5.3 Namibia

115. Namibia joined the SMFM project as the third partner country in April 2019. As a consequence, there was limited time to test and apply the tools. The Namibia Directorate of Forestry used SMFM Biota to generate a forest cover map for the entire country, using forest definition parameters adjusted to the Namibian forest situation. As Namibia did not participate in the 2018 SMFM field data collection campaign, no project-generated data for tool calibration and validation were available. As a consequence, the Namibia team used generic calibration data for southern Africa. The results were assessed and validated against a global data set (Bastin et al. 2017) and compared to other available land cover data sets, such as the ESA Climate Change Initiative and Global Forest Watch.

116. First analysis of the results appears to confirm that the SMFM tool has out-performed global maps. Generally, the results produced from the SMFM tools reveal higher forest cover than the global data sets. In the particular case of Namibia, with its low-biomass savannas and woodlands, more testing and research may be required to fully assess the usability of the tools in this particular context. A proper calibration, using ground data from Namibia instead of the generic calibration data set, also may improve results. Moreover, Namibia began using the two mosaicking tools, sen1mosaic and Sen2mosaic, for land cover mapping, a process that is still ongoing.

4.5.4 Other Countries and Users

117. While project support focused on the three partner countries, several other countries have independently been testing and using some of the SMFM methodologies and tools. In some cases, the original methodologies and tools were adapted to local needs and even developed further. While there is no systematic information on all users, the known users to date include the following:

- The Zimbabwe Forestry Commission used the SMFM Biota tool in February 2019 to prepare a national level deforestation and degradation map.
- The National Carbon Monitoring Centre in Tanzania has shown interest in using the SMFM Biota tool.
- Yale University in Connecticut, United States, tested Biota in Kruger National Park, South Africa, in September 2018, providing important feedback to the development process.
- The SMFM project learned in October 2018 that Biota was tested and used in Haiti as a tool for wood fuel quantification.
- Rwanda is collaborating with RCMRD on the use of Biota.
- The World Agroforestry Centre (ICRAF) in Kenya began testing and using Sen2mosaic in January 2019, following participation at the regional SSKE event in Nairobi in November 2018.
- The National Data Centre of Finland became aware of the SMFM tools in February 2019 and began using Sen2mosaic to produce biweekly data sets for national agencies.
- Taras Shevchenko University of Kyiv, Ukraine, began to test sen2mosaic in February 2019.
- Conservation Biology Institute, Oregon, United States.

4.6 Key Events and Meetings

118. Several events and key meetings have been held during the project period. Aside from the initial kick-off meeting between the World Bank, ESA, and the consultant consortium in December 2016 in Edinburgh, Scotland, other key meetings and events took place in partner countries or within the partner country region. The following list provides an overview of key project events and meetings.

- The consultant team organized **inception meetings** in Lusaka and Maputo in April 2017 to assess the local institutional EO capacity, existing tools, available data, and concrete needs of institutions in terms of dry forest assessment and monitoring. These meetings were attended by various direct stakeholders and other relevant sector institutions:

- The consultant team organized **in-country meetings and workshops** in February 2018 in Mozambique and Zambia to jointly prepare the field data collection campaign, together with the country teams. These were two-day workshops with the working group institutions of each partner country, leading to the elaboration of detailed country work plans and country-specific ToRs for the project implementation period.

