Interactive community-based tropical forest monitoring using emerging technologies

Arun Kumar Pratihast

Thesis committee

Promotor
Prof. Dr M. Herold
Professor of the Laboratory of Geo-information Science and Remote Sensing
Wageningen University

Co-promotors
Prof. Dr L. Ribbe
Professor of the Institute for Technology & Resources Management in the Tropics & Subtropics (ITT), TH Köln - University of Applied Sciences, Cologne, Germany

Dr S. de Bruin
Assistant Professor, Laboratory of Geo-information Science and Remote Sensing
Wageningen University

Dr V. Avitabile
Post Doc, Laboratory of Geo-information Science and Remote Sensing
Wageningen University

Other members
Prof. Dr F.J.J.M. Bongers, Wageningen University
Prof. Dr P.Y. Georgiadou, University of Twente, The Netherlands
Dr S. Fritz, International Institute for Applied System Analysis, Laxenburg, Austria
Dr M. Boissiere, Center for International Forestry Research, Addis Ababa, Ethiopia

This research was conducted under the auspices of the C.T. de Wit Graduate School of Production Ecology & Resource Conservation (PE&RC)

Interactive community-based tropical forest monitoring using emerging technologies

Arun Kumar Pratihast

Thesis
submitted in fulfilment of the requirements for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus
Prof. Dr A.P.J. Mol
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Monday 12 October 2015
at 4 p.m. in the Aula.

Arun Kumar Pratihast
Interactive community-based tropical forest monitoring
using emerging technologies
164 pages

PhD thesis, Wageningen University, Wageningen, NL (2015)
With references, with summaries in English and Dutch

ISBN 978-94-6257-478-6

Table of contents

Chapter

1

Introduction

1.1. Background

About one third of the earth's land surface is covered by forests and almost half of the forest area is located in the tropics (Gullison et al. 2007; Olson et al. 2001). More than 300 million people are directly dependent on these forests and their resources (Sunderlin et al. 2005). Tropical forests offer several ecological, social and economic services to humankind (Bonan 2008; Sunderlin et al. 2005) and provide shelter for a high proportion of global biodiversity. Additionally, tropical forests play critical roles in the regulation of the world's climate through exchanges of energy, water, carbon dioxide (CO_2) and other chemicals (Bonan 2008). During the last decade the loss of tropical forests has increased significantly with a rate of approximately 2.1×10^5 hectares per year (Hansen et al. 2013). These losses are mainly due to deforestation and forest degradation, and are recognised as a major cause of recent increases in anthropogenic greenhouse gases in the atmosphere. The latter influences various aspects of the Earth ecosystems, including global warming and changes in the world's hydrological cycle (Bonan 2008; Hansen et al. 2013).

To address this issue, the United Nations Framework Convention on Climate Change (UNFCCC) has proposed a new international carbon trade mechanism, named Reducing Emissions from Deforestation and Degradation (REDD+), in the developing countries to reduce global greenhouse gases (Sanz-Sanchez et al. 2013; UNFCCC 2009). For the implementation of such mechanism, various approaches (Herold and Skutsch 2011; Olander et al. 2011) have been applied in different countries, which involve effective monitoring of forests. Recent approaches that include the participation of local communities in forest monitoring and management have offered several benefits, which include (Conrad and Hilchey 2011; Larrazábal et al. 2012):

1) *Using local knowledge:* Local communities have in-depth understanding of local forests. They can provide access to indigenous knowledge systems which can be used for sustainable forest management.

2) *Communities are "on the spot":* Generally, communities have access to the areas to be monitored, and can perform regular field visits with less time and use of fewer resources, as compared to surveys carried out by external experts.

3) *Involvement of communities:* Effective implementation of approaches related to forest monitoring and management needs engagement of the local communities, which increases their sense of ownership and responsibility. Active involvement of communities in monitoring process may promote long-term sustainability of the REDD+ program.

During the last few decades, more than 200 million hectares of forest in 60 countries have been transferred to some form of community forest management regime (Agrawal et al. 2008; Sunderlin et al. 2008). Several studies have shown that forest monitoring and management activities carried out by the local people, communities and non-experts not only provide an additional level of data and information, but also promote the sustainability of local implementation plans at a wider level (Garcia and Lescuyer 2008; Whitelaw et al. 2003). Hence, direct involvement of communities have a high potential in effective monitoring and management of forests and usage of related resources.

The potential needs and benefits to engage local communities and indigenous groups in forest monitoring and management have been widely acknowledged in literatures (Danielsen et al. 2005; Danielsen et al. 2011; Fry 2011; Lawlor et al. 2013; Skutsch and Solis 2011; Skutsch et al. 2014). Despite these potentials, the effective implementation of community-based forest monitoring system is currently lacking due to two reasons: 1) the roles, responsibilities and (national) priorities for integrating community-based monitoring in national forest monitoring systems is unclear and 2) tools that can support local communities to explore opportunities and facilitate forest monitoring are still scarce.

This thesis addresses these two issues in an integrated nature by proposing technical solutions (computer and geo-information science) and assessing the capacities and needs of communities in the developing countries in a REDD+ implementation and forest monitoring context.

This chapter is further structured as follows: Section 1.2 provides UNFCCC context, requirements and existing methods for tropical forest monitoring. Section 1.3 describes the emerging role of mobile technology in tropical forest monitoring. Section 1.4 outlines the research gap and research questions of this work. Finally, Section 1.5 presents the outline of this thesis and potential future research activities.

1.2. UNFCCC context and requirements

REDD+ is a recent UNFCCC endorsed mechanism aiming to mitigate global climate change. The REDD+ mechanism includes reducing emissions from deforestation and forest degradation, forest enhancement, sustainable forest management and conservation (Danielsen et al. 2011; UNFCCC 2010a). Along with an important step towards reducing emissions from greenhouse gases, REDD+ also includes considerations for co-benefits, safeguards for biodiversity protection, sustainable livelihoods for local communities and the potential role of communities in monitoring efforts (Danielsen et al. 2011; Sanz-Sanchez et al. 2013; UNFCCC 2010a, 2013).

Nations participating in the REDD+ mechanism are required to establish a reliable, transparent and credible system of Measuring, Reporting and Verifying (MRV) changes in forest areas and forest carbon stocks (Herold and Skutsch 2008). Such nations should identify the drivers of deforestation and forest degradation which cause the forest carbon changes and should establish reference levels (Hosonuma et al. 2012; Umemiya et al. 2010). The national capacities for MRV should be developed in order to fill the gap between the existing national forest monitoring system and the requirements of the REDD+ MRV system (GOFC-GOLD 2014; Romijn et al. 2012). Each nation should establish an effective, efficient and sustainable institutional and implementation framework. The basic requirements of a national framework for MRV perspective are:

1) Coordination: Each nation should establish high-level coordination and cooperation mechanisms linking forest carbon MRV and national policy for REDD+. Furthermore, there should be specific roles and responsibilities for all other monitoring units (e.g., subnational, local level) (Kashwan and Holahan 2014; Wertz-Kanounnikoff and Angelsen 2009).

2) Measuring and monitoring: It is essential for each nation to develop a protocol and technical guidelines for acquiring and analysing different types of forest carbon and change data on national and subnational levels (DeVries and Herold 2013).

3) Reporting: Each nation should follow the Intergovernmental Panel on Climate Change (IPCC) Good Practice Guidelines and Guidance for reporting at the international level (IPCC 2006).

4) Verification: Verification is obligatory for the long-term effectiveness of REDD+ actions on different levels. It should be done by an independent body (Joseph et al. 2013).

Countries participating in REDD+ are requested to develop and implement efficient approaches to estimate their emissions (DeFries et al. 2007; Ramankutty et al. 2007). A simplified approach for calculating carbon emissions is as follows (GOFC-GOLD 2014; IPCC 2006):

$$\text{Emission} = \Sigma\ (\text{Activity x Emission factor}) \qquad (1.1)$$

Here, an activity is defined as the magnitude of human activity resulting in emissions or removals. In case of deforestation, forestation, forest degradation and forest enhancements, the activity refers to a forest area change (generally measured in hectares) and an emission factor is defined as the emission or removal of greenhouse gases per unit area (generally expressed in tons of CO_2 equivalents per hectare) (IPCC 2006). This factor is derived from assessments of the changes in carbon stocks in various forest carbon pools. The IPCC provides a three ‘tier’ approach for the monitoring and reporting of activity data and emission factor. Tier 1 estimates are based on coarse resolution land area data (pertaining to land use and land use change) paired with global default carbon stock values for each land category. Tier 2 expands on Tier 1 and provides estimates based on country specific carbon stock data and higher resolution land area data. Finally, Tier 3 requires more complete and accurate estimates, based on high resolution land area data and calculation of locally specific carbon stock data, including process based models for temporal variability and dynamics between carbon pools estimation and reporting (IPCC 2006). Moving from Tier 1 to Tier 3 increases the accuracy and precision of the estimates, but also increases the complexity and the costs of monitoring.

1.2.1. Earth observations for tropical forest monitoring

Since 1972, remote sensing technologies are constantly evolving in terms of available satellite and data acquisition sensors for earth observations (De Sy et al. 2012). Notably, several remote sensing satellites such as the Moderate Resolution Imaging Spectroradiometer (MODIS) and Landsat offer opportunities for forest monitoring by providing timely and consistent spatial data (Achard et al. 2010; De Sy et al. 2012; GOFC-GOLD 2014). In addition, the use of commercial satellites (e.g., RapidEye, SPOT) in forest monitoring application has increased considerably in recent years. These satellites are currently considered as the principal data sources to calculate forest area change, rates of deforestation; and to establish baselines for national forest area change databases (Achard et al. 2010; De Sy et al. 2012; DeVries and Herold 2013). Table 1.1 provides a synthesis of the utility of remote sensing sensors at multiple resolutions for forest monitoring.

Table 1.1 Utility of earth observation sensors at multiple resolutions for forest monitoring [adapted from (GOFC-GOLD 2014)].

Sensor resolution	**Minimum mapping unit**	**Cost**	**Utility for monitoring**
Course resolution (250-1000 m)	10-100 ha	Free or low	Consistent pan-tropical annual monitoring to identify large clearings and locate hotspots for further analysis with medium resolution data
Medium resolution (10-60 m)	0.5-5 ha	Free and low	Primary tool to map deforestation and estimate area change
High resolution (< 5 m)	< 0.1 ha	High to very high ($2 – 30 per km^2)	Used for validation of results from coarser resolution analysis and training of algorithms

Deforestation is defined as the conversion of forested land to non-forested land (UNFCCC 2010a). The availability of dense remote sensing time-series data and analysis methods are considered beneficial at national scales to monitor deforestation (Bocher et al. 2012; Li et al. 2015; Wulder et al. 2012). In particular, USGS open data policies and advancements of big data processing environments such as Google Earth Engine (https://earthengine.google.org/) have enabled researchers to process large amounts of remote sensing data and detect the deforestation at a global scale (Hansen et al. 2013). Recently, efforts have been made to establish an operational wall-to-wall near real-time (NRT) forest monitoring system (Wheeler et al. 2014). These efforts include the use of optical remote sensing satellites such as MODIS and Landsat (Anderson et al. 2005; Lynch et al. 2013; Shimabukuro et al. 2007; Xin et al. 2013). NRT systems contribute to better forest management allowing governments and local stakeholders to take action to avoid or to reduce illegal activities and enhance the transparency in the use of forest resources.

Optical remote sensing data are known to have limitations to detect low level forest degradation (Achard et al. 2010; Skutsch et al. 2011; Vargas et al. 2013). These degradation processes generally take place underneath the forest canopy and are not detectable using optical remote sensing data until canopy openings begin to appear. High resolution satellite imagery such as Ikonos, Quick Bird and RapidEye are able to small openings (e.g., 1 m) and therefore can better detect low-intensity forest degradation (Dons et al. 2015; GOFC-GOLD 2014). However, acquisition cost, cloud cover, seasonality and the limited temporal resolution of these observations compared to the processes to be observed limit their application in the tropics. Synthetic Aperture Radar satellites can alleviate the substantial limitations of optical data in persistently cloudy parts of the tropics but these satellites are currently not operational for tropical forest monitoring over large areas (Reiche 2015). Furthermore, enhancing the interpretation of these remote sensing analysis require substantial ground verification and validation (Strahler et al. 2006).

1.2.2. Community-based monitoring

About 22% of the world's forest area is under community forest management programs (White and Martin 2002). The engagement and participation of local communities and indigenous people within the design and implementation of forest monitoring process have been a key focus of the UNFCCC negotiation process (UNFCCC 2010a, 2013).

Community-based monitoring (CBM) has been described in literatures using several terms such as citizen science, crowdsourcing or volunteered geographic information and participatory monitoring (Connors et al. 2012; Conrad and Hilchey 2011; Danielsen et al. 2005; Danielsen et al. 2011; Fry 2011; Schepaschenko et al. 2015). Danielson et al. (2009) have identified five categories of CBM schemes: 1) externally driven, professionally executed monitoring, 2) externally driven monitoring with local data collectors, 3) collaborative monitoring with external data interpretation, 4) collaborative monitoring with local data interpretation and 5) autonomous local monitoring. Within the REDD+ contexts, countries should identify the appropriate monitoring scheme and provide adequate financial and human resource over a suitable time frame for the effective implementation of the chosen scheme.

The common goal of CBM is to engage local communities in the collection and even interpretation of forest monitoring data. Community collected forest monitoring data can be broadly classified in two main categories: 1) forest carbon stock measurements for emission factors and 2) forest change monitoring for activity data. Results from well-designed forest carbon measurement studies in developing countries like Nepal, Tanzania, Cameroon, India, Mexico and Guyana (Bellfield et al. 2015; Burgess et al. 2010; McCall and Minang 2005; Nagendra et al. 2010; Shrestha et al. 2014; Torres et al. 2015) have demonstrated that datasets acquired by local communities concerning diameter at breast height (DBH) and tree density are comparable to professional measurements, while being cheaper to obtain. Brofeldt el al. (2014) found that the accuracy of these local data sets improve notably over time through repeated measurements.

Few studies (Bellfield et al. 2015; Danielsen et al. 2011; Fry 2011; Skutsch et al. 2011) have demonstrated that CBM can play a useful role for assessing locally driven and small scale forest change activities (deforestation, forest degradation or reforestation). The impacts of these activities are rarely captured accurately in national databases or remote sensing studies (GOFC-GOLD 2014). In these cases, data acquired by communities are often essential and can include reporting on location, time, size, type and proximate drivers of the change events. Furthermore, CBM can also be applied in tracking the change processes and reporting on local REDD+ implementation activities (Skutsch et al. 2011). Thus, while remote sensing techniques are the main tools used at the national level to detect deforestation, local level community data can be an important input to analyse small scale deforestation and low-intensity degradation events. Furthermore, CBM can help to verify remote sensing estimates and to signal new changes even before the remote sensing data have been acquired (Skutsch et al. 2011). The CBM schemes not only leverage effort in data collection (Skutsch and McCall 2012), but also promote public participation to achieve government goals, empowering local communities to improve their livelihoods, establish ‘ownership’ of carbon savings and provide sustainable forest management (Danielsen et al. 2005; Larrazábal et al. 2012). Hence, local participation within monitoring programs holds promises for many developing countries, where forest monitoring data are typically scarce and conservation measures are urgently needed (Skutsch et al. 2014).

1.3. Emerging role of mobile technology

Recently, rapid developments in technology have brought unexpected growth in mobile device access and connectivity around the world. With decreasing prices, an increasing proportion of the world's population can afford a modern mobile device. As shown in Figure 1.1, currently there are more than 5 billion mobile cellular subscriptions with approximately 90 subscriptions per 100 inhabitants in developing countries (I.T.U. 2015). The ubiquity of mobile devices and the increasing wealth of device capabilities such as a global positioning system (GPS) receiver, camera, microphone, data storage and network data transfer are giving rise to a new research domain for human sensors in-situ measurements (Ferster and Coops 2013; Georgiadou et al. 2014).

Several researchers (Aanensen et al. 2009; Ferster and Coops 2013; Goodchild 2007; Parr et al. 2002) have viewed mobile devices as embedded sensors with the potential to take measurements of forest carbon and forest related change activities at the community level mainly for two reasons. Firstly, a mobile device supports mobility allowing community participants to immediately record a measurement. Secondly, the implementation of a mobile based data collection approach has become cost effective and sustainable thanks to the decreasing cost of the devices (I.T.U. 2015). Simple datasets collected with handheld devices such as tree density, DBH, forest changes and human activities affecting forest carbon are the variables that can be efficiently monitored by communities (Skutsch and Ba 2010). Furthermore, the advancement in geospatial technologies such as Web-GIS, spatial database and social media have allowed to better store, map and communicate forest monitoring information with local communities (Diga and Kelleher 2009; Newman et al. 2011). Hence, the combined use of mobile devices and geospatial technologies can significantly enhance the CBM data collection process for tropical forest monitoring.

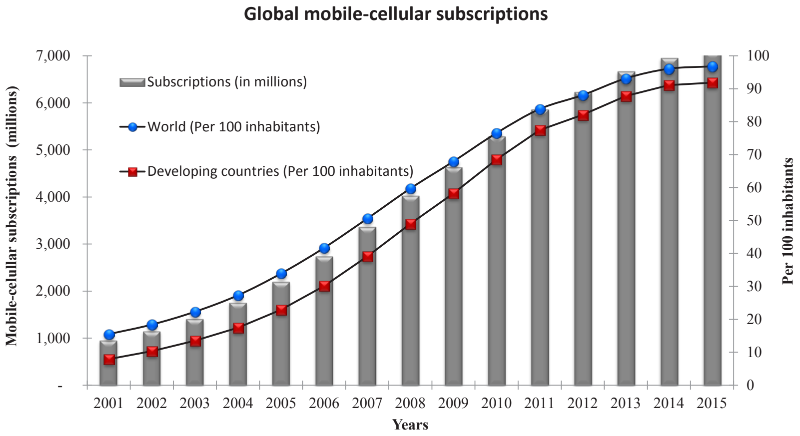


Figure1.1 Global mobile cellular subscriptions [Source: ITU World Telecommunication /ICT Indicators database (I.T.U. 2015)].

1.4. Problem definition

Local participation to forest monitoring activities can provide a substantial contribution to the successful implementation of the REDD+ mechanism. However, the use of locally collected data for forest monitoring purpose is limited due to several reasons.

Firstly, rules for forest monitoring and reporting requirements are decided at international (under the UNFCCC) or national level while CBM experiences have been carried out with local scope. The link between national and local efforts remains largely unknown and unstudied. Secondly, there is a lack of practical and "easy-to-use" tools to stimulate and involve local participation in forest monitoring data collection, transmission and visualization process. Thirdly, the use of locally collected data is limited due to: lack of confidence in the data collection procedure, inconsistent monitoring frequency, limited spatial coverage, variable data quality and lack of trust of data providers (Fry 2011; Hayes and Persha 2010; Larrazábal et al. 2012).

To this end, there is a necessity for systematically developed methods and quality control mechanisms for CBM. The proposed research is based on theoretical and practical perspectives for national MRV and lessons learned from policymakers for REDD+ implementation at local levels. Emerging mobile technologies, such as smartphones and personal digital assistant (PDA) incorporated with user friendly applications, may facilitate data collection for local communities. Furthermore, professional field measurements, medium and high resolution remote sensing satellite images, Web-GIS and social media may offer opportunities to resolve the above mentioned limitations of CBM.

This thesis addresses the shortcomings of CBM by proposing technical solutions (computer and geo-information science) and assessing the capacities and needs of communities in developing countries within a REDD+ and forest monitoring context. The following four research questions are answered in this PhD thesis:

1) What are the potentials to link community-based efforts to the national forest monitoring system?
2) How can information and communication technologies (ICTs) support the automation of the community data collection process for monitoring forest carbon stocks and change activities using modern handheld devices?
3) What is the accuracy and compatibility of community collected data compared to other data (e.g., optical remote sensing and expert field measurements) for quantifying forest carbon stocks and changes?
4) What is a suitable design for an interactive remote sensing and community-based near real-time forest change monitoring system and how can such a system be operationalized?

1.5. Thesis outline

This thesis consists of four main chapters, each addressing one of the research questions presented in section 1.4. The outline of this thesis in terms of chapters is depicted in Figure 1.2.

Chapter 2 addresses research question 1 by reviewing scientific literature to better define the role and technical conditions under which CBM can contribute to national forest monitoring systems. We developed a conceptual framework for linking local and national monitoring system.

Chapter 3 explores research question 2 by designing an integrated system based on mobile devices that streamlines the community-based forest monitoring data collection, transmission and visualization process. The developed system was tested in Tra Bui commune (Quang Nam province, Central Vietnam) where the performance of the local community was evaluated against professional expert measurements and visual analysis of high resolution SPOT images.

Chapter 4 demonstrates research question 3 by assessing the accuracy and complementarity of community collected forest monitoring data (mostly activity data related to forest change) with professional ground measurements and high resolution SPOT and RapidEye satellite images using spatial, temporal and thematic data quality factors.

Chapter 5 addresses research question 4 by describing the design and implementation of an interactive web-based near real-time forest monitoring system and evaluating its usability in the UNESCO Kafa Biosphere Reserve in Southwestern Ethiopia.

Chapter 6 discusses the findings for each research question in a broader context. It also presents the reflection and outlook based on the results obtained in this PhD research and suggestions for further research.

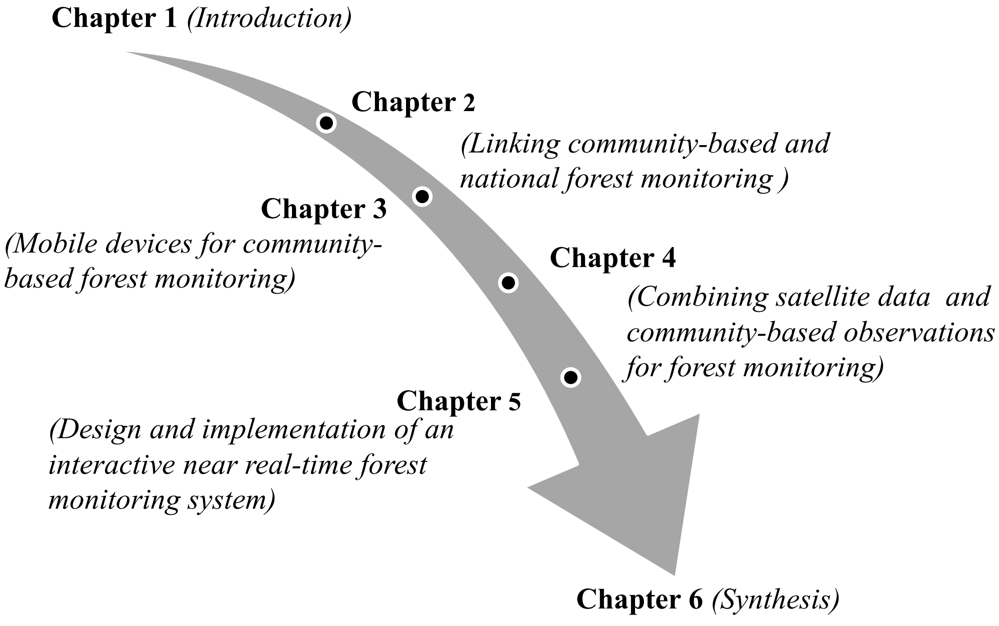


Figure 1.2 Overview of the chapters of this thesis.

Chapter

2

Linking community-based and national REDD+ monitoring: a review of the potential

Arun Kumar Pratihast, Martin Herold, Veronique De Sy, Daniel Murdiyarso and Margaret Skutsch

Published in Carbon Management, Volume 4, Issue 1, February 2013, Pages 91-104

Abstract

Countries participating in REDD+ schemes are required to establish a national monitoring system that keeps track of forest carbon changes over time. Community-based monitoring (CBM) can be useful for tracking locally driven forest change activities and their impacts. In this chapter, we review some of the key issues regarding CBM and options to link CBM and national forest monitoring systems. More specifically, we highlight the importance of local drivers of deforestation and degradation and, thus, the relevance of community involvement in REDD+ implementation and monitoring; we review the scientific literature to better define the role and technical conditions under which CBM can contribute to national level monitoring; we develop a conceptual framework for linking local and national monitoring; and we analyse and synthesize 28 REDD+ country approaches to CBM. Finally, we provide recommendations for integrating CBM data into national monitoring systems.

Keywords: REDD+; MRV; community-based monitoring; remote sensing; carbon stock

2.1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) has demonstrated that tropical deforestation and forest degradation (D&FD) generate a significant contribution to the increase of GHGs in the atmosphere (Solomon et al. 2007). In response to this, the UNFCCC is negotiating the details of a mechanism for REDD and enhancing forest carbon stocks in developing countries (REDD+) (Gullison et al. 2007). Currently, REDD+ includes five key activities, namely: reducing deforestation, reducing degradation, enhancing forest carbon stocks, sustainable management of forests and their conservation (Danielsen et al. 2011; UNFCCC 2010a). In addition to being an important step towards reducing emissions of GHGs, the UNFCCC REDD+ policy proposals include the issues of co-benefits and safeguards for biodiversity protection, sustainable livelihoods for local communities and the potential role of communities in monitoring efforts (Danielsen et al. 2011; UNFCCC 2010a).

Countries wishing to participate in the international REDD+ mechanism will be required to establish a reliable, transparent and credible system of measuring, reporting and verification (MRV) of changes in forest areas and forest carbon stocks by REDD+ activities (Herold and Skutsch 2009). The key to MRV is a consistent monitoring system, which keeps track of these changes over time. Countries are further asked to identify the drivers of D&FD that cause the forest carbon changes, and they should establish reference levels, building upon available data while taking into account national circumstances and the anticipated impact of REDD+ implementation activities (Pearson et al. 2006). Involving communities, local expert groups and civil society in REDD+ related forest monitoring is important, not only in providing additional local data, but also in establishing a mechanism by which the broader public may be engaged in the REDD+ implementation process, particularly given the prospect of compensations and credits for carbon and other environmental services, and the need for benefit sharing (Patenaude et al. 2004; Topp-Jørgensen et al. 2005; UNFCCC 2010a).

A variety of practical experiences from countries such as Nepal, Tanzania, Cameroon, India and Mexico have demonstrated that local communities can play a vital role in forest monitoring and management programs (Cochran 1946; Danielsen et al. 2011; Huang et al. 2011). Community-based monitoring (CBM) is of particular relevance in tracking locally driven change activities and causes of small scale forest degradation; for example, subsistence fuelwood collection, charcoal extraction and grazing in the forest. The impacts of these activities are rarely captured accurately in national inventory databases of developing countries or in commonly available remote sensing data sources (Achard et al. 2012; Ahrends et al. 2010; GOFC-GOLD 2014; Romijn et al. 2012). In these cases, data acquired by local people can include incidences of change events as well as their drivers, targeted ground measurements on forest carbon stock changes, and for tracking and reporting on local REDD+ implementation activities in the long-term (Danielsen et al. 2010; Danielsen et al. 2011; Fry 2011). Several analogous cases of community environmental monitoring have been reported in Canada (Sharpe and Conrad 2006; Whitelaw et al. 2003), the USA (Keough and Blahna 2006) and in other areas across the globe, indicating that CBM efforts are making an impact (Conrad and Hilchey 2011; Sultana and Abeyasekera 2008).

Despite the potential, CBM for REDD+ still faces challenges. First, rules for REDD+ implementation (under the UNFCCC) speak of national level estimation and reporting requirements, while the CBM experiences so far have been of local scope. The link between national and local efforts remains largely unknown and unstudied; for example, the use of locally collected data is still challenged by the lack of suitable and agreed data collection protocols (Fry 2011). Second, practical approaches to stimulating and integrating community acquired data in national REDD+ monitoring will likely work best if targeted and optimized for specific country and regional circumstances, taking into account the existing monitoring capacities, the drivers and types of ongoing D&FD processes, the existing roles and experiences of communities in forest management and conservation, and (national) priorities for REDD+ implementation activities. However, very little is known about these variables yet, and the long-term success of local monitoring programs will depend in part on sociocultural conditions as well as the sustained technical capabilities of the community members. Third, CBM acquired data streams are sometimes challenged on the grounds that they do not have the quality, consistency and credibility of centrally generated data, although CBM data has rarely been formally assessed against data from professional forest inventories or remote sensing data at national level, despite the increasing number of local case studies. A few studies have shown that CBM data at project level is not significantly different from ‘expert’ data at this level but in a national REDD+

program there is also a need for consistency of CBM data between different parts of the country (Coops et al. 2004; Skutsch and Solis 2011).

In this chapter, we review some of the key issues and options available to better link CBM and national REDD+ monitoring, starting from the national perspective. More specifically, we:

- Describe the importance of local drivers of D&FD from a REDD+ implementation perspective, to highlight the importance and relevance of community involvement in REDD+ implementation and monitoring;
- Review the scientific literature to better define the role and technical conditions under which CBM can contribute a dedicated and independent stream of measuring and monitoring data to national level monitoring efforts;
- Develop a conceptual framework and discuss the key technical issues involved in linking local and national monitoring efforts;
- Analyse and synthesize the status of REDD+ country approaches in regards to CBM, based on a review of 28 readiness preparation proposals (R-PP) to the World Bank Forest Carbon Partnership Facility (FCPF). Based on this assessment, we draw conclusions and recommendations for enhancing REDD+ monitoring with the formal integration of community acquired data into national MRV systems.

The review and assessments provided in these four sections are made from the broad perspective of likely requirements for MRV under international REDD+ policy, taking into account technical issues related to data integration and management, and we include a ‘reality check’ on how individual countries are advancing on these issues within their national REDD+ efforts. For the literature review, electronic databases such as Scopus, Web of Science, Google Scholar, national and international REDD+ reports and the FCPF webpage were searched. Search terms included ‘CBM’, ‘locally based monitoring’, ‘participatory monitoring’, ‘capacity building’ and ‘community capacity’, combined with ‘REDD+’ or ‘MRV REDD+’. Literature from 2005 onwards (the year REDD was first proposed) was taken into consideration.

Based on this assessment, we present conclusions and recommendations that will help in the evolution of REDD+ monitoring and enhance the integration of community acquired data into REDD+ program planning under different national circumstances and priorities.

2.2. Importance of local D&FD drivers from a national REDD+ perspective

D&FD are caused by a variety of proximate and underlying driving forces at local, national and global levels (Geist and Lambin 2002). Proximate drivers are human activities that directly affect forest change, such as agricultural expansion, wood extraction, charcoal production and livestock grazing. In the case of subsistence land use and wood extraction, local communities act as direct actors of change. Thus, their direct involvement in REDD+ activities is essential to plan, implement and monitor forest change successfully. For these kinds of D&FD processes, directly addressing local actors and drivers within REDD+ is even more critical and relevant than for other drivers such as urban expansion, mining and other commercial activities.

A recent study by Hosonuma et al. (2012) considered the relative importance of different D&FD drivers in developing countries based on a synthesis of national data. Figure 2.1 shows the contribution (relative importance) of local drivers to D&FD. We consider subsistence agriculture a local driver of deforestation, and charcoal and fuelwood extraction a local driver of forest degradation. Recently, it has been argued that commercial actors play an increasingly larger role in the expansion of agriculture into the forest, but locally driven D&FD is still a widespread phenomenon, especially in Africa and parts of Asia (Geist and Lambin 2002). Countries that have a large proportion of locally driven forest change must give priority to these drivers in their national strategies and, as a consequence, must particularly consider the role of local communities. It is important that the differences between drivers of D&FD are understood, for they are in many cases quite distinct, as are the appropriate strategies to deal with them (Angelsen et al. 2012).

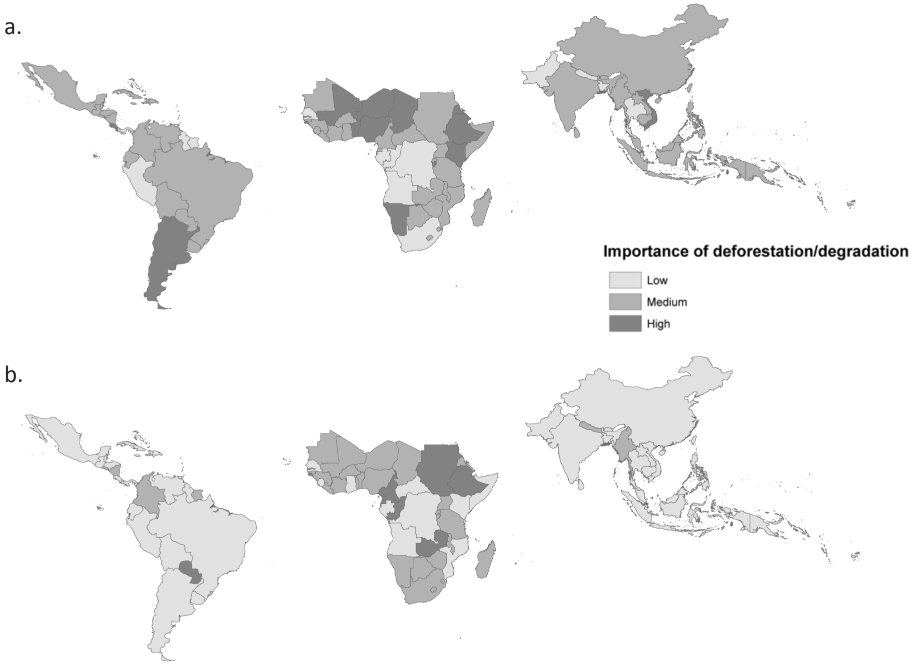


Figure 2.1 Relative importance of local drivers for deforestation and forest degradation. a) Relative importance of subsistence agriculture as local driver of deforestation. b) Relative importance of firewood/charcoal extraction as local driver of forest degradation. Low, medium and high importance denote that 0–33, 33–66 and 66–100% of deforestation/degradation is locally driven, respectively (Hosonuma et al. 2012).

2.3. Importance of local communities in a national MRV system

The specific and different drivers, actors and processes behind D&FD need to be known, not only to determine what strategies should be included in the national REDD+ program to combat them, but also to develop effective approaches and methods to monitor them. Our concern here is with the potential role of CBM within a national monitoring system, and Table 2.1 summarizes the niche for this by looking at broad forest change processes and comparing the potential of CBM with other approaches such as national inventories and remote sensing, for each of these change processes. Table 2.2 evaluates the role of community acquired data compared with other monitoring data sources.

Table 2.1 Comparison of data sources and observation methods, and the role of community-based monitoring for national REDD+ monitoring for different forest change activities (Herold et al. 2011; Skutsch et al. 2011).

Forest change activity		**Monitoring options at national level**	**Potential contribution of community-based monitoring**
Reforestation		Remote sensing, national forest inventory, monitoring through forestry companies	• Acquiring/signalling the location, time, area and type of change events (in near real-time) • Ground level measurements for local implementation (i.e. of reforestation plots) • Independent local reference for national/other data sources
Deforestation		Remote sensing, national forest inventory	
Forest degradation	Commercial activities, incl. selective logging	National forest inventory, commercial companies (i.e. harvest estimates), remote sensing	
	Wild fire	Remote sensing, national forest inventory	• Acquiring/signalling date, area and type of change event (near real-time)
	Subsistence forest use incl. fuelwood, charcoal, community forest management etc.	Limited historical data, possibly national forest inventory	• Regular ground level measurements and reporting of forests and carbon stocks, tracking growth/decrease of local activities (drivers)
Forest enhancement	Increases in carbon due to REDD+ activities at project level		

2.3.1. Community-based data in assessment of deforestation & reforestation

As shown in Table 2.1, forest area change and associated carbon stock changes from reforestation and deforestation are commonly monitored by remote sensing and forest inventory data sets at national level (Herold et al. 2011). However, even in these cases there could be important contributions from data locally sourced by communities:

- REDD+ requires tracking forest changes resulting from human activities: local people can help to track these changes by signalling change events when they happen and can especially provide information on why they happen (Skutsch et al. 2011). This information can be particularly useful when provided on a near real-time basis;
- REDD+ requires information about long-term performance: the capacity of communities to regularly revisit sites over long time periods means that implementation activities can be checked and verified;
- REDD+ MRV requires consistency, accuracy, comparability and transparency: the data and information coming from communities provides an additional independent data source that can serve as reference and validation for national datasets such as those originating from satellite-borne sensors (UNFCCC 2010a).

Thus, while remote sensing techniques are certainly the main tools to be used at the national level to detect deforestation, community generated data could be an important input to the analysis of deforestation and commercial degradation events (Fry 2011). CBM can help to verify remote sensing estimates and to signal new changes in near real-time (even before the remote sensing data have been made available or analysed). Important information could include location, time, area and type of the change events, and in particular could specify the driver of change, since this cannot easily be identified by other means (Skutsch et al. 2011). In this way, information acquired by communities and local experts can complement data derived independently at the national level using more established methods such as remote sensing.

2.3.2. Community-based data in the assessment of degradation & forest enhancement

Degradation and forest enhancement assessments in many, if not most, cases require on-the-ground measurement as the changes in stock are often quite small on an annual basis and cannot easily be identified, let alone measured, using remote sensing; here there may be a major role for CBM. Expert or professional forest inventories collect ground-based measurements (e.g., tree height, diameter at breast height [DBH] and tree species) on plots selected through a sampling design, and use these to estimate forest carbon stocks and changes using allometric relationships, or using a biomass expansion factor (Brown 1997) . This process is established but requires considerable resources, time and capacity. To date, only a few developing countries have established comprehensive forest inventories that allow for national forest carbon stock estimates (DeFries et al. 2007). Experience gained from studies conducted in Ghana, Tanzania (Brashares and Sam 2005; Danielsen et al. 2011) and the Philippines (Uychiaoco et al. 2005) shows that communities themselves can collect some forest inventory data adequately and more cost-efficiently than professional foresters. With proper field measurement equipment, hardware (e.g., GPS, personal digital assistant [PDA] and smart phone), software (user friendly data forms) and training, it has been shown that local communities can accurately measure and record basic variables such as DBH, height, tree species and tree count. Most importantly, local communities can repeat these measurements on a regular basis. Data collected by local communities have proven to be of a level of accuracy comparable to that produced by professional forest inventory staff (Skutsch et al. 2009; Verplanke and Zahabu 2009).

