Identifying and Overcoming Constraints on Establishing Feasible National REDD+ Measurement, Reporting and Verification Systems

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The candidate confirms that the work submitted is his own and that appropriate credit has been given where reference has been made to the work of others.

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Abstract

To participate in the REDD+ mechanism of the UN Framework Convention on Climate Change (UNFCCC), developing countries must upgrade their national forest monitoring systems to become Measurement, Reporting and Verification (MRV) systems that can monitor changes in forest carbon stocks. However, despite support from international REDD+ Readiness programmes, most developing countries still have limited forest monitoring capacity.

The sociology of remote sensing systems has been little studied until now, especially in developing countries. To evaluate the adoption of technologies proposed in these schemes, this research has devised and tested an Information Production (IP) Framework and a Technology Adoption System (TAS) Framework that enable the evaluation of more complex instances of technology adoption than current frameworks.

This research found that although REDD+ Readiness schemes have been implemented in Cambodia and Indonesia, the capacity to supply forest carbon information is still limited because upgrading forest monitoring systems has been limited by self-constrained optimisation that has led to only incremental evolution. Cambodia and Indonesia have shown relatively high improvements in forest area monitoring capacity, compared to growing stock monitoring capacity, but the quality of forest area and carbon information produced by the two countries is still insufficient to meet international demand. Technology adoption has involved self-constrained optimisation because adopting new technologies was constrained by human capital, institutions and perceptions, existing technologies, financial resources, and communication between organisations. Technology adoption and information production are also influenced by other factors, such as the relationship between national and international demand for forest information, organisational substitution, and difficulties in improving the organisation of forest monitoring. Since in both countries the improvement of forest monitoring has reached a plateau due to self-constrained optimisation and path dependency, escaping from the plateau may require increasing human capital and stronger financial incentives.

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Chapter 1
Introduction

1.1 Justification

Tropical deforestation accounts for at least 10% of all carbon dioxide emissions that are contributing to global climate change (Le Quéré et al., 2009; Smith et al., 2014). For this reason, the United Nations Framework Convention on Climate Change (UNFCCC) has negotiated a Reducing Emissions from Deforestation and Degradation (REDD+) mechanism to compensate developing counties for reducing deforestation and forest degradation. Progress made at the 19th Conference of the Parties (COPs) of the UNFCCC, held in Warsaw in November 2013, suggests that its REDD+ scheme is close to becoming operational (UNFCCC, 2014a), and two years later, implementing REDD+, including results-based payments, was encouraged by the Conference of the Parties as referred to in Article 5, paragraph 1 and 2 of the Paris Agreement (UNFCCC, 2015).

If this mechanism is to succeed then reductions in deforestation rates must be monitored reliably by national Measurement, Reporting and Verification (MRV) Systems (Baker et al., 2010). Thus, it is imperative for tropical countries that wish to participate in the REDD+ scheme to establish national MRV Systems (De Fries et al., 2007; Asner et al, 2010; Jha and Paudel, 2010; UNFCCC, 2010a; Pelletier et al, 2011), so they can monitor reductions in rate of deforestation and forest degradation, and associated rates of carbon emissions to provide reliable evidence for securing international compensation (Baker et al., 2010; UNFCCC, 2010b; Saatchi et al., 2011; Bucki et al, 2012; Romijn et al, 2012). Establishing a robust national MRV system in developing countries is one of the most significant and decisive factors in the implementation of the REDD+ scheme.

The requirement for developing countries participating in REDD+ to establish Measuring, Reporting and Verification (MRV) systems is established in two decisions by the Conference of the Parties (COPs). In Decision 4/CP.15, the Conference of the Parties:

Requests developing country Parties, to establish, according to national circumstances and capabilities, robust and transparent national forest monitoring systems and, if appropriate, sub-national systems as part of national monitoring systems that:

i. *Use a combination of remote sensing and ground-based forest carbon inventory approaches for estimating, as appropriate, anthropogenic forest-related greenhouse gas emissions by sources and removals by sinks, forest carbon stocks and forest area changes.*
ii. *Provide estimates that are transparent, consistent, as far as possible accurate, and that reduce uncertainties, taking into account national capabilities and capacities.*
iii. *Are transparent and their results are available and suitable for review as agreed by the Conference of the Parties.*

Encourages, as appropriate, the development of guidance for effective engagement of indigenous peoples and local communities in monitoring and reporting.

Encourages all Parties in a position to do so to support and strengthen the capacities of developing countries to collect and access, analyse and interpret data, in order to develop estimates (UNFCCC, 2010b).

This decision was later repeated as part of the overall Warsaw REDD+ Framework. In Decision 14/CP.19, the Conference of the Parties:

Decides that measuring, reporting and verifying anthropogenic forest-related emissions by sources and removals by sinks, forest carbon stocks, and forest carbon stock and forest-area changes ... is to be consistent with the methodological guidance provided in decision 4/CP.15

Recognizes the need to develop capacities for measuring, reporting and verifying anthropogenic forest-related emissions by sources and removals by sinks, forest carbon stocks, and forest carbon stock and forest-area changes

Decides that the data and information used by Parties in the estimation of anthropogenic forest-related emissions by sources and removals by sinks, forest

> *carbon stocks, and forest carbon stock and forest-area changes ... should be transparent, and consistent over time (UNFCCC, 2014a).*

Tropical countries are currently participating in various ‘REDD+ Readiness’ schemes to upgrade their national forest monitoring systems into MRV systems that meet UNFCCC criteria. Despite the technical assistance already offered to developing countries through such bodies as the Global Observation for Forest Cover and Land Dynamics (GOFC-GOLD) (2009), and the REDD+ Readiness schemes of UN-REDD and the World Bank’s Forest Carbon Partnership Facility (FCPF), they are, however, still lack MRV capacities at both technical and organizational levels to provide reliable estimates of activity data (i.e. land-use/land-cover changes including forest area) and carbon emissions/removals factors (i.e. the amount of forest carbon per unit area) (Hardcastle et al., 2008; Frechette et al., 2014; Minang et al., 2014; Turnhout et al., 2017).

Capacity is still limited because historically, most developing countries have only had a limited capacity to monitor their forests (Grainger, 2010). They have limited experience and human resources, and lack useful forest data for operating national forest monitoring systems (Hardcastle et al., 2008; Wertz-Kanounnikoff et al., 2008; Herold, 2009). The lack of national forest monitoring capacity is one of the main reasons for delaying the implementation of the REDD+ scheme (Baker, 2010; Houghton et al., 2010; Joseph et al, 2013), and thus major obstacles to establishing feasible MRV systems still remain in matching capabilities to requirements (Gibbs et al., 2007; Herold and John, 2007).

The crucial obstacle that most developing countries have only very limited capacity to undertake conventional national forest inventories and forest surveys (Hardcastle et al., 2008), leads to two inter-related types of challenges in making the transition from present capacity to a functioning MRV system. First, challenges in choosing from the wide range of available technologies, the combination of technologies most appropriate to each country. Second, challenges in changing the organization of government forestry departments to accommodate these new technologies and practices.

Such challenges that developing countries have already encountered in establishing national forest monitoring systems and in making their preparations for participating in the REDD+ scheme should be tackled, before the REDD+ scheme becomes operational, so that REDD+ scheme could be converted into reality (Turnhout et al., 2017; Romijn, 2012).

1.2 Aims of the Study

Developing countries are known to have limited forest monitoring capacity, and it should be improved to participate in the REDD+ programme. Yet, it still remains unknown why developing countries have limited forest monitoring capacity, and how it can be improved. As there is no universally agreed methodology for the research purposes, and existing methodologies showed limitations, the aims of this research are:

1. Evaluate tropical countries' existing national forest survey programmes and the programmes which have been upgraded by participating in the REDD+ Readiness programmes.

2. Identify constraints on adopting new technologies for forest area monitoring and forest carbon monitoring.

3. Propose solutions to the problem that developing countries still have limited forest monitoring capacity by identifying constraints on adopting new technologies for forest area and carbon monitoring.

4. Devise frameworks to evaluate the gap between current national forest area and carbon monitoring capacity in developing countries and the capacity needed to meet reporting needs of the UNFCCC REDD+ mechanism, and identify the socially optimal technologies which it would be feasible to adopt to raise monitoring capacity to REDD+ reporting standards.

5. Test these frameworks in two developing countries, Cambodia and Indonesia, for the purposes mentioned above.

1.3 Definitions of Key Concepts

Because of the interdisciplinary nature of this thesis, definitions of key concepts are provided throughout this thesis. 'REDD+' and 'MRVs' are explained in the first sections of Chapter 2, and different views on 'Technology Adoption' are reviewed in Chapter 3. The definition of Appropriate Technology is still controversial, and so it is discussed in detail in section 3.3.3. The definition of 'institutions' for this research is presented in Chapter 4.

1.4 Structure of the Thesis

This thesis consists of 8 Chapters. Chapter 1 elaborates 'justification for the necessity of this research', 'the aims of this research', 'definitions of key concepts', and 'structure of this thesis'. Background information on the REDD+ scheme, its evolution, and MRVs for that, in addition to the main features of remote sensing and forest inventory for forest monitoring are presented in Chapter 2. It also explains the current status of actual forest monitoring practices being undertaken by tropical countries using remote sensing and forest inventory methodologies. Key literatures on REDD+ MRVs and Technology Adoption are reviewed in Chapter 3 to find out the existing gaps to be filled by this research. They also provide a theoretical foundation for devising a methodology, which is presented in Chapter 4.

Chapter 4 presents a methodology and methods for this research. To evaluate tropical countries' existing national forest survey programmes and the programmes which have been upgraded by participating in the REDD+ readiness programme, and to propose new socially optimal programme designs which could be more effective, the Technology Adoption System (TAS) Framework and the Information Production (IP) Framework are presented, and detailed methods for collecting empirical data (i.e. interviews, direct observations, and secondary data), and research areas, Cambodia and Indonesia, where the frameworks were applied, are also explained.

Chapters 5 and 6 are results chapters. Chapters 5 and 6 first look at the ability of Cambodia and Indonesia's forest monitoring system to meet national demand for forest information before REDD+ negotiations, and then at how the organisation of forest monitoring changed to meet the much greater international demand for information after REDD+ negotiations began. Constraints on the evolution of the organisation of forest monitoring, and the adoption of available new technologies, are analysed with reference to key variables in the TAS Framework, including technologies, organisational structure, institutions, human capital, financial resources, and interactions between various organisations. The influences of international organisations on the growth in monitoring capacity are evaluated with particular reference to the REDD+ Readiness programmes in which Cambodia and Indonesia participated.

Chapters 7 and 8 summarises and generalises the main findings of this research, using the TAS and IP frameworks to look in more detail at the technology adoption processes and constraint on adopting new technologies. Conclusions to the research, limitations of the research, recommendations for future research, and recommendations for governments in developing countries, the UNFCCC, and overseas organisations are also presented.

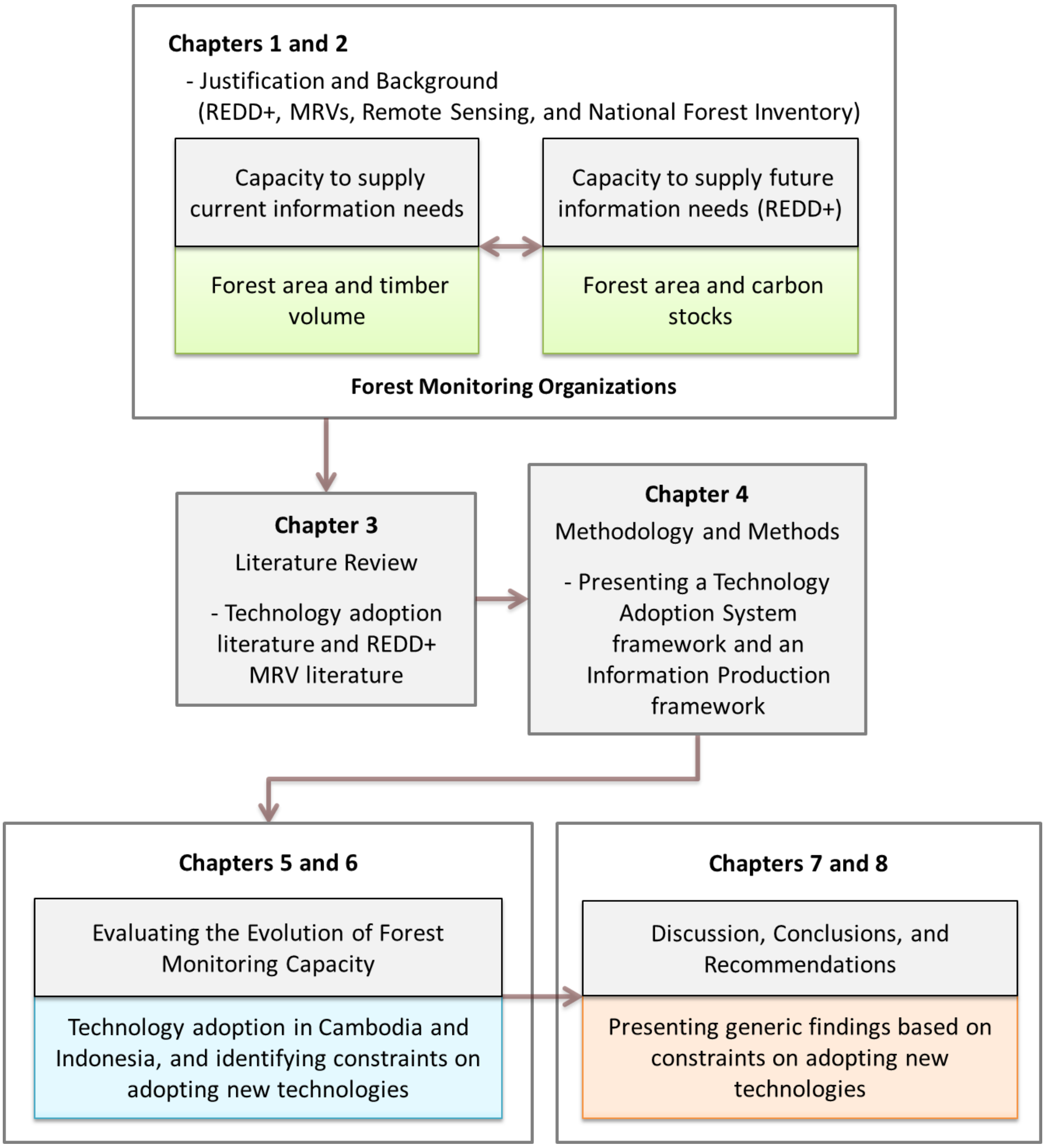

Figure 1.1 Structure of the thesis

Chapter 2
Remote Sensing and National Forest Inventory for REDD+ MRVs

2.1 Introduction

To explain why existing remote sensing techniques and inventory methods are not being used operationally in developing countries, and how appropriate combinations of these techniques and methods could form the basis for MRV systems for monitoring changes in forest carbon stocks for REDD+, it is important to review currently available technologies and find their characteristics, advantages and disadvantages.

In this regard, this chapter looks at existing remote sensing technologies and techniques for monitoring forest area and estimating forest carbon stocks, common methodologies used for National Forest Inventories to estimate timber stocks in developing and developed countries, and the combination of remote sensing and field data collection for monitoring forest carbon distribution.

Before explaining such characteristics, this chapter also outlines REDD+, REDD+ Measurement, Reporting and Verification (MRV), and methodology and data for estimating forest carbon stocks and changes to provide comprehensive, and fundamental, background information on this research.

2.2 REDD+ and Measurement, Reporting and Verification (MRV)

2.2.1 REDD+

Since forests are a significant carbon emissions source (IPCC, 2007), forest conservation mechanisms, by which the amount of carbon dioxide (CO_2) in the atmosphere can be reduced, had been getting attention, and the idea of “Reducing

Emissions from Deforestation (RED)" was first presented by Papua New Guinea and Costa Rica at the 11th Conference of the Parties (COPs) of the UNFCCC in 2005, after the concept of "Compensated Reductions" had raised at the 9th COP in 2003 (Table 2.1).