- The **field data collection campaign** was carried out in mid-2018, with Zambia completing the planned data collection during June and July 2018 and Mozambique between July and August. Both field campaigns were preceded by three-day training workshops that led to the elaboration of a data collection protocol.
- The main **regional SSKE event** was organized at the World Bank country office in Nairobi, Kenya, in November 2018. This was a three-day workshop covering project progress and outlook, and included technical presentations, examples of partner country tool applications, thematic panel discussions, and visits to regional institutions based in Kenya (ICRAF, RCMRD). The event was attended by partner country institutions, representatives from other dry forest countries in Africa, and international organizations and project representatives.
- The project's first **regional capacity building workshop** took place in March 2019 at Kenya's RCMRD, which was attended by partner country teams from Mozambique and Zambia.
- An **SMFM side event at the annual GFOI plenary** in Maputo, Mozambique, took place in April 2019, attended by representatives from several dry forest countries. The event was used to showcase SMFM EO methodologies and prototype tools, using live demonstrations, and to contact potential future users of SMFM approaches.
- With the joining of the third SMFM partner country, the team organized a **kick-off meeting in Namibia** on May 20-24, 2019, to introduce the Namibia country team to the project and its developed EO methodologies. The meeting also was used to provide a basic training session and webinar on F-TEP usage.
- A member of the consultant team provided presentations and live demonstrations of SMFM EO tools in May 2019 at a **World Bank internal presentation** in Washington, D.C. on May 29, 2019. The tool demonstrations were followed by a day of separate meetings with World Bank team leaders and remote sensing units on May 30, 2019.
- A **second regional capacity building workshop** was again held at the RCMRD in Nairobi, Kenya, in August 2019, participated by partner countries, this time including the Namibia country team.

5. KNOWLEDGE SHARING WITH GLOBAL COMMUNITY OF PRACTICE

119. In June 2018, the project designed and set-up a dedicated SMFM project website as a platform and communication channel to share information about the project, its approaches and the tools under development. The website provides details on the EO methodologies; provides access to tool directories; allows for the download of reports, documents and presentations; and provides links to related research and other relevant sources of information.[10]

120. The SMFM team presented the status of development of the SMFM tools at a Forests Monitoring Side Event within the Data.Space 2018 conference in Glasgow on February 1-2, 2018, to an audience that included government agencies (e.g., UK Department for International Development), the private sector, and academia. The SMFM project work is of relevance to the UK Space Agency's Forests 2020 project. At the same event, the ESA Head of the Copernicus Ground Segment and Data Management presented ESA's DIAS platforms.

121. In October 2018, a joint video conference was held between the World Bank Task Leader, Consultant team, and representatives of the NASA SERVIR project and RCMRD in Kenya to learn about SERVIR's main activities and to identify possible tie points for a later exchange of information and knowledge. Contact with the SERVIR project was further strengthened during the SMFM side event at the GFOI plenary in February 2019, where SERVIR presented project publications.

5.1 South-South Knowledge Exchange; Global Engagement

122. The regional SMFM project workshop in Nairobi, Kenya, on November 19–21, 2018, was one of the major SSKE activities for the exchange and sharing of experiences and knowledge, not only among project partner countries but also with representatives and stakeholders of other potentially relevant dry forest countries (Figure 5.1). The event was hosted at the World Bank office in Nairobi and was attended by the following countries and institutions:

- Mozambique: FNDS
- Zambia: ZFD, NRSC
- Kenya: RCMRD, ICRAF, and Kenya Forest Service
- Burkina Faso: Ministry of Environment
- Ethiopia: Forestry Administration

123. Other participants included representatives from the World Bank, ESA, Embassy of Finland, Conservation International, and the UK Forests 2020 project. Main conclusions drawn from the discussions and exchange showed an overall consensus on the importance of modern EO technologies in the forestry sector on a global basis. It was stressed that technology projects have to gear up from piloting methodologies to full-scale national applications. It also became significantly clear, however, that technological progress must be guided and supported by a sound policy and legislation framework, and that institutional development is required in most tropical dry forest countries. Another important outcome of the event was to identify the RCMRD as a suitable hub for regional capacity building. Subsequently, two training workshops on the use of SMFM EO tools were organized at RCMRD during 2019.

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[10] The website will be operational until June 2021.

Figure 5.1 Regional South-South Knowledge Exchange Event in Nairobi, Kenya

Photo credit: SMFM project team

124. Involvement of RCMRD as a regional platform for capacity building, training, and knowledge provided a number of advantages to the SMFM project. Instead of conducting separate country-level trainings, participants from the SMFM countries could be brought together at RCMRD to simultaneously learn and to share experience and knowledge. In addition, RCMRD's role is to provide knowledge and capacity to its member countries in Eastern and Southern Africa, thus leveraging the project's SSKE efforts in disseminating the methodologies and tools. In addition, RCMRD functions as the regional hub for the NASA SERVIR project.