This may be particularly useful both to assess changes in rates of degradation with in forests and to quantify rates of forest enhancement, particularly in areas that are under community management. Here, it will be essential for performance reporting in the case of local REDD+ implementation activities that are designed to address forest degradation caused by local fuelwood collection or grazing, and to measure the impacts of improved community forest management. Forest inventory-type measurements for forest enhancement, for example, maybe repeated each year and sites allocated for reforestation or sustainable management can be regularly checked. Even a proof of ‘no change’ is an important finding to ensure that new activities do not negatively affect the carbon performance of REDD+ implementation activities.

Table 2.2 further shows that forest change and carbon stock data can be acquired in many ways, from different sources. While there are preferred data sources for different change types (Table 2.1), the fact that phenomena can be observed independently from different data sources is important, for reasons of transparency, assessment accuracy, studying and estimating uncertainties, and to continuously improve the estimates at the national level.

Table 2.2 Matrix to compare and evaluate the quality of community acquired data with existing remote sensing and professional monitoring approaches at the national level [adapted from (Achard et al. 2012; Bottcher et al. 2009; Danielsen et al. 2011; De Sy et al. 2012; GOFC-GOLD 2014; Herold et al. 2011)].

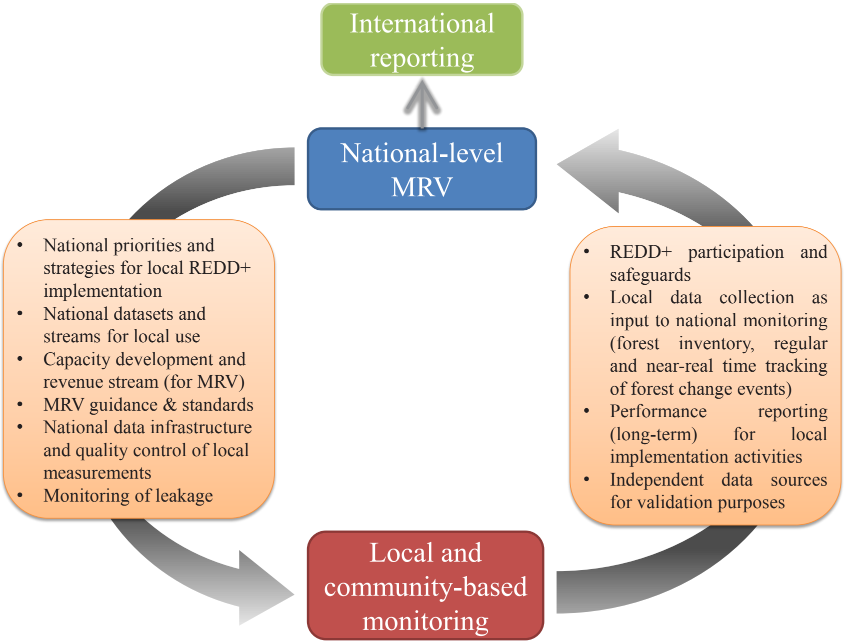
Acquisition type	**Forest Inventory**				**Deforestation Area**			**Degradation Area**				**Cost per Area**
	DBH	**Height**	**Tree species**	**Number of tree per plot**	**Clearing for commercial purpose, agriculture forestry**	**Subsistence Agriculture**	**Infrastructure expansion (Road, mines, urban etc.)**	**Selective logging**	**Fuelwood**	**Forest grazing**	**Wildfire**	
Coarse resolution (250-1000 m) satellite data	-	-	-	-	+	-	+	+	-	-	++	$
Medium resolution (10-60 m) satellite data	-	-	-	-	+++	++	+++	+	-	-	++	$$
Fine resolution (<5 m) satellite data	-	-	-	++	+++	+++	+++	++	+	++	++	$$$
Airborne laser scanning	-	+++	-	++	+++	+++	+++	++	++	++	++	$$$
Community-based monitoring	++	+	++	++	+	+	+	+	+++	+++	++	$
Professional forest inventory	+++	+++	+++	+++	++	++	++	+++	++	+	+	$$

Quality indicator: (-): very low, (+) low, (++) medium, (+++) high; ($) low, ($$) medium, ($$$) high

2.4. A conceptual framework to link local & national monitoring

Opportunities to link local and national REDD+ monitoring are best considered in terms of contributions and relative benefits. If both sides contribute and benefit at the same time, a win–win situation can be created that can help to stimulate a suitable level of collaboration. Global Observation for Forest Cover and Land Dynamics provides some general guidance for evolving CBM and for conceptualizing how communities can be linked to national MRV in a mutually beneficial way (GOFC-GOLD 2014). In forming this link, it is clear that all monitoring processes need to follow the principle of consistency, transparency, comparability, completeness and accuracy (GOFC-GOLD 2014; IPCC 2006). Indeed, if well organized and systematic, CBM could provide a very strong basis for 'nested' systems of REDD+, allowing performance at the local or project level to be assessed within a national system of REDD+ (Dalle et al. 2006; Olander et al. 2011).

Figure 2.2 highlights some of the contributions and potential benefits of linking CBM with national REDD+ MRV. Clearly, this relationship is likely to work best in countries where the engagement of communities to address local drivers has been identified as a key component in the national REDD+ strategy. In this case, actors at the national level are expected to provide strategies, incentives and policies that stimulate such community involvement in REDD+ implementation. Existing national data (i.e. maps, remote sensing images and so on) may be utilized (e.g., to identify areas at risk of deforestation/degradation or to identify areas of potential forest enhancement), capacity development (both for forest management and for monitoring) can be provided and potential revenue streams can be identified to support local efforts. In addition, national level actors would need to provide a data infrastructure system such that locally acquired data could be uploaded, verified, disseminated and shared, thereby continuously improving the national monitoring efforts. Only consistent national scale monitoring is capable of properly accounting for the displacement of emissions (leakage), and a national data infrastructure system can thus provide a service to local level activities.



- National priorities and strategies for local REDD+ implementation
- National datasets and streams for local use
- Capacity development and revenue stream (for MRV)
- MRV guidance & standards
- National data infrastructure and quality control of local measurements
- Monitoring of leakage

- REDD+ participation and safeguards
- Local data collection as input to national monitoring (forest inventory, regular and near-real time tracking of forest change events)
- Performance reporting (long-term) for local implementation activities
- Independent data sources for validation purposes

Figure 2.2 Contributions and benefits of community-based monitoring for national REDD+ MRV (Measuring, reporting and verification).

In order for CBM to make an important contribution to the national level emission reporting, a number of issues need to be considered. First, there should be a set protocol with standards and guidelines for data acquisition at community level, since systems used by communities should be consistent across the country. Second, communities should be made aware of the value of monitoring and should be trained in monitoring activities and related issues. Local data such as DBH, height, tree species and small scale degradation, deforestation and reforestation activities can be acquired using different handheld technologies such as smart phones, tablet personal computers and PDA devices with integration of GPS, cameras and so on, provided these devices have user friendly interfaces (Parr et al. 2002; Pratihast et al. 2012). Third, the national implementing agencies would need to develop a robust system to collect and store the locally monitored data. In brief, a national level strategy to process local data can be summarized as follows:

- Data collection system: the national government should design a system/protocol to collect and report CBM data. The community can easily provide these data to a national data repository if internet access or wireless networks are available.

- Integrating local data into national databases: national authorities should also develop quality standards to evaluate the quality of locally collected data and ensure overall data accuracy and consistency. Local data, if meeting all the national requirements, can then be integrated into the national database. The national database will be used to identify and analyse both areas of forest cover change and carbon stock change within forests.
- Information processing and analysis: the information will be processed, analysed and translated into estimations of emissions and removals at the national level. The results can be reported according to the IPCC Good Practice Guidance (IPCC 2006) to an international body for carbon crediting.

One of the central elements of data exchange is quality control, which should be applied both to local and national level datasets. Table 2.2 shows that there is often more than one type of observation available for each parameter and, thus, data should be checked and (as far as practical) validated using an independent source. In this sense, light detection and ranging, fine resolution satellite data and professional forest inventories can be used in selected cases to check the monitoring provided by communities, at least on some variables. At the same time, local data on forest change events can be used to assess the quality of national forest area change monitoring using remote sensing. In addition, an open exchange and universal access to data is fundamental and important to ensure the issue of transparency.

A further aspect of CBM relates to the distribution of benefits among the many stakeholders that may have contributed to reduced emissions. At the international level, REDD+ is a performance-based instrument, and many observers believe that local stakeholders within a national REDD+ program should also be rewarded according to their carbon achievements. In practice, it is very difficult to attribute reductions in deforestation to individual communities, not least because this would require individual baselines, and accounting for leakage, but forest enhancement could easily be measured by annual carbon surveys at the local level and rewarded directly (FCPF 2010). An alternative option might be for communities to be paid, not for their carbon achievements, but simply for carrying out the monitoring; for example, as part of a payment for environmental services scheme, given that this data strengthens the national forest monitoring system and provide a credible basis for the government to make carbon claims internationally.

CBM for REDD+ is new and the national investment needed for developing an institutional framework to provide technical and perhaps financial support to local monitoring activities needs to be explored. However, there is no country comprehensively implementing CBM schemes at the moment. Furthermore, there is a huge capacity difference among the country participating in REDD+, so it is difficult to assess what the national investment would be since it is dependent on country circumstances.

2.5. Overview & status of REDD+ country approaches

The FCPF of the World Bank is a global partnership focused on helping developing countries to develop coherent REDD+ national strategies, reference emission levels, MRV systems and implementation plans (FCPF 2012). The FCPF also strongly emphasizes the role of local communities in the national REDD+ process. To date, 37 developing forest countries (14 in Africa, 15 in Latin America and the Caribbean, and eight in Asia-Pacific regions) are participating in the FCPF. Out of 37, 28 countries (summarized in Table A2.1 in the Annex) have submitted their R-PP. An R-PP is a policy document submitted to the FCPF Committee and to the UN Collaborative Program on REDD. Key elements of the R-PP template include: readiness organization and consultation; REDD+ strategy preparation; reference emission level; and a MRV Systems for forests and safeguards.

A review of the proposed strategies, as outlined in their in R-PPs, of 28 FCPF countries has been performed (Table A2.1 in the Annex) to assess community consultation, community involvement in monitoring, community involvement in forest management, the importance of subsistence agriculture as a driver for deforestation and the importance of fuelwood/charcoal extraction as a driver for degradation. Community consultation, and community involvement in monitoring and management, can take many forms. This assessment only considers whether any type of community consultation, CBM and forest management were mentioned in the R-PPs. Thus, we assess whether countries consider these options but not if and how these activities are actually happening in practice, since it is too early to make such an assessment. Furthermore, there is lack of consistency regarding the status of CBM in all R-PP countries and we need to develop common indicators and a framework for more detailed analysis, which is beyond the scope of this chapter.

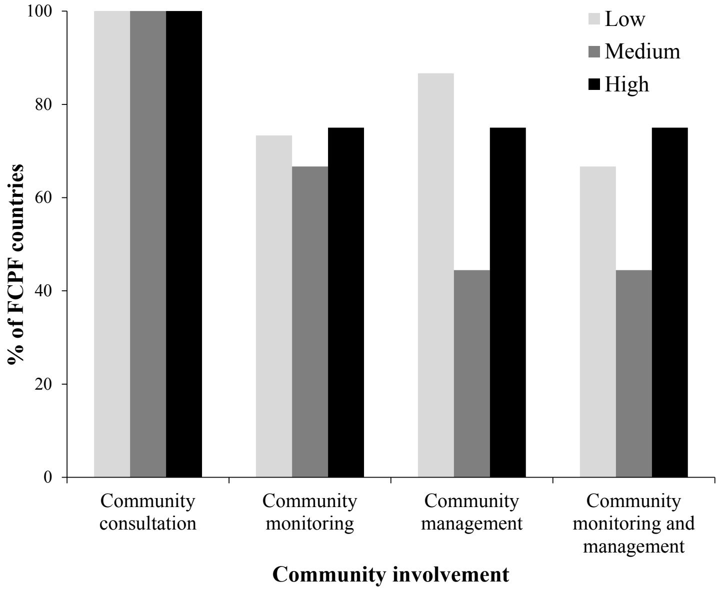


Figure 2.3 Community involvement as outlined in the readiness preparation proposals of 28 countries, regarding different levels of importance of locally driven degradation [adapted from (FCPF 2012; Hosonuma et al. 2012)].

The analysis of country efforts highlights that these countries have rather different national circumstances and strategies to deal with them (Table A2.1 in the Annex). Looking deeper into the link between the proposed strategies and the importance of local drivers for degradation (Figure 2.3) shows that all 28 FCPF countries have consulted with communities during the design phase of the R-PP and propose their participation during the implementation of the program. Different information sharing tools such as local newspapers, community radio and national television were used for community consultation during the design phase of R-PP. The relationship between CBM and/or community forest management and the importance of local drivers (e.g., fuelwood collection and charcoal production) for degradation is not clear cut (Figure 2.3). Countries with low importance of local drivers seem to engage more in CBM and management of forests than countries with high importance of local drivers for degradation (Figure 2.1) (Hosonuma et al. 2012). This could be for several reasons. Figure 2.3 shows that community-based management is often linked to community forest management and whether countries involve their communities in forest monitoring might have more to do with a tradition of involving communities in forest management than with the importance of local drivers for degradation. In general, the link between analysis of drivers of D&FD, REDD+ strategy development and MRV design is weak in most R-PPs (FCPF 2010).

In several of the R-PP countries, community involvement is a driving force to improve forest management and its sustainable use (Jupp et al. 2005; Yao et al. 2011; Yoccoz et al. 2001). Some countries (in particular Mexico, Tanzania, Vietnam and Nepal (Danielsen et al. 2011; Topp-Jørgensen et al. 2005)) are in advanced stages of developing community-based forest management and monitoring strategies (or systems), and have been able to demonstrate these activities at the project level. These countries have also provided more detail on the plans to involve local communities in monitoring and the results are presented and compared in Table 2.3. All four countries recommend that local participation should be based on already existing community forest management programs. Capacity building of communities will be done through government institutions, NGOs, academics and/or community leaders, depending on country circumstances. Furthermore, plans to involve local people in measuring forest parameters for above ground biomass estimation are present. However, only two countries (Vietnam and Mexico) have also mentioned the involvement of local communities in monitoring forest area change per management unit. Case studies are available from Mexico, Nepal and Tanzania regarding forest carbon measurement, whereas only one case study is available from Mexico regarding forest degradation monitoring. All countries propose that national government institutions will provide the overall coordination, protocol development, information management, data evaluation and reporting to international level. Roles for subnational or regional units are foreseen and should focus on planning of forest area to be monitored, training material preparation, equipment lending and distribution of funds to initiate the activities. The local level, such as local governments and communities, is anticipated to contribute to data acquisition and data management. There is quite some congruency in the general plans of these four countries, and all approach the idea with a similar perspective, presenting the CBM concept as a two-way exchange process, outlined in Figure 2.2.

Table 2.3 Key elements of different proposals for community-based monitoring (Danielsen et al. 2011; Shrestha 2011; Topp-Jørgensen et al. 2005; Zahabu and Malimbwi 2011).

Activity		**Functional elements**	**Example of countries consideration**			
			Vietnam	**Mexico**	**Nepal**	**Tanzania**
Participation in monitoring		Forest usage rights allocated to communities	x	x	x	x
Responsibility for Training and orientation		Government institutions	x	x	x	x
		NGO´s		x	x	x
		Academics	x	x		
		Community leader	x			
Parameters of measurements		Forest measurement for above ground biomass stocks	x	x	x	x
		Monitoring forest area change per management unit	x	x		
Number of case studies		Carbon stocks measurement †	0	2	2	2
		Forest degradation monitoring ‡	0	1	0	0
Coordination and data management	National	Overall coordination, protocol development, information management, data evaluation and reporting	x	x	x	x

Activity		**Functional elements**	**Example of countries consideration**			
			Vietnam	**Mexico**	**Nepal**	**Tanzania**
	Sub-national / Regional	General coordination planning of forest area to be monitored, training, equipment lending and funds to initiate	x	x	x	x
	Local level	Public participation, data acquisition, data management	x	x	x	x

†Carbon stocks measurement consists of the measurement of tree parameters; for example, diameter at breast height, height and species for deriving above ground biomass.
‡Forest degradation monitoring represents the tracking of the area affected by forest degradation activities that cause the changes in forest carbon stocks.

2.6. Conclusion

The main aim of this chapter was to study the prospects for enhancing the linkages between CBM and national REDD+ monitoring. The review and assessments provided here consider this from a national perspective, which is commonly lacking in the literature, since studies on community monitoring mostly consider only the local situation. The review also includes a broader international REDD+ priorities perspective, focusing on technical considerations, data integration and management, and provides a status check on how countries are advancing in considering CBM in their national REDD+ efforts. Several conclusions and recommendations can be made:

- The consideration of locally driven deforestation, and particularly forest degradation in national strategies and REDD+ implementation, as well as the link with the role local communities can play both in forest monitoring and management in many FCPF countries, is not always recognized. Information acquired by communities and local experts constitutes an increasingly justified and independent data stream for national level monitoring, where it may be complementary to the more traditional and established data streams. Local communities can play a useful role in ground monitoring of degradation and forest enhancement by measuring and monitoring forest carbon stocks, but they may also provide useful information on deforestation by signalling its occurrence in near real-time and its drivers (e.g., agriculture and mining). In addition, they can provide other ground-level information on the impact of REDD+ implementations activities on issues such as biodiversity and equal distribution of REDD+ benefits.

- Forest change and carbon stock data can be acquired in various ways and from different sources. There are preferred sources for different forest change types, with community acquired data being most important for small scale forest disturbance activities (i.e. degradation) that are more complicated to observe from other data sources. The fact that the same phenomenon can be monitored independently from different data streams has many advantages as regards reliability, precision and transparency, and thus helps to continuously improve national level estimations and reporting.
- The linkage between local CBM and national level efforts requires careful consideration of issues such as data transmission, data infrastructures, standards and guidelines, capacity development and flow of resources (e.g., equipment, supervision and incentives). Implementation will be most successful and efficient if both the local and the national level contribute and benefit at the same time, and a win–win situation can be created that can help to stimulate a suitable level of collaboration for integrated monitoring.
- Systematically gathered and reported CBM data could form the backbone of a nested REDD+ structure in which the efforts of different levels (local, subnational and national) are integrated into one MRV system (Pedroni et al. 2010). It could even form the basis for a system of benefit sharing, since it would help determine the performance of different communities or land owners at a local level, which could be used as the basis for allocation of rewards or payments (Balderas Torres and Skutsch 2012).

These results emphasize why and how it is useful for countries to build into their MRV systems an explicit role with specified tasks for CBM. However, it is to be recognized that monitoring capacities in many countries are still rather low and the development of these capacities will take time and resources. So far, dedicated country efforts (i.e. for Vietnam, Mexico, Nepal and Tanzania) have reflected and recognized the importance and the elements of such an integrative monitoring framework, but have not yet moved beyond including these considerations in their general plans. It is expected that these efforts will continue and that they could be enhanced by considering some general principles that have been emphasized in this review:

- The role of communities could be defined for specific REDD+ monitoring efforts, carefully selected to dovetail with and support national monitoring procedures, and this may vary from country to country.
- CBM data could form the basis for a nested system and even for the distribution of rewards within a national REDD+ program.
- There is a need for creating a win–win situation with the local and the national level contributing and benefiting at the same time. Local data streams may be integrated with other national data sources and monitoring efforts.
- Investing in further demonstration activities and research will help to better link the local and national monitoring in practice and for different country circumstances.

2.7. Future perspective

Over the next 5–10 years, the involvement of local communities will be a vital data source in REDD+ monitoring and integration with national REDD+ reporting, and implementation could create joint benefits. Advancements in handheld devices such as smart phones and PDA devices will improve local participation within the monitoring program. This will stimulate a near real-time data stream from satellites and the local communities that can serve a new way of monitoring forest carbon and its change.

To make local data useful on the national level, there are a number of key technical issues to be addressed. There will be a need for systematically developed methods, common guidelines and quality control mechanisms for CBM. Dedicated tools such as smartphones and PDA, incorporated with user friendly applications, are required to facilitate data collection and transmission for local communities. Furthermore, ongoing nested MRV structures are expected to narrow the gaps of different levels (local, subnational and national) monitoring data for effective REDD+ implementation (Balderas Torres and Skutsch 2012).

Acknowledgements

The authors gratefully acknowledge the support of DAAD funded Center for Natural Resources and Development (CNRD) Fellowship Programme, Norwegian Agency for Development Cooperation (Grant Agreement #QZA-10/0468) and AusAID (Grant Agreement #46167) for the Center for International Forestry Research Global Comparative Study on REDD+. The authors have no other relevant affiliations or financial involvement with any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript apart from those disclosed. No writing assistance was utilized in the production of this manuscript.

Annex: additional material of chapter 2

Table A2.1 Status of RPP submitted countries regarding community forest management and monitoring [adapted from (FCPF 2012; Skutsch and Ba 2010)].

Country	**Community consultation**	**Community-based monitoring**	**Community forest management**	**Importance of deforestation for subsistence agriculture**	**Importance of degradation for fuelwood/charcoal**
Argentina	Yes	Yes	Yes	Low	Low
Cambodia	Yes	Yes	Yes	Low	Low
Central African Republic	Yes	No	Yes	Medium	Low
Colombia	Yes	Yes	No	Medium	Medium
Costa Rica	Yes	No	Yes	Low	Low
Democratic Republic of Congo	Yes	Yes	Yes	Medium	High
El Salvador	Yes	No	No	Low	Medium
Ethiopia	Yes	Yes	Yes	Low	High
Ghana	Yes	Yes	No	Medium	Low
Guatemala	Yes	Yes	Yes	Medium	Low
Guyana	Yes	Yes	Yes	Low	Low
Honduras	Yes	No	No	Medium	Low
Indonesia	Yes	Yes	Yes	Low	Low
Kenya	Yes	Yes	Yes	Low	Low
Lao People's Democratic Republic	Yes	No	Yes	Low	Low
Liberia	Yes	Yes	Yes	Medium	Medium
Madagascar	Yes	Yes	No	Medium	Medium
Mexico	Yes	Yes	Yes	Low	Low
Mozambique	Yes	Yes	Yes	Low	Low
Nepal	Yes	Yes	Yes	Medium	Medium
Nicaragua	Yes	No	No	Medium	Medium
Panama	Yes	Yes	Yes	Low	Low
Peru	Yes	Yes	Yes	Medium	Low
Republic of Congo	Yes	No	No	Medium	High
Suriname	Yes	No	No	Low	Medium
Tanzania	yes	Yes	Yes	Medium	Medium
Uganda	Yes	Yes	Yes	Medium	Medium
Vietnam	Yes	Yes	Yes	Low	High

Chapter

3

Mobile devices for community-based REDD+ monitoring: a case study for central Vietnam

Arun Kumar Pratihast, Martin Herold, Valerio Avitabile, Sytze de Bruin, Harm Bartholomeus, Carlos M. Souza Jr and Lars Ribbe

Published in Sensors, Volume 13, Issue 1, December 2012, Pages 21-38

Abstract

The Monitoring tropical deforestation and forest degradation is one of the central elements for Reduced Emissions from Deforestation and Forest Degradation in developing countries (REDD+) scheme. Current arrangements for monitoring are based on remote sensing and field measurements. Since monitoring is the periodic process of assessing forest stands properties with respect to reference data, adapting the current REDD+ requirements for implementing monitoring at national levels is a challenging task. Recently, the advancement in information and communications technologies (ICTs) and mobile devices has enabled local communities to monitor their forest in a basic resource setting such as no or slow internet connection link, limited power supply, etc. Despite the potential, the use of mobile device system for community-based monitoring (CBM) is still exceptional and faces implementation challenges. This chapter presents an integrated data collection system based on mobile devices that streamlines the community-based forest monitoring data collection, transmission and visualization process. This chapter also assesses the accuracy and reliability of CBM data and proposes a way to fit them into national REDD+ Monitoring, Reporting and Verification (MRV) scheme. The system performance is evaluated at Tra Bui commune, Quang Nam province, Central Vietnam, where forest carbon and change activities were tracked. The results show that the local community is able to provide data with accuracy comparable to expert measurements (index of agreement greater than 0.88), but against lower costs. Furthermore, the results confirm that communities are more effective to monitor small scale forest degradation due to subsistence fuelwood collection and selective logging, than high resolution remote sensing SPOT imagery.

Keywords: mobile devices; REDD+; MRV; community-based monitoring; forest carbon; forest change

3.1. Introduction

Tropical forests play an important role in the global carbon cycle. Human related destruction activities such as deforestation and forest degradation lead to significant emissions of greenhouse gases (GHGs) in the atmosphere, resulting in accelerated global warming (Achard et al. 2012; Eggleston et al. 2006; Gullison et al. 2007). To mitigate this, Reduced Emissions from Deforestation and Forest Degradation in developing countries (REDD+) has been put forward for negotiation under the United Nations Framework Convention on Climate Change (Herold and Skutsch 2011; Skutsch 2010; UNFCCC 2009). The recently agreed REDD+ mechanism includes reducing deforestation and forest degradation, forest enhancement, sustainable forest management and conservation. Besides reduction of carbon emissions, REDD+ also provide co-benefits in terms of biodiversity and livelihoods of the local community (Danielsen et al. 2011; Skutsch 2010). Currently, several REDD+ financial mechanism have been suggested for forest carbon credits including market-based mechanisms, fund-based systems, and their combinations (Gupta 2012; Karsenty 2008). All of these mechanisms are likely to distribute credits based on the amount of emissions reduction and to raise local participation to support the sustainability of the REDD+ program.

In order to implement the REDD+ mechanism, each nation needs to setup an effective, efficient and sustainable Measuring, Reporting and Verification (MRV) system at national, sub-national and local levels (Herold and Johns 2007; Herold and Skutsch 2009; Pratihast et al. 2013). Thus, it is important to prepare a national MRV system from reliable, robust, transparent, creditable datasets that contribute to effective implementation of REDD+. Remote sensing and national forest inventory are principal data sources used to calculate forest area change, rates of deforestation and degradation, and are hence used to establish baseline reference emission levels (Angelsen 2008). However, national forest inventories are often outdated and inconsistent because they lack adequate financial support as well as technical and skilled human resources to acquire and update the data. Community-based monitoring (CBM) is an alternative and effective way to reduce costs and to increase the reliability of forest monitoring data (Bowler et al. 2011; Burgess et al. 2010; Phelps et al. 2010). CBM can play a useful role for monitoring locally-driven change activities and small scale forest degradation due to, for example, subsistence fuelwood collection, charcoal extraction and grazing in the forest

(Herold and Johns 2007; Hosonuma et al. 2012; Skutsch and Solis 2011). The impacts of these activities are rarely captured accurately in national databases or observed in remotely sensed imagery (GOFC-GOLD 2014). Data acquired by communities can include reporting on incidence of change events as well as ground measurements on carbon stock changes, which are essential for REDD+ reporting at national level (Danielsen et al. 2011; Fry 2011). Furthermore, CBM can also create a strong local commitment to protect forests and biodiversity augment the chance to succeed in REDD+.

Mobile devices such as smart phones and personal digital assistants (PDA) have shown great potential to increase the local participation in data collection processes and hence, contribute to the effective implementation of CBM. Practical experiences from developing countries such as Nepal, Tanzania, Cameroon, India, and Mexico have demonstrated that local communities can play an essential role in acquiring forest inventory data (Danielsen et al. 2011; Verplanke and Zahabu 2009). Compared to traditional paper-based methods, mobile devices offer the following immediate advantages (Bravo et al. 2012; Ruesch and Gibbs 2008; Wakholi et al. 2011):

1) Mobile devices support mobility i.e. supporting community participants to immediately record the measurement in a digital system;
2) The implementation of mobile based schemes is becoming cost-effective and sustainable because of the low cost of the devices;
3) Mobile devices have the potential to signal recent forest changes, including area of change and type of disturbance in near real-time.

Despite these potentials, mobile based systems for CBM are still exceptional and they face implementation challenges when used by minimally-trained local communities in a REDD+ context. Additionally, fitness for use of these applications in terms of interaction and local suitability is often overlooked (Bruin et al. 2001; Orfali et al. 2007; Parr et al. 2002). Currently available open source technologies such as CyberTracker (Parr et al. 2002), EpiCollect (Aanensen et al. 2009), ODK (Hartung et al. 2010) and Xform (XForms1.1 2012) facilitate implementation, but they do not directly address fitness for use.

The main objective of this chapter is to present an integrated mobile device based data collection system that allows streamlining the community-based forest monitoring data collection, transmission and visualization process, in order to improve the usability, accuracy and reliability of national MRV schemes. Such a system aims to bridge the information gap at national level and also facilitates timing and consistent reporting of forest monitoring data. A prototype was built based on pervasive computer technologies and on the open source Android platform. The system performance was evaluated at the Tra Bui commune, Quang Nam province, central Vietnam by assessing the technical suitability of the proposed system. Finally, this chapter assesses how CBM could contribute to an independent data stream for REDD+ implementation programs by comparing the locally gathered data to expert (local, regional and national) field measurements and a high resolution SPOT remote sensing image.

3.2. Material and methods

3.2.1. System requirement

To implement a proper CBM, the local community needs a reliable way to record, store and deliver the collected information to the central database server (Pratihast et al. 2013; Skutsch et al. 2011). Accordingly, the system needs to satisfy both hardware and software requirements. The hardware for data gathering should enable maintaining consistency with existing national MRV systems. Since the remote sensing and forest inventory data include images and geo-location points, the system should incorporate a positioning system and a camera. Popular smartphones with GPS and camera operating on Android satisfy these demands. The usability requirements of the system are specific to the local user. These requirements include:

- Multi-language support;
- Multi-user for simultaneous use;
- Applicability in remote location;
- Voice recording as desired functionality;
- Local data storage facilities.

3.2.2. System design

The proposed system provides a complete end-to-end platform which allows the local community to gather forest data and deploy forest measurements effectively.

The general overview of the functional architecture of the system is outlined in Figure 3.1. The whole system is integrated into four-tier architecture: the data tier, logical tier, presentation tier and communication tier.

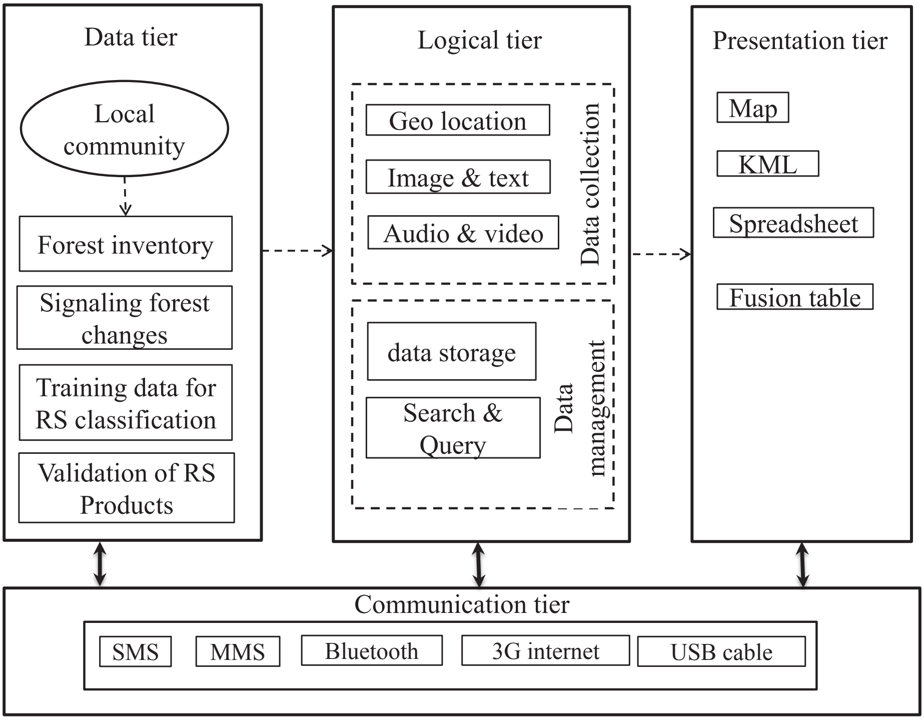


Figure 3.1 Service platform architecture for community-based monitoring.

3.2.2.1. Data tier

The data tier represents the data acquired at ground level. Figure 3.2 depicts a unified modeling language (UML) class diagram that illustrates the conceptual structure of the data acquisition system. Classes are portrayed as boxes with three sections: the top one shows the name of the class, the middle one lists the attributes of the class, and the third one lists the methods. The unfilled triangle shape (Δ) represents the aggregation among the classes. User class is designed as a root class which is associated with the following subclass: 1) forest inventory, 2) signalling forest change, 3) acquisition of training data for remote sensing classification and 4) validation data for remote sensing products. Many similarities in attributes and functions are designed to keep the data acquisition independent among these subclasses. A bi-directional association is showed by a solid line between the two classes, namely user and location. The user class is associated with a specific location, and the user class recognizes this association. The user takes on the role of "assignedLocation" in this association. The multiplicity value next to the user class of 0..* indicates that when an instance of a user exists, it can either have one instance of a user associated with it or no user associated with it (i.e. maybe a user has not yet been assigned). In addition to that the location instance can be associated either with no user or with up to an infinite number of users.

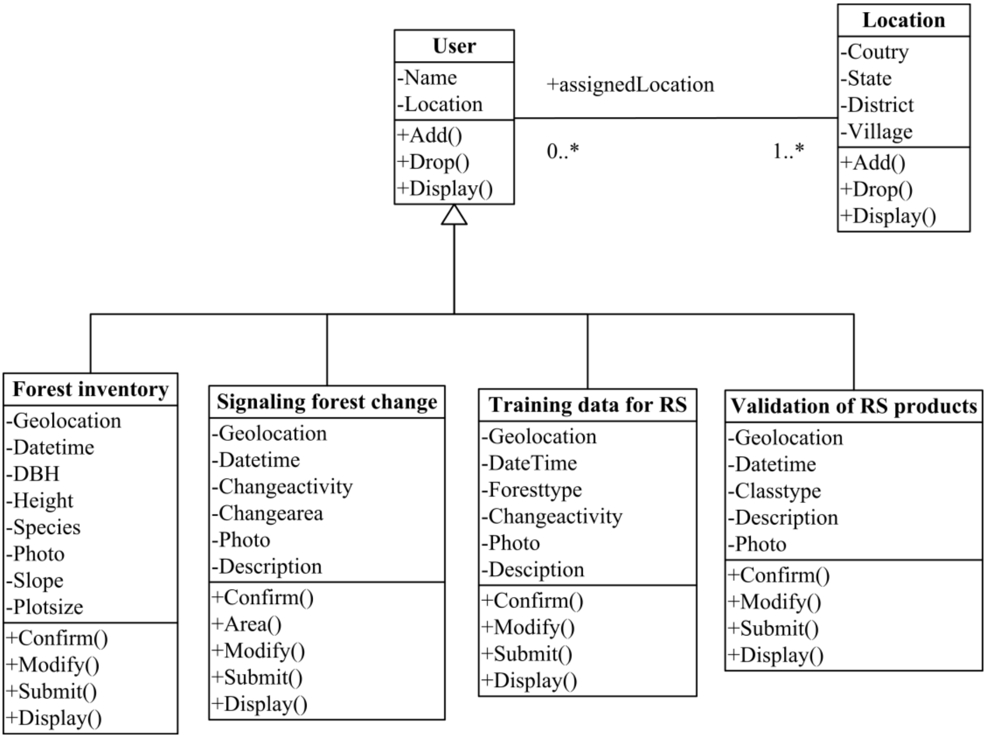


Figure 3.2 Class diagram of data acquisition form.

3.2.2.2. Logical tier

The logical tier consists of overall system design units such as data collection and management units. The data collection component comprises optional input constraints such as text, image, audio/video, geo-location, flow depending on previous answers; icon based user friendly graphics and local language support. Central data management is one of the major goals of the system. It facilitates data access and exploration for end-users. Furthermore, Search tools allow users to search, query and modify particular data. The local data, upon meeting all the national requirements, can also be integrated into a third-party national or international database.

3.2.2.3. Communication tier

In order to avoid data loss, the proposed system allows for local storage of the collected data in an extensible markup Language (XML) format along with associated binary files (image, audio, and video). These locally stored data can be transmitted to the server using thick and thin client-server architecture (Orfali et al. 2007). A thin client provides limited applications on the client and all the data storage and processing occurs on the server. In contrast, a thick client is embedded with the bulk of data storage and processing capacity. With thick clients, there is low level performance required from the server resulting in minimum server load and a faster response time. The communication tier allows users to synchronize with a data server at any time using any available data transmission means such as Short Message Service (SMS), Multimedia Messaging Service (MMS), Bluetooth, 3rd generation (3G) internet and Universal Serial Bus (USB) cable. Table 3.1 presents the data transmission means in terms of data type, data volume and cost.

Table 3.1 Comparison of Mobile data transmission means [adapted from (Bose and Shin 2006; Verkasalo and Hämmäinen 2007)].