Table 2.1 Progress of REDD+ negotiations

Year	COP*	Place	Key decisions and Remark
1992	Earth Summit	Rio de Janeiro	The United Nations Framework Convention on Climate Change (UNFCCC) adopted as an international environmental treaty
2003	COP 9	Milan	Idea called "Compensated Reductions" raised
2005	COP 11	Montreal	Reducing Emission from Deforestation (RED) proposed (Launch of a two-year process)
2006	COP 12	Nairobi	Agreement on a second workshop SBSTA 26** - Consideration of workshop reports and draft for COP 13
2007	COP 13	Bali	**Bali Action Plan** - Non-Annex-1 Parties to undertake measurable, reportable and verifiable NAMAs*** – REDD+ activities introduced, Guidance on demonstration activities
2008	COP 14	Poznan	Paving the way for COP15 SBSTA 29: Expert meeting on Reference Emission Level (REL), Draft decision for COP15
2009	COP 15	Copenhagen	Methodological guidance on REDD+ activities, including - Establishing NFMSs**** required to estimate GHGs from forestry activities - Using a combination of remote sensing and ground-based forest carbon inventory approaches - The development of guidance for effective engagement of indigenous peoples and local communities in monitoring and reporting - Supporting and strengthening the capacities of developing countries to collect and access, analyse, and interpret data for estimating GHGs (UNFCCC, 2010b)
2010	COP 16	Cancun	**Cancun Agreement** - Guidance on implementation of REDD+ activities, including national forest monitoring systems required to monitor and report on REDD+ activities
2011	COP 17	Durban	Guidance on Forest Reference Emission Levels and Reference Emission Levels (FREL/RELs) for REDD+ activities and on systems for providing information on REDD+ safeguards

2013	COP 19	Warsaw	**Warsaw Framework** - The need to develop capacities for Measurement, reporting and verification (MRV) - Establishing transparent and consistent MRV systems for estimating anthropogenic forest-related emissions and removals, forest carbon stocks, and forest carbon stock and forest-area changes - Implementing MRVs in accordance with the methodological guidance provided in decision 4/CP.15 (UNFCCC, 2014a).
2015	COP 21	Paris	**Paris Agreement** – Encourages actions to implement and support REDD+, including results-based payments, and reaffirms the importance of incentivizing non-carbon benefits (UNFCCC, 2015)

* Conference of the Parties
** Twenty-sixth session of the Subsidiary Body for Science and Technological Advice of the UNFCCC
*** Nationally Appropriate Mitigation Actions (NAMAs)
**** National Forest Monitoring Systems (NFMSs)

(Source: produced base on UN-REDD programme (2012), UNFCCC (2010b), UNFCCC (2014a), UNFCCC (2014b), UNFCCC (2015) and other UNFCCC decisions related to REDD+)

As the idea was negotiated, ‘Forest Degradation’ was added to the scheme, and demonstration activities and assessment of drivers of deforestation in developing countries were called for in Decision 2/CP.13, known as the Bali Action Plan (UNFCCC, 2008). In accordance with decisions made during CP.16, the scheme evolved as “Reducing Emissions from Deforestation and forest Degradation, forest conservation, sustainable management of forests, and enhancement of forest carbon stocks” (UNFCCC, 2011), which is simply called REDD+.

As REDD+ is part of international efforts to mitigate climate change, it “aims to provide positive incentives to developing countries for reducing GHG emissions from forestry activities and conserving, sustainably managing and/or increasing the carbon stocks in their forests” (UN-REDD, 2012). Actions to conserve and enhance forest carbon stocks, and to implement and support REDD+, are formally encouraged by the decisions made at the 21st Conference of the Parties (COPs) of the UNFCCC (UNFCCC, 2015).

To implement REDD+, a three-Phased approach – Readiness, Results-based demonstration activities, and Results-based payments – was adopted by the 16th COP to the UNFCCC (see UNFCCC, 2010a) (Figure 2.1), and agreements on ‘Results-based payments’ for the full implementation of REDD+ activities were made during the

19th Conference of Parties, known as the Warsaw Framework for REDD+ (Decision 9/CP.19, UNFCCC, 2014a).

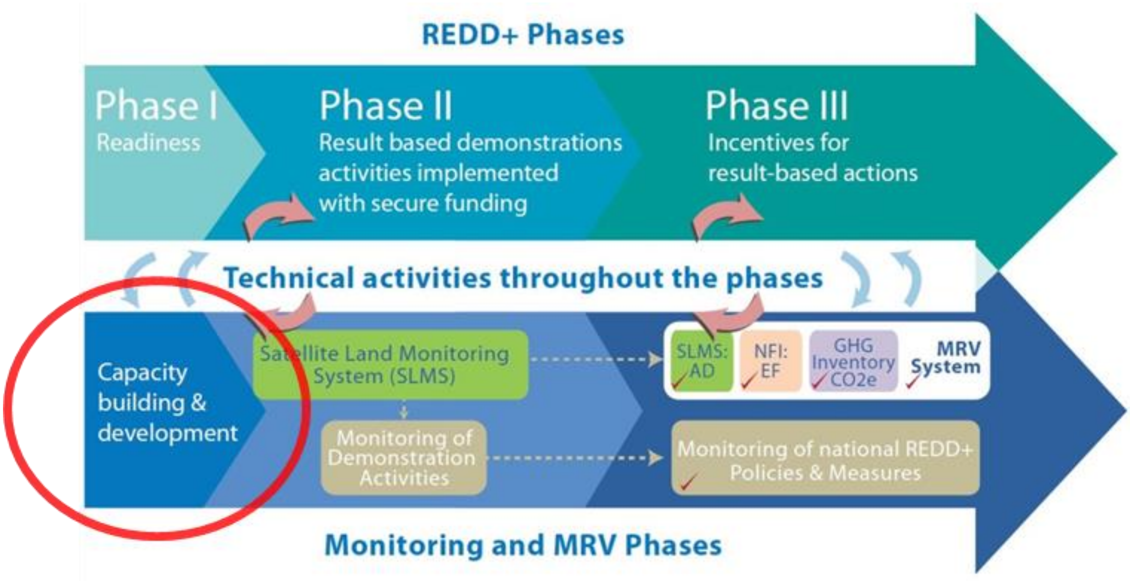

Figure 2.1 REDD+ phases and technical activities for establishing MRV systems

(Capacity building for MRVs is implemented during the REDD+ Phase 1, Readiness, Source: UN-REDD, 2013a)

The four key elements for the development and implementation of national REDD+ are stated in the Cancun Agreements, Decision 1/CP.16, (UNFCCC, 2011), and further explanations were given through other decisions such as 4/CP.15, 12/CP.17, and 11-13 and 15/CP.19 (UN-REDD, 2015a). The elements include: (1) National Strategy or Action Plan; (2) National Forest Reference Emission Level and/or Forest Reference Levels (FREL/FRLs); (3) National Forest Monitoring System (NFMS); and (4) Safeguards Information System (SIS). Of the four elements, SIS is a system for 'protecting and developing social and environmental sustainability', while NFMS is a system for collecting, analysing and archiving forest data for REDD+ MRVs that is constructed by 'institutional arrangements in a country' (GFOI, 2016). MRV and FREL/FRLs are explained in detail in the following sections.

2.2.2 Measurement, Reporting and Verification (MRV) for REDD+

Developing countries that ratified the UNFCCC needed to develop transparent, comparable and consistent Measurement, Reporting and Verification (MRV) systems in accordance with their REDD+ strategy in order to comply with international environmental policies. Article 4.1 (a) of the Convention (UNFCCC, 1992) states that all

Parties shall "Develop, periodically update, publish and make available to the Conference of the Parties … national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases … using comparable methodologies to be agreed upon by the Conference of the Parties."

MRV is "procedures associated with the communication of all mitigation actions of developing countries" (GFOI, 2016, p.xix). The effect of CO_2 emissions mitigation actions undertaken by Parties is estimated by 'Measurement', while 'Reporting' is a way of communication to international communities through, for example National Communications (NCs) and Biennial Update Reports (BURs) (GFOI, 2016). For REDD+, the reported data and information related to estimations are verified by third parties, two independent LULUCF technical experts.

Although the UNFCCC does not provides specific definitions of the MRV concept, the UN-REDD interprets the term as "the means to address countries' commitments to collect and share information on the progress of the implementation of provisions and/or commitments of Parties" " (UN-REDD, 2013a).

An MRV system is one of four main elements of REDD+, through which the amount of CO_2 emissions and removals from forests is measured, reported and verified, and accurate and transparent estimates of CO_2 emissions and removals from forests for MRVs are facilitated by a robust National Forest Monitoring System (NFMS) for collecting forest data by remote sensing and ground-based forest carbon inventory from different forest types (GFOI, 2016; Ochieng, et al., 2016).

As 'modalities for MRV of forest-related actions' are continuously evolving through international negotiations, whilst maintaining consistency with tropical countries' Forest Reference Emission Levels (FRELs) and/or Forest Reference Levels (FRLs), methodologies and data for transparent MRVs are also encouraged to be improved over time (UNCCS, 2014; Decision 14/CP.19, UNFCCC, 2014a).

Although MRVs are concerned with all greenhouse gases (GHGs) that include CO_2, N_2O, and CH_4, as the proportion of CO_2 in total GHGs emitted from forested areas is extremely significant, this section focuses mainly on CO_2, when explaining methods and parameters for GHG estimations.

2.2.2.1 Estimating CO_2 emissions and removals from forests

When estimating CO_2 emissions and removals from forest activities, which incorporate deforestation, forest degradation, forest conservation, sustainable management of forests, and enhancement of forest carbon stocks, following the most recent IPCC guidance and guidelines is recommended (Decision 12/CP.17, UNFCCC, 2012). In accordance with IPCC land categories (i.e. Forest land, Cropland, Grassland, Wetland, Settlements and Other land), in which there are carbon pools, GHGs emissions and removals from LULUCF occur both when land categories are converted to other land categories, and when land categories remain in the same category. For REDD+, emissions from the former is called 'Deforestation' and from the latter is 'Forest Degradation'.

Generically, CO_2 emissions at a certain time are calculated by multiplying "data on the extent of human activity causing emissions and removals" and "GHG emissions, or removals, per unit of land area" (GFOI, 2016). The former is '*Activity Data*', and the latter is '*Emission* and *Removal Factors*' that represent changes in carbon density (Figure 2.2). For REDD+, Activity Data and Emission Factors simply mean data on changes in land covers including forest areas, and changes in forest carbon stocks in a unit area of carbon pools, namely Above Ground Biomass (AGB), Below Ground Biomass (BGB), dead wood, litter, and soil, respectively (IPCC, 2003; UN-REDD, 2013a).

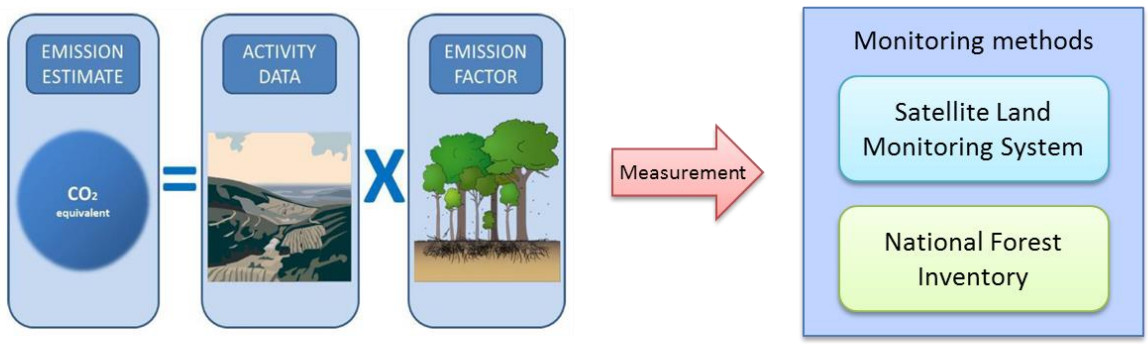

Figure 2.2 Estimating human-induced CO_2 emissions from forests
(Source: IPCC, 2003; UN-REDD, 2013a)

In the IPCC guidelines, CO_2 emissions and removals from such forest activities can be estimated using either the gain–loss method or the stock–difference method (for more details, and methods for estimating CO_2 emissions from forest fires, fuel wood removal and forest disturbances, see IPCC, 2003; 2006; GFOI, 2016).

The gain-loss method also employs the generic method for estimating CO_2 emissions and removals from carbon pools, and annual net CO_2 emissions are calculated by subtracting carbon removals from emissions. Emissions from deforestation are estimated by using activity data that show the area of land use categories converted to other land use categories, while emissions from forest degradation is estimated by applying different emission factors representing carbon density. An equation for estimating annual carbon stock change in a given pool as a function of gains and losses is provided by IPCC (2003; 2006):

$$\Delta C = \sum_{ijk} [A_{ijk} \bullet (C_I - C_L)_{ijk}]$$

Here,

ΔC = Carbon stock change in a pool (Tonnes C yr^{-1})

A = Area of land (ha)

ijk = Corresponds to climate type i, forest type j, management practice k, etc.

C_I = Rate of gain of carbon (Tonnes C ha^{-1} yr^{-1})

C_L = Rate of loss of carbon (Tonnes C ha^{-1} yr^{-1})

Although parameter values, such as AGB growth values and Biomass Conversion and Expansion Factors (BCEF) (or Biomass Expansion Factors (BEF) and wood densities for different forest and climate types), are needed for the gain-loss method (IPCC, 2006), it does not necessarily require data collected by implementing NFIs, and both IPCC default values for estimating carbon stocks and country specific emission/removal factors can be used for it. As emissions/removals factors in the method can be applied to various strata (GFOI, 2016), the gain–loss method is suitable for all Tiers, and tropical countries that have limited inventory data may adopt this method for their estimates.

On the other hand, by the stock–difference method, annual changes in carbon stocks are estimated by dividing by the number of years between measurements, so it requires at least two cycles of plot data collected by field surveys, or repeated NFIs. An equation for estimating annual carbon stock change in a given pool is also given by IPCC (2003):

$$\Delta C = \sum_{ijk} (C_{t2} - C_{t1}) / (t_2 - t_1)_{ijk}$$

Here,

C_{t1} = Carbon stock in the pool at time t_1 (Tonnes C)

C_{t2} = Carbon stock in the pool at time t_2 (Tonnes C)

In the method, annual change in carbon stocks in biomass, in land remaining in the same land-use category, is estimated by (IPCC, 2006):

$$C = \sum_{ij} \{A_{ij} \bullet V_{ij} \bullet BCEF_{Sij} \bullet (1+R_{ij}) \bullet CF_{ij}\}$$

Here,

C = Total carbon in biomass for time t_1 to t_2

A = Area of land remaining in the same land-use category (ha)

V = Merchantable growing stock volume (m^3 ha^{-1})

i = Ecological zone i (i = 1 to n)

j= Climate domain j (j = 1 to m)

R = Ratio of BGB to AGB (Tonnes d.m. BGB (Tonnes d.m. AGB)$^{-1}$)

CF = Carbon Fraction of dry matter (Tonnes C (Tonnes d.m.)$^{-1}$)

$BCEF_S$ = Biomass Conversion and Expansion Factors for growing stocks

In the equation, 'merchantable growing stock volume' is expanded and transformed into AGB by the $BCEF_S$. As 'volume-based inventoried data' or 'operational records' are directly converted into AGB by the $BCEF_S$, it does not need to apply wood density values in the conversion process (IPCC, 2006). Instead of $BCEF_S$ values, Biomass Expansion Factors for growing stocks (BEF_S) and wood density values (D) can also be used alternatively, i.e. $BCEF_S = BEF_S \bullet D$ (IPCC, 2006).

The stock–difference method requires more intensive field survey, compared to the gain-loss method, so it requires more resources for estimates. To produce data for the method, existing NFI sampling designs that are focused on commercial trees need to be modified.

2.2.2.2 Quality of data and methodological complexity

General methodologies for estimating CO_2 emissions and removals from wide forest areas rely mainly on data collect by field measurements and remote sensing to produce Activity Data and Emission/Removal Factors, which are to be integrated and analysed by using a GIS.