125. The SMFM project attended the annual GFOI plenary held in Maputo, Mozambique, on April 8–11, 2019. This was considered a first major step toward addressing the global level and presenting the project and EO tools to the wider community of practice. On the final day of the plenary, the project organized a side event, during which the team presented the project and showcased the SMFM EO tools and their use on the F-TEP platform. As the plenary was hosted in Mozambique, the partner country used the occasion to present its ongoing work with SMFM tools sen2mosaic and Biota on the annual monitoring of deforestation. Mozambique has built its own methodology for identifying deforestation probability classes that builds upon Biota. The side event and the entire plenary meetings enabled direct discussions with participants from Angola, Côte d'Ivoire, Nepal, Kenya, Cambodia, Cameroon, and Mexico. (Figure 5.2).

126. NASA's SERVIR project presented its new Synthetic Aperture Radar (SAR) handbook to the audience at the SMFM side event as a part of earlier initiated exchange and collaboration. Following the GFOI plenary, the SMFM project registered the EO tools at the GFOI global registry of forest monitoring tools, which helps provide access to SMFM tools by interested users. In addition, the SMFM project and its country work in Mozambique and Zambia is presented under the inventory of activities on the GFOI website, www.gfoi.org.

127. The SMFM project was mentioned in an abstract produced by the F-TEP team, entitled "Forestry TEP Enables EO Service Providers to Boost Their Operations," where the SMFM project and its tools were mentioned as one of the early adopters of F-TEP platform services. The abstract was presented at the ESA Phi-week in September 2019 under the research infrastructure topic.

Figure 5.2 Satellite Monitoring for Forest Management: Side Event at the Global Forest Observing Initiative Plenary, 2019

Photo credit: *SMFM project team*

5.2 Tool Delivery and Documentation

128. All SMFM EO tools are available as open source code from dedicated repositories on Bitbucket (https://bitbucket.org). Direct links from the project web site (www.smfm-project.com) point directly to the respective GitHub tool repositories. The Sen1mosaic and Sen2mosaic tools are also openly accessible on F-TEP, along with the Biota tool for users registered on this platform. In addition, all tools have been packaged in a single, self-contained docker file that includes all required code and libraries for installation on different operating system environments. The docker installation process can be accessed at https://hub.docker.com/r/smfmproject/docker.

The following online locations provide access to the tool code:

- Sen1mosaic: https://bitbucket.org/sambowers/sen1mosaic
- Sen2mosaic: https://bitbucket.org/sambowers/sen2mosaic
- Biota: https://bitbucket.org/sambowers/biota
- Deforest: https://bitbucket.org/sambowers/deforest
- Acacia: https://bitbucket.org/sambowers/acacia

129. Following interest generated at the GFOI SMFM side event, discussions were initiated with FAO on hosting the SMFM EO tools on FAO's SEPAL platform. This would require a partial rewrite of the tools to provide a direct installation with all required dependencies or, alternatively, conversion of worked tool examples in Jupyter notebook format. At the time of writing the final report [October, 2020], the FAO SEPAL team is conducting tests on integrating the SMFM tools. First tests have shown that Biota works properly. The Deforest tool also will be integrated entirely, while Sen1mosiac and sen2mosaic may be merged into existing SEPAL routines that perform preprocessing and mosaicking. Initially, all tools will be in command-line version only but, gradually, widgets may be added to make the tool interfaces more user friendly. SMFM tool Acacia will not be integrated, as it is still at the experimental stage.

130. All tools come with specific documentation in the form of comments and explanations inserted directly into the source code. This type of documentation is available together with the source code in the tool repositories. There is separate online documentation available for each SMFM tool at https://readthedocs.org. These documents cover (a) installation and setup, (b) use of the command line, (c) GUI (Biota and Acacia), and (d) worked examples. This documentation is kept alive for the time of the project and is updated whenever changes are made to the tools.