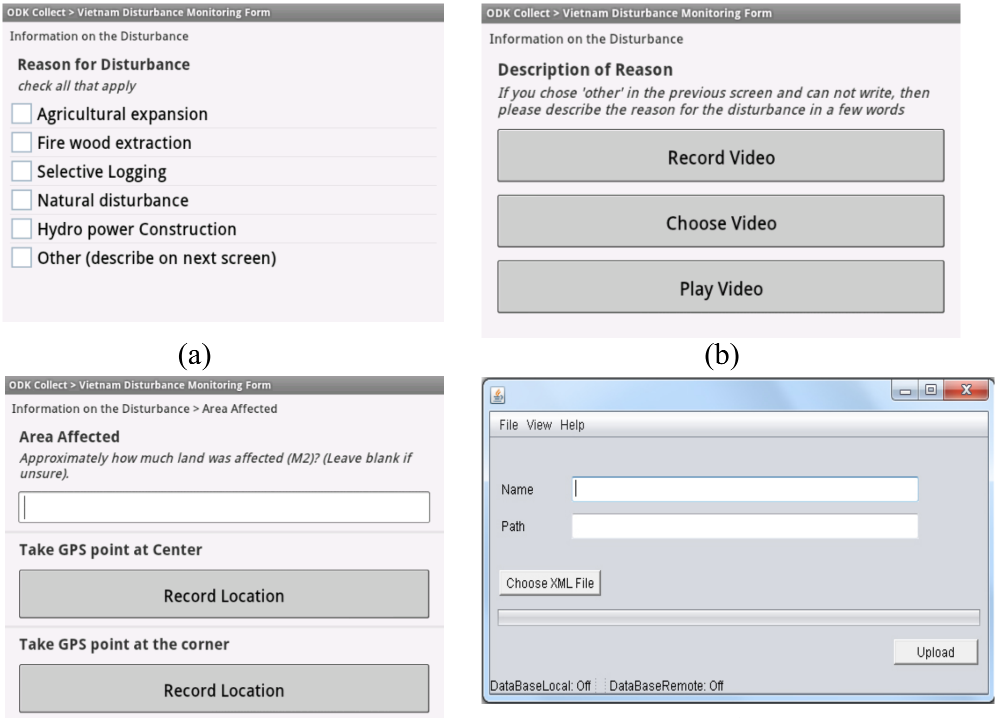
Mode of data transfer	**Data types**			**Data volume**	**Cost**
	Number	Text	Multimedia		
SMS	Yes	Yes	No	Low	Low
MMS	Yes	Yes	Yes	Low	Medium
Bluetooth	Yes	Yes	Yes	Medium	Free
3G internet	Yes	Yes	Yes	High	Medium
USB cable	Yes	Yes	Yes	High	Free

3.2.2.4. Presentation tier

The presentation component intends to visualize the community collected data in a tabular and map form respectively. The tabular forms are spreadsheets, Comma Separated Values (CSV) format. Google fusion table whereas map forms allow visualisation in a static and in a dynamic mode through Hyper Text Markup Language (HTML) web browsers. Google fusion tables is an online data management application that facilitates easy collaboration, data visualization and web publishing (Gonzalez et al. 2010).

3.2.3. System implementation

The prototype was implemented in a hierarchical structure. Initially, the data tier described in Section 3.2.2 was implemented using the XML file format because it provides a flexible way to represent class attributes. Four types of forest monitoring forms were created in XML format, namely: forest inventory (for estimation of above ground forest biomass), signalling forest change (for reporting of forest disturbance) and training data for remote sensing classification and for validation of remote sensing products. Different means of data input design interface were used to facilitate data entry, such as selection option, multimedia (audio/video), photographs and entering text, number, selection options, dropdown menus. The developed form is deployed at the client side (mobile platform) through ODK collect. Considering the fact that users may not always have access to an internet connection, thick and thin client-server architectures of data transmission systems were implemented. Local people can upload their data from the mobile device to a local database through an USB connection or via SMS, MMS or Bluetooth. Consequently, the availability of an internet connection permits submission of monitored information to the remote server. Java 2 Enterprise Edition (J2EE) for Java netbeans was used to provide interfaces to manage data collection forms and the collected data is stored in PostgreSQL. QuantumGIS linked with PostgreSQL, allows the data analysis operations on managed data, visualized in a map form. The web map server (WMS) plugin of QuantumGIS allows map processing through HTML web browsers. Similarly, the system also allows interoperability to deploy the data on different kinds of cloud computing environments such as Google app engine. Some screenshots of the deployed application are shown in Figure 3.3.



Reason for Disturbance
check all that apply

☐ Agricultural expansion
☐ Fire wood extraction
☐ Selective Logging
☐ Natural disturbance
☐ Hydro power Construction
☐ Other (describe on next screen)

Description of Reason
If you chose 'other' in the previous screen and can not write, then please describe the reason for the disturbance in a few words

Area Affected
Approximately how much land was affected (M2)? (Leave blank if unsure).

Take GPS point at Center

Take GPS point at the corner

DataBaseLocal: Off DataBaseRemote: Off

(a) (b)

(c) (d)

Figure 3.3 Some screenshots of deployed application interface to: (a) select the reason for forest disturbance, (b) record video as forest disturbance description, (c) record area for forest disturbance and (d) upload form to the database server.

3.2.4. System evaluation in the case study of central Vietnam

3.2.4.1. Field setup

The capability of the developed system for monitoring the forest carbon and change activities was tested and evaluated at Tra Bui commune (15°17'54.65"N,108°08'08.01"E to 15°19'37.97"N, 108°08'13.42"E), Quang Nam province, central Vietnam (Figure 3.4). The forest of the Tra Bui commune area has been under threat since the construction of the Sông Tranh 2 hydroelectric dam, which caused the resettlement of the population of this community, mostly belonging to an ethnic minority.

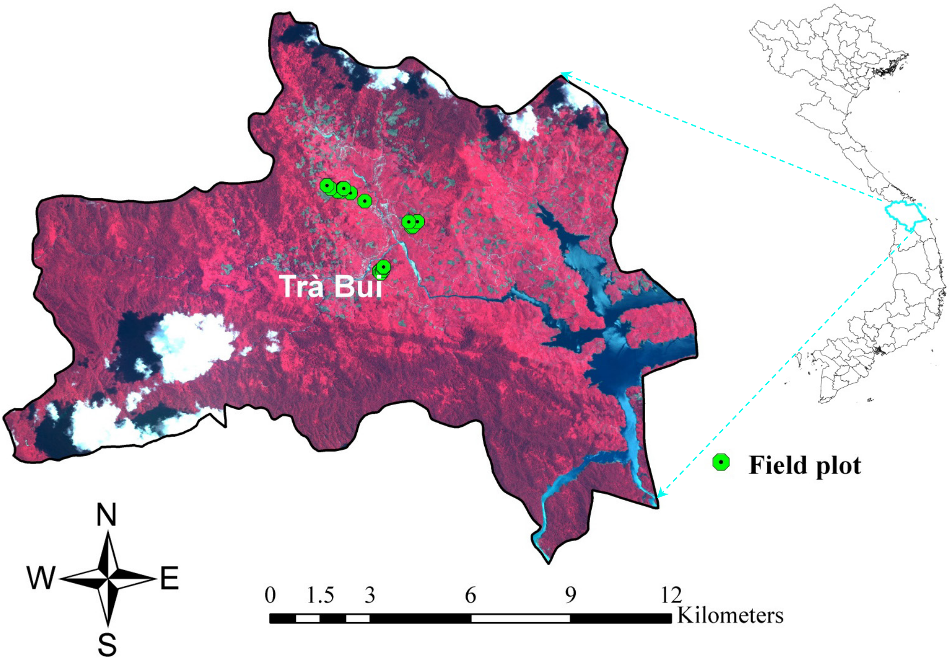


Figure 3.4 The study area overlaid with Spot remote sensing image and community measured field plots.

In order to regain land to cultivate crops the majority of the households have cleared parts of the forest. The following steps were carried out to deploy the prototype:

1) Initially, the questionnaires were designed based on the indicator required to assess the technical capacity of the community members. The questionnaires were used for the collection of data with the techniques of household surveys, interviewing commune leaders, and a participatory workshop based on Participatory Rural Appraisal (PRA) methods (Chambers 1994). More than 80 people were consulted during this process. In the meantime potential organizations were contacted for the collection of necessary documents for the research such as 3G coverage over the study area and the electricity supply time table.
2) User friendly training materials were produced in a local language for the developed technology and methods for acquisitions of data. Community training was conducted before implementation of the program. The training

was meant to enhance the capacity of the community and to envision approaches and strategies for program implementation.

3) A purposive sampling design was used to evaluate the intellectual interaction of the system with the local community within a limited time (Gibbs 2006). Specific types of local knowledge such as accessibility and indicated forest change areas were used as sampling information. Circular biomass plot with 10 m radius were designed in a homogeneous forest area. Diameter at Breast Height (DBH) and tree species of all trees inside the plot were measured. Also, time required to enter the data was recorded. Similarly, forest disturbances were recorded around the disturbed area. A Samsung Galaxy tab 7.0 mobile device, a diameter tape and clinometer were used as measuring equipment.
4) During the implementation, paper-based forms were also used in each location to enter the data. Data entry of each participant was compared to the paper-based data entry. Furthermore, structured interviews were conducted with individual users to receive feedback regarding the data entry interface and overall performance of the system. In total 80 people were interviewed during this process.

3.2.4.2. Comparisons

Two types of comparison data sets were acquired to evaluate the technical skills and measurement quality of the local community. Firstly, local experts (local forest rangers) and national experts (regional/national forest rangers) were trained with the system. Reference measurements were obtained by repeating the entire community measurements (17 biomass plots and 48 disturbance monitoring plots) by local experts. Due to cost constraints, only seven biomass plots and eight disturbance monitoring plots were repeated with national experts. Finally, above ground biomass was estimated from measurements made by local people and experts using biomass allometric equations (Brown 1997). The national forest inventory catalogue was used to covert local names of tree species to scientific names. Secondly, a time-series of high resolution remote sensing images acquired between 2007 and 2011 (pan sharpened SPOT 5 images) were used for this research (Table 3.2), provided by Planet Action for the Land Use and Climate Change Interactions project (LUCCi) in the Vu Gia Thu Bon basin, central Vietnam (Planetaction 2010). Locally reported disturbance monitoring signals were visually interpreted based on the Pohl and Van Genderen approach (Baccini et al. 2008). Following this approach, images were systematically examined and forest disturbed pixels area manually digitized as polygons. The forest disturbed areas were estimated by calculating the polygon area.

Table 3.2 Available SPOT 5 image properties.

Bands	Spectral ranges	Ground resolution
Green	0.50–0.59 μm	2.5 m
Red	0.61–0.68 μm	2.5 m
Near infrared	0.78–0.89 μm	2.5 m

3.2.5. Statistical analyses

Comparisons between measurements of community and local expert values were carried out by simple linear regression where locally measured values were used as the dependent variable and the expert data were used as the independent variable. Linear correlation parameters (r) were calculated, which expresses the strength and the direction of a linear relationship between two variables. Additionally, the Index of Agreement (IA) was computed as described by Willmott (Willmott 1981) (Formula 3.1). IA is standardized measure of the degree of locally observed error and varies between 0 and 1. A value of 0 indicates no agreement at all and 1 indicates a perfect match (Willmott 1981):

$$\mathrm{IA} = 1 - \frac{\sum_{i=1}^{n}(y_i - x_i)^2}{\sum_{i=1}^{n}[|(y_i - \bar{x})||(x_i - \bar{x})|]^2} \qquad (3.1)$$

Where y_i is the i^{th} locally observed value, x_i the i^{th} expert measured value, $\bar{x}$ is the mean of value and n is the number of observation.

3.3. Results and discussion

3.3.1. Technical capacity of the local community

The technical capacity of the local community turned out to be an important factor for deployment of the system. More than 60% of the local people use mobile phones as a daily means of communication. Among them, 12% use the mobile phone for calling, 30% for text messages and calling, 30% for calling, SMS and photography and 18% for calling, SMS, photography and internet.

3.3.2. System performance

The results of system performance in combination with user interactions are reported in Table 3.3, which shows that the accuracy of data entries varies from user to user. Entering data via the text interface produced the highest error rates. Most of the errors were due to double entering of text and symbols on the electronic forms. The visual examination of all the captured multimedia was done manually. The result shows that 89% of captured multimedia by local community and 95% from local rangers have good quality. A common mistake during captured multimedia was that the targeted object was not highlighted correctly. Remarkably, the selection interface options presented no errors by all user types.

Cost is a critical variable for REDD+ implementation. This chapter only considers the implementation cost of the system to monitor the forest. The device cost was not considered for the analysis. A simple cost analysis revealed that the community measurements costs were $1.20 United States Dollar per hectare (ha) whereas local expert costs were $3.2 per ha and the national expert cost $6.40 per ha (Table 3.3). Community measurements costs were significantly lower than expert-based measurements and they are expected to decrease as the size of sampled forest increases.

Table 3.3 Evaluation matrix of data entry types and costs.

User type	**Educational Level**	**Time for training (Hours)**	**Accuracy of data entries (%)**			**Cost of data acquisition ($ per ha)**
			Text/Number (Manual entry)	**Capturing Multimedia**	**Text/Number (Selection option)**	
Local community	Pre-secondary	4	72	89	100	1.20
Local expert	Secondary-University	4	82	95	100	3.20
National expert	University	4	93	100	100	6.40

3.3.3. System evaluation in terms of REDD+ implementation

Figure 3.5 presents the results of the simple linear correlation and error analysis for comparison between local and expert (local forest rangers) measurements. All the indices of agreement are equal or higher than 0.88, indicating a good overall agreement between local and expert measurements. Figure 3.5(a) shows that the number of trees per plot was the parameter with highest agreement between local and expert measurements (IA = 0.97). Figure 3.5(b) indicates that there was good agreement between the total basal area per plot measured by locals and experts (points close to the 1:1 line) for all observations.

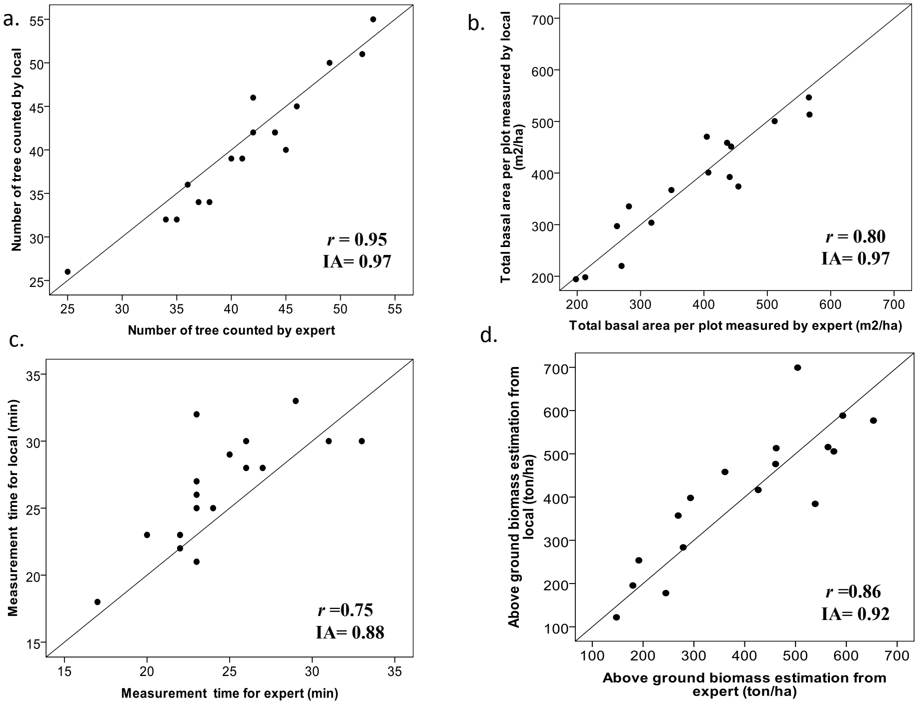


Figure 3.5 Simple linear correlation and error analysis statistics of the comparison between local (dependent variable y) and expert estimated (independent variable x) for: (a) Number of tree, (b) Total basal area per plot, (c) measuring time and (d) above ground biomass estimation. *r* is the linear correlation parameter, and IA is the index of agreement.

The third observation (Figure 3.5(c)) is the difference in measurement time for local people and for expert. It can be observed that local people needed more time than the expert. Finally, the comparison of above ground biomass estimates (Figure 3.5(d)) showed that biomass estimation by experts was on average higher than that estimated by local people. One source of error was related to tree species identification, which was used to estimate wood density and tree biomass: local people always reported the tree species in local name but its conversion to the scientific name was often lacking in the national catalogue.

However, REDD+ is not only about estimation of biomass but also about tracking forest disturbance, which provides an estimate of rates of deforestation and forest degradation. The number of forest disturbance events, their size and the timing of events are recorded by community members and were compared with remote sensing observations. Figure 3.6 shows the comparison of forest disturbance areas due to agriculture expansion captured by the local community and by remote sensing. The estimated areas show that there was high agreement for small and medium events but that local people underestimated a large area deforestation event compared to RS based estimates.

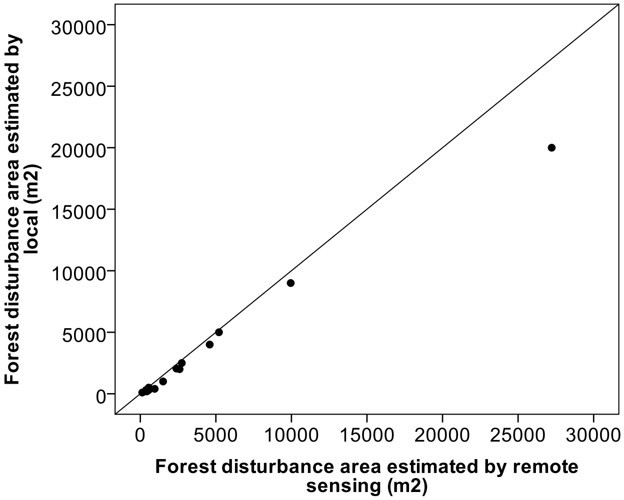


Figure 3.6 Relationship of forest disturbance area estimated by local and SPOT remote sensing image.

Similarly, Figure 3.7 shows the percentage of locally reported forest disturbance events identified through remote sensing. The result shows that only 18% of community reported selective logging events can be visually identified using remote sensing, whereas around 88% of subsistence agricultural expansion was recognised in the satellite data, showing that local people are better able to identify the small scale forest disturbances.

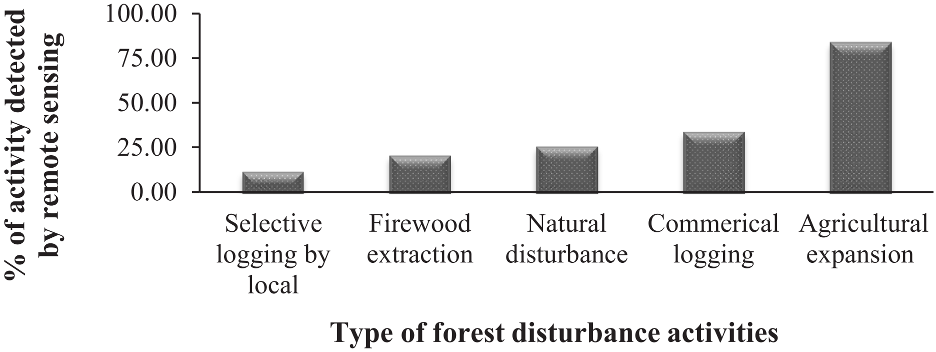


Figure 3.7 Percentage of locally reported forest disturbance types identified through SPOT image.

Finally, remote sensing time-series images were used to quantify the agreement with the disturbance date provided by the local community. Table 3.4 shows the delay in capturing forest disturbance signal by SPOT images. In general, the results show that a delay of 1 to 2 years can occur to capture events of disturbance and that between 14% and 36% of the events identified by the local communities were not detected in the SPOT images, highlighting the need of frequent ground monitoring. Nevertheless, the SPOT image of 2010 has captured 65% forest disturbance. The reason for this could be that the image was acquired immediately after the disturbance and most of the disturbances are due to agriculture expansion.

Table 3.4 Delay in capturing forest disturbance signal by SPOT image.

		Forest disturbance signal captured by SPOT		
	Date	**Detected on same year**	**Delayed detected (up to 2 year)**	**Not detected**
Forest disturbance captured by local communities	2007	16%	48%	36%
	2008	33%	53%	14%
	2009	33%	47%	20%
	2010	65%	20%	15%

3.4. Discussion

3.4.1. Opportunity from a national REDD+ perspective

From a national REDD+ monitoring and implementation perspective, it is important to involve local community groups and societies to carry out forest monitoring, in particular if there is any prospect of payment and credits for environmental services. This study evaluates the role of local communities in measuring above ground biomass and forest disturbance monitoring activities. The results show that the proposed system supports the idea of community-based monitoring (Skutsch and Solis 2011; Skutsch et al. 2011) enabling the capacity of a local community to monitor forest carbon and forest change activities effectively. Communities involvement allows the establishment of 'ownership' in forest management, strengthens their stake in the REDD+ reward system and greatly increase transparency in the sub-national/national governance of REDD finances.

Generally, forest inventory is carried out on the national level to collect ground-based measurements (such as tree height, DBH and tree species) on plots selected through a sampling design, and uses these measurements to estimate forest carbon stocks using allometric relationships (Avitabile et al. 2011; Brown 1997). This process can be expensive and time-consuming and few developing countries have comprehensive forest inventories that allow for national forest carbon stock estimates (DeFries et al. 2007). Experience gained from published studies shows strong agreement between local community and expert measurement in above ground biomass. Earlier studies conducted in Ghana, Tanzania, Nepal and Philippines (Brashares and Sam 2005; Danielsen et al. 2011; Uychiaoco et al. 2005) demonstrated that communities can collect some local forest inventory data adequately and at reduced cost than professional foresters. The results showed that local communities can measure and report the basic tree variables such as DBH, tree species and tree count; and most importantly, they can repeat the measurements on a regular basis. The collected data has proven to be of a level of precision comparable to that produced by professional forest inventory staff.

SPOT remote sensing data of 2.5 meters ground resolution has difficulties to capture small scale forest disturbance activities such as selective logging, firewood extraction and charcoal production by local communities (Ahrends et al. 2010; GOFC-GOLD 2014). The results of this experiment support these findings and indicated low agreement between forest disturbance monitoring through remote sensing and ground data. Therefore, data acquired through local communities can help to verify remote sensing estimates and to signal new changes (even before the remote sensing data are available). Essential information such as location, time, area and type of the forest change events provided by local people can be integrated with remote sensing observations to develop near real-time forest monitoring systems. Furthermore, even a proof of "no change in forest status" is an important finding to ensure that new activities do not negatively affect the carbon performance in REDD+ implementation. Thus, while remote sensing techniques are the main tools used at the national level to detect deforestation, local level community data can be an important input for analysis of deforestation and degradation events. Moreover, the findings also suggest that local community members can acquire large amount of data at relatively low cost.

3.4.2. Advantage of the mobile device system

Traditionally, forest monitoring data are collected through paper-based methods where paper forms are filled in with manually collected data. This leads to difficulties in data translation, digitization and handling, resulting in a lack of confidence in locally collected data. Compared with paper-based methods, the proposed system has the capability of automatically capturing a larger variety of data types such as Geo-location, date, text, audio, video and images through smart phones and PDA devices, adding more flexibility in data collection at the community level.

Cyber Tracker has been widely used under 'Kyoto: Think Global Act Local' (KTGAL) research programme in mapping, measuring and monitoring forest carbon services (Parr et al. 2002). It has the functionality of a user friendly form designer and data synchronization over web. Compared to CyberTracker, the system developed in this study provides easy to add features and low cost of deployment facilities. Furthermore, the proposed system reduces difficulties in data translation and digitization, and reduces the time lag for data to be available for national usage. User friendly data transmission features of the system enable the local community to feed the data directly to the database server.

3.4.3. Limitations of the mobile device system

The proposed system also faces some technical challenges. In general, one major drawback of this system is that it works only on Android based mobile phones. The second general issue is maintaining battery power for mobile devices in remote areas; nevertheless this problem can be now easily be resolved by using solar-powered mobile device chargers, which are now widely available at low cost.

The third is that this approach allows data storing locally on phones which may get lost or damage. One possible solution for this problem is to use higher storage capabilities inside the phone and transfer data from mobile device to a local computer or storage device on a regular basis. The fourth is data entry errors: it is noticed that local people are more accurate in entering information through a sleeting icon or a check box than through manual entering of text or numbers. The interface design may allow reducing this error. The fifth drawback is the cost. Initially, national support is needed to setup the system but the test case of this study shows that the digital data collection through local community offers cheaper and more timely data than the data collected by the experts, while reaching a comparable accuracy. Finally, it can be observed that there is need of technical supervision, trouble shooting and capacity building program for the local community in order to increase the reliability of the results.

3.5. Conclusions and future outlook

In this chapter, we have presented an integrated mobile based data collection system designed for local communities to support forestry data collection for their national REDD+ program. The use of mobile device is a very promising field with exponentially increasing number of sensors and opportunities available in the marketplace and has the potential to increase the efficiency of forest monitoring systems. A prototype application for the community-based monitoring was successfully developed and implemented in an ethnic minority community of Vietnam. The proposed system was able to facilitate data acquiring, storing, transmitting and displaying by local people.

In order to achieve an added value for CBM, system performance was evaluated in terms of data accuracy and cost. The comparison of community acquired forest inventory data and estimated above ground biomass with professional expert measurements showed that the local communities are able to acquire data with accuracy comparable to data acquired by an expert, but against lower costs. Furthermore, the disturbance monitoring activity of local people was examined with high resolution SPOT image. The results confirm that communities are more effective than remote sensing to monitor small scale forest degradation due to, for example, subsidence fuelwood collection or selective logging.

The presented system is able to support the acquisition of CBM data that can be directly linked to national MRV in the prospect of data demand, supply, management, reporting and quality assurance. Further development of the presented approach will focus on the establishment of an integrated two way data synchronization system for exchange of information between client and server. In such systems, the acquired data will be linked with cloud computing and it will be possible to deliver near real-time forest monitoring services.

Acknowledgements

The authors gratefully acknowledge support of the DAAD funded Center for Natural Resources and Development (CNRD), Germany and the project Land use and climate change interactions in Central Vietnam (LUCCi). Authors also like to thanks Planet Action (Planetaction 2010) for providing SPOT 5 satellite images for this research.

Chapter

4

Combining satellite data and community-based observations for forest monitoring

*Arun Kumar Pratihast, Ben DeVries, Valerio Avitabile, Sytze de Bruin,
Lammert Kooistra, Mesfin Tekle and Martin Herold*

Published in Forests, Volume 5, Issue 10, October 2014, Pages 2464-2489

Abstract

Within the Reducing Emissions from Deforestation and Degradation (REDD+) framework, the involvement of local communities in national forest monitoring activities has the potential to enhance monitoring efficiency at lower costs while simultaneously promoting transparency and better forest management. We assessed the consistency of forest monitoring data (mostly activity data related to forest change) collected by local experts in the UNESCO Kafa Biosphere Reserve, Ethiopia. Professional ground measurements and high resolution satellite images were used as validation data to assess over 700 forest change observations collected by the local experts. Furthermore, we examined the complementary use of local datasets and remote sensing by assessing spatial, temporal and thematic data quality factors. Based on this complementarity, we propose a framework to integrate local expert monitoring data with satellite-based monitoring data into a National Forest Monitoring System (NFMS) in support of REDD+ Measuring, Reporting and Verifying (MRV) and near real-time forest change monitoring.

Keywords

REDD+; MRV; national forest monitoring system; community-based monitoring; citizen science; remote sensing; accuracy assessment; Kafa; Ethiopia

4.1. Introduction

Forests cover approximately 30% of the Earth's land surface and are of immense value to humankind, as they provide habitats for a wide variety of species and play an important role in the global carbon cycle (Gullison et al. 2007; Hansen et al. 2013). However, a loss of approximately 2101 square kilometres of tropical forests per year (Hansen et al. 2013) has made a significant contribution to the increase of greenhouse gases (GHGs) in the atmosphere, resulting in accelerated global warming (Gullison et al. 2007; IPCC 2006). To mitigate this effect, the United Nations Framework Convention on Climate Change (UNFCCC) has proposed an international mechanism called Reducing Emissions from Deforestation and Degradation (REDD+) in developing countries (Gullison et al. 2007; UNFCCC 2009). The REDD+ mechanism includes reducing deforestation and forest degradation, forest enhancement, sustainable forest management and conservation (UNFCCC 2010b). Recently, the 19th Conference of Parties (COP) of the UNFCCC in Warsaw, November 2013, agreed on a collection of seven decisions on REDD+ (UNFCCC 2013). Together with the REDD+ decisions adapted at previous COPs, these decisions provide international policy guidance (the Rulebook on REDD+) on how countries should deal with REDD+ in the framework of the UNFCCC (UNFCCC 2013). Besides reduction of carbon emissions, the REDD+ mechanism also includes establishment of national institutions, ensuring co-benefits and safeguards and, above all, creating performance based financing mechanisms (Danielsen et al. 2011; GOFC-GOLD 2014; IPCC 2006).

A country participating in REDD+ requires a reliable, transparent and credible national level forest monitoring system (NFMS) for Measuring, Reporting and Verifying (MRV) activity data and emission factors (GOFC-GOLD 2014; Herold and Skutsch 2011; Sanz-Sanchez et al. 2013). Activity data is defined as the magnitude of human activity resulting in emissions or removals. In the case of forest related emissions and removals, activity data refers to forest area change (generally measured in hectares), whereas the emission factor is related to the rate of emission of a given GHG from a given source, relative to units of activity (generally measured in tons of carbon per hectare) (IPCC 2006). Given that forest change is a dynamic process, monitoring needs to be carried out on a regular basis to support national MRV requirements. Establishing such monitoring systems is presumed to be expensive for developing countries (Bucki et al. 2012; GOFC-

GOLD 2014; Romijn et al. 2012; Visseren-Hamakers et al. 2012). An activity monitoring system should be based on four broad monitoring objectives related to the location, area, time and drivers of forest change. These objectives should be properly integrated with monitoring and MRV systems at the national level. Current schemes for monitoring these activities are based on remote sensing and field measurements mainly from national forest inventories.

Remote sensing has proven to be very useful for deforestation monitoring at the global, national and subnational scale (Achard et al. 2010; De Sy et al. 2012; DeVries and Herold 2013; Hansen et al. 2013). However, remote sensing based monitoring of forest degradation and regrowth still remains problematic (Achard et al. 2006; DeFries et al. 2007; Vargas et al. 2013), due to cloud cover, seasonality and the limited spatial and temporal resolution of remote sensing observations. Enhancing the interpretation of remote sensing analyses requires substantial ground verification and validation (Strahler et al. 2006). Accomplishing these tasks through national forest inventory data is expensive, time-consuming and difficult to implement across large spatial scales (Gibbs and Herold 2007; Tomter et al. 2010).

Community-based monitoring (CBM) is an emerging alternative method for forest change monitoring that promises to be cheaper than conventional monitoring methods (Danielsen et al. 2011; Pratihast et al. 2013; Skutsch et al. 2011; Skutsch et al. 2014). CBM methodologies can be organized into two main categories: (i) forest carbon stock measurements for emission factors and (ii) forest change monitoring for activity data. Results from well-designed forest carbon measurement studies (Danielsen et al. 2013; Pratihast et al. 2012; Shrestha 2011; Topp-Jørgensen et al. 2005) have demonstrated that local datasets are comparable to professional measurements, while being cheaper to obtain. Furthermore, CBM can be considered as a tool to empower the local communities and raise awareness towards better forest management (Fry 2011; Lawlor et al. 2013).

While CBM-based forest carbon stock measurement has been shown to be feasible (Danielsen et al. 2013; Topp-Jørgensen et al. 2005), monitoring of forest change through CBM has not been thoroughly investigated yet. Forest change monitoring is a continuous process, which requires continuous data acquisition and local communities may act as active in situ sensors (Goodchild 2007). Their local knowledge could be especially valuable in signalling forest change activities (deforestation, forest degradation or reforestation) and providing valuable information, such as location, time, size, type and proximate drivers of the change events on a near real-time basis (Skutsch et al. 2011). The impacts of these activities are rarely captured comprehensively in national forest inventories or from remote sensing (Danielsen et al. 2011; GOFC-GOLD 2014; Pratihast et al. 2013). The recent development of hand-held technologies continues to improve and has significantly enhanced the local capacity in data collection procedures (Pratihast et al. 2012). Data acquired by communities can therefore play an essential role in enhancing the efficiency and lowering the cost of monitoring activities, while simultaneously promoting transparency and better management of forests. Thus, local participation within monitoring programs holds promise for national REDD+ MRV implementation.

Despite the potentials of CBM, the main challenge of using locally collected data lies in the lack of confidence in data collection procedures (Fry 2011). The accuracy and reliability of such datasets are often questionable due to inconsistencies arising from the fact that local participants collect data independently of each other. This can further result in incomplete data collection and a biased representation of changes in a study area (Danielsen et al. 2010). Therefore, data credibility and trustworthiness are major obstacles to the integration of CBM data in NFMS (Conrad and Hilchey 2011; Skarlatidou et al. 2011). This fact has triggered us to rectify the current shortcomings and expand the current state of knowledge in community-based forest monitoring and its utility in NFMS. Specifically, we aim to check the consistency of local datasets and investigate their complementary use to remote sensing.

The purpose of this research is to discover new perspectives and insights into community-based observations. The aims of this chapter are to: 1) present the details of a local expert-based forest monitoring system, 2) assess the spatial, temporal and thematic accuracy of local expert data against independent field-based measurements and high resolution SPOT and RapidEye satellite imagery and 3) explore the complementarity of local expert data with remote sensing data. While the UNESCO Kafa Biosphere Reserve in Southwestern Ethiopia is shown here as a case study, the concepts presented in this study are applicable to a broader geographic scope and can be scaled up to the national level in support of NFMS and REDD+ MRV.

4.2. Material and methods

4.2.1. Study area description

The study area is situated in the Kafa Zone, Southern Nations Nationalities and People's Region (SNNPR), in Southwestern Ethiopia (Figure 4.1). The Kafa Zone is over 700,000 ha in size and was recognized as a Biosphere Reserve by UNESCO's Man and the Biosphere (MaB) program in March, 2011. This region is characterized by Afromontane cloud forest, with approximately 50% of the land cover still forested. Average annual precipitation in the area is approximately 1700 mm and average annual air temperature is approximately 19°C (Schmitt et al. 2010). The topography of the Kafa Biosphere consists of mountains and undulating hills, with elevations ranging between 400 to 3100 m. The forest ecosystem provides an important contribution to the livelihoods of the people in the area, including wild coffee, valuable spices and honey from wild bees. It also represents a significant store of forest carbon as above ground biomass.

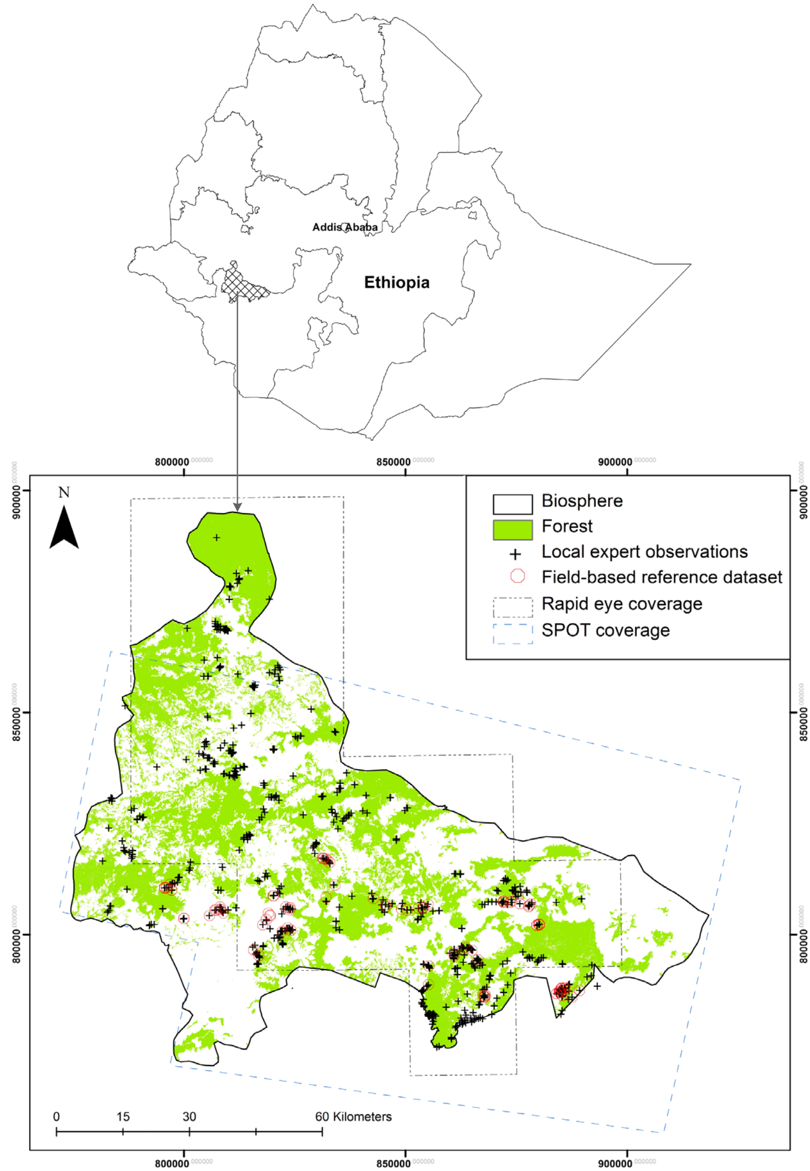


Figure 4.1 Study area in the UNESCO Kafa Biosphere Reserve, Southwestern Ethiopia; local expert observations (black crosses) were compared with a field-based reference dataset (red circles) and high resolution remote sensing data from the SPOT (footprint shown as a blue dotted line) and RapidEye (footprint shown as a black dotted line) sensors.

4.2.2. Description of the forest monitoring system in the Kafa biosphere reserve

The According to REDD+ monitoring and implementation guidelines, it is important to involve local community groups and indigenous societies to carry out forest monitoring, in particular if there is any prospect of payment and credits for environmental services (Lawlor et al. 2013; Stickler et al. 2009; UNFCCC 2013). A variety of practical experiences from developing countries such as Nepal, Tanzania, Cameroon, India, Mexico, Indonesia, China, Laos, Cambodia and Vietnam, have demonstrated that local communities can play an essential role in forest monitoring and management programs (Danielsen et al. 2013; Danielsen et al. 2011; Pratihast et al. 2012; Ratner and Parnell 2011; Shrestha 2011; Topp-Jørgensen et al. 2005). However, most of these experiences are limited to carbon stock measurements in support of REDD+ MRV, with few prescribed field methods for establishing activity monitoring (forest change) on the ground (Pratihast et al. 2012; Skutsch et al. 2011). In this study, we present a ground-based system to monitor activity data because of their increasing importance in the context of REDD+. The following setup was designed to contribute an efficient and continuous forest monitoring system for the Kafa Biosphere Reserve.