As activity data and emission factors used for estimations have different qualities, or accuracies, that are determined by frequency and intensity of measurements, the quality of data for land use changes and emission factors is standardized by Approaches and Tiers published by IPCC. IPCC guidelines provide non-hierarchical Approaches and hierarchical Tiers for carbon stock Measurements and Reporting in accordance with accuracy of activity data and emission factors that are used for estimating total carbon stocks and changes (Table 2.2).

Different Approaches and Tiers described in IPCC guidelines require different types of variables from field and satellite data for the estimates, and higher Tiers imply “increased accuracy of the method and/or emissions factor and other parameters used in the estimation of the emissions and removals” (IPCC, 2003). Ideally, to develop emission factors with low uncertainty, carbon stocks and changes in five carbon pools are needed to be measured in the field.

As activity data are for estimating land use changes, approach 1 refers to ‘total land use area, within defined spatial units, excluding data on conversions between land uses’, while approach 2 refers to ‘total land use area including data on changes between land use categories’ (IPCC, 2006). When using approach 1, ascertaining the exact location of land use categories, and the patterns and changes in land use classes, is impossible, and although land use conversions can be tracked by approach 2, it does not necessarily require spatially explicit land use data (IPCC, 2006). Most tropical countries may choose to adopt approach 3, as the approach uses ‘spatially explicit land use conversion data’ collected by, for example, remote sensing data that enables tracking land use changes through time.

For implementing REDD+, spatially explicit and accurate data and information on forest areas, produced after stratifying forest areas by forest types, age classes, climate types, topographic features, ecological zones, and management activities using various ancillary data, are needed to identify drivers of deforestation and forest degradation, and to track activities (GFOI, 2016). To provide data on land cover/land use changes and patterns with high uncertainty for REDD+, it is necessary to monitor forest area change, caused by human and/or non-human activities such as logging or forest fires, and forest degradation by repeating monitoring at high frequency, e.g. near real-time deforestation monitoring.

Table 2.2 Main characteristics of different Approaches and Tiers for Activity Data and Emission Factors

Activity Data		**Methods and Emission/Removal Factors**	
Approach 1	▪ Total land use area within defined spatial units ▪ No data on conversions between land uses ▪ Only net changes ▪ Not spatially explicit ▪ E.g. Forestry or agricultural statistics ▪ Double counting or omission when combining datasets	Tier 1	▪ Default values in IPCC guidelines ▪ Continental scale data ▪ Simplifying assumptions about some carbon pools ▪ Employs the gain-loss method ▪ Stock change method is not applicable ▪ E.g. IPCC default values applied to approach 3 activity data
Approach 2	▪ Total land use area ▪ Net gains or losses of the areas of land-use classes ▪ Changes in land use categories ▪ Conversions between land use categories ▪ Not spatially explicit data ▪ Between 2 points in time ▪ E.g. non-spatial matrix of changes	Tier 2	▪ Country specific data for emission factors and other parameters for different forest strata (National scale) ▪ Similar to Tier 1 in methodological approach ▪ Field survey needed for missing data ▪ Stock change method possible ▪ E.g. Country-specific emission factors and other parameters applied to highly stratified activity data
Approach 3	▪ Spatially explicit land use data ▪ Tracking of land use conversions and land use change patterns over time ▪ E.g. gridded map products produced by various sampling and/or wall-to-wall mapping techniques, including remote sensing	Tier 3	▪ Actual inventories with repeated measurements of carbon stock changes ▪ Well parameterised models using local scale data collected in the field ▪ Stock difference method possible ▪ Lower uncertainty than Tier1 and 2 ▪ Higher resolution data for identifying activities

- Appropriate Activity Data for different Tiers, for managed forests (IPCC, 2006)
    - Tier 1 - National and international statistic data on forest area from different agencies
    - Tier 2 - Country specific datasets with sufficient spatial resolution, classified by forest and climate types, and management activities
    - Tier 3 - Spatial datasets sufficient to track forest types and land use conversions, stratified by vegetation, climate and soil types

(Source: produced based on IPCC, 2003; 2006; Angelsen et al., 2012; Birdsey et al., 2013; GFOI, 2016)

Methodological complexities for estimating carbon stocks are represented by Tiers (Estrada, 2011) that are applied to both methodology for carbon stock estimations and data used for emission factors. The methodologies for estimating forest carbon stocks include how to produce activity data, how to collect data from different carbon pools for developing emission factors, and how to combine activity data and emission factors for calculating total emissions and removals. They also include models and equations for estimating CO_2 emissions and removals.

Higher Tiers require more accurate data and sophisticated methods. Tier 1 and 2 can employ methods provided by IPCC guidelines, but data used for estimates are different. Tier 1 can use default parameter values provided by IPCC and globally available activity data, while in Tier 2, the default values and activity data are wholly or partly replaced by higher temporal and spatial activity data and country specific data that can better represent land use systems, management systems, and environmental conditions of countries, such as climate and soil type and ecological zones (IPCC, 2006).

Focusing more on data for developing emission factors, Tier 1 uses IPCC default values for carbon stocks, which incorporate average AGB, net average annual AGB growth values, net volume increment values, wood density, root biomass to AGB ratio and carbon fraction, while Tier 2 uses country-specific carbon stock data for classified forest strata (Birdsey et al., 2013). Tier 3 requires actual inventories with repeated measurements of carbon stock changes, and it may also use well parameterized models for analysing the country-specific data collected in the field, and for simulating forest dynamics. For the Tier 3 method, especially for the stock-difference method, using country specific allometric equations and models for direct estimation of biomass growth, in addition to wood density and carbon fraction values, is required (IPCC, 2006). When estimating carbon stocks and changes with higher Tier methods, uncertainty can be reduced, but it requires greater resources and efforts (IPCC, 2006; GFOI, 2016).

For estimating forest carbon stock changes, multi-temporal NFI data at Tier 2 or Tier 3 levels are recommended to be considered more reliable and accurate. IPCC recommends tropical countries to adopt higher level methods if possible, such as Approach 3 and Tier 2 in its guidelines (FCPF, 2016). As limited resources, including data availability of tropical countries, can hamper feasibility of estimating forest carbon stocks, majority of countries participating in REDD+ may begin with lower level Approaches and Tiers for their MRVs by omitting some elements such as carbon pools (GOFC-GOLD, 2013), and using a combination of different Tiers is also possible for different REDD+ activities and carbon pools, e.g. enhancement of forest carbon stocks and soil carbon, respectively.

2.2.3 Forest Reference Emission Level and/or Forest Reference Levels (FREL/FRLs)

For REDD+, and MRVs, a Forest Reference Emission Level (FREL) and/or a Forest Reference Level (FRL) should be established, so that the amount of carbon emissions reduced by implementing REDD+ can be identified. FREL/FRLs are defined as “benchmarks for assessing each country’s performance in implementing REDD+ activities” (Decision 12/CP.17, UNFCCC, 2012). As the UNFCCC did not define the two concepts, the UN-REDD provided interpretation of the concepts of the terms. FRELs refer to "Gross emissions from deforestation or degradation", whereas FRLs refer to "Net emissions and removals", which thus include “enhancement of forest carbon stocks” (UN-REDD, 2015b).

Performances of REDD+ projects, i.e. reduced annual emissions, are estimated by comparing to historical average, which is called a FREL/FRL (Figure 2.3). For the historical average of a reference period, historical data is needed for about 10 years before the end-date of the reference period (FCPF, 2016), and annual emissions for a specific year is estimated by one of the methods explained in the previous section.

FREL/FRLs, which are established and submitted by tropical countries that participate in REDD+, are subject to a technical assessment (Decision 13/CP.19, UNFCCC, 2014a), and to reach the Result–Based Payments phase of REDD+, tropical countries need to improve their FREL/FRLs by adopting and incorporating better methodologies and/or data (Decision 13/CP.17, UNFCCC, 2012).

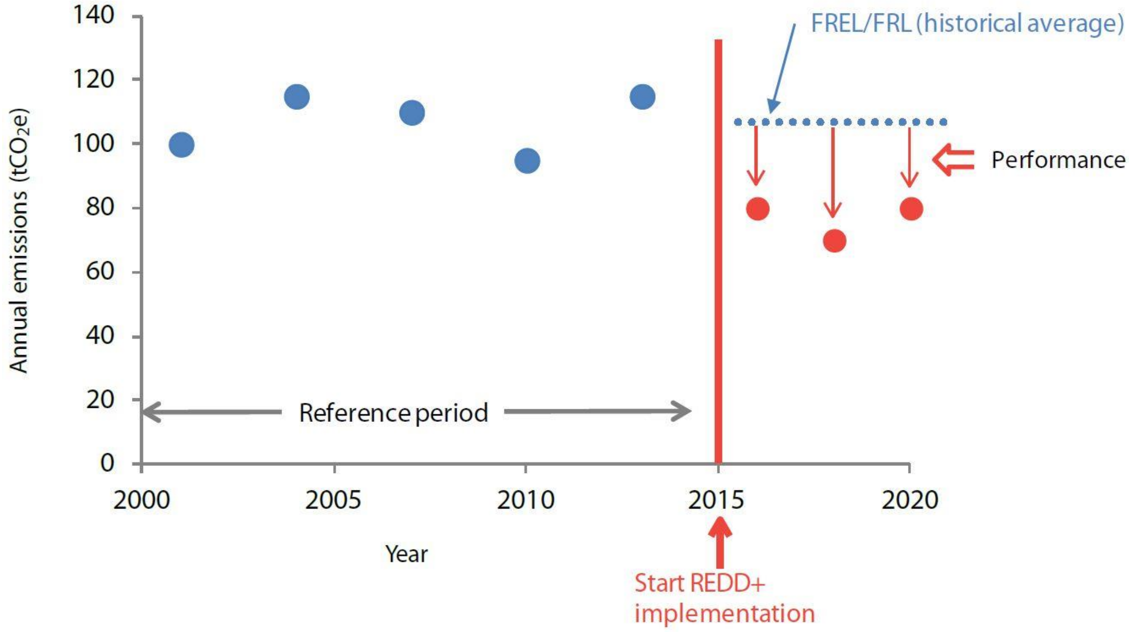

Figure 2.3 Averaged historical CO_2 emissions from forests as a FREL/FRL for national REDD+ implementation

(Source: UN-REDD, 2015a)

2.2.4 REDD+ Readiness Programmes

As most tropical countries do not have sufficient capacities for implementing REDD+, for establishing a system for Measurement, Reporting and Verification (MRV), and for other preparation activities for REDD+, implementing 'REDD+ Readiness programmes' has been encouraged by the UNFCCC.

REDD+ Readiness involves actions aimed at developing technical and institutional capacity in developing countries for implementing REDD+ (Minang et al., 2014). By Decision 1/CP.16, developed countries were encouraged to undertake "ambitious emission reductions and providing technology, capacity-building and financial resources to developing countries" for scaled-up mitigation efforts (UNFCCC, 2011).

In response to the UNFCCC decisions, two international-scale REDD+ Readiness programmes were launched to provide financial and technical support to developing countries to be ready for implementing REDD+ activities in their territories. These are the Forest Carbon Partnership Facility (FCPF) of the World Bank and the UN-REDD programme that were launched in 2007 and 2008, respectively. UN-REDD programme is a joint programme of the Food and Agriculture Organization of the United Nations (FAO), the United Nations Development Programme (UNDP) and the United Nations Environment Programme (UNEP). Of these three international organisations, FAO focusses mainly on establishing systems for Monitoring and MRV, while UNDP and UNEP focus more on REDD+ governance, payments, multiple benefits and some other elements such as engagement of indigenous peoples and local communities.

Tropical countries have been also financially and technically supported in REDD+ Readiness by other international organisations, such as the International Tropical Timber Organization (ITTO), and national aid agencies in developed countries, such as U.S., Norway, Finland, Japan and Australia, through bilateral or multilateral initiatives.

During the Readiness phase of REDD+, tropical countries are required to establish an emissions baseline for accounting carbon stocks and changes, an independent monitoring system for measuring annual activities and emissions in forests with low uncertainty, and a carbon accounting system for reporting, and for result-based payments that should be distributed to stakeholders for sustainable forest management (MoF, 2008).

This research adopts the broad definition of REDD+ Readiness programmes, and so the meaning of REDD+ Readiness programmes in this research refers to "all kinds of various REDD+ Readiness programmes implemented in tropical countries with assistance from UN-REDD, FCPF, other international organisations, or national aid agencies".

2.2.5 Discussion

This section presented background information on the REDD+ scheme, its evolution, and MRVs for that. For MRVs, it is essential to estimate forest carbon stocks and changes in accordance with the quality levels of data stipulated in the guidelines published by IPCC, using data collected by remote sensing and forest inventory. As MRVs are implemented by operating the technologies, the main features of them for forest area and growing stock monitoring are presented in the next sections.

2.3 Remote Sensing for Forest Area Monitoring

Remote sensing techniques for forest monitoring are likely to be both the only source of historical carbon emission trends and the only practical means of monitoring forest area changes over large areas, in countries in which forest surveys are not regularly conducted or in which forest monitoring systems are not established yet (Achard et al., 2007; GFOI, 2013). Optical sensors have so far been the main method used for forest area monitoring (Patenaude et al., 2005).

In this context, this section summarises the use and the accuracy of optical sensors in forest area monitoring and image interpretation methods for estimating forest area, including typical methods of remote sensing techniques such as image classification, change detection and ground truthing.

2.3.1 Optical Sensors for Forest Area Monitoring

Since the first Landsat satellite was launched on the 23rd of July in 1972, images obtained by optical sensors, which detect reflected visible and near-infrared (VIS/NIR) light from the earth surface passively, have been commonly used to measure land cover and forest area changes (Rosenqvist et al, 2003; Goetz et al., 2009), as the satellite imagery has several advantages such as the ease of change detection and update, repeatable data acquisition in addition to the utility of spectral bands (i.e. high relationships between spectral bands and vegetation parameters) in forest monitoring (Smith, 2002; Rosenqvist et al., 2003; Reams et al., 2005; Lu, 2006; Baccini et al., 2008).

Forest area monitoring methods based on optical remote sensing can be categorized by spatial (i.e. very high, high, medium and low spatial resolution), spectral and temporal resolution. However, estimates of forest area mainly depend on the spatial resolution of the sensors. In line with this, the use and the accuracy of optical sensors for forest area monitoring are categorized by spatial resolution of optical sensors.

2.3.1.1 Low spatial-resolution sensors

For monitoring land cover and forest area, optical sensors can be used in both wall-to-wall mapping, which monitors the entire area targeted, and sampling approaches (e.g. systematic sampling and stratified sampling) which focus on specific parcels of the entire area being monitored (Achard et al. 2008; Wertz-Kanounnikoff et al, 2008).

Low (≥200 m) spatial-resolution images (e.g., Terra/Aqua-MODIS, NOAA-AVHRR and SPOT-Vegetation) have been mainly used in monitoring land-cover changes at regional to continental or global scales (Achard et al., 2007), since the spatial coverage is wide but its spatial resolution is relatively low. Wynne et al. (2000) clearly reviewed the advantages and disadvantages of the AVHRR mounted on NOAA satellites for forest area monitoring in regional scale, although the study did not cover specific land-cover or forest area classification techniques. The images can be used at relatively low cost for monitoring forest area.

For monitoring local scale or partitioned forest areas, small scale forest cover changes in the areas are unlikely to be detected by low spatial-resolution satellite sensors due to the spatial resolution of the sensors. This is because the classification accuracy of low spatial-resolution images are affected by the rate of mixed pixels in the images (Lu, 2006). Although the limitations can be partly covered by certain level using image-fusion methods and algorithms developed or ancillary data, it is difficult using the low spatial-resolution image alone to estimate forest area smaller than regional scale.

Although it is difficult to estimate forest area with high accuracy by low resolution sensors alone (Morton et al., 2005), several low spatial-resolution sensors with high temporal resolution have potential to overcome the main obstacles of data acquisitions of optical sensors, such as cloud and haze cover (Baccini et al., 2008). Detecting significant forest area changes such as wildfire, logging and clearing can be limited by temporal resolution of satellite images (De Sy et al, 2012). The Moderate Resolution Imaging Spectroradiometer (MODIS) mounted on the Terra or Aqua satellite, for example, can provide images covering global scale on a near-daily basis (Morton et al., 2006; Achard et al., 2007) and thus rapid and large-scale clearing (larger than 20 ha) in forest area can be detected by low spatial-resolution sensors such as the MODIS (Morton et al., 2005; UNFCCC, 2006).