The following online locations provide access to the tool documentation:

- Sen1mosaic: https://sen1mosaic.readthedocs.io/en/latest
- sen2mosaic: https://sen2mosaic.readthedocs.io/en/latest
- Biota: https://biota.readthedocs.io/en/latest
- Deforest: https://deforest.readthedocs.io/en/latest
- Acacia: https://readthedocs.org/projects/acacia2/downloads/pdf/latest/

131. Aside from online documentation, the project produced manuals for each of the tools in the form of WP documents. These have been produced as more static PDF versions. In addition to this, there are separate specific sections for each EO tool in the SMFM GPG document. Several other documents have been produced by the SMFM project. Key reports and manuals of the SMFM project are the following:

- Project Inception Report
- Satellite EO Design Report
- Work Plan for Country Implementation and Validation Activities: Mozambique/Zambia
- Working Practice - Sen1mosaic Tool
- Working Practice - sen2mosaic Tool
- Working Practice - Biota; Annual Forest Change Mapping
- Working Practice - Deforest Tool
- Working Practice - Acacia Tool; Classifying Forest Change Properties
- Good Practice Guidance - Satellite-Based Assessment and Monitoring of Tropical Dry Forests
- Validation Compliance Report
- Final Report

6. LESSONS LEARNED

132. Given the novel character of much of the methodology development done under the project, there is a number of important conclusions and lessons to be drawn. Interesting insights have certainly been gained when exploring various avenues during technical development, even though some needed to be dropped. Other avenues, however, proved more successful and helped to move forward the potentials of EO methodologies in dry forest assessment.

133. Project implementation arrangements, with partner countries working relatively independently with mostly remote support and using online communication and collaboration techniques, led to lessons learned that could be useful in the delivery of similar projects in the future. The SMFM project took longer than expected to develop its EO methodologies and tools. To some extent, this can be attributed to the implementation arrangements, although other external factors played a role. The following sections provide a summary view of the most important lessons learned under the SMFM project.

6.1 Project Implementation

134. The global dimension of the project was not fully reflected in the actual distribution of project partner countries. The country selection was largely based on opportunities provided by other World Bank operations and all three partner countries are neighboring countries located in southern Africa. Aside from making project implementation easier from a logistical point of view, on the one hand, this brought the advantage of being able to use one single tool calibration across all three countries. On the other hand, however, it took away the opportunity of testing the tools in tropical dry forest scenarios that differ from southern African forest and woodlands. If project partner countries had been spread across continents – for instance, Africa, Asia, and the Americas – this would have helped to understand the potentials and limits of tool performance under various conditions. Also, project presence on each of these continents could have triggered additional interest and tool pick-up by other countries in the respective region. At the same time, it would have required increasing the number of countries to fully capture the diversity within each region.

135. Selection of implementing institutions within project partner countries was not always straightforward. The SMFM ToR suggested national forestry departments as implementing institutions. This implied that forestry officers would be capable of codeveloping and ultimately operating the EO tools. The reality in the selected project partner countries was different. In Mozambique, the forestry department, DINAF, did not have full capacity in key concepts for large-scale geospatial data processing', whereas FNDS, an institution not officially mandated with forestry, had more suitable personnel. The selection of FNDS as main implementer led to some interinstitutional conflict. In Zambia, the situation was similar, although in comparison, collaboration between the Forestry Department and the National Remote Sensing Centre was good. In Namibia, finally, the Department of Forestry did have a specialized and capable GIS and remote sensing unit that was naturally tasked with project implementation. Even if the new tools are increasingly user friendly, the project experience has shown that specialist skills are required to fully understand and exploit the potentials of the SMFM EO tools, and that remote sensing specialists are clearly better placed to operate the tools than forestry officers with no prior experience in operating EO data.