Selection of local experts: Selection and recruitment of local experts acts as the backbone for a forest monitoring system, as the success of these CBM systems largely depends on the knowledge, commitment, feeling of ownership and competencies of these individuals (Danielsen et al. 2005). The selection process featured in this study is based on a scheme of collaborative design of monitoring with external interpretation of the data, one of five schemes of local involvement in monitoring proposed by Danielson et al. (2009). A total of 30 local experts were recruited within the frame of the project called “Climate Protection and Primary Forest Preservation—A Management Model using the Wild Coffee Forests in Ethiopia as an Example” under the Nature and Biodiversity Conservation Union (NABU). The recruitment was done through the Kafa Zone Bureau of Agriculture and Rural Development (BoARD). The selection was done in such a way that it represents on average three experts from each of the 10 Woredas (administrative units in Ethiopia). All chosen local experts had at least a secondary level of education and some fundamental understanding of forest management. This selection procedure was seen as a step towards greater community involvement in monitoring activities with the representatives involved from all Woredas, assuring the potential for significant enhancement of the monitoring capacity of the project. Apart from monitoring, these experts also bear responsibilities for other project activities, such as the development of ecotourism, reforestation, community plantations, the distribution of energy saving stoves and awareness raising for the sustainable use of forest resources (e.g., honey and wild coffee).

Data acquisition: Two methods of data acquisition were implemented and tested in this study. In the first method, paper-based forest disturbance forms with GPS devices were used by local experts to acquire forest monitoring data. The data collection forms were designed primarily with project monitoring objectives in mind, but also were compliant with REDD+ MRV requirements. This form focused on capturing forest changes, including small scale forest degradation, deforestation and reforestation. In the second method, mobile devices with integrated GPS and camera functionality were used to increase the ease and simplicity in collection, entering and managing locally acquired data. For this purpose, a decision-based data collection form (Figure 4.2) was designed in XML and was deployed on mobile devices using the Open Data Kit (ODK) Collect application (OpenDataKit 2012). This form contains optional input constraints, flows that depend on previous input, icon-based user friendly graphics and local language support. Mobile devices stored the data asynchronously and transferred data to data servers over GPRS, Wi-Fi or USB, as connectivity was available. An online database management system based on ODK Aggregate, postgreSQL and PhP was designed for the proper storage, analysis and visualization of the acquired data. Further details of the adapted proposed data acquisition method can be found in Pratihast et al. (2012). A paper-based data acquisition system was used in 2012, whereas mobile devices were used to collect the data in 2013. Even though the tools used to acquire data were different, the overall form of the design was consistent, with a few key differences in terms of multimedia features.

Training and capacity building program: user friendly training materials were produced for the developed technology and data collection methodology. A series of training events was conducted before and during the implementation of the monitoring activities. The main purpose of training was to enhance the capacity of local experts and to develop approaches and strategies for program implementation.

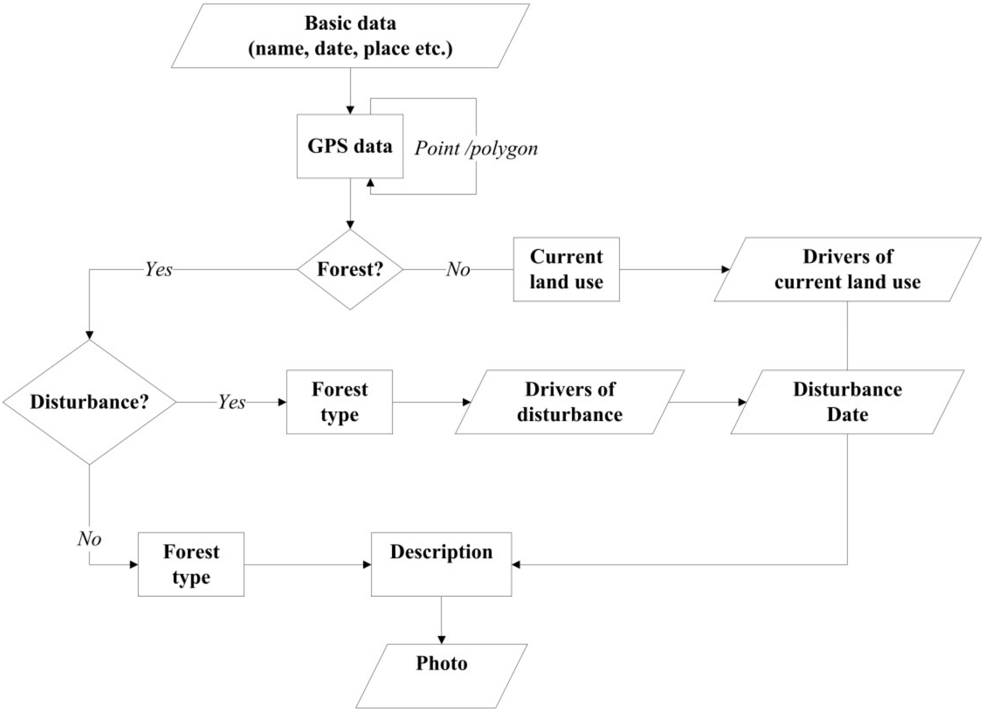


Figure 4.2 Decision-based data acquisition form for local experts; the questions that are posed in the forms depend on answers given to preceding questions; such a design ensures that the questions are relevant to the land cover change being described.

4.2.3. Reference datasets

Local experts are capable of reporting forest change process at a high temporal frequency. Finding suitable reference data that can thoroughly assess the spatial, temporal and thematic accuracy of these data is difficult, however. In this study, two types of accurate reference datasets were acquired to evaluate the accuracy of these local expert data: field-based reference dataset (FRD) and remote sensing (RS).

Field-based reference dataset (FRD): we conducted a field visit in order to validate the ground data collected by local experts. Due to cost constraints, it was not possible to visit all locations reported by local experts. We selected six accessible Woredas owing to practical considerations. These Woredas contain more than 65% of the local expert data. Within these Woredas, 140 locations (Figure 4.1) were randomly selected and were revisited during November–

December, 2013, by a team of professionals. The decision-based data acquisition form on the mobile devices (Figure 4.2) was used by the team of professionals to measure location, size, time, drivers and photographs of change events.

Remote sensing (RS): a time-series of high resolution remote sensing images acquired between 2005 and 2013 (including pan-sharpened SPOT and RapidEye images) were available for the analysis of reference data (Table 4.1) in the study area (Figure 4.1, Table A4.1 in the Annex). The SPOT 4 and SPOT 5 imagery have a ground resolution of 10 m and 2.5 m, respectively, whereas RapidEye has a ground resolution of 6.5 m. Locally-reported forest monitoring locations were visually interpreted based on an approach described by Pohl and Van Genderen (1998). Following this approach, images were systematically examined and pixels representing forest change areas were manually digitized as polygons. The forest change areas were estimated by calculating the polygon area.

Table 4.1 Summary of the SPOT and RapidEye scenes used in this study.

Sensor	Ground resolution	Year of acquisition	Number of scenes
SPOT 4	10 m	2005–2006	6
SPOT 5	2.5 m (Pan sharpened image)	2007–2011	8
RapidEye	6.5 m	2012–2013	27

4.2.4. Accuracy assessment

Several metrics have been proposed by researchers to describe the quality of geographic data (Castro et al. 2013; Devillers et al. 2007; Haklay 2010). However, no specific list of elements with a consistent definition has yet been agreed upon. The latest attempt to standardize data quality elements is ISO 19113 in 2002 (ISO/TC211 2002), which proposes the following five elements: completeness, logical consistency, positional accuracy, temporal accuracy and thematic accuracy. In this study, we limited the quality assessment to three of these major categories, namely spatial, temporal and thematic accuracy, since these are essential aspects of forest monitoring datasets (GOFC-GOLD 2014). The details of the accuracy measures employed in this study are listed in Table 4.2.

Table 4.2 Specific approaches used to assess the spatial, temporal and thematic accuracy of local expert data.

Category	Measured variable local expert data	Reference data	Measures of accuracy
Spatial Accuracy	Location variables (Qualitative) GPS accuracy Size of forest change	Field based	Confidence interval (95%)
Temporal Accuracy	Time of change	Remote sensing	Time lag
Thematic Accuracy	Presence of forest Forest change type Driver of forest change	Field based	Error matrix

4.2.4.1. Spatial accuracy

In this study, three aspects of the spatial accuracy of the local experts' data were assessed, including categorical location information, GPS location information and the estimated size of forest change. The categorical location information included categories for representing the administrative units, like Woreda, Kebele (administrative sub-unit of a Woreda) and a spatial category representing distance to core forest, nearest village and roads (i.e. less than 1 km, 1–2 km, 2–3 km and more than 3 km). To estimate the accuracy of these responses, comparisons were made between the local expert data and the FRD. From this sample, the fraction of correct observations in the total population of local expert reports was estimated using the hypergeometric distribution (Johnson et al. 2005), a discrete probability distribution that describes the probability of obtaining a correct response from a finite population size without replacement. The 95% confidence interval was calculated by using the 0.025 and 0.975 quantiles of this distribution.

In addition to the categorical location descriptors, local experts provided GPS readings for each report. Each reading was associated with a measurement error reported by the GPS receiver. The GPS measurement errors in the local expert dataset were compared with measurement errors in the FRD using a *t*-distribution (Johnson et al. 2005). Using this distribution, the mean bias (with 95% confidence interval) and the standard deviation between the local expert and FRD GPS errors were calculated.

Finally, the size of forest change polygons mapped by local experts were compared with change polygons digitized from visually interpreted high resolution SPOT and orthorectified RapidEye time-series imagery. Forty deforestation polygons falling within the spatial extent of the SPOT and RapidEye time-series were selected. The relationship between the size of field-delineated change areas and polygons digitized from high resolution imagery was evaluated using a *t*-distribution.

4.2.4.2. Temporal accuracy

Recording the timing of forest change is essential for the implementation of a robust forest monitoring system. Assessing the temporal accuracy of local monitoring data remains a challenge due to a lack of reference time-series imagery of sufficient temporal density and spatial resolution that can describe disturbances in near real-time (Kennedy et al. 2007; Schroeder et al. 2011). To overcome this limitation, only the area for which time-series images of SPOT and RapidEye were available (Table 4.1) was used for this analysis. Here, a visual interpretation of the time-series of satellite images for each local data set was carried out and the time of forest disturbance was estimated for each data set. Furthermore, a temporal lag between the reference satellite datasets and local expert datasets was calculated to determine the average time delay or temporal lag of deforestation (Equation 4.1):

$$\text{Temporal lag} = (\text{Year of detection by remote sensing} - \text{Year of detection by local experts}) \quad (4.1)$$

4.2.4.3. Thematic accuracy

Attributes, such as the presence or absence of forest, forest change type and drivers of forest change were included in the assessment of thematic accuracy. The accuracy of these variables was assessed by comparing local expert dataset with the field-based reference dataset. An error matrix was produced for each category and used to derive producer's accuracy, user's accuracy and the overall accuracy (Foody 2002).

4.3. Results

4.3.1. Characteristics of local monitoring data

4.3.1.1. Attributes of the local expert monitoring data

Local experts are capable of systematically monitoring forest change. In this study, we focused on deforestation and forest degradation processes to illustrate the major attributes of the data collected by local people (Figure 4.3, Table 4.3). The results show that local experts have documented forest change processes, which include spatial (location and size), temporal (time of change events) and thematic (type of change, driver of change and photograph from the North, East, West and South directions) information. Furthermore, deforestation, the conversion from forest to non-forest land (GOFC-GOLD 2014), and forest degradation, negative changes in forest biomass without conversion to another land cover type, could be mapped separately using data provided by local experts (Figure 4.3). In this case, local experts tried to delineate exact deforestation areas from the ground by recording multiple GPS location around the boundary (Figure 4.3a). On the other hand, forest degradation is a gradual process without a fixed boundary (GOFC-GOLD 2014) and could therefore not be mapped with such precision. In such cases, local experts provided the central location and approximate area affected rather than an exact change polygon (Figure 4.3b).

4.3.1.2. Monitoring frequency

During the period of January, 2012, to December, 2013, a total of 755 locations were observed (Figure 4.4). Of these, 46% were labelled as forest degradation, 25% as deforestation and 30% as reforestation. All data in 2012 were acquired using paper forms with hand-held GPS devices, whereas in 2013, data were acquired using mobile devices. In general, local observations were spread equally over the whole Biosphere Reserve (Figure 4.1). However, monitoring efforts were not consistent throughout the year (Figure 4.4). Irregularities in monitoring activities were influenced by a wide range of factors, including the timing of training and capacity building programs and adverse weather conditions. The number of received monitoring forms (in 2012) and digital observations (in 2013) increased during training and capacity building program (January to March), while it decreased during the rainy season (July to September).

4.3.1.3. Drivers of forest change

Drivers of forest change were mostly associated with agriculture expansion and settlement expansion, followed by charcoal and firewood extraction, intensive coffee cultivation, timber harvesting and natural disasters, which mainly included landslides erosion and windfall. Many of the drivers were found to co-occur at a single location (Table 4.4). In the case of agricultural expansion, 34 of the events were attributed to agriculture expansion alone, whereas 185 events were attributed to agriculture expansion together with charcoal and fire wood collection and 61 of those changes were found to be due to the co-occurrence of agriculture expansion and timber harvesting. This observation is logical considering that agriculture expansion in Kafa Biosphere Reserves is in fact a gradual process coupled with forest degradation. After demarcation of a portion of forest area for agricultural development, a farmer commonly keeps much of the forest for the first couple of years to harvest coffee, spices, fuelwood, charcoal and timber, before the forest is fully cleared to make way for agricultural activities.

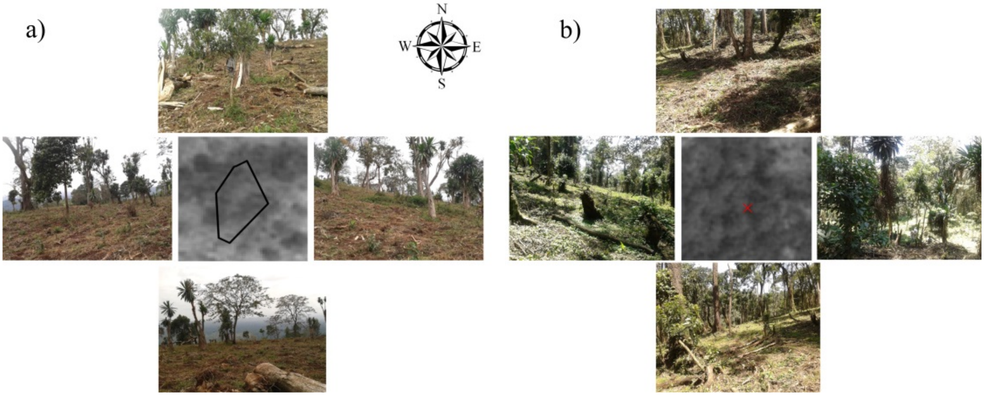


Figure 4.3 Examples of (a) deforestation monitoring and (b) forest degradation monitoring by local experts; observations were mapped either as polygons (a) or point (b) features, depending on the process being described; each form was accompanied by four photos representing the north, east, south and west perspectives; the attribute tables associated with these observations are shown in Table 4.3.

Table 4.3 Attribute tables derived from local expert observations of deforestation and forest degradation (shown in Figure 4.3a and 4.3b respectively).

Category	**Measured Variables**	**Value of Deforestation (Figure 4.3a)**	**Value of Forest Degradation (Figure 4.3b)**
Spatial	Woreda	Gawata	Gawata
	Kebele	Ganty	Ona
	Distance to road	More than 3 km	1–2 km
	Distance to nearest village	1–2 km	1–2 km
	Distance to core forest	More than 3 km	More than 3 km
	GPS coordinates (latitude, longitude)	7.53, 35.84	7.54, 35.81
Temporal	Disturbance date	03-18-2013	03-18-2005
Thematic	Disturbance type	Deforestation	Forest degradation
	Driver of disturbance	Agriculture expansion, timber harvesting and firewood	Coffee cultivation, timber harvesting and firewood
	Size of disturbance	2 ha	4 ha

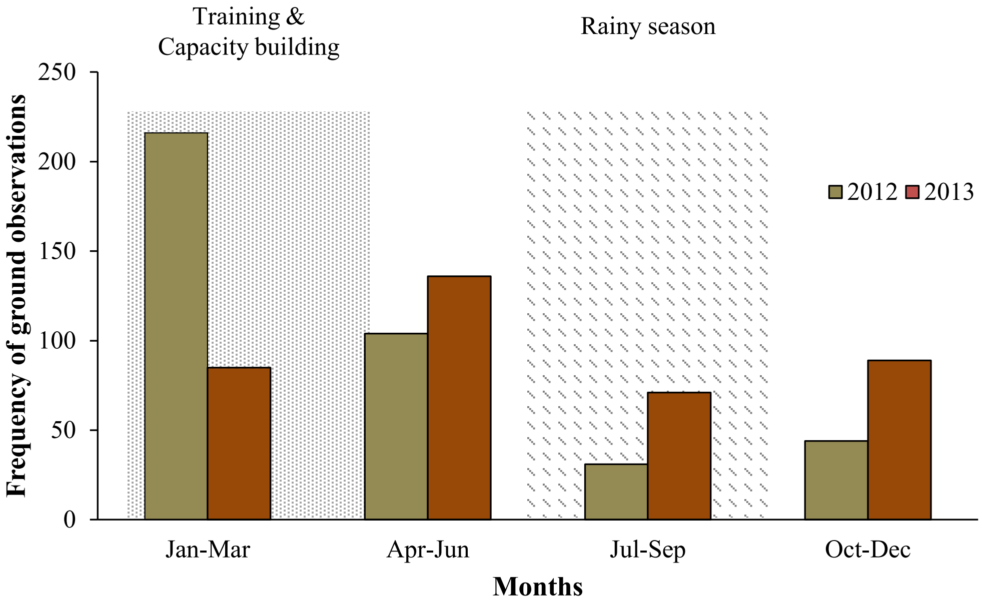


Figure 4.4 Number of observations collected by local experts in 2012 and 2013; all observations in 2012 were acquired using an analogue (paper-based) system, whereas observations acquired in 2013 were collected using either analogue or digital (smart phone-based) methods.

Table 4.4 Number of instances of the co-occurrence of forest change drivers. Numbers along the diagonal indicate the number of instances that a particular driver was reported alone.

Number of occurrences	**Forest change drivers**					
	Agriculture expansion	**Settlement expansion**	**Charcoal and fire wood**	**Intensive coffee cultivation**	**Timber harvesting**	**Natural disaster**
Agriculture expansion	34					
Settlement expansion	48	42				
Charcoal and fire wood	112	75	57			
Intensive coffee cultivation	0	55	76	19		
Timber harvesting	61	70	44	10	15	
Natural disaster	13	17	2	1	2	2
Total	268	259	179	30	17	2

4.3.2. Results on accuracy assessment

4.3.2.1. Spatial accuracy

A breakdown of the estimated fraction correct of assigned spatial categories with a 95% confidence interval is shown in Table 4.5. The spatial accuracy varied considerably across the various spatial categories included in the monitoring forms. The Woreda was recorded with the highest mean fraction correct of 0.92, whereas the estimated distance to core forest was found to have the lowest mean fraction correct of 0.71.

Table 4.5 Fraction correct of local data assignment to spatial categories.

Spatial category	**Fraction correct**	
	Mean	**Confidence interval (95%)**
Woreda	0.92	0.88 to 0.96
Kebele	0.78	0.72 to 0.84
Distance nearest village	0.77	0.71 to 0.83
Distance nearest road	0.75	0.68 to 0.81
Distance to core forest	0.71	0.64 to 0.77

A comparison of GPS errors reported by local experts with those reported in the FRD showed a slight systematic error of 0.65 m between the two datasets (Table

4.6). A similarly slight bias was found between forest change areas as reported by the local experts and forest change areas derived from high resolution remote sensing imagery, in cases where these areas did not exceed 2 ha (Table 4.6). In larger change areas (exceeding 2 ha), however, the absolute bias increased to 1.06, implying that local experts had systematically underestimated the area of large change polygons.

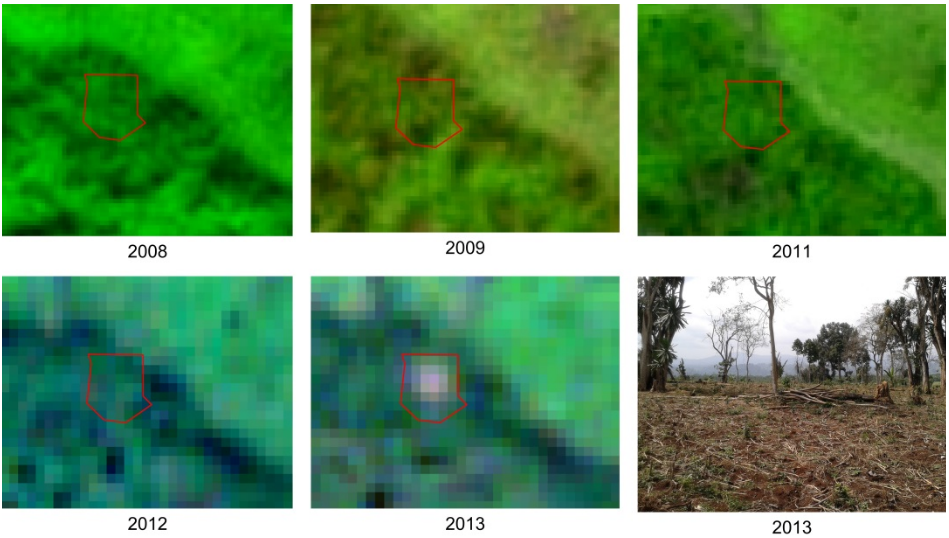
Table 4.6 Positional accuracy of local expert data.

Measure	Mean bias	Standard deviation	Confidence interval for mean bias (95%)
GPS error (m)	0.65	1.79	0.62 to 0.68
Size of forest change (ha); polygons <2 ha	0.16	0.29	0.13 to 0.20
Size of forest change (ha); polygons >2 ha	−1.06	1.26	−1.28 to −0.85

4.3.2.2. Temporal accuracy

Each forest change event was recorded by local experts with a time stamp that represents the time at which the process of change took place. In total, 40 deforestation and 60 degradation locations were visually assessed from high resolution remote sensing (SPOT and RapidEye) imagery. An example of the visual interpretation of high resolution time-series of SPOT5 (2008–2010) and RapidEye imagery (2012–2013) is shown in Figure 4.5. The locally mapped polygon is displayed at the center of each subset of image. The interpretation shows that the forest cover was significantly reduced after 2012.

The histogram of the temporal accuracy of locally determined change dates compared to high resolution imagery for deforestation and forest degradation is shown in Figure 4.6. Here, a positive temporal lag indicates that local experts indicated a change date earlier than that determined using remote sensing data and a negative time lag indicates the reverse situation. The results reveal that 33% of deforestation events reported by local experts corresponded accurately to the dates observed in the remote sensing data. In other cases, 25% and 20% of total deforestation events as observed from remote sensing were detected one and two years earlier than the local reported time, respectively (Figure 4.6). On the other hand, the comparison of dates associated with forest degradation as reported by local experts shows that the majority of these signals were recorded one (32%) to two (22%) years earlier than dates detected by remote sensing.



2008 2009 2011

2012 2013 2013

Figure 4.5 Example of visual interpretation to assess the temporal accuracy of the local expert dataset; the image subset is based on SPOT5 data from 2008 to 2011 (red = Band 3, green = Band 1, blue = Band 2) and two RapidEye images from 2012 and 2013 (red = Band 3, green = Band 2, blue = Band 1); a ground photograph taken by a local expert in 2013 is also shown; the red polygon is the forest change mapped by a local expert; the forest change occurred between 2012 and 2013.

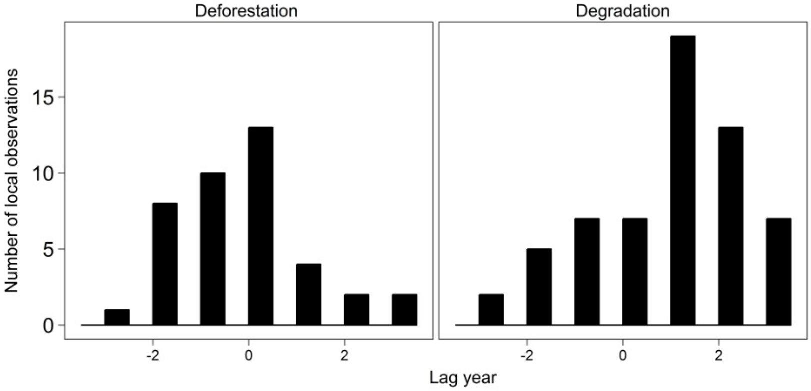


Figure 4.6 Histogram of time lags in capturing deforestation (left) and forest degradation by remote sensing (SPOT and RapidEye) imagery (right); a time lag is defined as the difference between change dates observed from remote sensing image interpretation and those dates recorded by local experts.

4.3.2.3. *Thematic accuracy*

Thematic information is one of the added values of the local expert dataset compared to remote sensing. Summaries of the accuracy assessment of three thematic elements (the presence of forest, forest change type and drivers of forest change) are shown in Table 4.7.

Table 4.7 Accuracy assessment of local expert data compared to field-based reference dataset in the thematic domain.

Elements	User accuracy	Producer accuracy	Overall accuracy
Presence of forest	93%	92%	94%
Forest change type	83%	84%	83%
Driver of forest change	71%	68%	69%

The results show an overall accuracy of 82% for thematic elements compared to the field-based reference dataset. The presence of forest was found to have a producer's accuracy of 92%, a user's accuracy of 93% and an overall accuracy of 94%. The drivers of forest change had a comparatively lower producer's accuracy of 71%, a user's accuracy of 68% and an overall accuracy of 69%.

4.4. Discussion

4.4.1. Local expert-based forest monitoring system

The establishment of robust and reliable NFMS in developing countries is an expensive and challenging task. Several studies have shown that CBM has the potential to increase the saliency, credibility and legitimacy of such forest monitoring systems (Danielsen et al. 2013; Danielsen et al. 2014; Danielsen et al. 2011; Fry 2011; Shrestha 2011; Topp-Jørgensen et al. 2005). However, current studies do not clearly describe the following aspects of forest change monitoring (related to activity data): 1) the long-term operational procedures of community involvement, 2) technology selection, 3) consistency of local datasets and 4) complementarity with remote sensing data. In this regard, we demonstrate an operational forest monitoring system that includes local expert activity monitoring data in the UNESCO Kafa Biosphere Reserve, Southern Nations, Nationalities and People's Region (SNNPR), Ethiopia. In general, our monitoring setup allows local experts to collect forest change variables, such as geo-location, size of forest change, time of forest change and proximate drivers behind the change, in more detail. Similar to previous studies (Bowler et al. 2011; Pratihast et al. 2012), we also found that the use of mobile devices has a clear advantage over a paper-based system in capturing photographs and multimedia information from the ground and improves the local capacity in data collection, transmission and visualization procedures (Figure 4.3 and Table 4.3). Furthermore, our results show that these datasets are fully structured in terms of spatial, temporal and thematic detail and capable of describing the forest change process well. While our results are based on a local case study, these monitoring activities have the potential to be scaled up to the national level and integrated with an NFMS.

The local expert-based forest monitoring system in this study faced some critical barriers, such as systematic coverage and consistency in monitoring frequency. Our results show that 53% of the local data were collected within 1 km of the local road network, hindering systematic coverage of the study area. This restriction is a result of poor road infrastructure or a lack of transportation means. A recent study in Southwestern Ethiopia has shown that most forest change occurs in remote locations far from urban areas (Getahun et al. 2013), suggesting that much of these changes could not be fully captured by local experts alone. This mobility barrier could be overcome by engaging local communities who live near the forest areas of interest.

We also observed that the frequency of local data collection depends largely on weather conditions and motivations towards monitoring activities. A decrease in data acquisition was seen during the rainy season, indicating that weather has a significant impact on the mobility of local people. This reduction in data frequency may also be due to a decrease in disturbance activities by farmers during this time. The motivation can be triggered by providing local experts with adequate incentives for conducting monitoring activities even during adverse weather conditions and also providing them with the necessary accessories and travel means. Regular training and capacity building programs should also be conducted to keep the local experts updated. While such initiatives in motivating the local experts towards efficient monitoring may not fill the data gap completely, they could help to substantially increase the commitment and long-term engagement of local people towards monitoring.

4.4.2. Critical review on the accuracy of local datasets

In this study, we assessed the spatial, temporal and thematic accuracy of the local expert dataset. Identifying the factors influencing these accuracies is important to understanding the role that this dataset can play in a forest monitoring system. The main influencing factors are explained in detail below.

4.4.2.1. Spatial accuracy

Spatial accuracy was influenced by three main factors: interpretation of administrative boundaries, GPS errors and failure to map full polygons. First, the administrative boundaries are not always visible on the ground. Local experts may incorrectly interpret these boundaries when they are away from their own villages. This error might be solved by providing base maps prepared by an Ethiopian mapping agency and regional governments during field work, which may contain the updated information regarding these administrative layers.

Second, GPS location error arises due to the weak signal caused by dense forests and high slopes. Mobile devices used in this study achieve maximum GPS accuracy by taking the average measurement from all available satellites reached in a given time. GPS accuracy could be improved by using averaging positional measurements over a longer period of time (Sigrist et al. 1999).

Third, the area of change estimated by local experts was found to be biased due to difficulties in mapping large change polygons in the field. When an insufficient number of polygon vertices was mapped by the local experts, resulting polygons were smaller than those delineated by visual interpretation from remote sensing imagery, giving rise to a negative bias in field-based area estimations. These errors could be avoided by implementing a visualization feature in the mobile device based forms, whereby local experts can see the polygon they have mapped while in the field. Based on observed errors that arise in the mapping process, these can be corrected by the local experts.

4.4.2.2. Temporal accuracy

To assess temporal accuracy of the local dataset, temporal lag was calculated based on forest disturbance dates determined using remote sensing time-series data. The temporal lag in detecting deforestation and degradation (Figure 4.7) is not necessarily a direct result of inaccuracies in the local dataset, but rather highlights differences in the interpretation of change between ground-based and satellite-based methods in the case of deforestation and forest degradation.

Evidence from our study indicates that deforestation is detected earlier using higher resolution SPOT and RapidEye imagery compared to local expert observations. This time lag in deforestation detection is likely due to differences in the interpretation of change events. Since optical remote sensing observes changes in the canopy cover of forests, changes delineated by visual interpretation of remote sensing time-series were directly related to land cover changes. Local experts, on the other hand, reported changes in land use (e.g., the conversion of forest land to agricultural land) (Verburg et al. 2011). The difference between the land cover and land use-based definition of deforestation is important in this case, because actual land use change typically follows several years of gradual canopy cover change. Whereas deforestation was understood by local experts to mean the conversion of forest land to cropland, changes in the canopy cover in the years preceding this change were often interpreted as land cover change (deforestation) by the remote sensing analyst, thus giving rise to the temporal lag observed in this study (Figure 4.6).

Interestingly, a reverse temporal lag was found in the case of forest degradation reported by local experts. Optical remote sensing data are known to have limitations with regards to the detection of low-level degradation, especially when driven by fuelwood collection (Skutsch et al. 2014), as was found in this study (Table 4.4). This low level degradation generally takes place underneath the forest canopy and is thus not detectable using remote sensing data until degradation rates are such that canopy openings begin to appear. For this reason, a delay in degradation detection by remote sensing was found in this study. In many cases, low-level degradation is not at all detectable with optical remote sensing data when degradation fails to result in canopy openings. In this case, local datasets convey a clear advantage when combined with remote sensing data to achieve a comprehensive description of the degradation processes.

4.4.2.3. Thematic accuracy

While analysis of the thematic accuracy of the local experts' dataset showed a high overall accuracy (82%), the drivers of forest change were reported with a relatively lower accuracy (69%). One possible explanation for this lower accuracy could be due to differences in perceiving the proximal drivers of forest change by local experts and the team of professionals who were involved in collecting FRD. Another explanation for this lower accuracy could be the complexity of multiple drivers and dynamic nature of land use changes, which make categorization of forest change drivers difficult. In the case of Ethiopia, multiple drivers, such as fuelwood extraction, grazing, timber harvesting and agriculture expansion, operate together and choosing the most prominent driver for such a situation is difficult (Table 4.4). The reporting of drivers could be improved through improved form design (e.g., using simplified classes and iconography).

4.4.3. Potential role of local datasets in an integrated monitoring system

4.4.3.1. Complementarity with remote sensing analysis

The local data stream presented in this chapter is not an investigation to replace or compete with remote sensing-based monitoring data, which is conventionally used in forest area change analyses, but is rather envisioned to be complementary to these data. The complementarity between remote sensing and community observations is described below in the context of several key REDD+ MRV questions (Figure 4.7).

The first question for REDD+ MRV is the location of change. Remote sensing approaches are highly suitable for answering this question. The value of remote sensing data and their successful implementation to monitor forest change on various scales (global, regional, national, etc.) and at various resolutions is well established (Achard et al. 2010; Hansen et al. 2013). The advantages of these methods include consistent data acquisitions, automated data processing and large area coverage (De Sy et al. 2012; Hansen and Loveland 2012; Roy et al. 2014). A main shortcoming is the need for spatially-explicit ground (in situ) data to enhance the reliability of these remote sensing products (Li et al. 2013). There is always a lack of spatially-explicit and statistically representative ground data, because this information is expensive and time-consuming to acquire. To address this deficiency, local data streams proposed in this study may provide a useful way to complement remote sensing data. The spatial accuracy results of the local expert data (Tables 4.5 and 4.6) show that local datasets can be used to better understand information related to local administration (e.g., the name of the district and village) or geographical characteristics (distance to roads, nearest village and core forest). Similarly, remote sensing may help to add value to local data streams by providing wall-to-wall coverage, which can be used to validate local data streams. The synergies of both methods may lead to a more efficient monitoring system for data acquisition and to rendering reliable information.

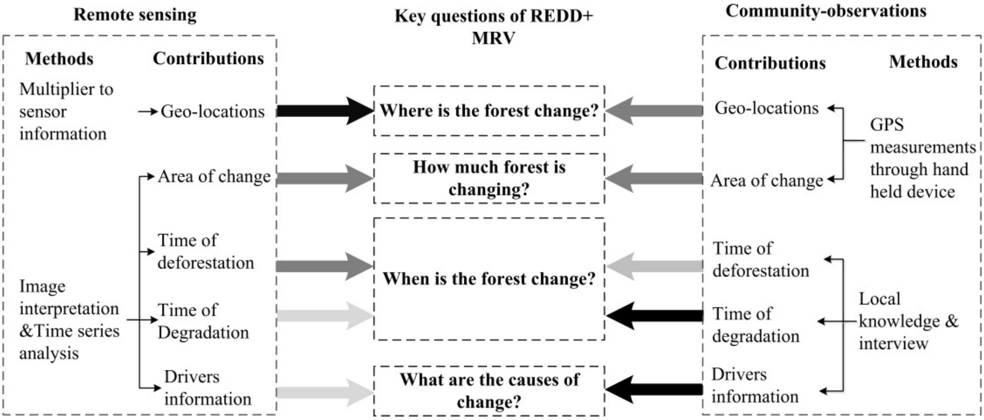


Figure 4.7 Contributions of remote sensing and community observation for REDD+ MRV monitoring objectives related to location, size, timing and drivers of forest change; black arrows indicate a very strong contribution; dark grey arrows indicate a reasonably strong contribution; and light grey arrows indicate a limited contribution to these monitoring objectives.

The second REDD+ MRV question is the area of forest change. Both remote sensing and local datasets have their own difficulties when used to map the area of forest change. In general, remote sensing plays a promising role for mapping larger areas, because of its ability to map wall-to-wall changes (Achard et al. 2010). However, the trade-offs between the spatial and temporal capabilities of remote sensing limits their use to monitoring small scale forest change (De Sy et al. 2012). Since we have shown that local datasets are sufficiently accurate to track small forest changes, the overall mapping of forest change area can be enhanced by exploiting the synergy between these datasets.

The third REDD+ MRV question is related to the timing of forest change. Historical archives of remote sensing imagery and the prospect of a continuous data stream based on new satellites, such as Landsat 8 and Sentinel-2, offer a possibility to analyse the temporal patterns of forest change and the impact of human activities (Drusch et al. 2012; Hansen and Loveland 2012). However, the temporal accuracy of detected changes based on this imagery depends on: 1) the availability of cloud-free observations, 2) the seasonality and climate trends and 3) the spatial scales of land cover change phenomena. In areas with high persistent cloud cover, the detection of actual changes can be delayed due to missing observations and the seasonality of vegetation can obscure actual changes. Climate events, such as major droughts, can result in temporal signals that resemble actual change, thus contributing to errors. Finally, the scale of change can influence the time at which a change is detected from space. Specifically, we have seen in this study that higher resolution SPOT and RapidEye imagery detect deforestation earlier than local experts, whereas the detection of forest degradation using remote sensing data is delayed compared to that of local experts. Reports of small scale deforestation and forest degradation from local experts can therefore contribute to an improved understanding of change processes, and the integration of both methods should lead to a more efficient system to signal new changes in near real-time.

The final REDD+ MRV question is related to the driver of forest change. NFMS for REDD+ needs to be designed to track and completely document the drivers of forest change processes (UNFCCC 2013). Drivers vary across regions (Hosonuma et al. 2012), leading to different dominant forest change processes and different approaches needed to tackle these drivers (Skutsch et al. 2011) . In general, remote sensing has limited capabilities to track forest change drivers, whereas community observations are very accurate in reporting these drivers. These drivers of change can be better understood with an intimate knowledge of forest change processes, and this information has the potential to enhance the pertinence of the remote sensing data analysis. Information on drivers collected by local experts thus presents new opportunities for monitoring forest change events.

4.4.3.2. Link to the national forest monitoring system ("Up-Scaling")

The UNFCCC encourages developing countries to establish an NFMS in support of REDD+ MRV (UNFCCC 2013). The NFMS needs to monitor forest carbon and changes in compliance with the five IPCC principles: consistency, transparency, comparability, completeness and accuracy (IPCC 2006). However, most developing countries have a low monitoring capacity, and the development of these capacities will take considerable time and resources (Romijn et al. 2012). In this research, we found that local communities can monitor forest changes in a cost-effective way. By scaling up CBM activities to the national level, these capacity gaps can be addressed in an efficient and cost-effective way. Developing countries should therefore give priority to CBM in developing their NFMS and MRV systems.