2.3.1.2 Medium spatial-resolution sensors

Medium (15-200 m) spatial resolution images have been commonly used to estimate forest variables and to detect forest cover changes at regional scale, because of the ease of image acquisition, the composition of spectral bands and the balance between spatial resolution and spatial coverage (Rosenqvist et al, 2003; Chubey et al., 2006). Amongst medium satellite sensors, Landsat 5 Thematic Mapper (TM) and 7 Enhanced Thematic Mapper Plus (ETM+), Terra-ASTER (spatial resolution: VNIR 15 m, SWIR 30 m, TIR 90 m) and SPOT-4 HRVIR (spatial resolution: B1-3 and SWIR 20 m, panchromatic 10 m) data have been frequently used to quantify and demonstrate forest area changes (Leimgruber et al., 2005; Sanchez-Azofeifa et al., 2009; Pelletier et al., 2011), in addition to Landsat 8 Operational Land Imager (OLI) launched in 2013. The extent of forest areas can be easily calculated by counting the number of pixels included in each forest area in the satellite images (McRoberts et al., 2006).

Landsat images can provide the longest time series of land cover data and can be downloaded at no cost (Leimgruber et al., 2005). In monitoring forest area using satellite images, thematic maps can be easily produced by image classification with certain level of accuracy (e.g. higher than 80 percent). Torahi and Rai (2011) showed the utility of multi-temporal Landsat TM and Terra-ASTER data in monitoring forest area and land-cover changes. However, the accuracy of land cover or forest area classification decreases as the number of classes of land cover or forest area is increased (Wynne et al., 2000; Foody, 2002). The time and effort for the classification can depend on the number of land cover classes and the extent of forest cover being monitored (Wynne et al., 2000).

It is difficult to achieve an accuracy higher than 85 percent in forest and non-forest classification with medium resolution images (Wynne et al., 2000). Although mosaicked global Landsat datasets were provided (e.g. Kim et al, 2014; Hansen et al., 2013), temporal resolution of the sensors and cloud cover are the main obstacles of medium spatial resolution sensors in making historical forest area maps.

2.3.1.3 High spatial-resolution sensors

High (≤15 m) spatial resolution sensors (e.g. IKONOS, QuickBird, worldview-1 and GeoEye-1) can detect small area changes and forest degradation in a targeted area

(Wertz-Kanounnikoff et al, 2008; Mitchard, 2016). Therefore, land-cover and forest classification errors can be reduced by the sensors since forest and nonforest areas can be distinguished by the sensors with 80-95 percent accuracy (DeFries et al., 2007).

High spatial resolution sensors can be used as a sampling tool in forest and land-cover classification or biomass estimation since the sensors can provide individual tree information in the area of interest (Wulder et al., 2004). The results of forest or land-cover classification and forest carbon stocks by using medium and/or low resolution images can be validated and verified by forest data obtained from high resolution images, since high spatial resolution images can be used as reference data in the process of accuracy assessment of land cover classification (Lu, 2006; Wertz-Kanounnikoff et al, 2008). Therefore, high spatial resolution sensors can complement the drawbacks of moderate and low spatial resolution images in forest monitoring and estimation of forest carbon stocks.

Nevertheless, the sensors still have difficulties in completely covering large areas and in producing wide area forest maps by image mosaics, since high resolution sensors have limitations in data acquisition and the size of the data. The cost of the images is still high since the majority of high spatial resolution images are obtained by commercial satellites.

2.3.2 Change Detection and Accuracy Assessment

Forest area changes can be estimated by change detection using multi-temporal images. Several methods are used, including post-classification comparison, principal component analysis and image differencing, to identify spatial distribution of forest and land-cover changes and to estimate the extent and rate of forest and land-cover areas change (Lu et al., 2004).

To use the results of forest area monitoring data derived from the satellite images, the results of thematic maps produced by image classification or change detection should be validated by accuracy assessment (Rosenqvist et al., 2003; Avitabile et al., 2011). This can be performed with ground data and/or other reference data such as finer resolution satellite images and aerial photographs (DeFries et al., 2007). Many previous studies employed error matrices in the process by which producer’s and user’s accuracy, overall accuracy and Kappa coefficient are derived (Foody, 2002; Lu et al., 2004; Torahi and Rai, 2011). Olofsson et al. (2014) gave some recommendations by his research for accuracy assessment, specifically sampling design, response design and analysis, in area estimates and classification, and presented a good example of accuracy assessment for estimating forest area changes.

However, obtaining appropriate corresponding ground datasets from forest areas to validate remote sensing data by the accuracy assessment is difficult (Foody et al, 2003). Field measurement data from field plots, which can be obtained during NFIs with high quality, may be used in forest area monitoring as reference data (Wertz-Kanounnikoff et al, 2008; Baker, 2010; Olofsson et al., 2014), and it is an efficient way using NFI data as ground reference data, after considering the size and shape of field plots and pixel size of satellite images (FAO, 2008).

2.3.3 Image Interpretation Methods

Remotely sensed images can be interpreted digitally and manually, and the interpretation methods can be conducted by computer-aided analysis and visual inspection, respectively (Foody, 2002; Hairiah et al., 2011). Manual interpretation is performed by visual delineation for land cover classification on hard copy or on a computer screen, while digital interpretation is performed by automatic or semi-automatic classification methods such as supervised and unsupervised classification. Recently, machine learning and data mining algorithms, including automatic and supervised learning methods such as decision trees algorithms, have been increasingly used by researchers for classification, regression, clustering, and anomaly detection for satellite image interpretation. Such methods, however, require expertise in statistics and computing.

Aerial photographs for forest area monitoring have been mainly analysed by visual interpretation since the late 1940s (Lu, 2006). Although the accuracy of manual-visual interpretation for forest and non-forest classification of aerial photographs, which was the standard survey method until the 1970s, is reported to be up to 95 per cent (Wynne et al., 2000), visual interpretation of satellite images, and aerial photographs, through manual digitisation of boundaries and changes in forested areas, is labour-intensive, costly and difficult to update (Lu et al., 2004; GFOI, 2013) as it relies on knowledge and experience of image interpreters. Therefore, the visual interpretation method had been expected to be replaced by digital image interpretation (Chubey et al., 2006), since computer-aided analysis has the possibility of overcoming most disadvantages of visual interpretation. Digital imagery has advantages in estimates of forest area, ease of updates and processing, and change detection of forest area using spectral features (Wynne et al., 2000), although there are some limitations in detecting selective logging and disturbance in forest areas (Lu et al., 2004).

Despite the rapid development of image classification and forest area monitoring techniques of remote sensing technology, automatic or semi-automatic image interpretation and forest area monitoring methods are not widely accepted by developing countries, and the visual interpretation method is still used by forestry departments in many countries as a principal approach in monitoring forest area (DeFries et al., 2007).

2.3.4 Accuracy Improvement using Various Sensors

Although in forest monitoring, current remote sensing techniques can be used for reducing the size of field surveys, verifying land cover changes and making forest or land-cover maps (IPCC, 2003; McRoberts and Tomppo, 2007), the accuracy of forest area monitoring using specific sensors can be limited by their inherent features such as spatial, temporal or spectral resolution. Synthetic Aperture Radar (SAR) sensors, for example, are valuable data sources for land cover classification, since the characteristics of forest area can be distinguished by the strength and the variation of Radar backscatter signatures (Fagan and DeFries, 2009). However, the accuracy of using Radar data alone in the forest and land-cover classification is lower than that of optical images (Hame et al., 2013) or the accuracy can easily depend on the effect of topography, shadows and surface moisture or texture (Rosenqvist et al, 2003).

The accuracy of forest and land-cover classification and vegetation mapping can be improved by multi-sensor data fusion since land cover and forest strata can be more accurately classified by the process. As satellite data from different sensors can be combined into one single image by image fusion techniques for the purpose of extracting more information from images, the fusion of optical data, e.g. Landsat and higher resolution satellite data, can provide higher spatial and temporal resolution. Limitations of Landsat data for forest monitoring can be partly covered by higher spatial resolution satellite data acquired by Worldview, RapidEye and SPOT (e.g. Potapov et al., 2014).

The combination of passive and active sensors can provide higher spatial resolution images by image sharpening, as spatial and spectral features of optical satellite data, e.g. Landsat data, for forest area monitoring will be enhanced by high spatial resolution SAR data. By using the combined Landsat and SAR data, forest areas covered by clouds can be monitored regularly due to the main advantage of Radar signals. Compared to using Landsat data alone, the combination of optical data can improve the frequency and accuracy of the estimates of forest carbon stocks (Lu et al., 2014), and the fusion of SAR and multispectral data showed possibility of transferability of the relationships derived from trained and tested sites (Cutler et al., 2012). It was also demonstrated that integrating Light Detection and Ranging (LiDAR) data with Radio Detection and Ranging (Radar) data and/or optical images (Montesano et al., 2013), and integrating optical images with Radar data (Vaglio Laurin et al., 2013; Joshi et al., 2016) could provide the amount of forest carbon stocks with higher accuracy, comparing to using either single active or passive sensor.

Hyperspectral sensors have also been used for the same purpose. Hyperspectral sensors with mid-infrared bands data (Patenaude et al., 2005), or hyperspectral data in combination with widely available multi-spectral and/or higher temporal resolution imagery, such as Landsat data, have possibility of improving accuracy of discriminating forest types (Fagan et al., 2015).

The combined use of passive and active sensors or image fusion methods, however, make data processing much more difficult, although vertical structure of forests and vegetation types can be more clearly identified by the fusion of satellite images such as Landsat in combination with LiDAR. Even if high accuracy and frequency of forest monitoring can be required by international bodies, using such methods may not be a practical way for tropical countries without experience in processing Radar or LiDAR data, and the fusion of optical data for obtaining higher spatial resolution data seems to be a practical alternative only for countries with high image processing ability for forest monitoring.

2.3.5 Discussion

The distribution of forest can be mapped using images collected by remote sensing. Forest areas can be monitored by various sensors with acceptable levels of accuracy (i.e. higher than 80 percent in many cases). The typical process of distinguishing forest area should be conducted with accuracy assessment in which the results of classification are validated by ground truth or high resolution images. The processes are well established, and the accuracy of forest area monitoring will be continually improved in accordance with developing image interpretation algorithms and launching new satellite sensors.

The accuracy of the estimates mainly depends on the characteristics of the sensors and the extent of forest area being monitored. Low spatial-resolution sensors have limitations in monitoring small area changes and distributed forest patches due to the spatial resolution of the sensors, although the limitations can be partly covered by certain levels using image-fusion methods, emerging algorithms and/or other ancillary data. The use of medium spatial resolution sensors has a long history in forest area monitoring. The main obstacles of medium spatial resolution sensors in making historical forest area maps are its temporal resolution and cloud cover. High resolution sensors can detect small forest area changes, and therefore images obtained by the sensors can be used as validating data in the process of accuracy assessment of land-cover classification of low or medium spatial resolution images. Yet, high resolution sensors have limitations in producing wide area forest maps by image mosaics due to data acquisition and the size of the data, and thus they cannot completely cover large forest areas yet.

Many developing countries in tropical regions have still not reached the level at which optical sensors are operationally used to monitor forest area. Forestry departments in many countries still rely on visual interpretation methods in monitoring forest areas. Therefore, in developing countries, effective use of the current technologies may be critical challenges in forest area monitoring.

2.4 Remote Sensing for Measuring Forest Carbon Stocks

Remote sensing data, obtained either by active or passive sensors or using both of them, can be used for monitoring forest biomass and carbon stocks in combination with field survey data (Myneni et al., 2001; Powell et al., 2010; Goetz and Dubayah, 2011; Harris et al., 2012; Devagiri et al., 2013; Kashaigili et al., 2013; Cartus et al., 2014; Thurner et al., 2014; Avitabile et al., 2016; Baccini et al., 2017).

As remote sensing packages for estimating forest carbon stocks can be generally distinguished by sensor types and spatial resolutions (Gleason and Im, 2011), this section summarises the use and the accuracy of current remote sensing techniques categorized by sensor types (i.e. passive and active sensors).

2.4.1 The Combination of Remote Sensing and Field Data for Estimating Forest Carbon Stocks

Forest biomass can be monitored by field sampling (both destructive and non-destructive), remote sensing and models (Lu, 2006; Herold et al., 2008), and forest biomass gathered by field surveys can be converted to the amount of carbon stocks by using specific factors (Gibbs et al., 2007; Avitabile et al., 2011; Kashaigili et al, 2013). In the process of estimating carbon stocks, measuring the amount of forest biomass, which can be derived by the calculation of forest information including species composition, age class and tree density, is thought to be the most important indicator (Turner et al, 2004; Lu, 2006; Vicharnakorn et al, 2014). To estimate forest carbon stocks and emissions in detail, both land use activity data and forest carbon factors (i.e., forest area change data and forest carbon density data, respectively) are needed to estimate carbon stock changes in the forest (IPCC, 2006; Holmgren, 2008; Wertz-Kanounnikoff et al, 2008; Herold, 2009; UN-REDD, 2011a; GFOI, 2016).

Field-based measurements are the most reliable and accurate data source in estimating forest carbon stocks (Lu, 2006; UNFCCC, 2006; Stephens et al, 2012) and they can provide emission factors. However, field-based measurements cannot provide land cover change data due to the factor that most of field plots are normally allocated inside forests in order to obtain forest data (Asner et al, 2010). Thus, although forest inventory data measured from field plots can provide reliable and precise biomass data of the specific sites, the accuracy of estimated biomass of a large area will be lower when the data apply to a wide area by scale-up or extrapolation (Gibbs et al., 2007; Baccini et al., 2008).

To complement field-based measurements, remote sensing techniques conducting by satellite or aircraft can be used for both detecting changes in forest area and forest above ground biomass, which is key element in estimating forest carbon stocks (IPCC, 2003; Gibbs et al., 2007). The combination of remote sensing data and field survey data can help to estimate forest carbon stocks and to detect forest area changes (DeFries et al, 2007; UNFCCC, 2010b; Mora et al., 2012; Mitchard et al., 2013).

2.4.2 Optical Remote Sensing Sensors

The choice of remote sensing sensors for carbon stock estimation depends on extent of a targeted area covered by imagery (i.e., global, continental, national, regional, landscape, stand and individual tree levels), attributes of the area of interest (e.g. species composition, age of forests and topography) and estimation methods combined (e.g. statistical models) (IPCC, 2003; Hairiah et al., 2011). In estimating forest carbon stocks and changes, optical sensors, such as MODIS, Landsat 5 Thematic Mapper (TM) and 7 Enhanced Thematic Mapper Plus (ETM+), IKONOS, have also been widely used.

2.4.2.1 Low spatial resolution sensors

Lu, (2006), DeFries et al. (2007) and Mitchard et al. (2013; 2014) mentioned that remote sensing cannot estimate forest carbon stocks over wide areas such as national or continental level. However, although it depends on the extent and attributes of targeted area, sensors and methods used and the accuracy of analysis, forest carbon stocks have been measured by direct or indirect remote sensing methods, mostly in combination with field measurement data (Rosenqvist et al, 2003; Gibbs et al., 2007). Although it is difficult to estimate carbon stock changes with high accuracy by low resolution sensors alone (Morton et al., 2005), estimating forest carbon stocks over large areas with acceptable level of accuracy can be achieved by using the low resolution data complemented by ancillary data, such as climate and topographic information, and statistical models (Baccini et al., 2004).