136. The way the project implementation was designed required the consultant team to assist the partner country teams mostly by remote means. While this was generally possible, given the information technology character of the tool development, it was at times perceived inefficient and impacted on the time used for developing the tools and, ultimately, the duration of the project. Videoconferencing can go a long way but agreeing with several institutions in a country on a date and time slot for a video conference can take substantial time and effort, even more so when a video conference was supposed to include participants from more than one country. The same applies to the availability of key persons. During the few occasions when the consultant team was in-country, key staff was fully available for a number of consecutive days and, on these occasions, the project made good progress. A similar intensity is not reached through remote assistance via video calls or emails. Therefore, longer periods of on-site support with key partner country personnel made available could have yielded better and faster results.

137. From the onset, the project was supposed to work with three partner countries; two countries playing a role in codevelopment and tool testing, and the third to test the independent application of the tools without prior involvement in development and training. The initial project partner countries, Mozambique and Zambia, were preselected at project inception, with the third country to be decided during project implementation. The main criteria for the selection of a suitable third partner country was—aside from a substantial coverage of tropical dry forest—an existing World Bank engagement. Initially, it was envisaged to select a country on another continent, such as Asia or the Americas. When Namibia was finally confirmed in April 2019 as the third project partner country, the project was already well into its final year of implementation, leaving little time for direct engagement and assistance. While the Namibian partner institution had good basic knowledge in remote sensing, it appeared that some SMFM tool-related training was required for the country team to apply the tools. The World Bank agreed to limited training input that was provided during the in-country kick-off mission. Namibia then also participated in the second regional SMFM tool training event at RCMRD in Kenya.

6.2 Required Capacity

138. Contrary to SMFM ToR expectations, the developed EO methodologies are neither suited for basic users nor for non-IT skilled forester officers. Technologies such as radar remote sensing and dense time series; the programming of application code and scripts; and even the use of cloud processing platforms require relatively advanced skills. To exploit fully the potentials of modern EO data and methodologies in complex dry forest environments requires users to understand, adjust, and calibrate the process correctly. Entirely packaged "black-box applications" that allow nonspecialist users to generate meaningful results from "pressing a single button" are unlikely to emerge in the near future. Even the presently available EO cloud processing platforms are far from being "one click" applications. For the time being, this kind of methodology is better placed with remote sensing specialists than with nonspecialist forester officers.

139. Another key lesson learned when working with partner country institutions is that even within specialized remote sensing teams, skills in Linux and Python are yet to be well developed. At least basic Linux skills are required to calibrate and operate the tools. Skills in Python would be required to adjust and customize the tool code, if required for national application. While this was not part of the project's activities, it became obvious that at least basic training in both had to be provided to the country teams. As a conclusion, the lack of Linux and Python skills may be similar in other tropical countries, potentially affecting uptake and use of the tools.

140. One important prerequisite for making full use of the SMFM Biota tool is the capacity to develop a radar backscatter model for local vegetation and dry forest types from L-band radar data for local tool calibration. This would require a network of permanent sample plots for AGB estimation, well distributed across different forest types and situations, and access to allometric equations. Other tropical dry forest countries might require assistance to set up a network of suitable plots and to derive the backscatter/AGB equation from the collected data.

6.3 Readiness of Earth Observation Platforms

141. Most EO cloud processing platforms are still under development. The F-TEP platform was under development until the end of 2019 and therefore basically for the entire project period. This repeatedly led to breaking of the deployed tools requiring, yet again, adjustments to the already functioning tools. F-TEP platform offerings and services continue to emerge and are constantly evolving. Under these conditions, it will be difficult to keep the tools functioning after the project expires.

142. Some features required for the SMFM tools are yet to be built into the platform services. F-TEP is, by design, not suitable for the SMFM Deforest dense time series analysis. Deforest, however, is the SMFM methodology that would benefit most from cloud processing and direct access to data repositories. At the end of the project, the partner countries were generally convinced of the benefits of cloud processing, but the main lesson was that the services are insufficiently flexible and not yet ready for operational use. Resulting from the fact that the cloud processing services are still developing, uncertainty persists around the actual cost implications an operation at national scale of forest assessment and monitoring would have for a dry forest country. This is a an issue that is yet unresolved and can understandably prevent tropical dry forest countries from relying on EO cloud processing platforms.