The UNFCCC REDD+ also offers an opportunity for safeguards, biodiversity conservation and other ecosystem services beyond carbon sequestration (Balderas Torres and Skutsch 2012; Chhatre et al. 2012; Dickson and Kapos 2012). Monitoring all of these elements within REDD+ is a challenge. Our proposed local monitoring system is based on well-established monitoring principles and experiences. The main advantage of the system is the flexibility in design. The data acquisition side of the system can be easily modified and it can incorporate other types of environmental monitoring variables. Thus, the integration of other environmental monitoring variables may lead to long-term benefits (DeFries et al. 2007) and shape the future of REDD+ monitoring and implementation efforts (Visseren-Hamakers et al. 2012).

4.4.4. Future research directions

Although our study is founded on the argument that considerable progress can be made towards community-based forest monitoring in REDD+, there is a clear need for improvements to the monitoring set-up. The first area of improvement is the engagement of local communities that have an impact on the success of the proposed monitoring setup. In our study, local experts were employed and the acquaintance of the local people with their local area was a clear advantage in monitoring local changes. Moreover, the feeling of ownership that local people have for their locale has a strong influence on the motivation to participate. Local capacities should therefore be developed through extensive training. The second area of improvement is related to data entry errors. Advancements in hand-held devices, such as smart phones and PDA devices, will improve local participation within monitoring programs. The application of mobile devices can improve the local participation and reduce data entry error within monitoring programs (Pratihast et al. 2012). However, further improvement is needed in terms of user friendly form design. Specifically, drop-down selection options and multimedia (photos, video and audio) are preferable to manual text entry, which is prone to entry errors. Finally, there is a need to integrate near real-time data streams from both satellites and CBM. Recently, efforts have been made towards improving near real-time forest monitoring using remote sensing data (Achard et al. 2010; Verbesselt et al. 2012). However, the efficacy of near real-time monitoring from ground-based sources, such as CBM, has not yet been investigated. Addressing these gaps in CBM is an important next step in the arena of REDD+ MRV and NFMS.

4.5. Conclusions

Community-based monitoring is gaining popularity and large volumes of ground observations that can potentially enhance forest monitoring are being generated. To tap into this potential, we need a better understanding of local data contributions, in particular their consistency and complementarity with remote sensing.

In this article, we present a novel approach to monitor forest change through local experts and evaluate the accuracy and complementarity of local datasets over field-based reference measurements and high resolution satellite imagery from SPOT and RapidEye. We demonstrate the application of the approach by implementing a CBM case study with 30 local experts in the Kafa Biosphere Reserve in Ethiopia. The proposed approach helps us to understand the characteristics and competencies of local datasets. The results show that the local experts are accurate compared to field-based observations and high resolution remote sensing in providing the spatial, temporal and thematic details of the forest change process. Local monitoring data also offer a way to complement and enhance remote sensing-based forest change analysis. In future research, we foresee new ways to integrate local expert monitoring data with satellite-based monitoring data into NFMS in support of REDD+ MRV and near real-time forest change monitoring.

Acknowledgements

The work presented in this chapter was made possible with funding and data from a number of sources and valuable input from a number of individuals. Funding for *the work of Arun Kumar Pratihast was provided by the DAAD funded Centre for Natural Resources and Development (CNRD), the Institute for Technology and Resources Management in the Tropics and Subtropics (ITT), Cologne University of Applied Sciences, Germany and the project, Google Deforestation Monitoring (5120906). The work of Ben DeVries was provided in the frame of the project "Climate Protection and Preservation of Primary Forests—A Management Model Using the Wild Coffee Forests in Ethiopia as an Example", implemented by the Nature and Biodiversity Conservation Union (NABU), German and Ethiopian branches, with funding from the International Climate Initiative (IKI) of the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMU) (IKI-1 Project Number 09 II 066 ETH A Kaffeewälder). SPOT data were provided through a SPOT Planet Action project entitled "Forest biomass and change monitoring in UNESCOs Kafa Biosphere Reserve (Ethiopia) and the implementation of REDD+ carbon crediting". RapidEye imagery was obtained through Blackbridge. We would also like to thank NABU and their local partners in Ethiopia for supporting this study. We particularly acknowledge Muluken Mekuria, Terefe Woldegebriel and the 30 local forest rangers of the Kafa Zone Bureau of Agriculture and Rural Development for their support and assistance in forest monitoring observations. Finally, we would like to thank the three anonymous reviewers for their helpful comments on this manuscript.*

Annex: additional material of chapter 4

Table A4.1 The details of SPOT and RapidEye scenes used in this study; the tile IDs of SPOT images are based on the SPOT K-J reference grid.

Sensor	Tile ID	Date of acquisition
SPOT4	133–336	2-03-2005
	133–335	2-03-2005
	132–335	12-22-2005
	134–336	12-11-2006
	134–335	12-11-2006
	133–336	6-07-2006
SPOT5	133–335	11-02-2007
	133–335	12-28-2008
	133–335	1-12-2009
	133–335	1-01-2010
	133–335	24-3-2011
	134–336	2-06-2011
	134–335	2-06-2011
	134–335	2-06-2011
	133–336	2-15-2011
	133–336	1-26-2011
	133–335	3-24-2011
	133–335	3-24-2011
	133–335	3-24-2011
	132–335	2-05-2011
RapidEye	3642428	12-12-2012
	3642528	12-12-2012
	3642528	2-24-2013
	3642627	12-12-2012
	3642628	2-24-2013
	3642727	2-24-2013
	3642728	2-24-2013
	3742302	10-17-2012
	3742401	1-02-2013
	3742402	10-17-2012
	3742501	2-24-2013
	3742502	1-05-2012
	3642428	1-02-2013
	3642527	12-12-2012

Sensor	Tile ID	Date of acquisition
RapidEye	3642827	2-24-2013
	3642828	2-24-2013
	3742302	1-01-2012
	3742302	2-25-2013
	3742402	1-01-2012
	3742402	2-25-2013
	3742403	1-01-2012
	3742403	10-17-2012
	3742403	2-25-2013
	3742501	1-02-2013
	3742502	10-17-2012
	3742502	1-02-2013
	3742502	2-25-2013

Chapter

5

Design and implementation of an interactive web-based near real-time forest monitoring system

Arun Kumar Pratihast, Ben DeVries, Valerio Avitabile, Sytze de Bruin,

Martin Herold and Aldo Bergsma

PLoS ONE (Submitted).

Abstract

This chapter describes an interactive web-based near real-time (NRT) forest monitoring system using four levels of geographic information services: 1) the acquisition of continuous data streams from satellite and community-based monitoring using mobile devices, 2) NRT forest disturbance detection based on satellite time-series, 3) presentation of forest disturbance data through a web-based application and social media and 4) interaction of the satellite-based disturbance alerts with the end-user communities to enhance the collection of ground data. The system is developed using open source technologies and has been implemented together with local experts in UNESCO Kafa Biosphere Reserve, Ethiopia. The results show that the system is able to provide easy access to information on forest change and considerably improves the collection and storage of ground observation by local experts. Social media leads to higher levels of user interaction and noticeably improves communication among stakeholders. Finally, an evaluation of the system confirms the usability of the system in Ethiopia. The implemented system can provide a foundation for an operational forest monitoring system at the national level for REDD+ MRV applications.

Keywords

REDD+; remote sensing; time-series; near real-time; community-based monitoring; social media; Web-GIS; Kafa; Ethiopia

5.1. Introduction

Tropical forests play an important role in stabilizing the climate, providing food, water, wood products and provide a habitat for biodiversity (Gullison et al. 2007). Deforestation and forest degradation are now widely acknowledged by the scientific community as a major contributor to recent increases in atmospheric greenhouse gas (GHG) concentrations and changes to the world's hydrological cycle (Bonan 2008; Hansen et al. 2013). To reduce atmospheric GHG concentrations, the United Nations Framework Convention on Climate Change (UNFCCC) has proposed an international carbon trade mechanism; Reducing Emissions from Deforestation and Degradation (REDD+) to enable forest conservation, sustainable management of forests and the enhancement of forest carbon stocks in developing countries (UNFCCC 2009). Aside from being an important step towards reducing GHG concentrations, REDD+ also includes considerations for co-benefits, safeguards and biodiversity protection (Dickson and Kapos 2012; GOFC-GOLD 2014; IPCC 2006).

Several bilateral and multilateral efforts, such as the World Bank administered Forest Carbon Partnership Facility (FCPF), the UN Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (UN-REDD Programme), and the Norwegian International Climate and Forests Initiative are currently supporting developing countries to prepare Readiness Preparation Proposals for the implementation of REDD+ projects at the national level (FCPF 2012; Skar 2012; UN-REDD 2009). One of the main tasks for countries participating in REDD+, as requested by the UNFCCC (Decision 2/CP.19) (UNFCCC 2013), is to develop an operational, robust, transparent and cost-effective national forest monitoring system (NFMS) that supports measuring, reporting and verification (MRV) of actions and achievements of REDD+ activities (DeVries and Herold 2013; Herold and Skutsch 2008; Romijn et al. 2012).

Currently most forest monitoring focuses on activity data i.e. data on forest cover changes (DeVries and Herold 2013) and two approaches are used: top-down and bottom-up. The top-down approach utilizes satellite systems (De Sy et al. 2012; DeFries et al. 2007) whereas the bottom-up approach utilizes ground observation through government agencies (Tomppo et al. 2010), community-based monitoring (CBM) (Danielsen et al. 2011), participatory monitoring (Danielsen et al. 2009) or volunteered geographic information (Connors et al. 2012). Satellite data provides systematic coverage and higher frequency acquisition at a low cost which is crucial for near real-time (NRT) forest monitoring (De Sy et al. 2012; Lynch et al. 2013). Recently, efforts have been made to establish an operational time-series based NRT forest monitoring system (Wheeler et al. 2014). These efforts include the use of optical remote sensing satellites such as MODIS (Anderson et al. 2005; Shimabukuro et al. 2007) and Landsat (Hansen et al. 2008). NRT system contributes to better forest management, allows governments and local stakeholders to take action which may avoid or reduce illegal activities and enhances transparency in the use of forest resources. However, the operational use of these systems are influenced by several factors such as cloud cover, seasonality and the limited spatial, spectral and temporal resolution of satellite observations that lead to inevitable lag in forest change detection (Asner 2001; De Sy et al. 2012). Furthermore, existing systems are not capable of providing information on forest degradation and regrowth, and do not consider community involvements for ground verification, validation and law enforcement activities.

Bottom-up ground observations have traditionally been produced, analysed and disseminated by trained experts, often from government agencies. The major drawbacks bottom-up data are that they are expensive, often not NRT and therefore are not fit for REDD+ MRV needs (Pratihast et al. 2013; Romijn et al. 2012). In the last few years, CBM has become popular in REDD+ countries as a way to increase local participations and engagements in forest monitoring and management processes (Danielsen et al. 2013; Fry 2011; Pratihast et al. 2013; Skutsch et al. 2014). Several transparent, logical, feasible and repeatable methods have been proposed by researchers to demonstrate that communities can contribute to: 1) forest carbon stock measurements and emission factor assessments (Brofeldt et al. 2014; Danielsen et al. 2013; Pratihast et al. 2012; Shrestha et al. 2014) and 2) forest change monitoring (activity data quantification) (Bellfield et al. 2015; Pratihast et al. 2014; Pratihast et al. 2012). Because of communities' presence on the ground, they are able to signal forest change activities (deforestation, forest degradation or reforestation) and to provide information, such as location, time, size and proximate drivers of the change events on a NRT basis (Pratihast et al. 2014; Skutsch et al. 2011; Torres et al. 2014). Modern electronic communication devices, such as smartphones, have simplified efforts in data collection and transmission (Aanensen et al. 2009; Gouveia et al. 2004; Pratihast et al. 2012).

However, issues have arisen when integrating CBM data into NFMS including: 1) lack of confidence in the data collection procedure, 2) inconsistent monitoring frequency, 3) limited spatial coverage, 4) variable data quality and 5) lack of trust of data providers (Conrad and Hilchey 2011; Danielsen et al. 2010; Pratihast et al. 2014; Skarlatidou et al. 2011). Recent advances in technologies like Web 2.0, GIS, remote sensing, big data processing, mobile devices and social media have however provided possible solutions to the identifies issues (Gouveia et al. 2004; Li et al. 2015; Newman et al. 2011).

In the past, two independent approaches have been used to monitor the forest of UNESCO Kafa Biosphere Reserve, Ethiopia: remote sensing analysis (DeVries et al. 2015b) and community-based monitoring (Pratihast et al. 2014). Both approaches have shown advantages and disadvantages but neither of the approaches was comprehensive enough to monitor all types of forest change (i.e. deforestation, forest degradation and reforestation). In the first approach, dense Landsat Normalized Difference Vegetation Index (NDVI) time-series were used to monitor small scale deforestation with high accuracy (DeVries et al. 2015b). However, it has limitations in monitoring forest degradation. In the second approach, CBM using local experts was found to be more reliable in monitoring forest degradation with spatial, temporal and thematic details (Pratihast et al. 2014). Nevertheless, these data had limited spatial coverage, and a lack of consistency in monitoring frequency and temporal accuracy in deforestation detection (Pratihast et al. 2014). Hence, effective monitoring will likely require an integrated approach, where detailed community-based observations are combined with remote sensing satellites (Pratihast et al. 2014). Compared to traditional systems, our proposed an interactive forest monitoring system (IFMS) offers some immediate advantages:

1) up-to-date information on forest change location, size, timing and drivers of forest change which are consistent over time.
2) cost-effective and sustainable data collection due to open source software and open data policies.
3) transparent results which can be integrated into to NFMS/national MRV systems.
4) potential to enhance participation of stakeholders in forest monitoring and management.

Despite this potential, the effective development of interactive NRT forest monitoring system is currently lacking due to several reasons. Firstly, there are no operational methods to analyse forest change information from multisource data streams (i.e. Satellite and CBM in NRT). Secondly, there is no system that can systematically store, visualize and provide access to the forest change information via the internet to the local stakeholders. Thirdly, there is a lack of spatial and temporal forest change search query capabilities. Lastly, interaction between users and the system is generally “passive”, in the sense that individuals do not receive feedbacks on the submitted data. This has motivated us to develop an IFMS which uses Web-GIS as its integrating platform. We have used knowledge from distinct areas of research on public participation Geographic Information Systems (PPGIS) (Kingston et al. 2000), environmental monitoring through Web-GIS (Dragićević and Balram 2004), community-based monitoring (Pratihast et al. 2013), agricultural fields planning (De Bruin et al. 2014), satellite-based NRT forest and fire monitoring (Keramitsoglou et al. 2004; Vadrevu et al. 2008; Verbesselt et al. 2012; Werts et al. 2012), spatial data infrastructure (Maguire and Longley 2005), social networking (Daume et al. 2014; Van Oort et al. 2010) and open source technologies (Bocher et al. 2012). The aforementioned research and technologies demonstrate that developing a satellite-community forest monitoring systems is possible as technologies to support such system are mature. In addition web mapping platforms together with mobile technologies (OpenDataKit 2012) offer a unique opportunity to integrate satellite data and community-based observations to monitor forest disturbances whereby the participation of the local stakeholders in forest monitoring is ensured. However, implementation challenges need to be explored and evaluated on a case-by-case basis. In particular, open data policies (Wulder et al. 2012), big data processing environments (Li et al. 2015), and advancement in satellite time-series methods (DeVries et al. 2015b; Verbesselt et al. 2010) should be considered.

The objectives of this study are 1) to design an interactive system which combines Web-GIS technologies, satellite and CBM data, and social media to support near real-time forest monitoring, 2) to implement and operationalize the developed system in the UNESCO Kafa Biosphere Reserve in Southwestern Ethiopia and 3) to assess the usability of the system in Kafa.

5.2. Material and methods

5.2.1. Study area and project context

The study site is located in the Kafa Zone (7.22°E to 7.84°E and 35.59°N to 37.17°N) Southern Nations Nationalities and People's Region (SNNPR), in Southwestern Ethiopia. It covers an area of 700,000 ha. The Kafa region was recognized as a Biosphere Reserve within UNESCO's Man and the Biosphere program in March, 2011. It has a seasonal climate with annual rainfall of around 1700 mm; the rainy season lasting from June to September. The altitude ranges from 400 to 3100 m with an average annual temperature of 19°C. A large portion (~50%) is still covered by Afromontane cloud forests (Schmitt et al. 2010). The region is also recognised as the gene bank of Coffee Arabica (Aerts et al. 2015) and of many other endemic species of plants, mammals and birds. Although the forest has been protected through UNESCO's conservation programs, still there are many challenges that have threatened its ecological coherence. Subsistence agriculture, human settlements expansion, industrial coffee plantations, domestic firewood and charcoal extractions are recognised as the major drivers of deforestation that has negative impact on the integrity of the reserve (Pratihast et al. 2014).

The proposed study was conducted, within the framework of the Nature and Biodiversity Conservation Union (NABU) project. The Kafa Zone Bureau of Agriculture and Rural Development, Participatory forest management (PFM) group, Woredas and Kebeles (an administrative unit at different levels) authority were main Stakeholders of this project. Under collaborative scheme of monitoring (Danielsen et al. 2009), one local expert from each of the ten Woredas was recruited. These local experts had at least a basic education background and some fundamental understanding of forest monitoring. A mobile device (Samsung GT-S7710) equipped with a global positioning system (GPS) receiver was provided to each of these local experts to acquire forest monitoring data. These experts also have other responsibilities, such as the biodiversity monitoring, development of ecotourism, reforestation, community plantations and awareness raising for the sustainable use of forest resources (e.g., honey and wild coffee).

5.2.2. System architecture

Our web-based geospatial platform IFMS was designed in a collaborative manner with local stakeholder to assist them in identifying forest change locations in NRT and to facilitate the optimal allocation of information about the change (Dragićević and Balram 2004; Goodchild 2007; Pratihast et al. 2014; Werts et al. 2012). The functional features of the system are: 1) functionality to download, store and process NRT forest change detection using Landsat time-series images, 2) facility to upload ground observations and download forest change locations on-demand, 3) ability to map and show the hotspots of forest changes in space-time, 4) capability to provide feedback to local stakeholders and 5) functionality to provide interaction through social media.

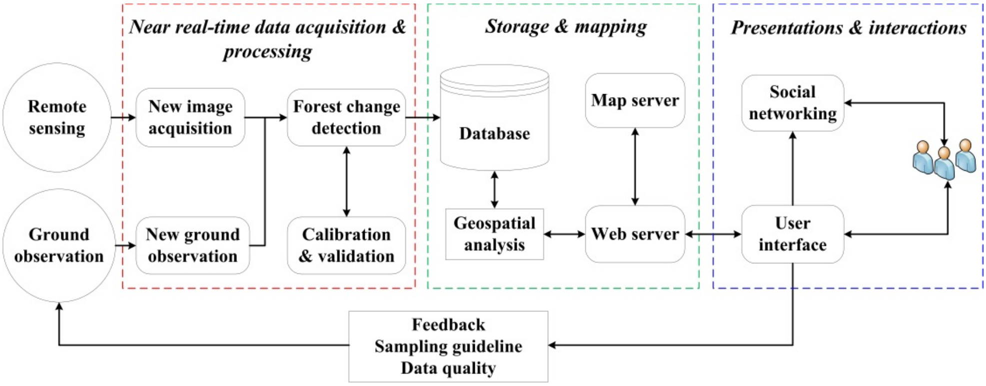


Figure 5.1 Diagram of the interactive web-based near real-time forest monitoring system.

Multi-layered software architectures are commonly used for the development of a distributed, dynamic, flexible and re-configurable service system over the internet that can ensure the service requirements of many different users (Bimber et al. 2000). In this research, we implemented multi-layered software architecture in a modular fashion. Figure 5.1 summarizes the general framework which was adapted to design the IFMS. The design of the IFMS is organized into four functional modules: 1) NRT data acquisition and processing, 2) storage and mapping, 3) presentation and interaction and 4) feedback. The above mentioned four modules comprise the primary server side functionality. On the client side, users (local stakeholders and forest professionals in charge of monitoring and decision making) send requests to the server via a Mobile device or Web-based graphic user interface (web-browser). The server carries out the corresponding spatial analysis and conveys the results to the client for feedback, interaction and visualization.

The framework is scalable and extensible so that additional functions or map layers of external data sources can be easily added to the application.

5.2.3. System implementation

Each of the modules was developed using open source tools (Table 5.1) and are described as follows:

1) The data entry is facilitated by a decision-based data acquisition form using open data kit (ODK) (Pratihast et al. 2014; Pratihast et al. 2012). The form renders on an Android platform through ODK collect, which allows multiple data records to be entered (text variables, GPS position, photo etc.) and stored on a mobile device. After data collection, users transfer the collected data to the database server through a general packet radio service (GPRS) message via 2G, 3G or other networks.
2) A semi-automated process chain was developed to download, store and process Landsat image time-series. All the historic as well as continuously acquired Landsat ETM + images with WRS-2 coordinates, path 170 and row 55 at processing level1 are obtained from the United States Geological Survey (USGS) server (http://earthexplorer.usgs.gov/). After downloading the Landsat data, multiple pre-processing steps are applied: LEDAPS method (Masek et al. 2006) for conversion of raw imagery from digital number to Top of Atmosphere Reflectance and Surface Reflectance, FMASK algorithm (Zhu and Woodcock 2012) for cloud masking, forest clipping to the specified region and NDVI extraction. We used the BFAST method (Verbesselt et al. 2012) for breakpoint detection in Landsat NDVI time-series images for NRT forest change detection.
3) The spatial database structure was designed, which allows different types of data, including basic geographic data, ground observation data and remote sensing information, to be stored, managed and accessed through structured query language (SQL). Basic geographic data include the geometry of Woredas, Kebeles and boundaries of the Biosphere Reserve. We used PostgreSQL with PostGIS extension to implement our design. Stored datasets are published using Geo-server as a Web Map Service (WMS) that is compliant with Open Geospatial Consortium (OGC) specifications. We used OpenLayers and JQuery JavaScript libraries to provide client side functionality to display and render maps in web pages.

4) A graphical user interface was developed using Hyper Text Markup Language (HTML), Cascading Style Sheets (CSS) and Hypertext Preprocessor (PHP). In addition to this, we also provide dynamic spatio-temporal query and social media plugins features. These features allow users to generate forest change locations on-demand; to download forest change locations in usable GPS exchange format (GPX) format which can directly be used on a GPS device; and to efficiently communicate results using social media sites. The "Near Real-Time Disturbance Monitoring - Kafa Biosphere Reserve" is a Facebook group for posts, discussions and comments regarding the results.

Table 5.1 Open source tools used for the development of the interactive web-based near real-time forest monitoring system.

Open source tools	**Version**	**Function**	**Source**
ODK Design		Decision-based ground data acquisition form design	https://opendatakit.org/help/form-design/
ODK Collect	1.4.5	Renders forms into a sequence	http://opendatakit.org
ODK Aggregate	1.3.2	Deploy data into server	http://opendatakit.org
Bulk Download Application	1.1.4	Downloading Landsat imagery	http://earthexplorer.usgs.gov/bulk/
R	2.14.1	Time-series analysis	http://r-project.org
BFASTSpatial		Time-series analysis	http://dutri001.github.io/bfastSpatial/
PostgreSQL	9.1	Database	http://postgresql.org
PostGIS	2.0.6	Spatial extension for PostgreSQL	http://postgis.org
Apache	2.2.22	Web server	http://httpd.apache.org
GeoServer	6.0.3	Web mapping server	http://geoserver.org
OpenLayers	1.12	Frontend web mapping library	http://openlayers.org
jQuery	1.8	Frontend JavaScript library	http://jquery.org
PhP	5.4.36	Web development	http://php.net/

5.2.4. System evaluation

Several approaches have been proposed by researchers to evaluate Web-GIS systems (Bugs et al. 2010; Li et al. 2006; Werts et al. 2012). Most of these approaches are focused on technological aspects rather than usability aspects

(Renate Steinmann 2004). In this study, we emphasize the usability aspects of Web-GIS system in terms of “fitness for purpose”. Fitness for purpose concerns the degree to which a system fits the users’ needs, thus bringing the utility of the system closer to the users requirements (Pôças et al. 2014). The evaluation framework of the IFMS is shown in Table 5.2 which comprises a three-step process: 1) identifying the purpose, 2) exploring the indicators associated with the purpose and 3) finding out an appropriate data source for each indicator. Each of these steps was performed in a systematic way to perceive ease of use of the offered system.

In the first step, the purpose of the IFMS design is reviewed. The main purposes of IFMS is 1) to ensure stakeholder participation and interaction in forest monitoring process, 2) to provide up-to-date and accurate information on forest change which are consistent over time that can be integrated into NFMS/national MRV system and 3) to increase awareness and law enforcement. These purpose were identifies primarily with forest monitoring objectives in mind, but also were compliant with REDD+ MRV requirements (Danielsen et al. 2009; Pratihast et al. 2014; Pratihast et al. 2013; Visseren-Hamakers et al. 2012). In the second step, the set of evaluation criteria of the IFMS was defined. After defining the evaluation criteria of the system, a list of indicators associated with each criteria were compiled. We compiled a list consisting of 12 potential indicators. The evaluation criteria served as a necessary intermediary link between purpose and indicators that enabled more systematic and coherent evaluation of the system. In the third step, we employed both qualitative and quantitative research approach to achieve the relevant information. First, we established email communication with NABU project co-ordinator, the qualitative approach, to gather all relevant and existing records on IFMS systems and their uses as perceived by different stakeholders in Kafa Biosphere. Second, the quantitative source of information was obtained from ground-based forest monitoring alerts provided by local experts and forest change alerts obtained from Landsat analysis. Furthermore, user interaction statistics were obtained from social media page and system log analysis.

Table 5.2 Indicators used for the evaluation of interactive web-based near real-time forest monitoring system in context of REDD+.

Purpose 1: stakeholder participation and interaction in forest monitoring process		
Evaluation criterion	**Indicators**	**Source**
Training and capacity building activities	Number of training and capacity events	Training and capacity events after the launch of the system *[Source : Institutional record*]*
	Number of participants	Registration forms of participant *[Source : Institutional record *]*
Use of services	Number of visitors of the system	System view statistics Multiple requests from the same IP address are counted as one view *[Source : System* log analysis]*
Engagement in debate and knowledge sharing	Number of users in social media group	User statistics Facebook group *[Source : Facebook group*]*
	Number of post/feed in the social media group	Post statistics Facebook group *[Source : Facebook group*]*
	Responses to posts	Post seen, like and comments Percentage of user engagements= [Number of user seen+ Number of user like+ Number of user comments on the post] / Total number of user*100 *[Source : Facebook group*]*
Purpose 2: Provide up-to-date and accurate information on forest change which are consistent over time and can be integrated into the national forest monitoring system/ national MRV system		
Ground-based forest monitoring alerts	Number of ground observations alerts	Near real-time ground-based forest monitoring *[Source: ground observation datasets]*
Satellite-based forest change alerts	Number of satellite-based forest change alerts	Near real-time satellite-based forest change alerts concerning patches larger than 0.5 ha *[Source: Landsat time-series analysis]*
Consistency of ground-based observations and satellite-based alerts	Spatio-temporal coincidence	Number of ground observation associated to identified satellite-based alerts (within the radius of 1 km) *[Source: ground observation datasets]*
	Thematic agreement	Percentage of agreements (‘true’, ‘success’) or disagreement (‘false’, ‘failure’) of a series of satellite-based alerts visited by local experts *[Source: ground observation datasets and Landsat time-series alerts]*

Purpose 3: Increase awareness and law enforcement		
Law enforcement	Number of illegal activities	Illegal activities reported by local experts *[Source: ground observation datasets]*
Awareness	Awareness approach	List of Awareness program *[Source: Institutional record*]*

*Institution:- NBAU project office, Kafa Ethiopia (http://www.kafa-biosphere.com/)
*System:- Web-based interactive near real-time forest monitoring system (www.cbm.wur.nl)
*Facebook group:- Near Real-Time Disturbance Monitoring - Kafa Biosphere Reserve (https://www.facebook.com/groups/kafa.forest.monitoring/)

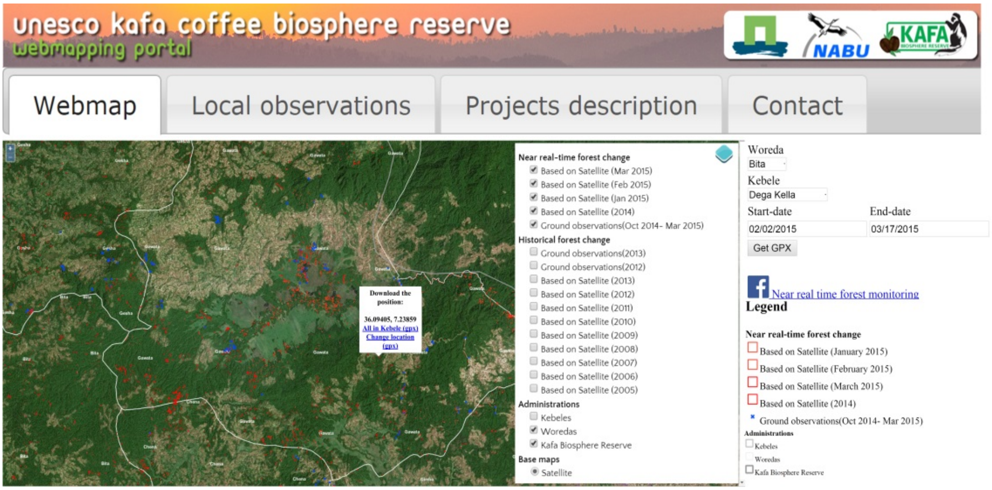
5.3. Results

5.3.1. Overview of the system

The developed web-based IFMS can be accessed at: http://www.cbm.wur.nl. A screenshot of the deployed IFMS is shown in Figure 5.2. The right panel of Figure 5.2 shows the mapping interface of the system. This interface provides the overview of the mapping layers and adequate mapping functionalities (e.g., layer selection, zooming and panning facilities). The data layers are organised into three information categories: administrative boundaries, historical forest change and near real-time forest change. By default, the interface shows Bing Maps image as background layer overlaid with NRT satellite-based forest change alerts (in Red) and ground observation (in Blue), which are also shown in Figure 5.2. The left panel shows the interface for spatial and temporal querying. A temporal query is defined by a start date and an end date, while a spatial query identifies a location window. The SQL meeting both conditions are selected from the database and are available for download in GPX format. This GPX format helps the local experts to transfer the monitoring alerts on their GPS device. These alerts empower local expert to reach at suspected locations of recent forest change.

Figure 5.3 exemplifies ground observation data collected by local experts. The screenshot demonstrates that these data contain three categories of information: spatial, temporal and thematic. The spatial category includes GPS location, administrative boundary information of forest change location and the estimated size of forest change. The temporal category includes time of forest change. Finally, thematic category provides the information about Land use type, forest change type, drivers of forest change, photo and multimedia description of the forest change location. These datasets contain some sensitive information such as driver of forest change, photo and multimedia description about the process of change. Hence, access restrictions have been made for the general public, but authorised users can have full access and download facilities to all the attributes of these ground data.

Figure 5.4 shows a social network group meeting in which stakeholders discuss about the illegal firewood extraction from one of the PFM sites. The page provides a number of services to the stakeholders such as: 1) posting information about forest monitoring, 2) encouraging discussion on controversial issues, 3) engaging user in the expression of feelings for monitoring of areas of concern and hotspots and 4) instant messaging among participants.



Near real-time forest change
- ☑ Based on Satellite (Mar 2015)
- ☑ Based on Satellite (Feb 2015)
- ☑ Based on Satellite (Jan 2015)
- ☑ Based on Satellite (2014)
- ☑ Ground observations(Oct 2014- Mar 2015)

Historical forest change
- ☐ Ground observations(2013)
- ☐ Ground observations(2012)
- ☐ Based on Satellite (2013)
- ☐ Based on Satellite (2012)
- ☐ Based on Satellite (2011)
- ☐ Based on Satellite (2010)
- ☐ Based on Satellite (2009)
- ☐ Based on Satellite (2008)
- ☐ Based on Satellite (2007)
- ☐ Based on Satellite (2006)
- ☐ Based on Satellite (2005)

Administrations
- ☐ Kebeles
- ☑ Woredas
- ☑ Kafa Biosphere Reserve

Base maps
- ● Satellite

Woreda: Bita
Kebele: Dega Kella
Start-date: 02/02/2015
End-date: 03/17/2015

Legend

Near real-time forest change
- ☐ Based on Satellite (January 2015)
- ☐ Based on Satellite (February 2015)
- ☐ Based on Satellite (March 2015)
- ☐ Based on Satellite (2014)
- × Ground observations(Oct 2014- Mar 2015)

Administrations
- ☐ Kebeles
- Woredas
- ☐ Kafa Biosphere Reserve

Figure 5.2 Web interface showing an example of a visualization interface for the Kafa case study. In this example, forest change polygons derived from Landsat data are displayed in red and local observation points in blue.

Form Forest Disturbance Monitoring Form Filter none

Submissions per page 100

☐ Display Metadata

Forest Disturbance Monitoring Form

ApproximateAreaAffected	DriverOfDisturbance	is_Disturbance_No	counttree	reforestation	GeneralDescription DescriptionOfArea	GeneralDescription DescriptionAudio	TakePhoto PhotoNorth	TakePhoto PhotoSouth	TakePhoto PhotoEast	TakePhoto PhotoWeast
9.0	ICOFF SETE		4	NO	generally, the areas are distrebed	▶				
3.0	SETE		15	NO						
3.0	SETE		26	NO	The area is completely change into dEming Landy	▶				
20.0	SETE OTH		30	NO	Cultivated land with some trees remaining. Next to Tyra wetland. Maize, cattle. Sense forest to the east.					
2.0	SETE		51	NO		▶				
6.0	SETE		15	NO		▶				
2.0	ICOFF TH SETE		30	NO						
4.0	SETE		18	NO	The area ha fastened	▶				

Figure 5.3 Web interface showing an example of a visualization interface for ground observation collected by local experts.

Abera Hoeto
December 22, 2014

This is unfortunately which I get from one pfm site. I have asked to government to discard their using certificate.

You and Kassim Mohammed like this. ✓ Seen by 20

Nasir Ousman You should be make onther opportunity for thise community!
December 22, 2014 at 12:20pm · Like · 1

Muluken Mekuria abera this is sign of site supervision by you but please let us know what woreda government action after your information
December 22, 2014 at 12:26pm · Like

Abera Hoeto Ok I will post after 3-4 days the result.
December 22, 2014 at 12:42pm · Like

Kassim Mohammed Fake pfm
December 22, 2014 at 12:50pm · Like

Kassim Mohammed Fake pfm please push to discard
December 22, 2014 at 12:52pm · Like

Figure 5.4 Screen dump of social network Facebook group “Near Real-Time Disturbance Monitoring - Kafa Biosphere Reserve”.

5.3.2. System evaluation result

The IFMS was launched in October 2014. The evaluation was conducted for seven months to allow adequate time for the target user community to use the application. We have divided these seven months of implementation into three phases: a kick-off phase, a demonstration phase and an operational phase. During the kick-off phase (October 2014), the system was launched and a series of intensive training and capacity building programs were conducted to encourage user participation. In the demonstration phase (November- December 2014), the system was used with some improvements and limited assistance was provided to the users. During the operational phase (January to April 2015), users were able to use the system independently. The following subsections summarize the evaluation result of IFMS under three categories of purpose indicated in Table 5.2.

The overall evaluation results concerning stakeholder participation and interaction are shown in Table 5.3. During the kick-off phase of the system, stakeholders were indicated the need for training and capacity-building programs. Hence, one week training workshop (27th October 2014 to 3rd November 2014) was conducted in Kafa, Ethiopia. Whereas in demonstration and operational phase, users are already well trained with the implemented system and thus less training and capacity-building efforts were needed. In total, 37 participants participated during kick-off phase, but the participants' number dropped to 15 during the demonstration and operational phase of the system. The main reason behind this drop is that participants from different organisation such as Kafa Zone Bureau of Agriculture and Rural Development, PFM groups, Woredas and Kebeles were invited to join the training during the kick-off phase of the system. However, all of these participants were not directly involved in ground observation, hence only the interested one joined for the follow-up training.

The web log history about the number of visitors the IFMS (Table 5.3) shows that the use of the system in Kafa biosphere reserves doubled in the operational phase compared to the kick-off and demonstration phases. In line with this, the Facebook group user statistics shows a small increment of users during demonstration and operational phase of the system. The Facebook post results increased by factor 2 in the demonstration phase and by factor 3 in the operational phase of the system (Table 5.3). The average users' engagements in each of post also increased throughout this implementation phase of the system.

Table 5.3 System performance for stakeholder participation and interaction in forest monitoring processes.

Indicators	**Indicator value (per month)**		
	Kick-off phase	**Demonstration phase**	**Operation phase**
Number of trainings and capacity-building events	7 days	2 days	1 day
Number of participants in training and capacity-building activities	37	15	15
Number of visitors of the services	4	4	8
Number of users in social media page	24	26	28
Number of post feed on Facebook group	5	10	15
Percentage of engagement in debate and knowledge sharing	72%	78%	87%

The evaluation results concerning up to date and accurate information on forest change are summarized in Table 5.4. Local experts uploaded many NRT ground observation alerts during the kick-off phase of the system. The numbers of ground observation decreased in the demonstration phase while they slightly increased during the operational phase of the system. It might be due to topography, seasonality and weather condition. In contrast, the number of satellite-based NRT forest change alerts (greater than 0.5 ha) increased to 88 locations per month during the operational phase of the system. The number of spatio-temporal coincidence analysis shows that more than 50% of the local monitoring reports were recorded within 1 km radius of identified hotspot sites. The thematic agreement results (Table 5.4) show that the accuracy of satellite-based forest change alerts improved to 77% during the operational phase.

Table 5.4 System performance for near real-time information on forest change.