Some previous studies using low spatial-resolution image, mainly MODIS images, used vegetation indices and spectral bands data (i.e. visible red and infrared bands) from the image and field data in order to estimate forest carbon stocks over a wide area. It is because the forest distribution data obtained by field data can be expanded by Normalized Difference Vegetation Index (NDVI) derived from the MODIS image by means of the relationship derived from locally calibrated regressions (Maselli, 2011). Devagiri et al. (2013) estimated forest carbon stocks and vegetation carbon pool at regional scale in India by using vegetation indices and spectral bands data from the MODIS image in combination with field data. The study derived a regression equation between AGB data obtained by field measurements and vegetation indices (i.e. NDVI) and spectral bands data derived from each pixel of the multi-temporal MODIS images to estimate forest carbon stocks. Le Maire et al. (2011) employed NDVI value from the MODIS time series images to improve the accuracy of forest biomass estimates on Eucalyptus plantation.

Nevertheless, it is limited to use the image alone in estimation of carbon stocks, as the mixed pixels in the image reduce the accuracy of classification and matching field data to the pixels of the image is difficult (Lu, 2006; Le Maire et al., 2011). A range of research employed low resolution images to estimate forest carbon stocks over large areas including pan-tropical areas, but the research is normally conducted in combination with higher spatial resolution optical image or Lidar data. Baccini et al. (2008) mapped AGB of tropical Africa at 1 km resolution by using pixel mosaic data of MODIS in combination with field and Lidar measurements. Spectral band data from the MODIS imagery was applied by Random Forest Model in order to predict the amount of AGB in entire area based on field data.

2.4.2.2 Moderate spatial resolution sensors

Using Landsat images, forest carbon stock over large areas can be estimated by radiometric relationships and extrapolating based on the ground data with certain level of accuracy (Foody et al., 2003; Labrecque et al., 2006).

Kashaigili et al. (2013) estimated above-ground carbon stocks in forest reserves in Tanzania. The study used multi-temporal Landsat images in combination with field plot data from forest inventory to analyse carbon stocks and changes in GIS environment. Such methods rely on the relationships between the data from field surveys and remote sensing image (e.g., specific visible and/or near-infrared bands, canopy parameters and vegetation indices) (Rosenqvist et al, 2003; Hame et al., 2013), since the relationships between field-based measurement data and spectral bands data derived from remote sensing image including vegetation indices can be assumed by empirical and statistical regression models (Dong et al. 2003).

The majority of previous studies have employed several regression approaches such as K nearest-neighbour, neural network and multiple regression analysis to identify the relationships (Foody et al., 2003; Lu, 2006). Vicharnakorn et al (2014) demonstrated strong relationships between above-ground biomass (AGB), estimated by field measurements in various types of land cover, and the spectral bands and vegetation indices of Landsat Thematic Mapper (TM) data. Field measurement data was converted into forest biomass by allometric equations, and multiple linear regression analysis was used to identify the relationships between total carbon stocks from each vegetation class and Landsat TM data.

McRoberts and Tomppo (2007) reviewed the use of remote sensing data with k-nearest neighbor (k-NN) technique in the process of NFI to estimate AGB in Finland and Sweden. The method can improve the accuracy of estimating AGB and reduce the costs of forest resource monitoring. However, the accuracy and performance of carbon stock estimates is limited (Brewer et al., 2011), since the assumed relationships between spectral bands and/or vegetation indices of the sensors and the magnitude of AGB in forest may not be adequate to determine forest carbon stocks (Goetz and Dubayah, 2011). Furthermore, the derived relationships between field measurement data and spectral band data, and the algorithms used to estimate carbon density for a specific site, cannot be applied to other areas, as the difference of forest composition and structure amongst the sites will decrease the accuracy of the estimates (Foody et al., 2003; IPCC, 2003; Lu, 2006).

2.4.2.3 High spatial resolution sensors

Using high or very high spatial resolution images to extract detailed forest information or individual tree parameters by image texture measures or object-based analysis, and considering various spectral bands can improve the accuracy of the estimation of carbon stock changes and emission (Wulder et al., 2004; Lu, 2006; Asner et al, 2010).

Much research on the use of high resolution image for forest condition and change has been focused on the possibility of obtaining data on tree diameter, height, crown size and density (Gomez et al., 2012). Forest data extracted from the image can be converted into forest biomass by statistical methods, such as allometric equations and linear regression. To extract forest parameters precisely, numerous studies have been conducted to examine the methods that can improve the accuracy of extracting individual forest information from high resolution image.

Gomez et al. (2012) tested the capacity of extracting individual tree information from high spatial resolution images. The study employed the statistical method, Classification and Regression Tree Analysis (CART: decision tree data analysis), to model forest attributes such as tree density and diameter, using multispectral and panchromatic imagery from Quick-Bird-2. Wulder et al. (2004) presented the use and process of high spatial resolution remote sensing data for monitoring forest ecosystems, which includes forest structures and distribution of biomass, with the examples of species classification and tree-crown isolation. Pouliot et al. (2002) showed the technical approach of tree crown detection in high resolution digital imagery. Chubey et al. (2006) presented the object-based analysis method, which can derive forest parameters by image segmentation, to extract tree crown closure and species composition from Ikonos-2 imagery.

Although high resolution images can play an important role in estimating forest carbon stocks, image interpretation in large areas is very demanding due to the size of data, shortage of analysis skill and the shadows of trees (Rosenqvist et al, 2003; Lu, 2006; Vicharnakorn et al, 2014). It is difficult to apply high resolution images to estimate forest carbon stocks over extensive areas because of the limitation of spatial coverage of the sensors.

2.4.3 Active Remote Sensing Sensors

Active sensors, such as Synthetic Aperture Radar (SAR) and Laser sensors (e.g. LiDAR: Light Detection and Ranging), have also been widely used in monitoring land cover changes and accounting carbon storage since the sensors have unique advantages. Radar sensors can overcome the constraints (e.g. light conditions, moderate precipitation, cloud cover and haze) of image acquisition conditions of optical sensors (Patenaude et al., 2005; Fagan and DeFries, 2009; Sanchez-Azofeifa et al., 2009) although the image acquisition could be affected by ground conditions and surface topography (Rosenqvist et al, 2003; Lu, 2006; Gibbs et al., 2007), and LiDAR can provide detailed vertical structure and canopy information of forest or individual tree in three-dimensions (Naesset, et al., 2004; Li et al., 2008; Goetz et al., 2009). The use and the accuracy of active sensors for estimating forest carbon stocks are discussed in the following sections.

2.4.3.1 Radio Detection and Ranging

Radar sensors, such as ERS-1/2 (C-band, launched in 1991, 1995), RADARSAT-2 (C-band, 2006), ENVISAT/ASAR (C-band, 2002), TerraSAR-X (X-band, 2007) and ALOS/PALSAR (L-band, 2006), transmit microwave energy, which can penetrate through cloud and forest canopies, to the earth's surface, and the signals of the radar sensor, including X (wavelength of ~3.8 cm), C (wavelength of ~5.5 cm), L (~23.5 cm) and P (~68 cm) bands (Rosenqvist et al, 2003), has strong relationships with forest attributes and vertical structure (i.e. Height, DBH and AGB of trees or individual tree) (Ranson et al., 1997; Turner et al, 2004; Lu, 2006; McRoberts and Tomppo, 2007; Goetz et al., 2009; Mitchard et al., 2011). Thus, forest carbon stocks can be directly quantified by the linear relationships between AGB and the amount of radar return signals or indirectly converted from tree height, derived from the radar signals reflected from tree canopies or trunks and the ground, using allometric equations (IPCC, 2003; Rosenqvist et al, 2003; Gibbs et al., 2007; Goetz et al., 2009). Hame et al. (2013) estimated forest biomass in central Laos using ALOS PALSAR L-band data, which can penetrate into forest canopy cover (i.e., the leaves of trees) and interact larger branches and stems of trees, in combination with ground plot data. Mitchard et al. (2011) used JERS-1 and ALOS PALSAR L-band to detect forest expansion and loss in a savanna region of Africa.

Even so, early studies (Luckman et al., 1997; 1998) of estimating of forest carbon stocks using SAR showed the range of saturation of SAR data. Radar bands are sensitive to forest biomass, but they are more sensitive in lower biomass ranges in estimation of forest carbon stocks, although the saturation levels vary amongst the bands of the sensor (e.g., C-band : 20–30 Mg/ha, L-band : 60–100 Mg/ha and P-band less than 150 Mg/ha; Ranson et al., 1997; Rosenqvist et al, 2003) and optical sensors tend to fully saturate at much lower levels (Turner et al, 2004; Saatchi et al., 2007; Goetz and Dubayah, 2011; Mitchard et al., 2011). Using longer wavelength microwaves (e.g., VHF-band of airborne SAR) have potential to overcome the limitation of the saturation levels of Radar sensor in estimating forest carbon stocks (Rosenqvist et al, 2003). Patenaude et al. (2005) explained the potential and limitations of the radar sensors in monitoring vegetation structure and forest carbon stocks. The use of SAR, and LiDAR, data for monitoring forest degradation for REDD+ MRVs is reviewed by Mitchell et al. (2017), who also include explanations for remote sensing approaches for monitoring changes in quantification of forest carbon stocks, AGB, and canopy height and gaps. The accuracy of using radar data in estimating forest carbon stocks tend to be determined by the effect of topography, shadows and surface moisture or texture (Rosenqvist et al, 2003).

High expertise is needed to analyse the radar images (Wertz-Kanounnikoff et al, 2008), and the collection of extensive field measurement data will be required to estimate forest carbon stocks using radar data, as the estimation process is conducted by deriving the relationships between forest parameters and radar data (Ranson et al., 1997).

2.4.3.2 Light Detection and Ranging

Light detection and ranging (LiDAR; e.g., airborne LiDAR, and spaceborne LiDAR such as the Geoscience Laser Altimeter System mounted on NASA’s Ice, Cloud, and land Elevation Satellite (ICESat/GLAS), which was launched in 2003), which measures the return time of laser pulses emitted, has higher potential than other sensors in provision of high accuracy forest data, including tree height, stem volume and vertical structure of forest, in measurements of forest carbon stocks (Lim et al., 2003; Turner et al., 2004; Wulder et al., 2004; Lu, 2006; Wertz-Kanounnikoff et al., 2008; Goetz and Dubayah, 2011; Hayashi et al., 2014; GOFC-GOLD, 2017; Malhi et al., 2018). Estimation of forest carbon stocks using LiDAR data mainly relies on allometric models which can derive the relationships between forest biomass and forest parameters obtained by field measurements or Lidar scanning (McRoberts and Tomppo, 2007; Goetz and Dubayah, 2011), and the approach allows to achieve higher levels of accuracy in estimation of forest carbon stocks (Rosenqvist et al, 2003; Li et al., 2008).

Stephens et al (2012) indicated that LiDAR inventory, which is a combination of field survey and LiDAR in estimating carbon stocks, can achieve similar precision in comparison to field survey. The integration of forest data from field survey and Lidar scanning by using regression in carbon stock estimate was expected to improve accuracy and reduce costs, since the method, LiDAR inventory, can reduce the number of ground plots which should be surveyed to satisfy a specific level of precision

(Stephens et al, 2012). Asner et al. (2010) reported that the correlation between LiDAR sampling and field-based carbon measurement was 92 percent.

For estimating carbon storage over wide areas, LiDAR sensors are mostly used in combination with medium or low optical sensors and/or ancillary data such as topographic and climate maps because of the spatial coverage of the sensor. Asner et al. (2014) used airborne LiDAR data integrated with field plot information and high-resolution satellite image to make a high-resolution carbon map in Peru. The study employed environmental factors as ancillary data. Asner et al. (2014) reported that the combination of climate and topographic data and sampling survey by airborne LiDAR can reduce forest monitoring costs and improve the accuracy.

Some previous research showed the use of LiDAR data combined with hyperspectral or multi-temporal data. Vaglio Laurin et al. (2014) estimated forest biomass in a forest of the Gola Rainforest National Park (GRNP) using height metrics from small footprint airborne LiDAR in combination with airborne hyperspectral data from which canopy information can be derived using its 244 bands. Asner et al. (2010) used a new estimating method which integrates multi-scale and multi-temporal data from satellite image, airborne LiDAR and field plots to estimate carbon density and emissions in the Amazon region. It showed that the method could map aboveground forest carbon stocks and changes at 0.1 ha spatial resolution.

Other studies showed the usefulness of spaceborne LiDAR data for estimating forest carbon stocks over wide areas with limited field data (e.g.; Baccini et al., 2008; Saatch et al. 2011; Baccini et al., 2012; Tyukavina et al. 2015). Baccini et al. (2012) employed satellite-based LiDAR data in combination with field measurement information to generate aboveground carbon density maps of pan-tropical scale with 500 m spatial resolution. The GLAS LiDAR data applied to the MODIS image to expand estimated carbon density data. Chi et al. (2015) also used the ICESat/Geoscience Laser Altimeter System (GLAS) data in combination with the MODIS and field inventory data to estimate AGB in China. The study areas for estimating forest carbon stocks were wider than national scale, as calibrated spaceborne LiDAR data using limited field data can be expanded by using machine learning techniques such as Random Forest or Maximum Entropy Modeling. It was demonstrated that spaceborne LiDAR data can provide forest height data with greater accuracy, and forest canopy height data can be converted into above ground biomass using allometric equations such as Lorey’s mean height and Weighted mean height. Processing LiDAR data is more difficult than that of optical data although spaceborne LiDAR seems more practical than airborne LiDAR system in terms of data acquisition, as forest structure data with high accuracy can be obtained without operating aerial survey systems. Collecting field data in tropical regions is difficult, but by using spaceborne LiDAR data, the number of field plots for collecting field data can be extremely reduced. Previous research using spaceborne LiDAR mainly exploited the ICESat/GLAS data for their studies, but the ICESat satellite collected the Earth's surface data only between 2003 and 2010, and next mission for the successor of the GLAS is planned to be launched in 2018.

LiDAR is the technology with the greatest potential to improve forest monitoring practice as it can provide detailed information on tree height and canopies (Li et al., 2008). Nevertheless, there are limitations in operating LiDAR surveys over large areas, and the cost of operating LiDAR systems in a large area is still high because of its spatial coverage (Lu, 2006; Asner et al, 2010). LiDAR can be also affected by weather conditions such as cloud cover and heavy rains (Goetz et al., 2009). Moreover, the accuracy of measuring forest parameters and forest biomass may depend on the footprint scale of the sensor and topographical environment of targeted areas (McRoberts and Tomppo, 2007; Goetz and Dubayah, 2011), and LiDAR system still has a limitation in discriminating tree species (Rosenqvist et al, 2003).

2.4.4 Discussion

Although no perfect method for measuring forest carbon stocks and changes using remote sensing has been identified yet, remote sensing techniques, mostly in combination with national forest inventories, have high potential to estimate the amount of Above Ground Biomass (AGB) in forests with high accuracy, which can be used to predict other carbon pools such as dead wood, litter and belowground biomass (Goetz and Dubayah, 2011; Vicharnakorn et al, 2014), and carbon stock changes caused by continuing forest's growth, reforestation and deforestation (IPCC, 2003; Asner, 2009).

In the case of optical images, forest carbon stocks can be monitored by analyzing spectral reflectance and/or extracting forest and/or individual tree information (i.e., forest density and crown diameter) of remote sensing image (Baccini et al., 2004; Gibbs et al., 2007), since forest biomass and carbon stocks can be predicted by spectral response of remotely sensed data with ground data (Brewer et al., 2011) and can be inferred from individual tree parameters and forest attributes by using allometric relationships (Gibbs et al., 2007). To improve the accuracy of analysis, climate and topographic information, such as elevation, aspect, slope, soil type, precipitation and land-use history, has been used as ancillary data or variables which are used in regression analysis (Baccini et al., 2004; Lu, 2006; Gibbs et al., 2007; Asner et al., 2014).

Using active sensors, forest carbon stocks can be directly quantified by radar sensors or indirectly converted from tree height, since radar signals have strong relationships with forest attributes and vertical structure. The main limitations of radar sensors in estimating forest carbon stocks are the saturation levels of the sensor and topography, shadows, moisture and texture of the earth surface, and high expertise is needed to analyse radar data. LiDAR is a very attractive technology and is mostly used in combination with medium or low optical sensors and/or ancillary data due to the spatial coverage of the sensor. Its spatial coverage and operating cost are the main limitations, and it can be also affected by weather conditions.