6.4 Limitations to Dry Forest Monitoring

143. Despite the technical progress made under the SMFM project, there are still underlying challenges that are not easy to address or cannot be addressed by technology alone. These relate, in the first place, to the biophysical characteristics, complexity, and heterogeneousness of dry forest landscapes themselves. Open forest and vegetation types are generally difficult to detect or classify with EO data, as ground or soil signals unavoidably intermix with vegetation signals. This underlying limitation cannot be resolved by, for instance, cloud processing or through the use of dense time series. With ever increasing spatial and spectral resolution of EO data, however, these difficulties are likely to diminish in the future.

144. As already described in the project background section (Section 1), there is still no widely accepted or applied definition of tropical dry forests, making assessment and monitoring of dry forests a particular challenge. Furthermore, the concept of "dry forest degradation" is still vague. It can be either understood as a structural change in vegetation cover or in a forest stand, or it can be seen as the loss of its capacity to provide a particular environmental or livelihood service. As a way out of this uncertainty, dry forest monitoring approaches—including the SMFM ones—are using AGB as a proxy for dry forest condition, since AGB is detectable by EO methods and can interpret a reduction of AGB as a degradation of dry forests. This is based on the assumption that degradation can actually be captured by AGB or, in other words, that AGB is a good measure for dry forest condition and change. To be able to measure AGB "from space" (i.e., from EO data), the relationship between satellite data and actual AGB on the ground needs to be quantified.

145. Most tropical dry forest countries do not have such a relationship or equation at hand. It would require a network of sample plots (ideally permanent sample plots), large enough (> 0.5 ha) and sufficiently distributed across different dry forest types and conditions on which actual AGB can be established using allometric equations. These AGB values could then be analyzed against the radar backscatter values in the EO data (e.g., L-band radar), as in the case of the SMFM Biota tool, to establish the AGB equation or model required to calibrate the tool. If such data are not available or a network of plots cannot be established and maintained, more assumptions or approximations are necessary (e.g., literature values from other, similar dry forest types) making the results less reliable. The key lesson, therefore, is that dry forest countries and users of the SMFM tools – or any other EO tools – have to understand that there are upstream tasks to accomplish before making full use of SMFM tool potentiality. Ideally, countries would attempt to establish their own AGB/backscatter model.

146. Another limitation lies in the availability of high-frequency L-band radar data that are accessible to tropical dry forest countries. Annual ALOS PALSAR mosaics are freely available and present a good basis for national forest monitoring efforts. At the time they are released, however, the mosaics are at least one or two years old and are composed of imagery from various dates, making dry forest monitoring at a particular date or season rather difficult. Until new L-band radar missions come online and are freely available, this will continue to limit the potential of this monitoring methodology.

147. Attempting to use EO data to identify the drivers behind deforestation or degradation in dry forest has made it clear that substantial limitations still exist. The SMFM project examined physical and spectral parameters of deforestation events to try to identify common characteristics that may be related to particular drivers or resource use activities. This yielded only limited results. In reality, there is often a combination or a sequence of drivers that cause degradation or deforestation, which are not easily separable. For instance, initial degradation from fuel wood cutting can lead to more substantial degradation from charcoal production and, finally, to deforestation through small-scale farming in the wake of charcoal burning. The key lesson to be drawn is that it actually may not be possible at all to reliably identify drivers of degradation and deforestation from EO data alone, thus implicating the potential success of methodologies such as the SMFM Acacia.

7. THE WAY FORWARD

148. The following sections provide general recommendations of a more technical nature, addressed to the community of forest monitoring practitioners and others, including donors for further support to tropical dry forest countries.

7.1 Opportunities for Further Tool Development and Hosting

149. The SMFM tools should to be hosted on a widely recognized and utilized platform that is fully operational and easily accessible to tropical dry forest countries. The FAO SEPAL platform was already known to or used by SMFM partner countries prior to the project. It is thus the ideal long-term location for the SMFM tools, and the World Bank—assisted by the SMFM Consultant team—has engaged with FAO on integrating the SMFM tools into SEPAL.