Indicator	**Indicator value (per month)**		
	Kick-off phase	**Demonstration phase**	**Operation phase**
Number of ground observations alerts	173	103	114
Satellite-based near real-time forest change alert	27	20	88

Indicator	Indicator value (per month)		
	Kick-off phase	**Demonstration phase**	**Operation phase**
Number of spatio-temporal coincidence	90	65	62
Thematic agreement	74%	71%	77%

Increased awareness was evaluated based on two aspects. The first aspect involves a decrease in the number of illegal activities. During the Kick-off phase of the system, 22 incidents were reported. This number decreased by almost 50% in the subsequent phases in it, i.e. 15 events were reported in the demonstration phase and 12 in the operational phase. The second aspect involves two modes of public awareness events that were organized to increase awareness of locals about forest protection. On 17th March 2015 there was a (30 minutes) radio program on the Kafa Community Radio to disseminate information about the forest disturbance alerts and protection efforts. Secondly, awareness meetings were conducted by spiritual leaders of the community throughout the Biosphere reserve. In total 447 peoples participated in these meetings. Details on the awareness programs are provided in Table A5.1 in the Annex.

5.4. Discussion

5.4.1. Reflection on design and implementation of the system

Several authors (Reiche et al. 2015; Shimabukuro et al. 2007; Xin et al. 2013) and some governmental initiatives (e.g., Brazil Detecção de Desmatamento em Tempo Real (DETER) (Assunção et al. 2014)) have emphasized the importance of combining technologies, services and data sources to build credible and legitimate NRT forest monitoring system at the appropriate scale, either at local or provincial or even at national scales. These systems provide the information about deforestation hotspots. Such information have made it possible for law enforcement, mobilize civil society organizations, and the media to react to illegal activities quickly and reduce the rate of deforestation (Börner et al. 2015; Souza Jr et al. 2009). However, the reality is that most of the tropical countries have limited technical and financial capacities to design and operate such kind of system (Romijn et al. 2012). In this regard, we have been able to demonstrate the design and implementation of a web-based NRT IFMS and evaluate its usability in the Kafa Biosphere Reserve, Ethiopia.

Compared to the existing forest monitoring system, our IFMS differs in the following aspects:

1) Open source-based system: Recently, some efforts have been made towards developing interactive NRT forest monitoring system using open source technologies (e.g., DETER (Assunção et al. 2014), Global Forest Watch http://www.globalforestwatch.org/) but these systems need to be improved by incorporating local data streams to make them more interactive and to ensure the participation of local stakeholders in monitoring their forests. In this regard, our system is able to demonstrate the novel aspects that integrate multiple data sources (satellite and CBM data) and open source technologies in modular fashion (Figure 5.1, Table 5.1). Each of these models is functionality independent, such that each modules contains everything necessary to execute one aspect of the desired functionality (Bimber et al. 2000).
2) Spatial coverage: The NRT system such as DEETE has been used since 2004 as a part of government plan to control the Amazon deforestation (Assunção et al. 2014). This system is based on MODIS satellite and is able to monitor larger scale forest change (Greater than 25 ha) in almost real-time (every 15 days). However, this system has spatial limitation to implement in sub-Saharan African countries and especially in Ethiopia, where the forest change is in small scale and mostly driven by small holder subsistence agriculture (Getahun et al. 2013). In this regard, our proposed system utilises higher spatial resolution sensor (i.e. Landsat satellite) and thus the system is able to detect the forest change cluster size greater than 0.6 ha (DeVries et al. 2015b).
3) Community participation: Our system also engages local community in NRT ground based forest monitoring. The ability to signal forest degradation and describe the process of change with high temporal detail highlights the advantage of the local approach (Pratihast et al. 2014) used in this study over conventional satellite-based NRT system [70,71]. Similar to the previous study conducted by Pratihast et al. (2012), the result of this study also shows that mobile device improves local expert's data acquisition capacities about the location, time, size and type of forest change events.

4) Enhanced stakeholder's interaction: Our system offers better interaction between the local stakeholders. These stakeholders can contribute data to the server and access the forest change information for decision making. Rather than just using monologic transmission model (publishing the forest change alerts on web), our system utilises dialogic transmission system with interactive means of communication such as social media. Combining social media and web interface have increased the information exchange and help to mitigate the problems of interactivity. Hence, this enables the stakeholders to access forest change information, collaborate on a common effort or build relationships among each other. These findings confirm the results of many other studies showing the capabilities of social media in effective communication (Daume et al. 2014; Diga and Kelleher 2009; Werts et al. 2012).

5.4.2. Critical review on the system evaluation results

In this study, we assessed the usability of the implemented IFMS in terms of fitness for purpose. A number of findings have emerged from this research regarding community-based forest monitoring systems, many of which are new while some resonate with the findings of previous studies. This section discusses the three aspects of this research in light with the three purposes outlined in subsection 5.2.4.

Overall the results (Table 5.3) indicate that the number of participants decreased during the demonstration and operational phase of the system. This issue has also been noticed in previous research of community-based forest monitoring, citizen science and PPGIS research (Danielsen et al. 2009; Kingston et al. 2000). The number of participants might be improved through appropriate collaborative and benefit schemes (Balderas Torres and Skutsch 2012; Danielsen et al. 2009). The collaborative schemes may encourage the involvement of more potentially interested organisations and individuals such as local communities, PFM groups, non-governmental organization and government authorities in IFMS. The benefit schemes such as financial, political (e.g., empowerment, participation in decision making) or indirect benefits can also increase the participation of local stakeholders (Boissière et al. 2014).

Second aspect is about the integration of satellite and community-based approach for forest change monitoring. As exemplified by Claudio et al. (Sassi et al. 2015), our result (Table 5.4) indicates that the integrated approach helped to improve the spatial, temporal and thematic details of forest change information. We used Landsat satellite data, as top-down approach to detect forest change. Similar to the work of DeVries et al. (DeVries et al. 2015b), our results (Table 5.4) show that the Landsat based NDVI time-series method is able to detect small scale forest change alerts in NRT. However, the thematic quality of these alerts i.e. forest change process and drives of change are very limited. Furthermore, the persistent cloud cover over the area induced data gaps and hampered forest change detection. We expect that Landsat8 and the future Sentinel 2 missions (Drusch et al. 2012) will play a major role to overcome these problems. On the other hand, we have utilised CBM, as bottom-up approach to monitor and verify the satellite-based forest change alerts. The result of this study shows (Table 5.4) that the satellite-based alerts were able to mobilize the local experts to visit the targeted locations. The ground observation alerts provided by the local experts had high thematic details (Pratihast et al. 2014). However, lack of coverage of the whole study area and consistency of datasets is the limitations of this approach. This can be solved by engaging more local experts, volunteers, PFM groups and citizens in monitoring and providing appropriate training and benefit schemes (Balderas Torres and Skutsch 2012).

Final aspect concerns the interaction of stakeholders with the system. The results show that the local stakeholders were actively engaged in social media compared to the IFMS (Table 5.3). As explored by Diga and Kelleher (Diga and Kelleher 2009), we also believe that mobile social media application and their capabilities to run over the limited access are expected to be the main cause of the interactions. Moreover, the limited access of the internet is also the possible explanations for the low use of the IFMS. This issue might be solved in the future with the improvement of internet coverage.

5.4.3. Limitations of the system

This study is a proof of concept about design and implementation of IFMS. An initial fitness for purpose evaluation of our implementation has been carried out and the results are being prepared for this publication. Overall, the evaluation results are favourable but more research over the longer time period with more participants is required to realise its true benefits and potentialities in terms of NRT forest monitoring.

At the moment our IFMS faces two key limitations in terms of design, which introduce some time lag in NRT forest change monitoring. First, the system utilises semi-automatic process chain for Landsat data processing. At the moment, USGS does not allow automatic download facilities for Landsat scenes. Hence, the images need to be downloaded manually. This restriction limits us to establish an automatic process chain for Landsat data. We expect that in future USGS will improve their data distribution infrastructures so that this process can be automatized. Second, the IFMS provides manual download functionalities for NRT forest change alerts. Hence, users have to download the alerts manually from our web-interface. This manual interaction introduces some time lag in disseminating the alerts to the local stakeholders. This limitation could be overcome by sending the forest change alerts directly to the mobile phone and utilising geo-fence service to notify people about the forest change locations (Biezen 2015).

5.5. Conclusions

Near real-time forest monitoring is necessary for better forest management. It allows local stakeholders to take prompt action which may avoid or reduce illegal activities and enhance transparency in the use of forest resources.

In this research, we describe the design and implementation of an interactive web-based NRT forest monitoring system and its evaluation in the UNESCO Kafa Biosphere Reserve in Southwestern Ethiopia. The proposed IFMS integrates three components: Web-GIS technologies, satellite and CBM data source and social media. The functional features of our IFMS are as follows: 1) functionality to download, store and process and run NRT forest change detection on Landsat time-series images, 2) facility to upload ground observations and download forest change location from the analysis of remote sensing on-demand, 3) ability to map and show hotspots of forest changes in space-time, 4) capability to provide feedback to local stakeholders and 5) functionality to provide interaction through social media. The evaluation result shows that the IFMS empowers local experts participation and interaction in forest monitoring process; provides up-to-date and accurate information on forest change. These information are consistent over time and can be integrated into NFMS/national MRV system; and ultimately enhances the effective communication among the stakeholders for forest managements.

5.6. Outlook

The remote sensing satellites, mobile technologies, web mapping platforms together with internet services technology are constantly improving. These improvements will provide new opportunities for NRT forest monitoring system. A number of future outlooks have been identified with regards to IFMS:

1) Testing over the larger area with more diversified user community is required.
2) Integrating multi-sensor remote sensing data streams such as Landsat, Sentinel 1 and Sentinel 2 mission may improve the forest change detection (Drusch et al. 2012; Reiche et al. 2015).
3) Developing mobile data acquisition tools and utilising geo-fence service can enhance the local stakeholders participation in forest monitoring (Biezen 2015).
4) Extension of the system is recommended in the domains of biodiversity and safeguards for National REDD+ implementation.

Acknowledgements

The work presented in this chapter has been carried out with in the frame of the project "Forest, Carbon and Biodiversity Monitoring", implemented by the Nature and Biodiversity Conservation Union (NABU), German and Ethiopian branches, with funding from the International Climate Initiative (IKI) of the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMU) (IKI-1 project number 05/2014-2). Funding for the work of Arun Kumar Pratihast was provided by the project google deforestation monitoring (5120906). We also like to thank NABU and their local partners in Ethiopia for supporting in this study. We particularly acknowledge Mesfin Tekle, Muluken Mekuria, Terefe Woldegebriel and the 10 local forest rangers of the Kafa Zone Bureau of Agriculture and Rural Development for their support and assistance in forest monitoring observations.

Annex: additional material of chapter 5

Table A5.1 Forest protection awareness meeting in Kafa, Ethiopia.

Date	Kebele	Participants		
		Male	Female	Total
15-16 November 2014	Yeyebito	61	35	96
29-30 November 2014	Boka	14	59	73
6-7 December 2014	Saja	52	19	71
13-14 December 2014	Kasha	49	19	68
20-21 December 2014	Tula	48	19	67
28-29 March 2015	Mera	51	21	72

Chapter

6

Synthesis

6.1. Main results

The main goal of this thesis is to develop an approach that combines emerging technologies and community-based monitoring (CBM) for tropical forest monitoring. The development of this research is driven by four specific research questions, presented in the Introduction (**Chapter 1**, Section 1.4). Each research question is answered in the core chapters of this thesis. In the following sections, the findings relative to each research question are summarized.

Research question 1: What are the potentials to link community-based efforts to the national forest monitoring system?

This research question is formulated to understand the potential role, consensus, divergence and gaps in the community-based forest monitoring program and to better link CBM information to the national forest monitoring system. This research question is addressed in **Chapter 2** in four steps.

In the first step, the need for local communities engagements in the national forest monitoring system is analysed. This analysis is extended to explore the relative importance of two main local drivers of deforestation as presented by Hosonuma et al. (2012), namely: 1) subsistence agriculture and 2) charcoal and fuelwood extraction. The results show that Africa and parts of Asia have a large proportion of locally driven forest change activities. These regions need to develop appropriate strategies to engage local communities to monitor these drivers of change.

In the second step, the potential role of CBM for monitoring forest carbon and change activities is explored. Various data sources such as coarse, medium and fine resolution satellite data, airborne laser scanning and professional forest inventory are available at national level for quantifying forest carbon stocks and detecting change activities. Each of these data sources has their own strengths and limitations in terms of acquisition, accuracy assessment and cost. However, the comparative study in **Chapter 2** shows that the CBM data can enhance monitoring by identifying small scale forest disturbance activities associated with forest degradation better than the other data sources. These results are in line with a recent study conducted by Bellfield et al. (2015).

In the third step, a conceptual framework is developed to link local and national forest monitoring systems. The conceptual framework is based on previous research (Conrad and Hilchey 2011; Conrad and Daoust 2008; Larrazábal et al. 2012) in the field of CBM of natural resource monitoring. The implementation of this framework requires careful consideration regarding data transmission, data infrastructures, standards and guidelines, capacity development and flow of resources (e.g., equipment, supervision and incentives).

In the fourth step, a status check on how countries are advancing in considering CBM in their national REDD+ efforts is provided. To this aim, the 28 readiness preparation proposals of the World Bank Forest Carbon Partnership Facility were reviewed. The results show that all countries have acknowledged the involvement of communities as a driving force to improve forest management and its sustainable use. However, only few countries; in particular Mexico, Tanzania, Vietnam and Nepal (Danielsen et al. 2013; Danielsen et al. 2011; Shrestha 2011; Topp-Jørgensen et al. 2005; Torres et al. 2015); are in advanced stages of developing community-based forest management and monitoring strategies and have been able to demonstrate these activities at project level.

Hence, this chapter shows that there is a need for enhancing the linkages between CBM and the national forest monitoring system. The technology to support CBM is available, but the possibilities are still underexplored.

Research question 2: How can information and communication technologies (ICTs) support the automation of the community data collection process for monitoring forest carbon stocks and change activities using modern handheld devices?

This research question is answered in C**hapter 3** and C**hapter 4**. Previously, researchers have explored the potential use of mobile devices to take measurements of forest carbon and forest related change activities at community level (Aanensen et al. 2009; Ferster and Coops 2013; Parr et al. 2002). However, they do not directly address the usability requirements specific to the community user. Hence, an integrated mobile device based data collection system is presented in **Chapter 3**.

The system is designed based on service platform architecture and is integrated into four tiers: data, logic, presentation and communication. Each of these tiers is implemented using open source technologies. The result of system implementation shows that the developed system offers four distinct features: 1) multi-language support, 2) multi-user support for simultaneous use, 3) applicability in remote locations and 4) voice recording as a desired functionality and local data storage facility. The evaluation of the system is performed based on fitness-for-use, which includes data entry accuracy, data transmission and measurement costs.

Two types of forest monitoring forms are designed using open data kit (ODK) and deployed in an Android platform: forest inventory forms for estimation of above ground forest biomass and forest change monitoring forms for reporting and mapping activity data. The data acquisition performance is tested at TraBui commune, Quang Nam province of Central Vietnam. The data entry accuracy is assessed by comparing locally gathered data with expert (local, regional and national) field measurements. The data entry errors are high while entering the text category, compared to the multimedia and selection options of the form. Furthermore, results show that the proposed system is able to overcome difficulties in data translation and digitization. User friendly data transmission features of the system further enabled the local community to feed the data directly to the database server. Similar to other studies (Danielsen et al. 2011; Lawlor et al. 2013; Topp-Jørgensen et al. 2005), this study also shows that community-based measurements costs are significantly lower than expert-based measurements.

To support the findings of **Chapter 3**, the data acquisition form (for activity data related to forest change) for mobile devices is further improved in **Chapter 4**. The system is implemented through 30 local experts in the UNESCO Kafa Biosphere Reserve, Ethiopia. These local experts are recruited within the frame of the project through a collaborative scheme of monitoring with external interpretation of the data. All chosen local experts have at least a secondary level of education and some fundamental understanding of forest management.

The results show that a mobile device based system motivates local experts to collect more data during the rainy season as compared to the paper-based system. The digital system facilitates local experts to collect forest change variables; such as geo-location, size of forest change, time of forest change and proximate drivers behind the change, in a more efficient way. Similar to previous studies (Bellfield et al. 2015; Gouveia et al. 2004), this study indicates that the use of mobile devices has a clear advantage over a paper-based monitoring system in capturing photographs and multimedia information from the ground; hence, improves the local capacity in data collection, transmission and visualization procedures. Furthermore, the results show that attributes of these datasets are fully structured in terms of spatial, temporal and thematic details and are capable of describing the forest change processes.

Research question 3: What is the accuracy and compatibility of community collected data compared to other data (e.g., optical remote sensing and expert field measurements) for quantifying forest carbon stocks and changes?

Chapter 3 and C**hapter 4** describe the accuracy and compatibility of community collected data compared to other data sources (e.g., optical remote sensing and expert field measurements) for quantifying forest carbon stocks and changes.

Generally, forest inventories are carried out at the national level to collect ground-based measurements for estimating forest carbon stocks which allow to estimate emission factors (Brown 1997). This approach is expensive, time-consuming and only a few developing countries have such comprehensive forest inventories that allow for national forest carbon stock estimates (DeFries et al. 2007). **Chapter 3** presents that local communities are able to measure and report the basic tree variables such as diameter at breast height, tree species and tree counts. The collected data is found to be of a level of accuracy comparable to that produced by professional forest inventory staff.

The results show that the number of trees counted per plot is obtained with highest agreement between local and professional measurements (index of agreement = 0.97). There is a good agreement between the total basal area per plot measured by locals and professionals (points close to the 1:1 line) for all observations. It is observed that local people needed more time than the professional to perform the measurements. Finally, the comparison results of above ground biomass estimation show that biomass estimation by professionals is on average higher than that estimated by local people. The results confirm findings of earlier studies conducted in several countries such as Ghana, Tanzania, Nepal and Philippines (Brashares and Sam 2005; Shrestha et al. 2014; Zahabu and Malimbwi 2011).

Other studies (Boissière et al. 2014; Danielsen et al. 2011; Skutsch et al. 2011; Torres 2014) have demonstrated the potential of CBM in assessing locally driven and small scale forest change activities (deforestation, forest degradation or reforestation). However, none of the studies have extensively investigated the consistency and complementary use of local datasets to remote sensing. Hence, the accuracy of community collected forest change data is assessed with high resolution SPOT imagery in **Chapter 3**. The results show that community participation is more effective compared to professionals and high resolution remote sensing SPOT imagery in detecting small scale forest degradation caused by subsistence fuelwood collection and selective logging.

In **Chapter 4,** the accuracy and complementary use of local datasets is further examined in the UNESCO Kafa Biosphere Reserve, Ethiopia. High resolution SPOT and RapidEye satellite imagery and professional measurements are used as validation data to assess more than 700 forest change observations collected by the local communities. Results show that the local communities are capable of describing the processes of change associated with deforestation, forest degradation and reforestation in terms of three categories: spatial, temporal and thematic.

The spatial category includes the categorical location information, GPS location information and the estimated size of forest change. The results show that the spatial accuracies vary considerably across the various location categories, like Woreda (administrative unit), Kebele (administrative sub-unit of a Woreda) and a spatial category representing distance to core forest, nearest village and roads (i.e. less than 1 km, 1–2 km, 2–3 km and more than 3 km) included in the monitoring forms. The Woreda is recorded with the highest mean fraction correct of 0.92, whereas the estimated distance to core forest is found to have the lowest mean fraction correct of 0.71. A comparison of GPS errors reported by local experts with those reported in the field-based reference dataset show a slight systematic error of 0.65 m between the two datasets. A smaller bias (0.16) is found between forest change areas as reported by the local experts and forest change areas derived from high resolution remote sensing imagery, in cases where these areas do not exceed 2 ha. In larger change areas (exceeding 2 ha); however, the absolute bias increased to 1.06, implying that the local experts have systematically underestimated the area of large change polygons.

The temporal category includes the timing of deforestation and forest degradation. To assess temporal accuracy of the local dataset, temporal lag is calculated based on forest disturbance dates determined using high resolution remote sensing time-series data. The results reveal that 33% of deforestation events reported by local experts correspond accurately to the dates observed in the remote sensing data. In other cases, 25% and 20% of total deforestation events as observed from remote sensing are detected one and two years earlier than the local reported time respectively. On the other hand, the comparison of dates associated with forest degradation as reported by local experts shows that the majority of these signals are recorded one (32%) to two (22%) years earlier than dates detected by remote sensing.

The thematic category is one of the added values of the local expert dataset compared to remote sensing. The thematic category includes three thematic elements: the presence of forest, forest change type and drivers of forest change. The results show an overall accuracy of 82% for thematic elements compared to the professional measurements. The presence of forest is found to have a producer's accuracy of 92%, a user's accuracy of 93% and an overall accuracy of 94%. The drivers of forest change have a comparatively lower producer's accuracy of 71%, a user's accuracy of 68% and an overall accuracy of 69%.

In **Chapter 4,** the complementary use of local data and remotely sensed data is investigated based on four key forest monitoring questions.

The first question for forest monitoring relates to the location of change. The spatial accuracy results of the local expert data show that local datasets can be used to better understand information related to local administration (e.g., the name of the district and village) or geographical characteristics (distance to roads, nearest village and core forest). Similarly, remote sensing helps to add value to local data streams by providing wall-to-wall coverage, which can be used to validate local data streams. The synergies of both methods can lead to a more efficient monitoring system for data acquisition and to rendering reliable information.

The second question for forest monitoring relates to the area of forest change. Both remote sensing and local datasets have their own difficulties when used to map the area of forest change. Remote sensing plays a promising role for mapping larger areas (Hansen et al. 2013), but the trade-offs between the spatial and temporal capabilities of remote sensing limit their use to monitoring small scale forest change (De Sy et al. 2012). Since the results of this chapter show that local datasets are sufficiently accurate to track small forest changes, the overall mapping of forest change area can be enhanced by exploiting the synergy between these datasets.

The third question for forest monitoring is related to the timing of forest change. Specifically, the results of this study show that higher resolution SPOT and RapidEye imagery detect deforestation earlier than local experts, whereas the detection of forest degradation using remote sensing data is delayed as compared to that of local experts. Reports of small scale deforestation and forest degradation from local experts can therefore contribute to an improved understanding of change processes and the integration of both methods should lead to a more efficient system to signal new changes in near real-time.

The final question for forest monitoring is related to the drivers of forest change. Results show that remote sensing has limited capabilities to track forest change drivers, whereas community observations are very accurate in reporting these drivers. These drivers of change can be better understood with an intimate knowledge of forest change processes and this information has the potential to enhance the pertinence of the remote sensing data analysis. Information on drivers collected by local experts thus presents new opportunities for monitoring forest change events.

Research question 4: What is a suitable design for an interactive remote sensing and community-based near real-time forest change monitoring system and how can such a system be operationalized?

Recently, some efforts have been made towards developing interactive near real-time (NRT) forest monitoring system using open source technologies (e.g., DETER (Assunção et al. 2014), Global Forest Watch (http://www.globalforestwatch.org/)). However, these systems need to be improved by incorporating local data streams to make them more interactive and to ensure the participation of local stakeholders in monitoring their forests. In this regard, **Chapter 5** addresses research question 4 by designing an interactive forest monitoring system (IFMS). This system uses four levels of geographic information services: 1) the acquisition of continuous data streams from satellite and CBM using mobile devices, 2) NRT forest disturbance detection based on satellite time-series, 3) presentation of forest disturbance data through a web-based application and social media and 4) interaction of the satellite-based disturbance alerts with end-user communities to enhance the collection of ground data. The system is developed using open source technologies and has been implemented together with ten local experts in UNESCO Kafa Biosphere Reserve, Ethiopia.

The results of a usability assessment revealed that IFMS empowers local experts participation, provides easy access to information on forest change and considerably improves the collection and storage of ground observation by local experts. Evidence was obtained that the integration of satellite and CBM helped to improve the spatial, temporal and thematic details of forest change information. Satellite-based NRT disturbance alerts were used to mobilize the local experts to visit targeted locations. The ground observation alerts provided by the local experts have high thematic detail in terms of their location, extent, timing and causes of forest change associated with deforestation, forest degradation and reforestation. Furthermore, the results show that social media lead to higher levels of user interaction and noticeably improved communication among stakeholders. These findings confirm the results of other studies (Daume et al. 2014; Werts et al. 2012) showing the capabilities of social media as a new perspective for effective communication in forest monitoring.

6.2. General conclusions

This thesis aims at addressing the need for advancing community-based forest monitoring methods that combine emerging technologies, optical remote sensing and CBM in order to improve tropical forest monitoring. The main scientific contributions of this work are towards better defining the role of local communities, technical and operational conditions under which CBM can contribute to national forest monitoring systems. Two novel schemes: integrated satellite and CBM (**Chapter 3** and **Chapter 4**) and interactive near real-time CBM (**Chapter 5**) are designed and implemented to improve community-based forest monitoring. Figure 6.1 summarises the key achievement of this thesis in three aspects of CBM namely: timeliness, data accuracy and levels of engagement.

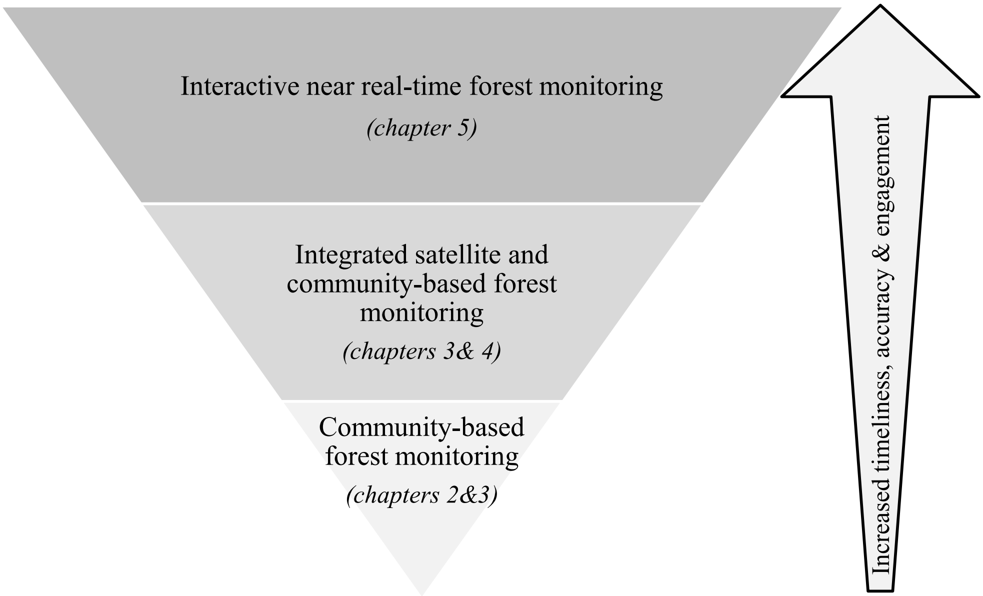


Figure 6.1 Overview of the main results obtained in this thesis. The arrow shows the direction of progressive achievements towards community-based forest monitoring system.

Based on the results of this thesis, it can be concluded that:

- CBM is becoming more relevant in national forest monitoring system for monitoring local drivers of deforestation and forest degradation.
- The establishment of community-based forest monitoring system requires systematically developed methods, common guidelines and quality control mechanisms.
- Use of mobile devices with user friendly applications improves community-based forest monitoring data collection, transmission and visualization processes.
- Local communities are able to acquire some basic forest inventory measurements such as diameter at breast height, tree species and tree counts with accuracy at lower costs compared to professional expert measurements.
- The strength of CBM lies in describing processes of change associated with deforestation, forest degradation and reforestation, in terms of their spatial location, extent, timing and causes.

- CBM data offers a way to complement and enhance remote sensing-based forest change analysis.
- An interactive web-based forest monitoring system provides NRT information on forest change and considerably improves the data accuracy, level of stakeholder engagements, community capacity and effectiveness of the monitoring program.

6.3. Reflection and outlook

In recent years, advances in technologies have offered solutions to tackle the tropical forest monitoring challenges at global and national level. The advancements of remote sensing satellites (e.g., Landsat, sentinel, RapidEye, SPOT) and ground sensors (e.g., Terrestrial LiDAR, mobile devices, citizen sensors) have provided a large amount of potential for new forest monitoring data. At the same time, the advent of large scale data processing and storing platforms offer a complementary solution to process and analyse these forest monitoring data. A viable technical solution could be realized using big data techniques to store and process such a large scale of data (Yuan et al. 2012). The processing of such big data is possible with the emerging cloud computing paradigm. One such platform in evolution is Google technologies (e.g., Google Earth Engine, Map Engine, ODK) which enables automated remote sensing and ground observation data processing and forest mapping. Hansen et al. (2013) used this Google platform to quantify of global forest change from 2000 to 2012 at a spatial resolution of 30 meters. Recently, Global Forest Watch (http://www.globalforestwatch.org/) used Google technologies to build an interactive online forest monitoring and NRT alert system. This system is aimed to empower public institutions and civil society with the information which lead to better manage and conserve forest landscapes.

Figure 6.2 provides a synthesis of the use of emerging technologies and highlights the need to capitalize this development towards improving participatory forest monitoring and management processes. Technological advances are largely of global scale. But the utility of these technologies at a local scale is linked to certain uses. In this regard, this thesis scientifically contributes to the development and testing of emerging technologies and explores their practical use at local scale. Emerging technologies help the local communities to get engaged in forest monitoring and the methods presented in this thesis are applicable to a broader geographic scope. However, monitoring happens for a reason and local forest monitoring needs to link to forest management and land use decision making processes. This thesis is focused to address monitoring needs imposed by REDD+ but the sustainable use of these technologies in the same way relates other land use and management processes as well.

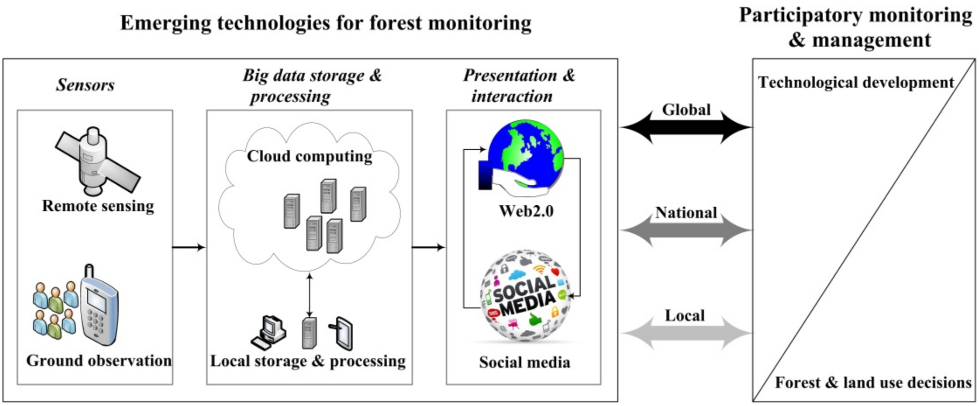


Figure 6.2 Emerging technologies in participatory forest monitoring and management processes.

To address this limitation, the following section reflects on four key aspects of the proposed community-based forest monitoring approaches and further discusses opportunities and developments.

6.3.1. Overcoming technical limitations of emerging tools

The potential of using mobile devices for supporting community participants to immediately record measurements in a digital system is highlighted in this thesis. However, effective utilisation of such technology for CBM is still exceptional and it faces several implementation challenges when used by minimally-trained local communities. The following limitations are observed in this study.

The first limitation of the proposed approach is observed in terms of using the mobile device in developing countries. Implementation of the mobile device in forest monitoring faces several challenges such as: inadequate memory (including phone memory card capacity) and insufficient battery life, GPS functioning not being sensitive enough to work under forest canopy, cover for use in challenging environments not being robust, and inappropriate screen size, brightness and sensitivity. These limitations may be solved in the future by improved technologies and functionalities of mobile devices.

The second limitation of the proposed approach is that ODK lacks the spatial mapping capabilities on the client side. Hence, local communities are not able to map the data while in the field. Recently, ODK released an extended version called GeoODK (http://geoodk.com) in which the spatial mapping capabilities are incorporated. These capabilities will enable the local community to load base maps and visualise the data on these maps while in the field.

The third limitation is observed in data entry errors. The results in **Chapter 3** show that local people are more accurate in entering information through selecting an icon or a check box than through manually entering text or numbers. This issue is partially addressed in **Chapter 4** by improving data acquisition forms. Molinier et al. (2014) proposed image acquisitions techniques to measure forest inventory measurements such as stem biomass, tree species, tree height and age through the image. These techniques can be a viable solution to address data entry errors.

The fourth limitation is in the capture and interpretation of ground photographs. This thesis uses visual image interpretation techniques and derives only the qualitative information from the photographs. However, Confalonieri et al. (2013) explored the potential to use hemispherical (fish-eye) lenses in mobile devices. Additionally, they developed the PocketLAI tool to automatically process the images to derive the leaf area index. Utilisation of this tool in community-based forest monitoring can enhance potential interpretation of ground photographs. Further research is needed to evaluate the fitness for use of these applications in terms of local suitability.

The last limitation of the proposed approach is that it is designed for Android based mobile phones only. The ODK framework is used to deploy the data acquisition forms. In the future, the ODK framework might become compatible with other devices. Future work would be to make the proposed approach compatible with windows and iPhone operating system based devices.

6.3.2. Linking the local to forest measuring, monitoring and mapping

This thesis has addressed the three aspects of CBM: measuring, monitoring and mapping of forest carbon and change activities. The measuring aspect related to local communities is explored in **Chapter 3**. The results of this study have proven that with some training and suitable protocols, it would be beneficial to involve communities in measuring forest carbon stocks in their territories. These data might not be able to meet the national forest inventory requirements, but community involvement together with professional experts may link to the implementation of forest protection and carbon savings mechanisms.

Limited progress has been made towards the long-term sustainability of CBM, despite many studies indicating its potentials. Hence, **Chapter 3**, **Chapter 4** and **Chapter 5** of this thesis focus on the scientific developments of CBM data in monitoring forest change activities (mainly for activity data). The results show a wide range of factors, including the motivation and timing of training and capacity building programs, and the influence of adverse weather conditions on the monitoring activities of local communities. Therefore, further research might require addressing these factors.

The mapping aspect of local community members has been demonstrated in Participatory Geographical Information Systems (McCall 2010). Numerous studies have shown that mobile technologies such as CyberTracker (Parr et al. 2002), Epicollect (Aanensen et al. 2009) and ODK (OpenDataKit 2012) enable local communities to create maps of forest resources. **Chapter 4** and **Chapter 5** of this thesis demonstrate that local communities are more accurate in mapping small scale deforestation, forest degradation and reforestation compare to remote sensing. One key area of future work is the integration of local and remote sensing datasets for mapping change events over larger areas in the tropics. More recently, DeVries et al. (2015a) demonstrated the potential of mapping deforestation and forest degradation using random forest models trained with data from CBM data. Further improvements towards the integration of CBM data with other data sources such as Sentinel 2, terrestrial or airborne LiDAR or other airborne remote sensing approaches are essential for applying these methods in tropical countries.

6.3.3. Capitalising on new satellite-based observations for near real-time tropical forest monitoring

Advancements in satellite open data policies (Wulder et al. 2012), big data processing environments (Li et al. 2015) and satellite time-series methods (DeVries et al. 2015b; Verbesselt et al. 2010) offer a unique opportunity to establish NRT forest change monitoring. Recently, efforts have been made to develop NRT forest monitoring systems (e.g., DETER (Assunção et al. 2014), Global Forest Watch) at large spatial scales. While these systems are increasingly providing data for local studies, these systems need to be accompanied by suitable ground data measurements to build a suitable synergy between remote sensing and in-situ measurements. This synergy will allow the system to be more accurate, interactive and legitimate for local stakeholders in monitoring their forests. In this regard, **Chapter 5** provides a detailed design and implementation framework of an interactive forest monitoring system (IFMS) which combines Web-GIS technologies, Landsat satellite and CBM data, and social media to support NRT forest monitoring in the UNESCO Kafa Biosphere Reserve in Southwestern Ethiopia. The results show that CBM can fill the data gap of remote sensing to some extent during wet periods.

A number of future research directions have been identified with regards to IFMS:

- Interactive communication between the local communities and stakeholders such as local institutions, participatory forest management groups and non-government organizations is vital for the forest monitoring system. It helps to build the relations between local people and the authorities, and results in more rapid management interventions. Some researchers (Daume et al. 2014; Werts et al. 2012) have shown the potential of social media in interactive communications, but further investigation is needed on the appropriate complementary use of these data sources in developing countries.
- Integrating multi-sensor remote sensing data streams such as Landsat 8, Sentinel 1 and Sentinel 2 missions, can improve NRT forest change detection. Reiche et al. (2015) proposed a Bayesian approach to combine Landsat and ALOS PALSAR time-series for NRT deforestation detection. Further, improvement of this method by combing CBM data can lead to better prediction of deforestation and degradation in NRT.

- Recently, Schepaschenko et al. (2015) explored the synergy of remote sensing, crowdsourcing and Food and Agriculture Organisation (FAO) of the United Nations statistics to develop a global hybrid forest mask. These efforts need to be further extended at the local level to explore the usability of CBM data as reference data for remote sensing map validation.

6.3.4. Linking to the issue of multi-level governance

This thesis is founded on the argument that considerable progress can be made towards community-based forest monitoring. However, there are many avenues which need to be explored in order to ensure long-term sustainability of CBM program and, in particular, to link the local with the national level. For any further progress, it is essential to understand how monitoring operates within a framework of multi-level governance. CBM programs need legitimate support and collaboration from the governance structures. Some researchers (Cronkleton et al. 2011; Kashwan and Holahan 2014) have explored multi-level governance issues and proposed the following four recommendations for shaping, planning and implementation of CBM.

Firstly, countries need to form policy to promote the CBM program. These policies should not only consider the monitoring activities but should also focus on improving forest tenure security by harmonizing local tenure rules with national laws and the international framework, governing forest use with sustainable management (Doherty and Schroeder 2011).

Secondly, continuous engagement of local communities in the CBM program is crucial. The findings from this thesis show that participation of local communities decreases over the time. Hence, continuous interaction and adequate funding are deemed necessary. Boissiere et al. (2014) have proposed some incentives schemes, including financial, political (e.g., empowerment, participation in decision making) and/or indirect benefits for motivating people. This needs to be tested under various local circumstances.