Currently, many satellite sensors are operating and many more will be launched, and each sensor has its specific advantages and disadvantages in forest carbon stock monitoring. Yet even scientific methods for forest carbon stocks monitoring which were developed by previous research are not widely used in operational forest monitoring in many developing countries due to various obstacles, e.g. image analysis capacity, technical infrastructure and accessibility to remote sensing data (DeFries et al., 2007). In some countries, it is difficult to operationally use even simple scientific remote sensing methods for estimating forest carbon stocks and changes.

2.5 National Forest Inventories

Although remote sensing techniques can be used to obtain a range of forest information, National Forest inventory (NFI) is still essential to provide reliable information on forest attributes and timber stocks to support forest management. This can be upgraded to estimate forest carbon stocks and changes in these. In the following sections, the use and importance of NFI data, the general practice of NFIs, including forest stratification, plot array and prescribed field measurements, and the intensity of NFIs in different countries will be discussed in detail.

2.5.1 The Use and Importance of National Forest Inventories

The forest information obtained by NFI, which reports and assesses current forest variables in a country, can be used for managing forest land, decision-making in government policy and forest industry, and planning or conducting environmental projects (Tomppo, 2000; McRoberts et al., 2006; McRoberts and Tomppo, 2007; FAO, 2008; Gomez et al., 2012;).

Since the early 1920s, when the first forest inventory was conducted in Finland, forest inventories were focused on the estimation of timber resources (Tomppo et al., 2008; Tomppo et al., 2010). However, current NFIs in the majority of developed countries measure ground vegetation, tree growth, deadwood, biodiversity features, forest condition and structure as well as soil information, as the needs of forest information and the purpose of NFIs have been becoming more diverse and wider (FAO, 2008; McRoberts et al., 2010; Tomppo et al., 2010; FAO, 2012).

Forest inventory data can be converted to the amount of AGB by using several regression models developed, since the AGB of a tree is determined by its stem diameter (i.e. Diameter at Breast Height: DBH), height and wood specific gravity (Chave et al., 2005). Therefore, it can be used to account for forest carbon stocks and changes in these (Maniatis and Mollicone, 2010; Avitabile et al., 2011), as the estimation of forest carbon stocks and changes for international forest conservation projects is becoming more important.

In the remote sensing data analysis for forest monitoring, NFI field survey data can be used as training data in the initial process of the land use and/or forest type classification, and as verification data of the accuracy of classification (Baker, 2010; Maniatis and Mollicone, 2010). Therefore, conducting field surveys in the process of NFIs is unlikely to be completely replaced by remote sensing techniques in the near future (McRoberts and Tomppo, 2007).

2.5.2 General Practice of National Forest Inventories

The practice of NFIs have been changing and evolving continuously (Tomppo et al., 2010). Herold et al. (2008) mentioned that there are great differences amongst countries in regard to quality of results, standards of procedure or protocols, and definitions of terms in NFIs. The definitions of terms which are used in NFIs (e.g. definition of forest and standards of growing stock volume) vary from country to country (Tomppo et al., 2010). However, the general practice of NFIs in the countries conducting NFI on a regular basis is performed with typical process due to the basic purposes and principles of the NFIs. There are only subtle differences in the process of sampling design (i.e. configuration and shape of plots) and classification and stratification in addition to principal forest variables to be measured.

The Food and Agriculture Organization of the United Nations (FAO) provides manuals and guidelines, which include procedures and methods for collecting forest data by field measurements and observations, for countries (FAO, 2012), and the U.S. Forest Service standardized procedure and analytical techniques, including measurement protocols, variables estimation, plot configuration, sampling design, formulae and reporting standards, for conducting the Forest Inventory and Analysis (FIA) programme (McRoberts, 2005; Tomppo et al., 2010). The procedure consists of three phases: producing stratifications of land area, measuring the forest variables in permanent ground plots by field crews, and measuring additional variables for identifying forest health (McRoberts, 2005).

To satisfy the trade-off between efficiency and accuracy of NFIs, majority of NFIs are mainly conducted by following procedures: sampling design, land-cover/land-use classification and forest stratification and field measurements, as variables to be measured, technical capacity and methods and the accuracy and standard error level are being considered (FAO, 2008; 2012). These processes are discussed in the following sections in detail.

2.5.2.1 Sampling design

In modern NFIs in Europe and North America and some East Asian countries, sample-based estimates are employed to measure forest variables by nearly all countries conducting NFI in order in order to save time and lavour of field surveys and to overcome financial constraints for forest measurements (McRoberts and Tomppo, 2007; McRoberts et al., 2010). Permanent sample plots, in which localized forest information for estimating forest carbon stocks can be effectively obtained, are also adopted by many countries because of the ease of re-measurement and obtaining of changing trend data of individual tree and forest (Tomppo, 2000).

Sampling designs consist of the selections of the shape, size and types of field plots/clusters (including the number of the plots in each cluster) and sampling density (including the distances between plots in each cluster and between clusters). In many cases, the processes are conducted with digital data such as land-use/land-cover maps derived from satellite image (FAO, 2008). Majority of countries conducting NFIs employed statistical sampling methods to improve reliability and efficiency of NFI and to estimate sampling errors (Tomppo et al., 2010). Tomppo and Katila (2008) compared different designs in sampling densities in terms of the error estimates in forest parameters and time, costs and distances of field surveys.

Probability-based sampling designs and systematic sampling components based on two-dimensional grids are employed by many countries (Tomppo et al., 2010). In many cases of the plot configuration, sampling plots are randomly or systematically assigned on regularly spaced grids overlaid aerial photograph, project maps or satellite image (Pearson et al 2005; Scott et al., 2005; Asner et al, 2010). In the case of the USA, for example, field plots for the Forest Inventory and Analysis (FIA) programme are randomly distributed within hexagonal array to generate equal-probability samples in the process of sampling design (McRoberts et al., 2006). In that case, sufficient number of plots should be assigned in each stratum (e.g. four or five plots in a stratum) to achieve reliable estimation or certain level of precision by reducing sampling error, and sufficient number of plots can be achieved by combining adjacent similar strata when a stratum does not contain sufficient number of plots (Pearson et al 2005; Scott et al., 2005; McRoberts et al., 2006). In addition, the center of each plot should be linked with the pixel or the grid associated to precisely assign plots to a specific stratum and to accurately collect field data (Scott et al., 2005; McRoberts et al., 2006; McRoberts et al., 2010).

The shape (e.g. size of plots, circular or rectangular plots) and types (e.g. single or cluster plots, permanent or temporary plots) of the sample plots vary and can depend on variables to be measured, desired precision or forest structure (Pearson et al 2005; McRoberts and Tomppo, 2007; Tomppo et al, 2008; Tomppo et al., 2010). However, many countries commonly use similar plot shape and types for their NFIs (Tomppo et al., 2010; Brewer et al., 2011).

In many cases, the shapes are square, circular or rectangular plots, and assigned plots for NFIs are clusters of four circular plots which consist of several sub-units (Bechtold and Scott, 2005; Pearson et al 2005). Clustered plots are the most cost-efficient amongst plot types and suitable to measure diameters or diameter changes of trees (Pearson et al 2005), and each cluster of four plots can be measured by field crews within a day (Bechtold and Scott, 2005). More than 90 percent of countries conducting their NFI regularly employed circular plots, and concentric circular plots, in which different sizes of variables can be measured from plots of different scales with certain precision, are also adopted by majority of the countries (McRoberts et al., 2010; Tomppo et al., 2010). FAO (2012) suggested 1 km x 1 km square sampling units and 20 m wide and 250 m long rectangle plots which consist of three sets of subplots.

2.5.2.2 Land-use/land-cover classification and forest stratification

Since 1989, Finland have been utilising the multi-source National Forest Inventory, which is using data obtained from satellite image and digital maps with field survey data, in order to reduce NFI costs and to improve NFI efficiency (Tomppo et al, 2008). The efficiency and accuracy of NFIs can be enhanced by using remote sensing data including satellite imagery and aerial photography (McRoberts et al., 2010), since the distribution and extent information on forest areas can be obtained by the data (Smith, 2002). Therefore, land-use/land-cover classification and forest/non-forest stratification become common methods for NFIs (Reams et al., 2005).

Stratification in the process of NFIs is a statistical method and produces homogenous strata (e.g. forest and non-forest or more detailed classes distinguished by species group, density of trees and age classes of forest areas) by segmenting an area targeted. By using the method, the precision of the estimation of forest variables (e.g. extent of forest areas and volume of trees in unit areas) can be increased, and estimation variables which should be measured can be reduced, even if sample sizes are not expanded (Scott et al., 2005; McRoberts et al., 2006; McRoberts et al., 2010). McRoberts et al. (2006) reviewed the stratification approach using satellite image of the US Forest Service for implementing the Forest Inventory and Analysis (FIA) program. Maniatis and Mollicone, (2010) proposed a stratification method to fulfil the REDD+ requirements by conducting NFIs.

In land-use/land-cover classification or forest stratification phase for the NFIs, remote sensing data, including satellites images and aerial photographs, is used as principal data in order to distinguish forest and non-forest, to improve the accuracy of the surveys, or to support the field measurements (Mandallaz, 2008). The land-use/land-cover classification maps can also be useful in sampling design of the countries which do not have enough available data for planning NFIs (FAO, 2008). Previous inventory data and/or thematic maps can also be used to identify forest area or land-use changes, which affect the determination of plots to be surveyed or not to be surveyed, or to compare forest growth or removals occurred after last NFIs. Digital maps, ecological data and elevation data are used in the classification of forest land and other land-cover classes in order to improve the accuracy of classification or to calibrate topographic effects of satellite image (Reams et al., 2005; Tomppo et al, 2008).

2.5.2.3 Field measurements

Forest resource information for NFIs, such as growth of trees (species, DBH and height), characteristics of stands (removals, deadwood, forest health and biological diversity) and soil information in addition to land information (i.e. area of forest cover, land-use and land-cover, ownership) and management activities, has normally been obtained from sample plots including temporary plots and permanent plots (Tomppo, 2000; McRoberts and Tomppo, 2007; Tomppo et al, 2008; USDA Forest Service, 2012). The Forest Inventory and Analysis (FIA) program of the US Forest Service additionally measured understory vegetation structure, soil information and tree-crown layer to analyse forest health in the FIA phase 3 (Reams et al., 2005). The data can be mainly obtained by field measurements, observations and interviews, and the location of field measurements should be documented by using a global positioning system (GPS) or by manual digitisation (FAO, 2012).

The number of variables collected by NFIs varies amongst countries and data collection levels (FAO, 2012). Tomppo et al, (2008) mentioned that forest data on about 200 variables from each plot is collected by field measurements of NFIs, and European countries measure roughly 100–400 variables during field survey of NFIs (McRoberts and Tomppo, 2007). Finland measured approximately 150 variables during the NFI8 (Tomppo, 2000). The forest variables can be measured at either tally tree level (e.g. crown assessment and species groups) or sample tree level (e.g. age and height of trees, and diameters of individual tree) (Tomppo, 2000).

The extent of forest land and other land-use/land-cover classes, height and ages of trees in addition to species composition are the most important variables to be measured (FAO, 2008; Tomppo et al, 2008) to estimate forest carbon stocks and changes, as AGB and changes can be derived by the information (i.e. estimating changes of areas and volumes by tree species). Volume increment by tree species can be generally estimated by measuring increased individual tree volumes and/or trees reached specific DBH level from permanent plots, and removals or losses of tress can be estimated by measuring stumps and/or dead trees (i.e. cleared by human or naturally died) since the last field survey (Tomppo et al, 2010).

2.5.3 Intensity and Frequency of National Forest Inventories

The accuracy or quality of NFIs, including historical data, can depend on the intensity of forest survey and the methods employed, and the accuracy of forest carbon stock estimation, and the uncertainty of evaluation of carbon stock estimation depend on the number of field measurement conducted or the frequency of field data collection (Lu, 2006; UNFCCC, 2006; Baccini et al., 2008). The intensity of NFIs includes intervals of field survey (i.e. the cycle of field measurements and report), the area covered by each plot (i.e. plot densities) and prescribed requirements of NFIs. In the case of Finland, for example, approximately half a million tallied trees in 70,000 field plots were measured during the 8^{th} NFI (Tomppo, 2000).

The cycle and prescribed requirements of NFI is different from country to country due to specific county circumstances, financial matters and techniques applied. The intervals of field-based measurements to obtain forest data are generally limited by the circumstances of countries (Houghton, 2005). Conducting and/or repeating field measurements over large areas is a labour and time-consuming work (Baccini et al., 2004; Houghton, 2005; Korhonen et al. 2006; Lu, 2006; Gibbs et al., 2007). The USDA Forest Service, for example, collect forest data annually in each state and report their NFI nationally every five years (Smith, 2002; McRoberts, 2005), since the periodic monitoring (mostly five year cycle) enables improving biodiversity conservation and sustainable land management (FAO, 2012).

However, the frequency in other developed countries does not match this, and repeating and conducting type of field surveys of NFIs varies amongst countries. Estonia, France, Italy, China, Norway and South Korea conduct their NFIs every 5 years, whereas Czech Republic, Denmark, Germany, Canada, Hungary, Latvia, Netherlands, Spain conduct their NFI on a 10 year cycle (Tomppo et al., 2010; Mirck and Mabee, 2013; Alvarez-Gonzalez et al., 2014). Sweden, for example, conducted their NFI every 10 year, but the cycle was changed to 5 year intervals since 2000 (Axelsson et al., 2010), and Belgium conducts their NFI on a 5 year basis for half of the entire plots. The other half of the plots is measured on a 15 year basis (Rondeux et al., 2010).

Some developed countries use annual or rolling inventories, which are conducted by the majority of countries, measure 10-20 percent of plots every year and next their NFIs begin when all plots are completely measured, while other countries use periodic inventories, which are conducted by some countries, complete their NFI within 1-4 years (depending on financial conditions and/or human resources, the area of forests and the number of sampling plots of countries) and start it again after several years (Wynne et al., 2000; McRoberts, 2005; Tomppo et al., 2010; McRoberts et al., 2010). Nevertheless, some countries, repeating their NFI every specific period, do not map AGB with spatial data (Houghton and Goetz, 2008).

The frequency of NFIs in developing countries is much lower than that of developed countries, although Mexico and Myanmar conduct their NFI on a 5 year cycle. In the case of Brazil, the first forest inventory was conducted in the 1980s to collect data of timber supply, and this inventory was the only NFI conducted in Brazil until the Brazilian Forest Service (BFS) was established in 2006 to design and conduct their NFI again (Freitas et al., 2006; UNFCCC, 2006; Freitas et al, 2010). Field measurements were conducted as a part of the NFI between 2007 and 2011, but the whole country was not covered (McRoberts et al., 2010). Indonesia conducted their forest inventory between 1990 and 1994, which updated between 1996 and 2000, and Thailand conducted their NFI just once between 1992 and 1996 (Hardcastle et al., 2008).

To estimate forest carbon stocks and changes with certain reliability, the national forest monitoring system in each country should measure five carbon pools (i.e. aboveground biomass, belowground biomass, dead wood, litter and soil organic matter) as described in the IPCC guidelines (IPCC, 2003). It is the most efficient way of reducing the costs and labour of field surveys to collect the carbon pools data during NFIs to estimate forest carbon stocks. However, the estimates of forest carbon stocks for Forest Resources Assessments (FRA) of FAO, which were based on data from NFIs, showed that estimates for more than half of countries in tropical region have significant uncertainty, since their forest inventory data used to estimate forest carbon stocks are based on insufficient sampling or not actual field measurements at national scales

(UNFCCC, 2006; Gibbs et al., 2007). Reports from Equatorial Guinea, Gabon and Ghana were based on one or two reports produced by FAO or external agencies (Hardcastle et al., 2008). About 20 percent of countries in tropical region did not submit forest carbon stock data of their countries to FAO for compiling Forest Resources Assessments 2005 (FRA), due to lack of detailed forest information (Grainger, 2010). In Africa, for example, countries hardly have their NFIs, and even though they have NFIs, majority of them are outdated and/or obsolete (Baccini et al., 2008; Avitabile et al., 2011). Cameroon and Republic of the Congo have conducted forest inventory once only, and Venezuela, Sierra Leone, Liberia, Guyana, Cambodia and Democratic Republic of Congo have little or no national forest inventory capacity due to lack of human resources and monitoring technology for the NFIs (Hardcastle et al., 2008).