150. The SMFM project has developed the EO tools as standalone applications capable of performing specific tasks or a combination of tasks. This does not always respond to the concrete needs of a user. While the possibility exists to modify and customize the tools, future development could include tailoring tool modules rather than full applications. Users could then pick the modules they need and integrate these into existing workflows or combine them to create new ones. While it is unlikely that “single click” or “black box” applications can be developed in the near future, this should be an overall objective. Moving toward user-friendly interfaces with little or no command-line actions also would enable experienced nonspecialist forestry staff to use the applications.

151. At present, L-band radar data are the most suitable EO data for tropical dry forest assessment and monitoring. New radar satellite missions are coming up from a number of operators (including, potentially, the ESA Radar Observing System for Europe at L-band (ROSE-L) mission). These missions will expand the number of data sources and improve the availability of L-band radar data. Future tool development should include the option to ingest and process from these new data sources and formats.

7.2 Application of Tools by Other Countries

152. All SMFM products, materials, and documents have been only produced in the English language. Two of the SMFM partner countries are English-speaking, while one is lusophone (despite specialists and users in Mozambique being well versed in English). To make the SMFM outputs and tools more accessible to dry forest countries in West Africa, French-language support and translation of at least key documents and training materials should be envisaged. Similarly, a translation into Spanish could help promote tool use in Latin America.

153. National forestry agencies and remote sensing units in tropical dry forest countries should envisage providing training to their personnel to establish at least basic knowledge in Linux command line and Python programming. While these skills are not required when off-the-shelf commercial software is used, it opens a wide array of possibilities to make use of highly specialized open-source tools and applications that can then be customized and domesticated to respond to concrete national-level requirements.

154. The project focused, by design, on technical tool development, "proof of concept", and the identification of necessary technical skills. This is a necessary, yet not alone, adequate step in mainstreaming novel EO technologies in forest management, not to mention ensuring improved forest management. Further research and analytical work still are needed to understand the costs of using the new tools, how access to high-frequency satellite data can be incorporated into the decision-making of forest agencies and the formulation of forest policy. It also is likely that—despite the relatively high skills required—using EO will be increasingly done in-house by trained specialists in forest agencies rather than external experts and consultants. How that changes these agencies is yet to be seen.

7.3 Potential for Further Support

155. Experience from the SMFM project has shown that availability and quality of tool calibration data in dry forest countries is problematic. To promote the SMFM and other EO methodologies and tools to a wider group of dry forest countries outside the geographic scope of the SMFM project (i.e., Southern Africa), development partners should provide targeted support to interested tropical dry forest countries by establishing a suitable network of control points and sample plots (ideally networks of permanent sample plots), collecting AGB data in various dry forest conditions, and developing a locally valid AGB/backscatter model as a prerequisite to making full use of tool potentials. Ultimately, this could lead to the establishment of a library of AGB/backscatter calibration data from dry forest countries on different continents.

156. Testing of the SMFM tools on the ESA F-TEP platform confirmed the benefit of having direct access to the Sentinel data archives and of using a simple web-based user interface. Using F-TEP during the SMFM trainings convinced participants of the usefulness of EO cloud processing services. Unclear cost implications, however, may have potential users refrain from relying on this kind of service. ESA, therefore, should consider offering low-cost access to its F-TEP platform services for interested dry forest countries in the developing world to assist these in overcoming acute computing limitations when attempting to produce national-level map products from EO data.

157. SMFM partner countries consider the dense time series methodology a powerful and potentially useful approach. So far, available time series of Sentinel-2 data remain too short to fully exploit this potential and further testing by dry forest countries over an extended period appears necessary. Without adequate support, however, this may not take place. Further support, therefore, could be provided to assist one or more interested countries in further testing and applying the Deforest methodology. Results (i.e., early warning signals of deforestation) could be used and evaluated for practicability by, for instance, forestry departments and forestry law enforcement agencies, even without full-scale scientific validation of the results.

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