Thirdly, the capacity building programs will be needed for long-term success of this approach. Such programs should enable all members of the community and local institutions to develop skills and competencies so as to take greater control of their forests and also contributes to inclusive personal skill development.

Lastly, scaling up to the national scale can have significant impact on the success of the CBM. The scaling up requires learning by doing experiences. Countries should establish CBM cases at project level. Lessons learned from these projects should be incorporated into larger scale efforts. The implementation will be fruitful and efficient if both the local and the national level contribute and benefit at the same time.

While the four approaches mentioned above address the issues of multi-level governance, actual progress of CBM implementation relies on interdisciplinary research involving experts from forest management, forest governance, forest monitoring and the various national and local stakeholders engaged in such processes (Visseren-Hamakers et al. 2012).

References

Aanensen, D.M., Huntley, D.M., Feil, E.J., al-Own, F.a., & Spratt, B.G. (2009). EpiCollect: Linking Smartphones to Web Applications for Epidemiology, Ecology and Community Data Collection. *PLoS ONE, 4*, e6968

Achard, F., DeFries, R., Herold, M., Mollicone, D., Pandey, D., & de Souza, C. (2012). Guidance on monitoring of gross changes in forest area. A sourcebook of methods and procedures for monitoring and reporting anthropogenic greenhouse gas emissions and removals associated with deforestation, gains and losses of carbon stocks in forests remaining forests, and forestation, GOFCGOLD Report version COP 18-1. Wageningen University, The Netherlands: GOFC-GOLD Land Cover Project Office

Achard, F., Mollicone, D., Stibig, H.J., Aksenov, D., Laestadius, L., Li, Z., Popatov, P., & Yaroshenko, A. (2006). Areas of rapid forest-cover change in boreal Eurasia. Forest Ecology and Management, 237, 322-334

Achard, F., Stibig, H.J., Eva, H.D., Lindquist, E.J., Bouvet, A., Arino, O., & Mayaux, P. (2010). Estimating tropical deforestation from Earth observation data. Carbon Management, 1, 271-287

Aerts, R., Berecha, G., & Honnay, O. (2015). Protecting coffee from intensification. Science, 347, 139

Agrawal, A., Chhatre, A., & Hardin, R. (2008). Changing governance of the world's forests. Science, 320, 1460-1462

Ahrends, A., Burgess, N.D., Milledge, S.A.H., Bulling, M.T., Fisher, B., Smart, J.C.R., Clarke, G.P., Mhoro, B.E., & Lewis, S.L. (2010). Predictable waves of sequential forest degradation and biodiversity loss spreading from an African city. Proceedings of the National Academy of Sciences of the United States of America, 107, 14556-14561

Anderson, L.O., Shimabukuro, Y.E., Defries, R.S., & Morton, D. (2005). Assessment of deforestation in near real time over the Brazilian Amazon using multitemporal fraction images derived from Terra MODIS. IEEE Geoscience and Remote Sensing Letters, 315-318

Angelsen, A. (2008). How do we set the reference levels for REDD payments? , In moving ahead with REDD: issues, options and implications: Center for International Forestry Research (CIFOR), Bogor, Indonesia

Angelsen, A., Brockhaus, M., Sunderlin, W., & Verchot, L. (2012). Analysing REDD+: Challenges and choices, . Center for International Forestry Research (CIFOR), Bogor, Indonesia

Asner, G.P. (2001). Cloud cover in Landsat observations of the Brazilian Amazon. International journal of remote sensing, 22, 3855-3862

Assunção, J., Gandour, C., & Rocha, R. (2014). DETERring deforestation in the Brazilian Amazon: environmental monitoring and law enforcement

Avitabile, V., Herold, M., Henry, M., & Schmullius, C. (2011). Mapping biomass with remote sensing: a comparison of methods for the case study of Uganda. Carbon balance and management, 6, 7

Baccini, A., Laporte, N., Goetz, S., Sun, M., & Dong, H. (2008). A first map of tropical Africa's above-ground biomass derived from satellite imagery. Environmental Research Letters, 3, 045011

Balderas Torres, A., & Skutsch, M. (2012). Splitting the Difference: A Proposal for Benefit Sharing in Reduced Emissions from Deforestation and Forest Degradation (REDD+). Forests, 3, 137-154

Bellfield, H., Sabogal, D., Goodman, L., & Leggett, M. (2015). Case Study Report: Community-Based Monitoring Systems for REDD+ in Guyana. Forests, 6, 133-156

Biezen, J.V. (2015). An offline 'Geo-Fence' application: the development of a citizen science mobile application for REDD+ monitoring. Geographical Information Management and Applications (GIMA),Utrecht University, Utrecht, The Netherlands, Master thesis, 112

Bimber, O., Encarnação, L.M., & Stork, A. (2000). Multi-layered architecture for sketch-based interaction within virtual environments. Computers and Graphics (Pergamon), 24, 851-867

Bocher, E., Neteler, M., Steiniger, S., & Hunter, A.S. (2012). Free and Open Source GIS Software for Building a Spatial Data Infrastructure. Geospatial Free and Open Source Software in the 21st Century (pp. 247-261): Springer Berlin Heidelberg

Boissière, M., Beaudoin, G., Hofstee, C., & Rafanoharana, S. (2014). Participating in REDD+ Measurement, Reporting, and Verification (PMRV): Opportunities for Local People? Forests, 5, 1855-1878

Bonan, G.B. (2008). Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. Science, 320, 1444-1449

Börner, J., Kis-Katos, K., Hargrave, J., & König, K. (2015). Post-Crackdown Effectiveness of Field-Based Forest Law Enforcement in the Brazilian Amazon. PLoS One, 10, e0121544

Bose, A., & Shin, K.G. (2006). On mobile viruses exploiting messaging and bluetooth services. Proceedings of the Securecomm and Workshops, Baltimore, MD, USA, 28 August 2006–1 September 2006. In (pp. 1-10): Ieee

Bottcher, H., Eisbrenner, K., Fritz, S., Kindermann, G., Kraxner, F., McCallum, I., & Obersteiner, M. (2009). An assessment of monitoring requirements and costs of 'Reduced Emissions from Deforestation and Degradation'. Carbon balance and management, 4, 7

Bowler, D.E., Buyung-Ali, L.M., Healey, J.R., Jones, J.P.G., Knight, T.M., & Pullin, A.S. (2011). Does community forest management provide global environmental benefits and improve local welfare? Frontiers in Ecology and the Environment, 10, 29-36

Brashares, J.S., & Sam, M.K. (2005). How much is enough? Estimating the minimum sampling required for effective monitoring of African reserves. Biodiversity and Conservation, 14, 2709-2722

Bravo, J., Villarreal, V., Hervás, R., & Urzaiz, G. (2012). Using a communication model to collect measurement data through mobile devices. Sensors, 12, 9253-9272

Brofeldt, S., Theilade, I., Burgess, N., Danielsen, F., Poulsen, M., Adrian, T., Bang, T., Budiman, A., Jensen, J., Jensen, A., Kurniawan, Y., Lægaard, S., Mingxu, Z., van Noordwijk, M., Rahayu, S., Rutishauser, E., Schmidt-Vogt, D., Warta, Z., & Widayati, A. (2014). Community Monitoring of Carbon Stocks for REDD+: Does Accuracy and Cost Change over Time? Forests, 5, 1834-1854

Brown, S. (1997). Estimating biomass and biomass change of tropical forests: a primer; Food and Agriculture Organization of the United Nations: Rome, Italy. FAO Forestry Paper

Bruin, S.d., Bregt, A., & van de Ven, M. (2001). Assessing fitness for use: the expected value of spatial data sets. International Journal of Geographical Information Science, 15, 457-471

Bucki, M., Cuypers, D., Mayaux, P., Achard, F., Estreguil, C., & Grassi, G. (2012). Assessing REDD+ performance of countries with low monitoring capacities: The matrix approach. Environmental Research Letters, 7

Bugs, G., Granell, C., Fonts, O., Huerta, J., & Painho, M. (2010). An assessment of Public Participation GIS and Web 2.0 technologies in urban planning practice in Canela, Brazil. Cities, 27, 172-181

Burgess, N.D., Bahane, B., Clairs, T., Danielsen, F., Dalsgaard, S., Funder, M., Hagelberg, N., Harrison, P., Haule, C., & Kabalimu, K. (2010). Getting ready for REDD+ in Tanzania: a case study of progress and challenges. Oryx, 44, 339-351

Castro, P., Alonso, J., Guerra, C., Gonçalves, J., Pôças, I., Marcos, B., & Honrado, J. (2013). Novel tools to improve the management of spatial data quality in the context of ecosystem and biodiversity monitoring. In Proceedings of the GI Forum, Salzburg, Austria.

Chambers, R. (1994). Participatory rural appraisal (PRA): Analysis of experience. World Development, 22, 1253-1268

Chhatre, A., Lakhanpal, S., Larson, A.M., Nelson, F., Ojha, H., & Rao, J. (2012). Social safeguards and co-benefits in REDD+: a review of the adjacent possible. Current Opinion in Environmental Sustainability, 4, 654-660

Cochran, W.G. (1946). Relative accuracy of systematic and stratified random samples for a certain class of populations. The Annals of Mathematical Statistics, 164-177

Confalonieri, R., Foi, M., Casa, R., Aquaro, S., Tona, E., Peterle, M., Boldini, A., De Carli, G., Ferrari, A., & Finotto, G. (2013). Development of an app for estimating leaf area index using a smartphone. Trueness and precision determination and comparison with other indirect methods. Computers and electronics in agriculture, 96, 67-74

Connors, J.P., Lei, S., & Kelly, M. (2012). Citizen Science in the Age of Neogeography: Utilizing Volunteered Geographic Information for Environmental Monitoring. Annals of the Association of American Geographers, 102, 1267-1289

Conrad, C.C., & Hilchey, K.G. (2011). A review of citizen science and community-based environmental monitoring: issues and opportunities. Environmental Monitoring and Assessment, 176, 273-291

Conrad, C.T., & Daoust, T. (2008). Community-based monitoring frameworks: Increasing the effectiveness of environmental stewardship. Environmental Management, 41, 358-366

Coops, N.C., Wulder, M.A., Culvenor, D.S., & St-Onge, B. (2004). Comparison of forest attributes extracted from fine spatial resolution multispectral and lidar data. Canadian Journal of Remote Sensing, 30, 855-866

Cronkleton, P., Bray, D.B., & Medina, G. (2011). Community forest management and the emergence of multi-scale governance institutions: Lessons for REDD+ development from Mexico, Brazil and Bolivia. Forests, 2, 451-473

Dalle, S.P., de Blois, S., Caballero, J., & Johns, T. (2006). Integrating analyses of local land-use regulations, cultural perceptions and land-use/land cover data for assessing the success of community-based conservation. Forest Ecology and Management, 222, 370-383

Danielsen, F., Adrian, T., Brofeldt, S., van Noordwijk, M., Poulsen, M.K., Rahayu, S., Rutishauser, E., Theilade, I., Widayati, A., An, N.T., Bang, T.N., Budiman, A., Enghoff, M., Jensen, A.E., Kurniawan, Y., Li, Q., Mingxu, Z., Schmidt-Vogt, D., Prixa, S., Thoumtone, V., Warta, Z., & Burgess, N. (2013). Community monitoring for REDD+: International promises and field realities. Ecology and Society, 18

Danielsen, F., Burgess, N.D., & Balmford, A. (2005). Monitoring matters: Examining the potential of locally-based approaches. Biodiversity and Conservation, 14, 2507-2542

Danielsen, F., Burgess, N.D., Balmford, A., Donald, P.F., Funder, M., Jones, J.P.G., Alviola, P., Balete, D.S., Blomley, T., Brashares, J., Child, B., Enghoff, M., Fjeldså, J., Holt, S., Hübertz, H., Jensen, A.E., Jensen, P.M., Massao, J., Mendoza, M.M., Ngaga, Y., Poulsen, M.K., Rueda, R., Sam, M., Skielboe, T., Stuart-Hill, G., Topp-Jørgensen, E., & Yonten, D. (2009). Local participation in natural resource monitoring: A characterization of approaches. Conservation Biology, 23, 31-42

Danielsen, F., Burgess, N.D., Jensen, P.M., & Pirhofer-Walzl, K. (2010). Environmental monitoring: the scale and speed of implementation varies according to the degree of people's involvement. Journal of Applied Ecology, 47, 1166-1168

Danielsen, F., Jensen, P.M., Burgess, N.D., Altamirano, R., Alviola, P.A., Andrianandrasana, H., Brashares, J.S., Burton, A.C., Corpuz, N., & Enghoff, M. (2014). A multicountry assessment of tropical resource monitoring by local communities. BioScience, 64, 236-251

Danielsen, F., Skutsch, M., Burgess, N.D., Jensen, P.M., Andrianandrasana, H., Karky, B., Lewis, R., Lovett, J.C., Massao, J., Ngaga, Y., Phartiyal, P., Poulsen, M.K., Singh, S.P., Solis, S., Sorensen, M., Tewari, A., Young, R., & Zahabu, E. (2011). At the heart of REDD+: a role for local people in monitoring forests? Conservation Letters, 4, 158-167

Daume, S., Albert, M., & von Gadow, K. (2014). Forest monitoring and social media – Complementary data sources for ecosystem surveillance? Forest Ecology and Management, 316, 9-20

De Bruin, S., Lerink, P., La Riviere, I.J., & Vanmeulebrouk, B. (2014). Systematic planning and cultivation of agricultural fields using a geo-spatial arable field optimization service: Opportunities and obstacles. Biosystems Engineering, 120, 15-24

De Sy, V., Herold, M., Achard, F., Asner, G.P., Held, A., Kellndorfer, J., & Verbesselt, J. (2012). Synergies of multiple remote sensing data sources for REDD+ monitoring. Current Opinion in Environmental Sustainability, 4, 696-706

DeFries, R., Achard, F., Brown, S., Herold, M., Murdiyarso, D., Schlamadinger, B., & de Souza, C. (2007). Earth observations for estimating greenhouse gas emissions from deforestation in developing countries. Environmental Science & Policy, 10, 385-394

Devillers, R., Bédard, Y., Jeansoulin, R., & Moulin, B. (2007). Towards spatial data quality information analysis tools for experts assessing the fitness for use of spatial data. International Journal of Geographical Information Science, 21, 261-282

DeVries, B., & Herold, M. (2013). The science of Measuring, Reporting and Verication (MRV). In R. Lyster, C. MacKenzie, & C. McDermott (Eds.), In Law, Tropical Forests and Carbon: The Case of REDD+ (pp. 151-183). Cambridge, London: Cambridge Univ Press

DeVries, B., Pratihast, A.K., Verbesselt, J., Kooistra, L., & Herold, M. (2015a). Characterizing Forest Change Using Community-Based Monitoring Data and Landsat Time Series. PLoS One, (in Review)

DeVries, B., Verbesselt, J., Kooistra, L., & Herold, M. (2015b). Robust monitoring of small-scale forest disturbances in a tropical montane forest using Landsat time series. Remote Sensing of Environment, 161, 107-121

Dickson, B., & Kapos, V. (2012). Biodiversity monitoring for REDD+. Current Opinion in Environmental Sustainability, 4, 717-725

Diga, M., & Kelleher, T. (2009). Social media use, perceptions of decision-making power, and public relations roles. Public Relations Review, 35, 440-442

Doherty, E., & Schroeder, H. (2011). Forest tenure and multi-level governance in avoiding deforestation under REDD+. Global Environmental Politics, 11, 66-88

Dons, K., Smith-Hall, C., Meilby, H., & Fensholt, R. (2015). Operationalizing measurement of forest degradation: Identification and quantification of charcoal production in tropical dry forests using very high resolution satellite imagery. International Journal of Applied Earth Observation and Geoinformation, 39, 18-27

Dragićević, S., & Balram, S. (2004). A Web GIS collaborative framework to structure and manage distributed planning processes. Journal of Geographical Systems, 6, 133-153

Drusch, M., Del Bello, U., Carlier, S., Colin, O., Fernandez, V., Gascon, F., Hoersch, B., Isola, C., Laberinti, P., Martimort, P., Meygret, A., Spoto, F., Sy, O., Marchese, F., & Bargellini, P. (2012). Sentinel-2: ESA's Optical High-Resolution Mission for GMES Operational Services. Remote Sensing of Environment, 120, 25-36

Eggleston, S., Buendia, L., Miwa, K., Ngara, T., & Tanabe, K. (2006). IPCC guidelines for national greenhouse gas inventories. Institute for Global Environmental Strategies, Hayama, Japan

FCPF (2010). Harvesting Knowledge on REDD+: Early Lessons from the FCPF Initiative and Beyond. Forest Carbon Partnership Facility, Washington DC, USA

FCPF (2012). Forest carbon partnership facility Available online: https://www.forestcarbonpartnership.org (accessed on 17 March 2015)

Ferster, C.J., & Coops, N.C. (2013). A review of earth observation using mobile personal communication devices. Computers & Geosciences, 51, 339-349

Foody, G.M. (2002). Status of land cover classification accuracy assessment. Remote Sensing of Environment, 80, 185-201

Fry, B. (2011). Community forest monitoring in REDD+: the 'M' in MRV? Environmental Science & Policy, 14, 181-187

Garcia, C.A., & Lescuyer, G. (2008). Monitoring, indicators and community based forest management in the tropics: pretexts or red herrings? Biodiversity and Conservation, 17, 1303-1317

Geist, H.J., & Lambin, E.F. (2002). Proximate causes and underlying driving forces of tropical deforestation. BioScience, 52, 143-150

Georgiadou, Y., Lungo, J.H., & Richter, C. (2014). Citizen sensors or extreme publics? Transparency and accountability interventions on the mobile geoweb. International Journal of Digital Earth, 7, 516-533

Getahun, K., Van Rompaey, A., Van Turnhout, P., & Poesen, J. (2013). Factors controlling patterns of deforestation in moist evergreen Afromontane forests of Southwest Ethiopia. Forest Ecology and Management, 304, 171-181

Gibbs, H. (2006). Olson's Major World Ecosytem Complexes Ranked by Carbon in Live Vegetation: An Updated Database Using the GLC2000 Land Cover Product; Carbon Dioxide Information Analysis Center: Oak Ridge National Laboratory, Oak Ridge, TN, USA

Gibbs, H.K., & Herold, M. (2007). Tropical deforestation and greenhouse gas emissions. Environmental Research Letters, 2, 045021

GOFC-GOLD (2014). A sourcebook of methods and procedures for monitoring and reporting anthropogenic greenhouse gas emissions and removals associated with deforestation, gains and losses of carbon stocks in forests remaining forests and forestation. In, GOFC-

GOLD Report version COP20-1(GOFC-GOLD Land Cover Project Office, Wageningen University, The Netherlands).

Gonzalez, H., Halevy, A.Y., Jensen, C.S., Langen, A., Madhavan, J., Shapley, R., Shen, W., & Goldberg-Kidon, J. (2010). Google fusion tables: web-centered data management and collaboration. Proceedings of the 2010 international conference on management of data, Indianapolis, IN, USA, 6–11 June 2010. In (pp. 1061-1066): ACM

Goodchild, M.F. (2007). Citizens as sensors: the world of volunteered geography. GeoJournal, 69, 211-221

Gouveia, C., Fonseca, A., Câmara, A., & Ferreira, F. (2004). Promoting the use of environmental data collected by concerned citizens through information and communication technologies. Journal of Environmental Management, 71, 135-154

Gullison, R.E., Frumhoff, P.C., Canadell, J.G., Field, C.B., Nepstad, D.C., Hayhoe, K., Avissar, R., Curran, L.M., Friedlingstein, P., Jones, C.D., & Nobre, C. (2007). Tropical Forests and Climate Policy. Science, 316, 985-986

Gupta, J. (2012). Global forest and REDD+ governance: win-win or lose-lose? Current Opinion in Environmental Sustainability, 4, 620-627

Haklay, M. (2010). How good is volunteered geographical information? A comparative study of OpenStreetMap and ordnance survey datasets. Environment and Planning B: Planning and Design, 37, 682-703

Hansen, M.C., & Loveland, T.R. (2012). A review of large area monitoring of land cover change using Landsat data. Remote Sensing of Environment, 122, 66-74

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O., & Townshend, J.R.G. (2013). High-resolution global maps of 21st-century forest cover change. Science, 342, 850-853

Hansen, M.C., Shimabukuro, Y.E., Potapov, P., & Pittman, K. (2008). Comparing annual MODIS and PRODES forest cover change data for advancing monitoring of Brazilian forest cover. Remote Sensing of Environment, 112, 3784-3793

Hartung, C., Lerer, A., Anokwa, Y., Tseng, C., Brunette, W., & Borriello, G. (2010). Open data kit: tools to build information services for developing regions. In, Proceedings of the 4th ACM/IEEE International Conference on Information and Communication Technologies and Development (p. 18): ACM

Hayes, T., & Persha, L. (2010). Nesting local forestry initiatives: Revisiting community forest management in a REDD plus world. Forest Policy and Economics, 12, 545-553

Herold, M., & Johns, T. (2007). Linking requirements with capabilities for deforestation monitoring in the context of the UNFCCC-REDD process. Environmental Research Letters, 2, 045025

Herold, M., Román-Cuesta, R.M., Heymell, V., Hirata, Y., Van Laake, P., Asner, G.P., Souza, C., Avitabile, V., & MacDicken, K. (2011). A review of methods to measure and monitor historical carbon emissions from forest degradation. Unasylva, 62, 16-24

Herold, M., & Skutsch, M. (2008). Measurement, reporting and verification for REDD. Realising REDD+: national strategy and policy options, 7, 85

Herold, M., & Skutsch, M. (2011). Monitoring, reporting and verification for national REDD+ programmes: two proposals. Environmental Research Letters, 6, 014002

Herold, M., & Skutsch, M.M. (2009). Measurement, reporting and verification for REDD+: objectives, capacities and institutions. In A. Angelsen, K. M., M., E. Sills, Sunderlin, W. D., & S. Wertz-Kanounnikoff (Eds.), Realising REDD+: national strategy and policy options (p. 85). Bogor, Indonesia: Center for International Forestry Research(CFOR)

Hosonuma, N., Herold, M., De Sy, V., De Fries, R.S., Brockhaus, M., Verchot, L., Angelsen, A., & Romijn, E. (2012). An assessment of deforestation and forest degradation drivers in developing countries. Environmental Research Letters, 7, 044009

Huang, H.B., Li, Z., Gong, P., Cheng, X.A., Clinton, N., Cao, C.X., Ni, W.J., & Wang, L. (2011). Automated Methods for Measuring DBH and Tree Heights with a Commercial Scanning Lidar. Photogrammetric Engineering and Remote Sensing, 77, 219-227

I.T.U. (2015). World Telecommunication /ICT Indicators Database Available online: http://www.itu.int/ITU-D/ict/publications/world/world.html (accessed on 17 March 2015).

IPCC (2006). Guidelines for National Greenhouse Gas Inventories. ed H S Eggleston, L Buendia, K Miwa, T Ngara and K Tanabe, Prepared by the National Greenhouse Gas Inventories Programme, Institute for Global Environmental Strategies (IGES), Japan

ISO/TC211 (2002). Geographic Information—Quality Principles, ISO: Berne, Switzerland

Johnson, N.L., Kemp, A.W., & Kotz, S. (2005). Univariate discrete distributions;John Wiley & Sons: Newark, NJ, USA; pp. 1–633. John Wiley & Sons

Joseph, S., Herold, M., Sunderlin, W.D., & Verchot, L.V. (2013). REDD+ readiness: early insights on monitoring, reporting and verification systems of project developers. Environmental Research Letters, 8, 034038

Jupp, D., Culvenor, D., Lovell, J., & Newnham, G. (2005). Evaluation and validation of canopy laser radar (lidar) systems for native and plantation forest inventory. . In: Australian Government, Forest and Wood Products Research and Development Corporation, Melbourne, Australia

Karsenty, A. (2008). The architecture of proposed REDD schemes after Bali: facing critical choices. International Forestry Review, 10, 443-457

Kashwan, P., & Holahan, R. (2014). Nested governance for effective REDD+: Institutional and political arguments. International Journal of the Commons, 8, 554-575

Kennedy, R.E., Cohen, W.B., & Schroeder, T.A. (2007). Trajectory-based change detection for automated characterization of forest disturbance dynamics. Remote Sensing of Environment, 110, 370-386

Keough, H.L., & Blahna, D.J. (2006). Achieving integrative, collaborative ecosystem management. Conservation Biology, 20, 1373-1382

Keramitsoglou, I., Kiranoudis, C.T., Sarimveis, H., & Sifakis, N. (2004). A Multidisciplinary Decision Support System for Forest Fire Crisis Management. Environmental Management, 33, 212-225

Kingston, R., Carver, S., Evans, A., & Turton, I. (2000). Web-based public participation geographical information systems: An aid to local environmental decision-making. Computers, Environment and Urban Systems, 24, 109-125

Larrazábal, A., McCall, M.K., Mwampamba, T.H., & Skutsch, M. (2012). The role of community carbon monitoring for REDD+: a review of experiences. Current Opinion in Environmental Sustainability, 4, 707-716

Lawlor, K., Madeira, E., Blockhus, J., & Ganz, D. (2013). Community Participation and Benefits in REDD+: A Review of Initial Outcomes and Lessons. Forests, 4, 296-318

Li, W., Wu, Y., & Mao, G. (2006). WebGIS-based information system for evaluation of soil environment in prime farmland. Nongye Gongcheng Xuebao/Transactions of the Chinese Society of Agricultural Engineering, 22, 59-63

Li, X., Wang, S., Ge, Y., Jin, R., Liu, S., Ma, M., Shi, W., Li, R., & Liu, Q. (2013). Development and Experimental Verification of Key Techniques to Validate Remote Sensing Products. ISPRS-International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 1, 25-30

Li, Z., Yang, C., Jin, B., Yu, M., Liu, K., Sun, M., & Zhan, M. (2015). Enabling big geoscience data analytics with a cloud-based, mapreduce-enabled and service-oriented workflow framework. PLoS ONE, 10

Lynch, J., Maslin, M., Balzter, H., & Sweeting, M. (2013). Choose satellites to monitor deforestation. Nature, 496, 293-294

Maguire, D.J., & Longley, P.A. (2005). The emergence of geoportals and their role in spatial data infrastructures. Computers, Environment and Urban Systems, 29, 3-14

Masek, J.G., Vermote, E.F., Saleous, N.E., Wolfe, R., Hall, F.G., Huemmrich, K.F., Gao, F., Kutler, J., & Lim, T.K. (2006). A landsat surface reflectance dataset for North America, 1990-2000. IEEE Geoscience and Remote Sensing Letters, 3, 68-72

McCall, M.K. (2010). Local participation in mapping, measuring and monitoring for community carbon forestry. Community Forest Monitoring for the Carbon Market: Opportunities Under REDD

McCall, M.K., & Minang, P.A. (2005). Assessing participatory GIS for community-based natural resource management: Claiming community forests in Cameroon. Geographical Journal, 171, 340-356

Molinier, M., Hame, T., Toivanen, T., Andersson, K., & Mutanen, T. (2014). Relasphone—Mobile phone and interactive applications to collect ground reference biomass data for satellite image analysis. In, Geoscience and Remote Sensing Symposium (IGARSS), 2014 IEEE International (pp. 836-839): IEEE

Nagendra, H., Rocchini, D., & Ghate, R. (2010). Beyond parks as monoliths: Spatially differentiating park-people relationships in the Tadoba Andhari Tiger Reserve in India. Biological Conservation, 143, 2900-2908

Newman, G., Graham, J., Crall, A., & Laituri, M. (2011). The art and science of multi-scale citizen science support. Ecological Informatics, 6, 217-227

Olander, J., Seifert-Granzin, J., Chagas, T., Streck, C., & O'Sullivan, R. (2011). Nested approaches to REDD+. An overview of issues and options. Forest Trends and Climate Focus, Washington DC

Olson, D.M., Dinerstein, E., Wikramanayake, E.D., Burgess, N.D., Powell, G.V.N., Underwood, E.C., D'Amico, J.A., Itoua, I., Strand, H.E., Morrison, J.C., Loucks, C.J., Allnutt, T.F., Ricketts, T.H., Kura, Y., Lamoreux, J.F., Wettengel, W.W., Hedao, P., & Kassem, K.R. (2001). Terrestrial ecoregions of the world: A new map of life on Earth. BioScience, 51, 933-938

OpenDataKit (2012). Available online: http://opendatakit.org (accessed on 17 march 2014)

Orfali, R., Harkey, D., & Edwards, J. (2007). Client/server survival guide; Wiley India Pvt. Ltd. New Delhi, India

Parr, C.S., Jones, T., & Songer, N.B. (2002). CyberTracker in BioKIDS: Customization of a PDA-Based Scientific Data Collection Application for Inquiry Learning. Proceedings of Keeping Learning Complex: The Proceedings of the Fifth International Conference of Learning Sciences (ICLS), Seattle, WA, USA. In R.S. Bell, T. Satwicz (Ed.) (pp. 574–575)

Patenaude, G., Hill, R.A., Milne, R., Gaveau, D.L.A., Briggs, B.B.J., & Dawson, T.P. (2004). Quantifying forest above ground carbon content using LiDAR remote sensing. Remote Sensing of Environment, 93, 368-380

Pearson, T., Walker, S., & Brown, S. (2006). Sourcebook for land use, land-use change and forestry projects. BioCarbon Fund (World Bank) and Winrock International, Washington DC USA, 64

Pedroni, L., Porrua, M.E., & Cenamo, M.C. (2010). The 'Nested Approach'to REDD+: How Could it Be Implemented? Pathways for Implementing REDD, 89

Phelps, J., Webb, E.L., & Agrawal, A. (2010). Does REDD+ Threaten to Recentralize Forest Governance? Science, 328, 312-313

Planetaction (2010). Planet Action Website. Available online: http://www.planet-action.org/web/85-project-detail.php?projectID=7818 (accessed on 17 December 2012)

Pôças, I., Gonçalves, J., Marcos, B., Alonso, J., Castro, P., & Honrado, J.P. (2014). Evaluating the fitness for use of spatial data sets to promote quality in ecological assessment and monitoring. International

Journal of Geographical Information Science, 28, 2356-2371

Pohl, C., & Van Genderen, J. (1998). Review article Multisensor image fusion in remote sensing: concepts, methods and applications. International journal of remote sensing, 19, 823-854

Pratihast, A., DeVries, B., Avitabile, V., de Bruin, S., Kooistra, L., Tekle, M., & Herold, M. (2014). Combining Satellite Data and Community-Based Observations for Forest Monitoring. Forests, 5, 2464-2489

Pratihast, A., Herold, M., Avitabile, V., de Bruin, S., Bartholomeus, H., Jr., C., & Ribbe, L. (2012). Mobile Devices for Community-Based REDD+ Monitoring: A Case Study for Central Vietnam. Sensors, 13, 21-38

Pratihast, A.K., Herold, M., De Sy, V., Murdiyarso, D., & Skutsch, M. (2013). Linking community-based and national REDD+ monitoring: A review of the potential. Carbon Management, 4, 91-104

Ramankutty, N., Gibbs, H.K., Achard, F., Defries, R., Foley, J.A., & Houghton, R.A. (2007). Challenges to estimating carbon emissions from tropical deforestation. Global Change Biology, 13, 51-66

Ratner, B.D., & Parnell, T. (2011). Building coalitions across sectors and scales in Cambodia. Forests and people: Property, governance, and human rights; Sikor, T., Stahl, J., Eds.; Earthscan: Oxon, UK, 203-216

Reiche, J. (2015). Combining SAR and optical satellite image time series for tropical forest monitoring

Reiche, J., de Bruin, S., Hoekman, D., Verbesselt, J., & Herold, M. (2015). A Bayesian Approach to Combine Landsat and ALOS PALSAR Time Series for Near Real-Time Deforestation Detection. Remote Sensing, 7, 4973-4996

Renate Steinmann, A.K. (2004). Analysis of online public participatory GIS applications with respect to the differences between the US and Europe. In, 24th urban data management symposium

Romijn, E., Herold, M., Kooistra, L., Murdiyarso, D., & Verchot, L. (2012). Assessing capacities of non-Annex I countries for national forest monitoring in the context of REDD+. Environmental Science & Policy, 19-20, 33-48

Roy, D., Wulder, M., Loveland, T., Allen, R., Anderson, M., Helder, D., Irons, J., Johnson, D., Kennedy, R., & Scambos, T. (2014). Landsat-8: Science and product vision for terrestrial global change research. Remote Sensing of Environment, 145, 154-172

Ruesch, A., & Gibbs, H. (2008). New IPCC Tier-1 Global biomass carbon map for the year 2000; Carbon Dioxide Information Analysis Center: Oak Ridge National Laboratory, Oak Ridge, TN, USA

Sanz-Sanchez, M., Herold, M., & Penman, J. (2013). Conference Report: REDD+ related forest monitoring remains a key issue: a report following the recent UN climate conference in Doha. Carbon Management, 4, 125-127

Sassi, C.D., Joseph, S., Bos, A.B., Duchelle, A.E., Ravikumar, A., & Herold, M. (2015). Towards integrated monitoring of REDD+. Current Opinion in Environmental Sustainability, 14, 93-100

Schepaschenko, D., See, L., Lesiv, M., McCallum, I., Fritz, S., Salk, C., Moltchanova, E., Perger, C., Shchepashchenko, M., Shvidenko, A., Kovalevskyi, S., Gilitukha, D., Albrecht, F., Kraxner, F., Bun, A., Maksyutov, S., Sokolov, A., Dürauer, M., Obersteiner, M., Karminov, V., & Ontikov, P. (2015). Development of a global hybrid forest mask through the synergy of remote sensing, crowdsourcing and FAO statistics. Remote Sensing of Environment, 162, 208-220

Schmitt, C.B., Denich, M., Demissew, S., Friis, I., & Boehmer, H.J. (2010). Floristic diversity in fragmented Afromontane rainforests: Altitudinal variation and conservation importance. Applied Vegetation Science, 13, 291-304

Schroeder, T.A., Wulder, M.A., Healey, S.P., & Moisen, G.G. (2011). Mapping wildfire and clearcut harvest disturbances in boreal forests with Landsat time series data. Remote Sensing of Environment, 115, 1421-1433

Sharpe, A., & Conrad, C. (2006). Community based ecological monitoring in Nova Scotia: Challenges and opportunities. Environmental Monitoring and Assessment, 113, 395-409

Shimabukuro, Y., Duarte, V., Anderson, L., Valeriano, D., Arai, E., Freitas, R., Rudorff, B.F., & Moreira, M. (2007). Near real time detection of deforestation in the Brazilian Amazon using MODIS imagery. Ambiente & Água-An Interdisciplinary Journal of Applied Science, 1, 37-47

Shrestha, R.K. (2011). Participatory carbon monitoring: An experience from the Koshi Hills, Nepal. In proceedings of the National Conference on Forest-People Interaction, NUFU HIMUNET Project, Institute of Forestry, Pokhara, Nepal, 1-14

Shrestha, S., Karky, B., & Karki, S. (2014). Case Study Report: REDD+ Pilot Project in Community Forests in Three Watersheds of Nepal. Forests, 5, 2425-2439

Sigrist, P., Coppin, P., & Hermy, M. (1999). Impact of forest canopy on quality and accuracy of GPS measurements. International journal of remote sensing, 20, 3595-3610

Skar, C. (2012). The Norwegian International Climate and Forest Initiative: an analysis of the process and motivations of policy making

Skarlatidou, A., Haklay, M., & Cheng, T. (2011). Trust in Web GIS: the role of the trustee attributes in the design of trustworthy Web GIS applications. International Journal of Geographical Information Science, 25, 1913-1930

Skutsch, M. (2010). Rural Development through Carbon Finance: Forestry projects under the clean development mechanism of the Kyoto protocol. Climate and Development, 2, 75-76

Skutsch, M., & McCall, M.K. (2012). The role of community forest management in REDD+. Unasylva, 63, 51-56

Skutsch, M., & Solis, S. (2011). How much carbon does community forest management save? In M. Skutsch (Ed.), Community forest monitoring for the carbon market: opportunities under REDD: Earthscan, London, UK

Skutsch, M., Torres, A., Mwampamba, T., Ghilardi, A., & Herold, M. (2011). Dealing with locally-driven degradation: A quick start option under REDD+. Carbon balance and management, 6, 16

Skutsch, M., Zahabu, E., & Karky, B. (2009). Community forest management under REDD: policy conditions for equitable governance. In, Presented at: World Forest Congress (pp. 18-25). Buenos Aires

Skutsch, M.M., & Ba, L. (2010). Crediting carbon in dry forests: The potential for community forest management in West Africa. Forest Policy and Economics, 12, 264-270

Skutsch, M.M., McCall, M.K., & Larrazabal, A.P. (2014). Balancing views on community monitoring: The case of REDD+: A response to "towards a more balanced view on the potentials of locally-based monitoring". Biodiversity and Conservation, 23, 233-236

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K., Tignor, M., & Miller, H. (2007). IPCC, 2007: Climate change 2007: The physical science basis. Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. In. UK: Cambridge University Press

Souza Jr, C.M., Pereira, K., Lins, V., Haiashy, S., & Souza, D. (2009). Web-oriented GIS system for monitoring, conservation and law enforcement of the Brazilian Amazon. Earth science informatics, 2, 205-215

Stickler, C.M., Nepstad, D.C., Coe, M.T., McGrath, D.G., Rodrigues, H.O., Walker, W.S., Soares, B.S., & Davidson, E.A. (2009). The potential ecological costs and cobenefits of REDD: a critical review and case study from the Amazon region. Global Change Biology, 15, 2803-2824

Strahler, A.H., Boschetti, L., Foody, G.M., Friedl, M.A., Hansen, M.C., Herold, M., Mayaux, P., Morisette, J.T., Stehman, S.V., & Woodcock, C.E. (2006). Global land cover validation: Recommendations for evaluation and accuracy assessment of global land cover maps; Report No. 25. GOFC-GOLD. European Communities, Luxembourg, 1-51

Sultana, P., & Abeyasekera, S. (2008). Effectiveness of participatory planning for community management of fisheries in Bangladesh. Journal of Environmental Management, 86, 201-213

Sunderlin, W.D., Angelsen, A., Belcher, B., Burgers, P., Nasi, R., Santoso, L., & Wunder, S. (2005). Livelihoods, forests, and conservation in developing countries: an overview. World development, 33, 1383-1402

Sunderlin, W.D., Hatcher, J., & Liddle, M. (2008). From exclusion to ownership? Challenges and opportunities in advancing forest tenure reform. Rights and Resources Initiative

Tomppo, E., Gschwantner, T., Lawrence, M., McRoberts, R.E., Gabler, K., Schadauer, K., Vidal, C., Lanz, A., Ståhl, G., & Cienciala, E. (2010). National Forest Inventories. Pathways for Common Reporting. European Science Foundation, 541-553

Tomter, S., Hylen, G., Nilsen, J., Norway, E.T., Gschwanter, T., Lawrence, M., & McRoberts, R. (2010). National Forest Inventories, Pathways for Common Reporting. In: Springer

Topp-Jørgensen, E., Poulsen, M.K., Lund, J.F., & Massao, J.F. (2005). Community-based monitoring of natural resource use and forest quality in montane forests and miombo woodlands of Tanzania. Biodiversity and Conservation, 14, 2653-2677

Torres, A.B. (2014). Potential for integrating community-based monitoring into REDD+. Forests, 5, 1815-1833

Torres, A.B., Acuña, L.A.S., & Vergara, J.M.C. (2014). Integrating CBM into land-use based mitigation actions implemented by local communities. Forests, 5, 3295-3326

Torres, A.B., MacMillan, D.C., Skutsch, M., & Lovett, J.C. (2015). 'Yes-in-my-backyard': Spatial differences in the valuation of forest services and local co-benefits for carbon markets in México. Ecological Economics, 109, 130-141

Umemiya, C., Amano, M., & Wilamart, S. (2010). Assessing data availability for the development of REDD-plus national reference levels. Carbon balance and management, 5, 6

UN-REDD (2009). About REDD+ Available online: http://www.un-redd.org (accessed on 17 March 2015)

UNFCCC (2009). Methodological guidance for activities relating to reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries 4/CP.15. In proceedings of the UNFCC COP 15. In. Copenhagen Denmark

UNFCCC (2010a). Methodological guidance for activities relating to reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing country,4/CP.15 Bonn, Germany

UNFCCC (2010b). Outcome of the Work of the ad Hoc Working Group on Long-Term Cooperative Action under the Convention Policy Approaches and Positive Incentives on Issues Relating to Reducing Emissions from Deforestation and Forest Degradation in Developing Countries and the Role of Conservation, Sustainable Management of Forests and Enhancement of Forest Carbon Stocks in Developing Countries, Decision 4/cp.16. Proceedings of the UNFCC COP 16 In. Cancun, Mexico

UNFCCC (2013). Guidelines and procedures for the technical assessment of submissions from Parties on proposed forest reference emission levels and/or forest reference levels, Decision 13/cp.19. In Proceedings of the UNFCC COP 19, Warsaw Polland

Uychiaoco, A.J., Arceo, H.O., Green, S.J., Cruz, M.T.D.L., Gaite, P.A., & Alino, P.M.