Conducting NFIs is costly and not easy to update due to the extent of forest areas and the number of variables to be measured (Pouliot et al., 2002; Brewer et al., 2011; Gomez et al. 2012). As the intensity and the scope of NFIs increase, the costs and labour of NFIs will also increase. However, some countries proposed conducting midcycle updates or reducing cycle lengths to respond to increasing demands of NFI data by improving sampling intensity (McRoberts, 2005).

2.5.4 Discussion

Forest information from the NFIs is becoming more important for forest policy and forest conservation projects in both national and international scales. There are common practices and protocols for conducting NFIs which can reduce time and cost and improve efficiency, and international organizations such as FAO provide manuals for NFIs and support developing countries to improve their NFI capacity.

However, to conduct the NFIs, countries should build certain levels of forest monitoring capacity and need minimum resources and techniques. As explored in this review, the intensity and/or frequency of NFIs vary from country to country. NFIs in most of developing countries do not reach specific level of reliability and accuracy, and the capacity building supported by international organizations or institutions for estimating forest carbon stocks is not much progressed or not very effective.

2.6 Conclusions

This chapter has shown that there are many remote sensing techniques which developing countries are not taking advantage of even to monitor forest area operationally. National Forest Inventory methods to monitor timber stocks in forests are also well established, but NFIs are not undertaken frequently in developing countries either. The challenge in designing practical MRV systems for REDD+ will be to select those combinations of remote sensing techniques and/or NFI methods which are feasible operationally. To meet this need, it is important to learn from the findings of decades of research into technology adoption, which is reviewed in the next chapter.

Chapter 3
Literature Review

3.1 Introduction

This chapter reviews the literature on Measurement, Reporting and Verification (MRV) systems for implementing the REDD+ mechanism, to which this thesis seeks to contribute. It also reviews research on technology adoption models, since the key obstacle to using remote sensing techniques for REDD+ is the historic difficulty in the adoption of these techniques by developing countries for operational purposes. One of these technology adoption models will form the basis of the model to be employed in this research to evaluate how developing countries upgrade their forest monitoring capacity to meet REDD+ needs.

3.2 Measurement, Reporting and Verification (MRV) Systems

This section reviews literature related to MRV systems for the REDD+ mechanism. It includes difficulties in establishing MRV systems, technological capacities for MRV systems of developing countries, and evaluating forest monitoring approaches for developing countries.

3.2.1 Measurement, Reporting and Verification (MRV) Capacity

Agreement in 2007 on the Bali Road Map to involve developing countries in international action to combat global climate change (UNFCCC, 2008) led to the start of negotiations on a Reducing Emissions from Deforestation and Forest Degradation (REDD, later REDD+) mechanism. Various scientific groups then suggested how to design the national MRV systems that would be used in an operational REDD+ mechanism, as scientific uncertainty on estimating forest carbon is one of main reasons for the delay of REDD+ (Baker et al., 2010).

A large amount of research regarding the technologies for forest monitoring using remote sensing has been conducted. It is because detecting forest area changes and estimating forest carbon stocks are a key element in MRVs. Research focused on the use of various sensors for forest monitoring and combination of sensors for MRV systems (see Chapter 2). Herold and Johns (2007) gave some recommendations on deforestation monitoring, based on current forest monitoring technologies, such as available satellite data, and minimum technical requirements of the REDD+. The discipline most directly concerned with satellite monitoring, remote sensing science, however, has traditionally not examined why global data collected by satellites has not been operationally converted into usable global information (Goward, 2008; Lippitt and Stow, 2015).

Some studies placed the development of new national MRV systems within an international context, e.g. to ensure agreement on international standards, availability of satellite data, and independent verification of MRV reports (e.g. Baker et al., 2010; Grainger and Obersteiner, 2011). Baker et al. (2010) investigated technical issues related to quantifying forest carbon emissions in developing countries for the operation of MRV systems, and outlined five principles for MRV systems at national and global scales. The research included roles of space agencies and international bodies in MRV systems.

Other research has evaluated the current state of forest inventory and surveying capacity in developing countries, to show the need for support to expand capacity. These studies show that the majority of tropical countries have a large capacity gap between existing forest monitoring capacities and minimum requirements of the REDD+. An early study showed that 64% of a sample of 25 leading tropical forest countries required major capacity increases (Hardcastle et al., 2008). A later study of 99 countries by Romijn et al. (2012) found that "very large capacity gaps were observed in 49 countries, mostly in Africa, while only four countries, i.e. Argentina, China, India and Mexico, had a very small capacity gap." The capacity gap was ranked by four criteria: "national engagement of a country in the REDD+ process; existing monitoring capacities; country-specific challenges that countries face in REDD+; and remote sensing technical challenges, such as high cloud cover. Even those countries which have high capacities in both technical and institutional ability for forest area monitoring still have difficulties in setting historical baselines for estimating the amount of carbon emissions and in combining field surveys and remote sensing techniques for collecting forest information efficiently (Korhonen-Kurki et al, 2013).

There have been various studies of the situation in individual countries, e.g. Jha and Paudel (2010) evaluated MRV conditions in Nepal by investigating the capacity gap between current national forest monitoring conditions including policy provisions and institutional infrastructure, in their country and basic requirements of REDD+ MRV. At the sub-national level, Joseph et al. (2013) evaluated MRV capacities of 20 REDD+ projects in six tropical countries using nine performance criteria, and found that capacities of project developers in Indonesia, Vietnam, Tanzania and Cameroon were lower than others in Peru and Brazil, and half of the projects had deficiencies in MRV capacity. Ochieng et al. (2018) evaluated the degree of institutionalisation of MRV systems in Indonesia, Peru and Tanzania. The research presented valuable findings on institutional arrangements with reference to discourses, policies, actors, resources, and rules in those countries, but was less concerned to evaluate technological aspects.

3.2.2 Proposed Solutions to MRV Systems and Capacity

There have been four main responses to addressing this capacity gap. The first is for member states of the UNFCCC to design REDD+ to minimize the reporting burden on developing countries (e.g. Herold and Skutsch, 2011). The second offers governments a simple guide to what different satellite sensors can offer (e.g. GOFC-GOLD, 2013). A useful concise summary was provided by De Sy et al. (2012). The third proposes a basic approach to designing MRVs that focuses on identifying minimum changes in forest cover which can then be multiplied by default carbon density values for reporting (e.g. Bucki et al., 2012). The fourth, which has been the least popular, suggests blueprints for MRV systems. For example, Birdsey et al. (2013, p.527) identify two options for integrating different remote sensing methods and existing national forest inventory systems: "spatially explicit methods which require that all information is available for each land cover polygon", and less demanding "spatially referenced methods" in which reporting is aggregated to states, provinces etc.; and using default values to fill data gaps. They provide an ideal development path from the simplest MRV system (IPCC Tier 1) to the most advanced (IPCC Tier 3). The limited number of studies in this approach indicates an important gap for researchers to fill.

Instead of trying to fill this gap, many recent publications have focused on the role of local monitoring. The best of these take an integrated approach by evaluating the potential for citizens to supplement national remote sensing and other monitoring.

Citizens could make local measurements, and communicate these to forestry departments by mobile phones, while also using the information themselves to make local forest management more sustainable (Pratihast et al., 2011; 2013). This could also be a strategy to improve forest monitoring capacity in the many countries where it is still low (Danielsen et al., 2011). Other studies are less relevant because they misunderstand the need for national monitoring, and assume that "locally-based monitoring should provide the backbone for" MRV systems (e.g. Fry, 2011). Since the technical monitoring capability of groups that have designed local REDD+ pilot projects is not generally good (Shijo et al., 2013), this suggests that countries should be careful when relying on foreign consultants to establish and operate MRV systems.

3.2.3 Evaluating Alternative Forest Monitoring Designs for Developing Countries

Just a few researchers have evaluated alternative designs for forest monitoring for developing countries to improve monitoring capacity for estimating forest carbon stocks, or for monitoring forest area changes and forest degradation. Although some of them didn't mention 'National Forest Monitoring System' or 'MRV system', most of the approaches have the possibility of being part of an MRV system or could be an alternative to existing forest monitoring systems in developing countries.

Halperin and Turner (2013) assessed three monitoring options, i.e. ground-based field measurements, remotely sensed imagery, and predictive modelling, for monitoring forest degradation of three forest types in a forest area in Cambodia. For the assessment, a conceptual assessment framework was developed for a qualitative ranking system. The authors defined "biomass reference for monitoring in each forest stratum of interest" and then identified and assessed "the scale and intensity of forest degradation drivers" and "monitoring approaches based on defined biomass change thresholds", in order to rank monitoring options based on some criteria such as 'technological difficulties', 'existing capacity', 'sustainability', 'existing research', and 'possibility of being used in an MRV system'. After considering "important drivers of degradation, operational circumstances, and expected capacity for implementation", an integrated monitoring system combining elements of all three approaches were then proposed.

However, although a conceptual framework for selecting alternatives was presented, the theoretical foundation of the methodology suggested for the research was very weak, and variables for the assessment were less carefully selected. The evaluation focused only on forest degradation and monitoring options for establishing biomass reference levels at the sub-national scale for the future, meaning that the research did not consider historical changes and historical baselines of forest biomass. Although biomass monitoring options were classified into three categories, specific methods and technologies for forest carbon monitoring were not evaluated in detail. In addition, the study proposed new technologies for forest degradation monitoring without collecting empirical data for evaluating existing capacity and available resources, which means that social factors such as institutions and human resources who will actually operate new technology to be adopted were not investigated in detail. As social and organisational factors related to the adoption of new monitoring options, including perceptions and compatibility, were not considered, it could result in poor adoption rate and hinder practical use of new technology recommended.

The limited number of studies in evaluating and proposing alternative technologies to improve forest monitoring capacity indicates an important gap that should be filled too.

3.2.4 Discussion

Considering the importance of the MRV systems for REDD+, the number of previous studies related to the design of MRV systems has not been large. Previous research related to MRV systems mainly focused on remote sensing techniques for MRVs, collecting field data, roles of communities in developing countries, MRV capacity in developing countries and development of new MRV systems for developing countries. However, there is no clear solution yet, either in terms of technology or organization. The studies showed that majority of tropical countries have a large capacity gap between existing forest monitoring systems and basic requirements of the REDD+ MRV for information on changes in forest area and carbon stocks.

The sociology of remote sensing systems has been little studied until now, especially in developing countries (Grainger, 2017). Only a few studies have been made in developed countries (Lippitt et al., 2014).

Some researchers have tried to evaluate alternative forest monitoring approaches for developing countries to improve forest monitoring capacity of developing countries. However, most of them focused mainly on proposing alternatives for sub-national levels, and selected criteria for the evaluation without much consideration. Some crucial factors in technology adoption/transfer were not considered when forest monitoring options were being evaluated. This suggests another important gap that needs to be filled, namely the need of further investigation into technology adoption theories.

3.3 Adoption of New Technologies

A good way to categorise technology adoption research is by ‘the characteristics of technology’ or ‘the locus of adoption’ (Fichman, 1992). Adoption studies have been mainly conducted at individual, group, and organisational levels (Venkatesh, 2006). In this context, technology adoption models, theories or frameworks are reviewed in this section according to the levels of adoption, i.e. individual and organisational levels.

3.3.1 Individual Adoption

The earliest explanations of innovation focused on individual actors. Hicks (1932) proposed that innovation would occur in response to market forces, as changes in the relative prices of the factors of production, i.e. capital, labour and land, induce innovation to reduce the cost of the most expensive factor. Thirty years later, Boserup (1965) proposed that agricultural intensification is inevitable, when land becomes relatively scarce as a result of population pressure.

Another early model was the Diffusion of Innovations (DOI) model (Rogers, 1962), in which adoption of new technologies spreads between groups of people in a logistic way from 'innovators' to 'early adopters', then to the 'early majority' and 'late majority' groups, before finally being taken up by 'laggards'. This model can describe how adoption spreads spatially from the initial innovation centre. Rogers (1995) noted that Type of innovation (i.e., optional, collective, or authoritative), Communication channel (i.e., mass media or interpersonal), Time, Nature of social system (i.e., norms, degree of network interconnectedness) are the four main factors in the diffusion of innovation, and the procedures of innovation-decision are 1) knowledge, 2) persuasion, 3) decision, 4) implementation, and 5) confirmation (Rogers, 1983).

The assumption in economics that human beings are rational actors made it difficult to explain why new technologies were not adopted by farmers after the removal of all constraints to their response to market forces, e.g. insufficient credit, information and incentives. Only recently have agricultural economists begun to explore the role played in adoption by farmers' social networks, something which is assumed in the DOI model (Maertens and Barrett, 2012).

Individual adoption has also dominated studies of the adoption of new information technologies. Since the Technology Acceptance Model (TAM) was proposed by Davis (1989), other models have been proposed and applied to information science (Manross and Rice, 1986; Igbaria et al., 1995; Gefen and Straub, 2000), and they are reviewed here.

The TAM, one of the most prominent models in the technology adoption area (Venkatesh, 2006), explains the behaviour of people in the situation where people accept or reject new technology (Legris et al., 2003; Surendran, 2012; Marangunic and Granic, 2015). According to the TAM, the use of a technology depends on behaviour intention, which is a function of two attitudinal variables, "perceived usefulness" and "perceived ease of use", each of which can be ranked on a scale in laboratory psychometric studies (Davis, 1989). Specifically, the TAM examines the relationship between external variables and the probability of computer system use (Legris et al., 2003; Marangunic. and Granic, 2015). External variables (i.e. system characteristics such as political factors, cultural factors and social factors) on attitudes, intentions and internal beliefs indirectly influence potential system use (Legris et al., 2003; Surendran, 2012). Davis (1989) mentioned that perceived usefulness should be considered to implement or design systems, since usefulness has strong correlation with technology acceptance, however ease of use should not be ignored in the phase, since it may be an antecedent to usefulness in usage behaviours.

The TAM was strongly influenced by the Theory of Planned Behaviour (TPB) (Ajzen, 1985; 1991) and the Theory of Reasoned Action (TRA) (Fishbein and Azjen, 1975), which explain the factors regarding human behaviour (Marangunic and Granic, 2015). The TAM has been interpreted as "a special case of the Theory of Reasoned Action (TRA)" (Taylor and Todd, 1995), though Davis (1989) included no conceptual framework or a specific link to any theory. In the TRA, the *voluntary* intention of an individual to adopt depends upon their attitude and subjective norms (Fishbein and Azjen, 1975). The TAM divides 'attitude' into two beliefs and ignores subjective norms linked to social influences. The TRA was later refined to account for situations where an individual's freedom of action is no longer voluntary but constrained in some way. In the resulting Theory of Planned Behaviour (TPB), behavioural intention is a function of attitude, subjective norms, and also 'perceived behavioural control', which represents these constraints (Ajzen, 1985). Both the TRA and TPB portray behaviour solely in psychological terms through the actions of rational decision-makers who behave in a disconnected "atomistic" way. The limitations of this approach led to the development of sociological models that explain changes in behaviour by decisions made also in response to influences from wider society (e.g. Kollmuss and Agyeman, 2002).

The TAM model was expanded by later research, e.g. the combined Technology acceptance model and theory of planned behaviour model (TAM-TPB) (Taylor and Todd, 1995), and the Technology Acceptance Model 2 (TAM 2) (Venkatesh and Davis, 2000), which considered different variables (Surendran, 2012). Taylor and Todd (1995) tested two different groups, i.e. inexperienced user group and experienced user group, to examine IT usage and user’s behaviour. They integrated the TAM and TPB and added some determinants, such as Perceived Behavioural Control and Behavioural Intension, to distinguish the characteristics of inexperienced and experienced users (Venkatesh et al., 2007). The authors concluded that inexperienced users were strongly affected by perceived usefulness in their intension to use, and there was weak link between intention and usage, whereas the link between behavioural intention and usage in the experienced user group was strong. The Technology Acceptance Model 2 (TAM2) was proposed by Venkatesh and Davis (2000), and the model was examined for mandatory and voluntary user adoption behaviour in four different organisations. The study was focused on several crucial factors, such as subjective norm, voluntariness and perceived ease of use, influencing intension to use in technology acceptance.