(2005). Monitoring and evaluation of reef protected areas by local fishers in the Philippines: tightening the adaptive management cycle. Biodiversity and Conservation, 14, 2775-2794

Vadrevu, K.P., Badarinath, K.V.S., & Eaturu, A. (2008). Spatio-temporal analysis of fire events in India: implications for environmental conservation. Journal of Environmental Planning and Management, 51, 817-832

Van Oort, P., Hazeu, G., Kramer, H., Bregt, A., & Rip, F. (2010). Social networks in spatial data infrastructures. GeoJournal, 75, 105-118

Vargas, R., Paz, F., & De Jong, B. (2013). Quantification of forest degradation and belowground carbon dynamics: Ongoing challenges for monitoring, reporting and verification activities for REDD+. Carbon Management, 4, 579-582

Verbesselt, J., Hyndman, R., Newnham, G., & Culvenor, D. (2010). Detecting trend and seasonal changes in satellite image time series. Remote Sensing of Environment, 114, 106-115

Verbesselt, J., Zeileis, A., & Herold, M. (2012). Near real-time disturbance detection using satellite image time series. Remote Sensing of Environment, 123, 98-108

Verburg, P.H., Neumann, K., & Nol, L. (2011). Challenges in using land use and land cover data for global change studies. Global Change Biology, 17, 974-989

Verkasalo, H., & Hämmäinen, H. (2007). A handset-based platform for measuring mobile service usage. info, 9, 80-96

Verplanke, E., & Zahabu, E. (2009). A field guide for assessing and monitoring reduced forest degradation and carbon sequestration by local communities. Kyoto: Think Global, Act Local Project report, Enschede, The Netherlands. Avialable at http://www.communitycarbonforestry.org

Visseren-Hamakers, I.J., Gupta, A., Herold, M., Peña-Claros, M., & Vijge, M.J. (2012). Will REDD+ work? The need for interdisciplinary research to address key challenges. Current Opinion in Environmental Sustainability, 4, 590-596

Wakholi, P., Chen, W., & Klungsøyr, J. (2011). Workflow support for mobile data collection. In, Lecture Notes in Business Information Processing (pp. 299-313)

Werts, J.D., Mikhailova, E.A., Post, C.J., & Sharp, J.L. (2012). An Integrated WebGIS Framework for Volunteered Geographic Information and Social Media in Soil and Water Conservation. Environmental Management, 1-17

Wertz-Kanounnikoff, S., & Angelsen, A. (2009). Global and national REDD+ architecture. Realising REDD, 13

Wheeler, D., Hammer, D., Kraft, R., & Steele, A. (2014). Satellite-based forest clearing detection in the Brazilian Amazon: FORMA, DETER, and PRODES. In: Wri. org. Retrieved from http://www.wri.org/sites/default/files/FORMA-issue-brief_1.PDF

White, A., & Martin, A. (2002). Who owns the world's forests? Forest tenure and public forests in transition. Washington, DC, USA

Whitelaw, G., Vaughan, H., Craig, B., & Atkinson, D. (2003). Establishing the Canadian Community Monitoring Network. Environmental Monitoring and Assessment, 88, 409-418

Willmott, C.J. (1981). On the validation of models. Physical Geography, 2, 184–194

Wulder, M.A., Masek, J.G., Cohen, W.B., Loveland, T.R., & Woodcock, C.E. (2012). Opening the archive: How free data has enabled the science and monitoring promise of Landsat. Remote Sensing of Environment, 122, 2-10

XForms1.1 (2012). Available online: http://www.w3.org/TR/xforms (accessed on 17 December 2012)

Xin, Q., Olofsson, P., Zhu, Z., Tan, B., & Woodcock, C.E. (2013). Toward near real-time monitoring of forest disturbance by fusion of MODIS and Landsat data. Remote Sensing of Environment, 135, 234-247

Yao, T., Yang, X., Zhao, F., Wang, Z., Zhang, Q., Jupp, D., Lovell, J., Culvenor, D., Newnham, G., & Ni-Meister, W. (2011). Measuring forest structure and biomass in New England forest stands using Echidna ground-based lidar. Remote Sensing of Environment, 115, 2965-2974

Yoccoz, N.G., Nichols, J.D., & Boulinier, T. (2001). Monitoring of biological diversity in space and time. Trends in Ecology & Evolution, 16, 446-453

Yuan, B., Lei, R., Lin, Z., Xuesong, Z., & Yongliang, L. (2012). Massive sensor data management framework in Cloud manufacturing based on Hadoop. In, Industrial Informatics (INDIN), 2012 10th IEEE International Conference on (pp. 397-401)

Zahabu, E., & Malimbwi, R.E. (2011). The potential of community forest management under REDD+ for achieving MDG goals in Tanzania. In M. Skutsch (Ed.), Community forest monitoring for the carbon market. Opportunities under REDD (pp. 134-147). Earthscan, London, UK

Zhu, Z., & Woodcock, C.E. (2012). Object-based cloud and cloud shadow detection in Landsat imagery. Remote Sensing of Environment, 118, 83-94

Summary

Forests cover approximately 30% of the Earth's land surface and have played an indispensable role in the human development and preserving natural resources. At the moment, more than 300 million people are directly dependent on these forests and their resources. Forests also provide habitats for a wide variety of species and offer several ecological necessities to natural and anthropological systems. In spite of this importance, unprecedented destruction of tropical forest cover has been witnessed over the past four decades. Annually, approximately $2.1x10^5$ hectares of forests are lost, with serious negative consequences on the regulation of the world's climate cycle, biodiversity and other environmental variables. To mitigate these consequences, the United Nations Framework Convention on Climate Change (UNFCCC) has requested the developing countries to adapt new policy in reducing emissions from deforestation and forest degradation (REDD+). Under this policy, countries have been mandated to engage local communities and indigenous groups as critical stakeholders in the design and implementation of a national forest monitoring system (NFMS) that supports measuring, reporting and verification (MRV) of actions and achievements of REDD+ activities.

Current schemes for tropical monitoring are based on remote sensing and field measurements which typically originate from national forest inventories. Remotely sensed imagery has been considered as the principal data source used to calculate forest area change across large areas, assess rates of deforestation and establish baselines for national forest area change databases. Advancements in medium and high resolution satellites, open data policies, time-series analysis methods and big data processing environments are considered valuable for deforestation monitoring at local to global scales. However, cloud cover, seasonality and the restricted spatial and temporal resolution of remote sensing observations limits their applicability in the tropics. Enhancing the interpretation of remote sensing analysis require substantial ground verification and validation. Accomplishing these tasks through national forest inventory data is expensive, time-consuming and difficult to implement across large spatial scales.

Next to remote sensing, community-based monitoring (CBM) has also demonstrated potential in the collection and interpretation of forest monitoring data. However effective implementation of community-based forest monitoring systems is currently lacking due to two reasons: 1) the role of communities in

NFMS is unclear and 2) tools that can support local communities to explore opportunities and facilitate forest monitoring are still scarce. This thesis addresses these two issues by proposing technical solutions (computer and geo-information science) and assessing the capacities and needs of communities in developing countries with a REDD+ implementation and forest monitoring context.

The main goal of this thesis, therefore, is to develop an approach that combines emerging technologies and community-based observations for tropical forest monitoring. To accomplish the main goal, four specific research questions were formulated: 1) What are the potentials to link community-based efforts to national forest monitoring systems? 2) How can information and communication technologies (ICTs) support the automation of community data collection process for monitoring forest carbon stocks and change activities using modern handheld devices? 3) What is the accuracy and compatibility of community collected data compared to other data (e.g., optical remote sensing and expert field measurements) for quantifying forest carbon stocks and changes? and 4) What is a suitable design for an interactive remote sensing and community-based near real-time forest change monitoring system and how can such system be operationalized?

In Chapter 2, scientific literature and 28 readiness preparation proposals from the World Bank Forest Carbon Partnership Facility are reviewed to better define the role and technical conditions for CBM. Based on this review, a conceptual framework was developed under which CBM can contribute as a dedicated and independent stream of measuring and monitoring data to national level forest monitoring efforts. The following chapters are built upon this framework.

Chapter 3 describes a process of designing and implementing an integrated data collection system based on mobile devices that streamlines the community-based forest monitoring data collection, transmission and visualization process. The usability of the system is evaluated in the Tra Bui commune, Quang Nam province, Central Vietnam, where forest carbon and change activities were measured by different means such as local, regional and national experts and high resolution satellite imagery. The results indicate that the local communities were able to provide forest carbon measurements with accuracy comparable to that of expert measurements at lower costs. Furthermore, the results show that communities are more effective in detecting small scale forest degradation caused by subsistence fuelwood collection and selective logging than image analysis using SPOT imagery.

To support the findings of chapter 3, the data acquisition form (mostly activity data related to forest change) for mobile device was further improved in chapter 4. The system was tested by thirty local experts in the UNESCO Kafa Biosphere Reserve, Ethiopia. High resolution satellite imagery and professional measurements were combined to assess the accuracy and complementary use of local datasets in terms of spatial, temporal and thematic accuracy. Results indicate that the local communities were capable of describing processes of change associated with deforestation, forest degradation and reforestation, in terms of their spatial location, extent, timing and causes within ten administrative units. Furthermore, the results demonstrate that communities offer complementary information to remotely sensed data, particularly to signal forest degradation and mapping deforestation over small areas. Based on this complementarity, a framework is proposed for integrating local expert monitoring data with satellite-based monitoring data into a NFMS in support of REDD+ MRV and near real-time forest change monitoring.

Having identified the framework for integrated monitoring systems in chapter 4, chapter 5 describes an interactive web-based forest monitoring system using four levels of geographic information services: 1) the acquisition of continuous data streams from satellite and community-based monitoring using mobile devices, 2) near real-time forest disturbance detection based on satellite time-series, 3) presentation of forest disturbance data through a web-based application and social media and 4) interaction of the satellite-based disturbance alerts with the end-user communities to enhance the collection of ground data. The system was developed using open source technologies and has been implemented together with local experts in UNESCO Kafa Biosphere Reserve, Ethiopia. The results show that the system was able to provide easy access to information on forest change and considerably improve the collection and storage of ground observation by local experts. Social media lead to higher levels of user interaction and noticeably improved communication among stakeholders. Finally, an evaluation of the system confirmed its usability in Ethiopia.

Chapter 6 presents the final conclusions and provides recommendations for further research. The overall conclusion is that the emerging technologies, such as smartphones, Web-GIS and social media, incorporated with user friendly interface improve the interactive participation of local communities in forest monitoring and decrease errors in data collection. The results show that CBM can provide data on forest carbon stocks, forest area changes as well as data that help to understand local drivers of emissions. The thesis also shows, in theory and in practice, how local data can be used to link with medium and high resolution remote sensing satellite images for an operational near real-time forest monitoring system at a local scale. The methods presented in this thesis are applicable to a broader geographic scope. Hence, this thesis emphasizes that policies and incentives should be implemented to empower communities and to create institutional frameworks for community-based forest monitoring in the tropics.

Samenvatting

Bossen bedekken ongeveer 30% van het landoppervlak van de aarde en spelen een onmiskenbare rol in de maatschappelijke ontwikkeling en het behoud van natuurlijke hulpbronnen. Op dit moment zijn meer dan 300 miljoen mensen direct afhankelijk van bossen en hun hulpbronnen. Ook bieden bossen een habitat voor een breed scala aan soorten en leveren ze verschillende ecologische benodigdheden voor natuurlijke systemen en menselijke samenlevingen. Ondanks het enorme belang van tropische bossen is er de afgelopen vier decennia een ongekend oppervlakte aan tropisch bos vernietigd. Jaarlijks gaat er ongeveer $2.1x10^5$ hectare bos verloren, wat ernstige gevolgen heeft voor de regulering van de mondiale klimaatcyclus, biodiversiteit en andere omgevingsvariabelen. Om deze gevolgen te beperken heeft het United Nations Framework Convention on Climate Change (UNFCCC) ontwikkelingslanden verzocht hun beleid aan te passen om emissies door ontbossing en bosdegradatie (REDD+) te verminderen. Onder dit beleid zijn landen verplicht om lokale en inheemse gemeenschappen te beschouwen als kritische belanghebbenden in het ontwerpproces en de implementatie van een national forest monitoring system (NFMS) dat het meten, rapporteren en verifiëren (MRV) van de acties en resultaten van REDD+ activiteiten ondersteunt.

De huidige regelingen voor het monitoren van tropische bossen zijn gebaseerd op remote sensing en veldmetingen die over het algemeen afkomstig zijn uit inventarisaties van nationale bossen. Remote sensing beeldmateriaal wordt beschouwd als de belangrijkste bron om verandering in bos in grote gebieden te berekenen, om de snelheid van de ontbossing te beoordelen en om te gebruiken als basis voor databases om de verandering van het bosoppervlakte op een nationaal niveau vast te stellen. Ontwikkelingen in middelgrote- en hoge resolutie satellieten, open data beleid, tijdreeks-analysemethoden en big data verwerking zijn waardevol voor de controle van ontbossing op lokale en globale schaal. Echter, bewolking, seizoensgebondenheid en de beperkte ruimtelijke en temporele resolutie van remote sensing waarnemingen beperken de toepasbaarheid in de tropen. Het verbeteren van de interpretatie van remote sensing analyse vereist substantiële verificatie en validatie van in-situ data. Het vervullen van deze taken door middel van het inventariseren van nationale bossen is duur, tijdrovend en moeilijk uit te voeren op grote schaal.

Naast remote sensing heeft ook community-based monitoring (CBM) aangetoond dat het potentieel heeft in het verzamelen en interpreteren van bos monitoringsgegevens. Desondanks is de daadwerkelijke implementatie van community-based bos monitoringssystemen tot op heden gebrekkig. Twee redenen hiervoor zijn: 1) de rol van de gemeenschappen in NFMS is onduidelijk en 2) methoden die lokale gemeenschappen kunnen ondersteunen om de mogelijkheden te verkennen en bos monitoring te vergemakkelijken zijn nog schaars. Dit proefschrift richt zich op deze twee punten door het voorstellen van technische oplossingen (gebruikmakend van computerkunde en geo-informatica) en door het beoordelen van de capaciteiten en de behoeften van gemeenschappen in ontwikkelingslanden waar REDD+ implementatie en bos monitoring plaatsvinden.

Het belangrijkste doel van dit proefschrift is dan ook om een aanpak te ontwikkelen die opkomende technologieën en community-based tropisch bos monitoren combineert. Om dit doel te bewerkstelligen zijn vier specifieke onderzoeksvragen geformuleerd: 1) Wat zijn de mogelijkheden om community-based inspanningen te koppelen aan nationale bos monitoringssystemen? 2) Hoe kan informatie- en communicatietechnologie (ICT) ondersteuning bieden aan de gemeenschap bij de automatisering van het verzamelen van gegevens voor het monitoren van koolstofvoorraden en veranderingen in koolstofvoorraden met behulp van moderne handheld-apparaten? 3) Wat is de nauwkeurigheid en compatibiliteit van de door de gemeenschap verzamelde gegevens voor het kwantificeren van (veranderingen in) koolstofvoorraden in bossen vergeleken met andere data (bijvoorbeeld optische remote sensing of veldmetingen uitgevoerd door experts)? 4) Wat is een geschikt ontwerp voor een interactief remote sensing en community-based near real-time bos monitoringssysteem en hoe kan een dergelijk systeem in gebruik worden genomen?

In hoofdstuk 2 worden wetenschappelijke literatuur en 28 readiness preparation proposals van de World Bank Forest Carbon Partnership Facility beoordeeld om de rol en de technische voorwaarden voor het CBM beter te definiëren. Op basis van deze beoordeling is een conceptueel kader ontwikkeld waaraan het CBM kan bijdragen als een toepassingsspecifieke en onafhankelijke dienst voor meet- en monitoringsgegevens van bossen op nationaal niveau. De volgende hoofdstukken zijn gebaseerd op dit raamwerk.

Hoofdstuk 3 beschrijft het proces van het ontwerpen en implementeren van een geïntegreerd systeem voor het verzamelen van gegevens op basis van mobiele apparaten die het community-based verzamelen en visualiseren van bos monitoringsgegevens stroomlijnt. De bruikbaarheid van het systeem is geëvalueerd in de Tra Bui gemeente, gelegen in de provincie Quang Nam in Centraal Vietnam. In deze gemeente zijn veranderingen in bos-koolstof gemeten met door lokale, regionale en nationale deskundigen en met hoge resolutie satellietbeelden.

De resultaten laten zien dat de lokale gemeenschappen bos-koolstof metingen kunnen uitvoeren met een nauwkeurigheid die vergelijkbaar is met die van deskundigen, maar tegen lagere kosten. Bovendien tonen de resultaten dat de gemeenschappen effectiever zijn in het opsporen van bosdegradatie op kleine schaal (veroorzaakt door selectieve houtkap en het omhakken van bomen voor brandhout) dan beeldanalyse met behulp van SPOT-beelden.

Om de bevindingen van hoofdstuk 3 te ondersteunen wordt het data-acquisitie formulier voor mobiele apparaten (dat vooral gegevens betreft met betrekking tot veranderingen in bossen) verder verbeterd in hoofdstuk 4. Het systeem is getest door dertig lokale experts in het UNESCO Kafa Biosphere reservaat in Ethiopië. Hoge resolutie satellietbeelden en professionele metingen werden gecombineerd om de juistheid en het complementaire gebruik van lokale datasets te beoordelen op het gebied van ruimtelijke, temporele en thematische nauwkeurigheid. Resultaten uit tien administratieve eenheden tonen aan dat de lokale gemeenschappen in staat waren veranderingen door ontbossing, bosdegradatie en herbebossing te beschrijven in termen van locatie, omvang, tijdstip en oorzaak. Ook tonen de resultaten aan dat de gemeenschappen aanvullende informatie ten opzichte van remote sensing gegevens bieden. Dit betreft met name het markeren van aantastingen van bossen en het in kaart brengen van ontbossing in kleinere gebieden. Op basis van deze complementariteit wordt een kader voorgesteld om monitoringsgegevens van lokale experts en monitoringsgegevens op basis van satellieten te integreren in een NFMS ter ondersteuning van REDD+ MRV en near real-time monitoring van bosveranderingen.

Na het identificeren van het kader voor het geïntegreerde monitoringssysteem in hoofdstuk 4 beschrijft hoofdstuk 5 een interactief web-based bos monitoringssysteem met vier geografische informatiediensten: 1) Het verzamelen van continue datastromen uit satellietbeelden en gemeenschappen met behulp van mobiele apparaten, 2) Het detecteren van near real-time bosverstoringen op basis van tijdreeksen van satellietbeelden, 3) Het presenteren van bosverstoringsgegevens via een web-based applicatie en sociale media, 4) De interactie tussen verstoringswaarschuwingen op basis van satellietgegevens en verstoringswaarschuwingen op basis van gemeenschappen voor het verbeteren van het verzamelen van in-situ gegevens. Het systeem is ontwikkeld met behulp van open source technologieën en is uitgevoerd in samenwerking met lokale experts in het UNESCO Kafa Biosphere reservaat in Ethiopië. De resultaten tonen aan dat het systeem op eenvoudige wijze toegang tot informatie over bosverandering kon verschaffen. Ook verbeterede het systeem de inzameling en opslag van in-situ observaties door lokale experts aanzienlijk. Het gebruik van sociale media leidde tot een hoger niveau van interactie met de gebruiker en tot een betere communicatie tussen belanghebbenden. Op basis van een evaluatie werd de bruikbaarheid van het systeem in Ethiopië bevestigd.

In hoofdstuk 6 worden de conclusies gepresenteerd en worden er aanbevelingen gedaan voor verder onderzoek. De algemene conclusie is dat opkomende technologieën zoals smartphones, web-GIS en sociale media -verenigd binnen een gebruiksvriendelijke interface- de deelname van lokale gemeenschappen in het monitoren van bossen verbeteren. Bovendien worden fouten in de verzamelde gegevens verminderd. De resultaten tonen aan dat CBM kan bijdragen aan gegevens over koolstofvoorraden in bossen en veranderingen van bosoppervlakten, en dat het kan helpen om de drijvende factoren achter lokale uitstoot te begrijpen. Dit proefschrift demonstreert in theorie en in praktijk hoe op lokale schaal in-situ gegevens kunnen worden gecombineerd met middelhoge- en hoge resolutie satellietbeelden voor een operationeel, near real-time bosmonitoringssysteem. De methoden die in dit proefschrift worden gepresenteerd zijn ook elders toepasbaar. Daarmee benadrukt dit proefschrift de behoefte aan beleid om gemeenschappen te versterken en om institutionele kaders te creëren voor gemeenschapsgerichte bosmonitoringssystemen in de tropen.

Acknowledgements

At the completion of my PhD, I take this opportunity to acknowledge all the personalities and organizations for their immense support and valuable contribution throughout my research. I feel very lucky to be a part of the Institute for Technology & Resources Management in the Tropics & Subtropics (ITT), Cologne University of Applied Sciences, Cologne, Germany and the Laboratory of Geo-information Science and Remote Sensing Wageningen University, Wageningen, The Netherlands. I would like to acknowledge the DAAD funded Center for Natural Resources and Development (CNRD) Fellowship Programme that arranged the funding to pursue my studies, through the Government of the Germany. I would also like to thank Center for International Forestry Research (CIFOR) Global Comparative Study on REDD+ and Google Earth Outreach for the financial support.

First and foremost, my heartfelt thanks to my promoter, Prof. Martin Herold. I would like to thank you for believing in me and providing me this great opportunity to be a part of your team. Martin thanks for your immense patience, aspiring guidance, invaluably constructive criticism and friendly advice during my PhD. My PhD journey started at ITT, Cologne, Germany. I am equally indebted to prof. Lars Ribbe, the co-promoter, for his invaluable guidance, the freedom and trust that he offered me to find the path at my own during the PhD research. Thanks also to Alexandra, Udo, Rui, Claudia, Dominic, Christian, Firoz, Viet, Andreas, Magdalena, Sujan and all the staffs and the PhD researchers from ITT for their support.

This thesis would have never achieved this stage without the support and guidance of my daily supervisors, Valerio Avitabile and Sytze de Bruin. It has been an honour to have you both as supervisors for this PhD research. Your patience, scientific expertise and preciseness played a key role in the completion of this thesis and have truly shaped me for my future scientific career. Valerio, I will never forget the lesson which you taught me during our first field trip in Vietnam. Sytze thanks you for your commitment, constructive comments and careful corrections. Without your support, this thesis and I wouldn't be this far. There are no words that can express my gratitude for your guidance, advices and suggestions during the course of this PhD.

I am also very grateful to my reading committee. Thank you very much for your willing to be committee members, taking your time to review my PhD thesis. Special thanks to my paranymphs; Ben and Nandika. Thanks for your company throughout my PhD research.

I am extremely grateful to Ravi, Nirajan, Sarah, Gareth, Prajan, Ana and Rinchudoma for taking rigorous effort in proofreading. You read my numerous drafts and despite all efforts continued to find typos. Thanks.

I would like to thank all the Laboratory of Geo-information Science and Remote Sensing staffs for their help and co-operation during my stay here. My deep gratitude to Arnold, Lammert, Harm, Ron, Jan Clevers, John, Jan Verbesselt, Aldo, Willy, Brice, Lukasz, Philip, Jessica, Kathleen, Juha and Rosa for their endless support. I had the pleasure to share these years with Johannes, Roberto, Richard, Erika, Noriko, Laure, Sidney, Saed, Kim, Niki, Nadine, Michael, Benjamin, Maria, Giulia, Jose, Astrid, Simon, Alvaro, Eliakim, Mathieu, Kalkidan, Eskender, Loic, Peter, Marston, Yang, Manos, Johannes Eberenz, Tsoefiet, Konstantin, Qijun and Jalal for your support and delightful company. Special thanks goes to Truus and Antoinette for providing the endless administrative support. I would also like to thank my MSc students Stafen, Elias, Masih, Jim and Jost. I had a good time working with you all and your study contributed to my PhD as well.

This study is based on field work data from Vietnam and Ethiopia. The data collection from Vietnam would not have been possible without the support from Cuong, Hien, Uyen, Haigiap, Sinh, Chuong and the staffs of Forest Inventory and Planning Institute (FIPI) and sub-FIPI. I would like to express my heartiest thanks to them for their sincere support. The support provided by Tra Bui commune president and local communities are highly acknowledged.

Special thanks to Svane, Dani, Bianca, Bekele, Bety and all NABU team who greatly supported the field work in Kafa, Ethiopia. I would like to highly acknowledged Svane for providing nice photographs for my thesis cover. I am indebted to Mesfin Tekele for the support, he provided during the field work in Kafa, despite his busy schedule. I particularly acknowledge Muluken Mekuria, Terefe Woldegebriel and the 30 local forest rangers of the Kafa Zone Bureau of Agriculture and Rural Development for their support and assistance. I am thankful to Mengistu, Alemayehu and all the staffs of Ethiopian Wildlife and Natural History Society for their kind logistical support for my field research. Special

thanks to Tesfy for his safe drive service through the complex topography during my field work.

During my research period, I got ample opportunity to involve in community-based forest monitoring workshops and meeting around the world. I am grateful to Rebecca, Tanya, Dev and Google earth engine team for their support to attain the geo-user meetings. I would also take this opportunity to thank Carlos Souza, Victor, Marcio and the rest of the Imazon staff for their scientific support, technical assistance and their hospitality during my work stay in Brazil. I am also grateful to Sylvia, Coral and all Sylva-carbon team for their support to participate in various workshops.

I had a wonderful experience to be involved in social activities of the Wageningen Nepalese community. I extend my very special thanks to Sunil, Govinda, Ekaraj, Udit, Rajita, Suman, Barsha and Nirajan. Similarly, Sanjeeb, Deepak, Ram, Rajesh, Tilak, Tanka, Shailendra, Kishor, Endra, Suresh, Prerana, Indu, Shanti, Mary, Dharmin, Yogesh, Marina and the rest from the community are heartily acknowledged for sharing lots of memorable moments during this study period. I also feel very lucky that I got many support from friends in Enschede, Utrecht and Rotterdam who have made me feel at home in the Netherlands. Thanks to prof. Arbind Tuladhar, Chandra, Sujata bhauju, Ajit, Rubi, Reshma, Rehana, Prajan, Rabindra, Gaurab, Tek, Prajwol and Manish for creating a home away from home.

I would like to extent my sincere gratitude to Ganesh Prasad Bhatta and his family and their unconditional support and encouragements. Many thanks go to BN dai, Janak jee, Gopi jee, Uma Shankar, Jay, Rupesh, Narendra and all my friends that supported me in these past years. I also like to thank and former colleagues at Kathmandu University Prof. Bhola Thapa, Prof. Ramesh Kumar Maskey, Prachand Man Pradhan, Subash, Nawaraj, Ashwin, Shashish for their manifold support throughout the past four years.

My sincere appreciation goes to Fred, Walesi, Jerry and Unaisi in Twello for their kind hospitality and moral support during my staying in the Netherlands!

Finally, my heartfelt thanks are also due to my grandfather, grandmother, father, mother, mother-in-law and other family members for their invaluable love, support and encouragements. My deepest thanks to my brothers Santosh, Nabin, Sujit and Ajit who always supported and inspired me in my academic career. I am equally thankful to my sisters, sister-in-laws, brother-in-laws and nephews for their love and support. Last but not the least, I would like to take this opportunity to express my deepest thanks and immense love to my beloved soul mate Puja for her loving support, endless patience, encouragement and understanding over the past years.

Thank you!!

Arun Kumar Pratihast

Wageningen, 2015

List of publications

Peer reviewed journals

Pratihast, A.K., DeVries, B., Avitabile, V., de Bruin, S., Herold, M., & Bergsma, A. (in review). Design and implementation of an interactive web-based near real-time forest monitoring system PLoS ONE

DeVries, B., **Pratihast, A.K.**, Verbesselt, J., Kooistra, L., & Herold, M. (in review). Characterizing Forest Change Using Community-Based Monitoring Data and Landsat Time Series. PLoS ONE

Pratihast, A.K., DeVries, B., Avitabile, V., de Bruin, S., Kooistra, L., Tekle, M., & Herold, M. (2014). Combining Satellite Data and Community-Based Observations for Forest Monitoring. Forests, 5, 2464

Pratihast, A.K., Herold, M., De Sy, V., Murdiyarso, D., & Skutsch, M. (2013). Linking community-based and national REDD+ monitoring: A review of the potential. Carbon Management, 4, 91-104

Pratihast, A.K., Herold, M., Avitabile, V., de Bruin, S., Bartholomeus, H., Jr., C., & Ribbe, L. (2012). Mobile Devices for Community-Based REDD+ Monitoring: A Case Study for Central Vietnam. Sensors, 13, 21

Rutzinger, M., **Pratihast, A.K.**, Oude Elberink, S.J., & Vosselman, G. (2011). Tree modelling from mobile laser scanning data-sets. Photogrammetric Record, 26, 361-372

Other scientific publications

Pratihast, A.K., & Herold, M. (2011). Community-based monitoring and potential links with national REDD+ MRV. Proceedings of the FCPF workshop—Linking community monitoring with national MRV for REDD, 12-14

Pratihast, A.K., Souza Jr, C.M., Herold, M., & Ribbe, L. (2012b). Application of mobile devices for community-based forest monitoring. In, Proceedings of the Workshop Sensing a Changing World, Wageningen, 9-11 May 2012 (p. 6)

Rutzinger, M., **Pratihast, A.K.**, Oude Elberink, S., & Vosselman, G. (2010). Detection and modelling of 3D trees from mobile laser scanning data. In, International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives (pp. 520-525)

Short biography

Arun Kumar Pratihast was born in Parsa, Sarlahi district of Nepal on October 18, 1982. He spent his childhood and finished his schooling from Malangwa, Sarlahi. Then he moved to Kathmandu to attend the higher secondary education.

Arun commenced his undergraduate degree in Computer Engineering in 2006 from Himalaya College of Engineering, Tribhuvan University, Nepal. After the completion of the degree, he worked at WorldLink Technology, a software development company, and also in Kathmandu University (KU), Nepal. In WorldLink, he was actively involved in software development and, implementation of such software products whereas in KU he served as a Teaching Assistant, in Department of Computer Science and Engineering.

In September 2008, Arun received Faculty of Geo-Information Science and Earth Observation (ITC) fellowship award to do his Masters of Science degree in Geo-Information Science and Earth Observation at ITC, University of Twente, Enschede, The Netherlands. In his Master's thesis research, he developed a technique to generate 3D model of a tree using mobile laser Scanning scan data. His research includes not only detection of trees form huge amount of point clouds, but also the tree shape reconstruction, texturing and proper visualization in 3D environment like 3D virtual city model, Google earth. His MSc thesis was nominated for the best thesis award competition. After completion of his MSc, he returned to Nepal and worked as a lecturer and later as a program co-ordinator for Geomatics Engineering at Department of Civil and Geomatics Engineering, School of Engineering, KU, Nepal. He was the driving force behind the co-operation and research collaboration between the ITC and KU.

Arun received DAAD funded Centre for Natural Resource and Development (CNRD) scholarship to proceed his PhD in Institute for Technology and Resources Management in the Tropics and Subtropics (ITT), TH Köln - University of Applied Sciences, Cologne, Germany and Wageningen University, Wageningen, The Netherland. In his PhD research, he built up expertise in application development and testing on mobile device for community-based tropical forest monitoring, remote sensing image analysis and project management. He is also actively engaged in the training and capacity building activities of Sylva carbon Global Forest Observation Initiative in many countries around the world. Recently, he received Google Earth Engine Award 2015 together with Martin Herold, Jan

Verbesselt and Eliakim Hamunyela of the Laboratory of Geo-information Science, Wageningen university.

Arun's current research interests are related to citizen science, remote sensing and Geo-information technologies for interactive near real-time ecosystem monitoring. He will continue his work as postdoctoral researcher at Wageningen University.

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (4.5 ECTS)
- Evolving technologies and community-based monitoring for effective REDD+ implementation

Writing of project proposal (2.5 ECTS)
- A community-based interactive monitoring system for effective REDD+ implementation in Peru
- Interactive forest monitoring using satellite data and community-observations in the Google platform

Post-graduate courses (4.4 ECTS)
- Uncertainty propagation in spatial and environmental modelling; PE&RC (2011)
- REDD+ Science + governance: opportunities and challenges; REDD@WUR, PE&RC (2012)
- Sampling in space and time for survey and monitoring natural resources; PE&RC (2013)

Laboratory training and working visits (3 ECTS)
- Monitor forest change using mobile device; IMAZON, Belem, Brazil (2011)
- Monitoring deforestation from the ground to the cloud; IMAZON, Google Sao Paolo Office, Sao Paolo, Brazil (2012)

Invited review of (unpublished) journal manuscript (1 ECTS)
- Forest: integrating CBM into the projects of the alliance Mexico REDD+ programme (2014)

Deficiency, refresh, brush-up courses (1.2 ECTS)
- Spectral mixing analysis and image classification techniques to monitor forest change in the Brazilian Amazon; Wageningen, the Netherlands (2011)
- Geo-tool, geo-information science master; Wageningen University (2013)

Competence strengthening / skills courses (1.8 ECTS)
- Techniques for writing and presenting a scientific paper; Wageningen Graduate Schools (2013)
- Information literacy PhD + EndNote; Wageningen UR Library (2013)
- Last stretch of PhD; PE&RC (2014)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.2 ECTS)

- PE&RC PhD Weekend (2011)
- PE&RC Day (2014)

Discussion groups / local seminars / other scientific meetings (7.3 ECTS)

- Workshop for the world bank's forest partnership facility: linking community monitoring with national MRV for REDD+; Mexico City, Mexico (2011)
- Land use and climate change interactions project meetings in Central Vietnam (2011-2013)
- Remote sensing thematic group meeting (2011-2015)
- Climate protection and preservation of primary forest meeting UNESCO Kafa biosphere reserves, Ethiopia (2012-2014)
- REDD Discussion group (2012-2015)
- 3rd GOFC-GOLD Land monitoring symposium, Wageningen, the Netherlands (2013)
- Community-based forest monitoring meetings and capacity development program organised by with Silva carbon, USGS (2013-2015)

International symposia, workshops and conferences (9 ECTS)

- 3rd Remote Sensing Symposium (RSS): 21st century challenges; Wageningen, the Netherlands (2011)
- GEO-Carbon conference: carbon in a changing world; FAO, Rome, Italy (2011)
- Sensing a changing world; Wageningen University, Wageningen, the Netherlands (2012)
- ESA Living planet symposium; Edinburgh, United Kingdom (2013)
- EARSEL, Frontiers in earth observation for land system science; Berlin, Germany (2014)
- IGARSS; Milan, Italy (2015)

Lecturing / supervision of practical's / tutorials (2.4 ECTS)

- Remote sensing course; ITT Cologne University of Applied Science; Cologne, Germany (2011)
- Remote sensing and GIS integration course: in the geo-information science matter; Wageningen University (2012-2015)

Supervision of 4 MSc students

- Community-based forest monitoring using mobile devices in Kafa: a study on the potential of smart phones for forest monitoring in Kafa; Ethiopia (2013)
- Use of smartphones to derive the leaf area index (2014)
- Assessing local expert data quality for forest monitoring: a case of Kafa; Ethiopia (2014)
- An offline Geo-Fence application: the development of a citizen science mobile application for REDD+ monitoring (2015)