Subsequently, a Unified Theory of Acceptance and Use of Technology (UTAUT) Model was proposed by Venkatesh et al. (2003) by combining the TAM with seven other models (i.e. the theory of reasoned action, the motivational model, the theory of planned behaviour, a model combining the technology acceptance model and the theory of planned behaviour, the model of PC utilization, the innovation diffusion theory, and the social cognitive theory), though little attention was paid to inconsistencies between their different conceptual foundations. The aim of the model was to explain the influence of individual differences on IT adoption. Venkatesh et al. (2003) pointed out that individuals’ attitudes can be affected by social factors, such as social network and peers, in IT use. The advantage of the model is that the model can cover a range of factors influencing IT adoption. Four determinants of intention and usage (i.e. performance expectancy, effort expectancy, social influence and facilitating conditions), and moderators of key relationships (i.e. gender, age, voluntariness, experience) were examined by the model to identify effect on information technology use (Venkatesh et al., 2003). The models included both the TRA and the TPB, despite their different assumptions - and the Motivation Model, another psychological model. On the other hand, the list of models also included two models in which an individual's behaviour depends on social influences - Social Cognitive Theory (Bandura, 1977), and the Theory of Interpersonal Behaviour (Triandis, 1977) - and the DOI model, which has its own conceptual foundation.

Sargent et al. (2012) and Kijsanayotin (2009) modified the Unified Theory of Acceptance and Use of Technology (UTAUT) Model to examine information technology and heath IT adoption, respectively. The latter model validated the possibility of the UTAUT Model in identifying health IT acceptance in a developing country. The models are able to analyse various factors affecting technology adoption, such as intention to use, experience and facilitating condition.

Talukder et al. (2008) purposed an enhanced technology adoption model based on TRA, TAM and a conceptual framework proposed by Frambach and Schillewaert (2002). The model was focused on individuals within an organisation in adoption decisions, and ten factors affecting technology adoption of individuals were derived. The results of the study showed that managerial support, personal innovativeness, perceived usefulness and training can strongly influence technology adoption. The model considered demographic factors such as gender, age, academic divisions, tenure, occupation category and academic qualification, and training, managerial support and incentives were considered as organisational factors.

The application of the modified models mentioned above is limited to IT areas, and the models mainly focused on identifying the factors influencing on intension to use and influence of the factors in IT acceptance (e.g. Kamal, 2006). Technology adoption models focused on how an individual's intentions can overlook the importance of other determinants which cannot be controlled by individuals (King and Gribbins, 2002). While the TAM has been employed widely, its original justification by support from alternative theories was selective and lacking in coherence. Thus, findings by

Tornatzky and Klein (1982) that a new technology is adopted if it is also compatible with existing values and practices were quickly dismissed.

Both the TAM and the UTAUT Model have been tested extensively, and according to their protagonists, there is a strong case that they can explain most adoption behaviour (Venkatesh et al., 2007). However, their focus is on positivist explanations by groups of variables in regression equations, rather than on holistic and coherent explanations. Thus, critics argue that the absence of social influences on adoption is a major limitation of both models (Im et al., 2011). Legris et al. (2003) claimed that the limitation is so severe that the TAM is only effective if it is one component of a larger model that includes such influences.

Changing trends of the individual adoption models reviewed above indicate that, in the models for individual adoption, the scale of the effect of social and external factors on adoption decisions and intention to use has been gradually increased, as the models have been modified and expanded by their successors.

The practical importance of social influences is underlined by Hayami and Ruttan's (1971) refinement of the *induced innovation* model to include government and organizational influences, and in particular the role of public sector research organizations in developing new agricultural technologies. Without such organizations, the technologies would not exist. In this model, innovation depends not only on factor prices, as proposed by Hicks (1932), but also on "effective interaction among farmers, public research situations and private agricultural supply firms", and on "the institutions that govern the use of technology", e.g. changes in property rights or other regulations. In a REDD+ context, this implies that adoption of new monitoring technologies by governments will be induced by changes in carbon prices, while the availability of these technologies could also induce adoption of more sustainable forms of land use.

3.3.2 Adoption by Organizations

Rogers (1983) argued that organisations were the unit of adoption in many types of innovations. Technology adoption models at individual level can explain a range of cases of the acceptance process of new technology, however the models need to be expanded or modified in order to explain the adoption process at organisational level (Fichman, 1992).

The DOI model (Rogers, 1962) can be applied to organisations as well as entire societies. The model deals with diffusion of technology and new idea through cultures (Oliveira and Martins, 2011). Adoption again depends upon the ability of individuals to change, but here the development of social networks is replaced by both internal networks (i.e. the 'interconnectedness' of the organisation), and also external networks, which depend on the openness of the organization to its external environment. According to the theory, the innovation process within an organisation can be divided into several stages, i.e. initiation stages and implementation stages, specifically agenda setting and matching, redefining/restructuring, clarifying, and routinizing (Rogers, 1983). Near-peers, norms, pressure in organisations, and change agents can influence technology adoption (Rogers, 1995; Straub, 2009). Thus, the rate of adoption and implementation of new technology in organisations may not be determined by one specific variable, although innovation decisions can be made by a small number of individuals in centralised organisations (Rogers, 1983). Rogers (1995) mentioned that the adoption rate can be predicted by five attributes of innovations: Relative advantage, Compatibility, Complexity, Trialability and Observability (Rogers, 1995, pp.250-251). Although the DOI theory was criticised by some researchers due to the fact that the theory didn’t consider some demographic factors (e.g. education, age and gender), the theory well explains technology, the adoption process and factors, and helps distinguish the phases of adoption and the differences between adopters and non-adopters (Richardson, 2009; Abukhzam and Lee, 2010).

Another widely used model is the Technology, Organization and Environmental (TOE) framework (Depietro, et al., 1990). Here, the decision to innovate depends upon three sets of factors: the organizational context; the external environment context; and the availability and characteristics of technologies (Depietro, et al., 1990). Although the TOE framework is consistent with the DOI model, it contains greater detail on the role of the external environment (Baker, 2011). Oliveira and Martins (2011) argued that in some aspects, the TOE framework is more complete than the DOI theory. The model considers both internal and external factors of organisations in technology adoption, and unlike the DOI theory, the environment element such as competitive pressure and government encouragement is included (Oliveira and Martins, 2011; Awa et al., 2012). Kuan and Chau (2001) applied the TOE framework to study the role of perceptions in the adoption of electronic data interchange by small businesses. Hu et al. (2002, p.201) refined the organizational context in a healthcare setting to include organizational readiness, namely "the availability of the internal conditions necessary ... to adopt the technology." The importance of the external environment in the TOE reinforces the arguments of Hayami and Ruttan (1971), and is demonstrated by findings that the adoption of new technologies by organizations depends on the promotion of these technologies by governments (Exworthy et al., 2003), and on the imposition of new regulations to which organizations must respond, the latter being known as the Porter Hypothesis (Porter and van der Linde, 1995).

The TOE framework is a robust and effective tool to explain technology adoption at organisational level (Angeles, 2014). However, Awa et al. (2012) noted that technology adoption can be more clearly understood when the TOE model is integrated with models that focus on individual behaviour (e.g. TAM).

Many researchers have focused on IT adoption at organisational level. Aguila-Obra and Padilla-Melendez (2006) linked Internet technology adoption to different stages of organisations (i.e. Initiation, Adoption, Adaptation, Acceptance, Routinisation and Infusion). Based on previous studies, they grouped factors affecting technology adoption into organisational, external and technological factors in order to identify the influence of the factors in the technology adoption process. The model also considered the influence of the size of organisations on Internet technology adoption. The authors pointed out that managerial capabilities, technological resources and external support at an adoption/adaptation phase were important determinants in technology adoption in an organisation, but the influence of the size of organisations on Internet technology adoption was relatively weak. The research was more focused on internal and technological factors than external factors.

King and Gribbins (2002) examined IT adoption at organisational level and derived internal and external organisational factors (i.e. Characteristics of the technology, Organizations' existing business models and paradigms, Managerial logic, Locus of control, The availability of a knowledgeable IT staff, Organizational size, Financial resources and Pushes from within the industry), which affect decisions and implementation of technology adoption (King and Gribbins, 2002, p.4). From the organisational perspective, top management's effort and IT departments' technological readiness were important factors in adoption implementation. Iacovou et al. (1995) proposed small business Electronic Data Interchange (EDI) adoption model and suggested three steps for EDI initiators. The model adopted perceived benefits, organizational readiness, and external pressure as three major factors.

To understand the rate of adoption and organisational behaviour in the adoption process, considering both individual and organisational factors and task characteristics is important (Baker, 2011). Thus, technology adoption models at both individual and organizational levels have been expanded by some researchers by integrating the models in order to more clearly explain adoption decisions or influence of factors. Awa et al. (2012) proposed the Integrated TAM and TOE model in which some different factors, such as perceived service quality, organisation mission, facilitating conditions and individual difference, were considered. The model consists of factors from the TAM (Perceived Usefulness and Perceived Ease of Use), TPB (Perceived Behavioural Control and Subjective Norms) and TOE (firm's size, consumer readiness, trading partners' readiness, competitive pressure, and scope of business operation) model. He mentioned that "the integration of constructs of TAM, TPB, and TOE frameworks as well as the new ones proposed in the model, somewhat social and behavioural constructivism is enrolled to bring both human and non-human actors into the network. The postulate of this model is similar to Actor Network Theory (ANT) since it emphasises dynamic and mutual interplay of technical and social systems" (Awa et al., 2012, p.575).

Because the TAM has been so widely used, attempts have been made to modify it to address technology adoption in organizations, despite its inherent focus on the individual. For example, Wang and Qualls (2007) translated the TAM's two key variables of "perceived usefulness" and "perceived ease of use" into "perceived benefits of adoption" and "perceived ease of adoption" and linked these to: (a) a set of factors that describe the external environment and the openness of the organization to it, and hence the antecedents of adoption decisions; (b) the organization's technology capacity and commitment to technological innovation; and (c) the characteristics of the technology concerned. Melitski et al. (2010) took a different route, deriving their model directly from the TPB, linking behaviour intention to attitudes and organizational culture, regarding the latter as a closer fit to the "subjective norms" variable in the original TPB. They ranked organizational culture by four rather subjective factors: organizational climate, decision-making processes, leadership and behavioural outcome. Meanwhile, Chanasuc et al. (2012) assumed that the perceptions of benefits and perceptions of ease-of-use were *solely* related to organizational culture when they explained the adoption of information and communication technology in Thai public organizations.

A very different approach to conceptualizing adoption by organizations is to frame it solely in terms of a 'mainstream' management studies literature. Thus, Zorn et al. (2011)

used institutional theory to explain the adoption of information and communication technology by non-profit organizations in New Zealand, arguing that when there is a lack of reliable information about new technologies this will cause organizations to exhibit 'institutional isomorphism' and converge on a common technology that is generally thought to be reliable. On the other hand, the conceptual framework also included organizational characteristics and features of the external environment. It could not rank these different factors and nor could it explain whether pressures would overwhelm individual judgements about the organizational fit of the technology, although tests found that isomorphism and fit were mutually supportive.

Little research has been undertaken in order to assess the adoption of technologies to respond to climate change. Eichberger and Guerdjikova (2012) modified the DOI model to divide a society into optimistic agents (early innovators) and pessimistic agents (late adopters). Nordhaus (2002) employed induced innovation theory and found that when future changes in energy use were projected induced innovation was less important than substituting low carbon energy use for high carbon energy use.

3.3.3 Design of Appropriate Technology

REDD+ MRV systems need to be feasible to operate in developing countries, where there are limitations on the affordability of technologies and on the skills of people needed to operate them. This suggests that experience since the 1960s, in the design and implementation of "appropriate technologies" could be helpful. Schumacher (1973) proposed, based on his research and experiences, Appropriate Technology (AT) theories for endogenous technological development in order to overcome the failures of the technical aid efforts for recipient countries.

The earlier concepts of appropriate technology were alternatives to high-technology in developed countries for developing countries (Grieve, 2004). Therefore, appropriate technology had been recognized as low or cheap technology for developing countries, and people tended to consider the appropriate technology as a simple, labour-intensive or intermediate technology (Grieve, 2004; Sianipar et al., 2014). Tharakan (2006) mentioned that “Appropriate Technology is, in general, characterised by small capital requirements, the use of local materials and resources, and is usually relatively labour intensive, small scale and affordable to individual families. The core principle of appropriate technology is to include local communities in technology selection and development, innovation and implementation, all in an environmentally sustainable manner".

The concept of appropriate technology has changed due to globalisation, and the use of the Internet, and thus more sophisticated technologies are now considered as an appropriate technology (Grieve, 2004). Developing countries started to adopt high-technology applications for specific fields, for instance agricultural techniques, solar energy sources, building technology and information and communications technologies (Tharakan, 2006; Reijswoud, 2009). The concept of appropriate technology has also shifted "from only a technical artifact to become a socio-technical one", and AT has "become a powerful technological solution that addresses both suitable internal specifications and potential impacts to surrounding routines in a contextual way" (Sianipar et al., 2014).

Although there are still big gaps in technological capability amongst developing countries, the main concerns of appropriate technology are "the conditions for effective transfer and absorption of advanced-country technologies and to learning from these technologies with the view to building technological capabilities in developing countries" (Grieve, 2004, p.174).

By appropriate technology transfer, recipient communities, organizations or countries can improve their performance with limited human or natural resources (Choi, 2009; Sianipar et al., 2013). However, appropriateness of technologies from developed countries tends to be determined by the circumstances of recipient countries (Choi, 2009). Thus, the technology, which consists of object, process, and knowledge, needs to be modified for the cultural or natural environments of local communities and regions for the technology transfer process to be successful (Choi, 2009; Diehl, 2009; Reijswoud, 2009). One consideration in determining if a technology is appropriate to a country is total factor productivity, i.e. the productivity of the three neoclassical factors of production. As Jerzmanowski (2008) states: "rich countries invent technologies that are compatible with their own factor mix, but these technologies do not work well with the very different factor mix of poor countries". The productivity of human capital in developed countries tends to be much higher than that in developing countries. Another consideration that is more specific to the design of technologies concerns the selection of indicators of 'appropriateness'.

Parr and Shaw (1996) explained the procedure of selecting appropriate technology for developing countries. The process consists of three stages including objectives, analysis and output. In the analysis stage, appropriate technology was evaluated by 'SHTEFIE' criteria developed by the Water, Engineering and Development Centre. The criteria evaluate the effect of social, health, technological, economic, financial, institutional and environmental factors. Bauer and Brown (2014) tried to assess an appropriate technology by measuring the appropriateness of the technology, and the most prevalent indicators were derived to identify appropriateness of 'EZ heat'. The indicators include community input, affordability, autonomy, transferability, community control, scalability, local availability of raw materials, and adaptability. Wicklein (1998; 2004) also presented several criteria, such as Systems independence, Image of modernity, Individual technology versus collective technology, Cost of technology, Risk factor, Evolutionary capacity of technology, and Single-purpose and multi-purpose technology, to identify the appropriateness of technology for developing countries.

Although the term "appropriate technology" is controversial, the original intention of those who devised it, and its predecessor "intermediate technology", was to focus on meeting the needs of end-users in developing countries rather than the needs of firms in developed countries (Hollick, 1982). It is significant that debate now is not over whether it is still relevant, but on the relative contribution to production made by indigenous firms in recent decades (Kaplinsky, 2011; James, 2014).

The studies mentioned above investigated different areas, but showed that appropriateness of new technology needs to be selected or designed by specific criteria, which are identified by considering the characteristics of technology and environmental conditions in order to achieve successful technology adoption. Some indicators selected for village energy products are not transferable to MRV systems, e.g. "locally available raw materials", but other indicators have more generic applicability, e.g. "accessibility", "ease of use", "adaptability" and "autonomy" (Bauer and Brown, 2014).

3.4 Conclusions

There is a great need for new research to analyse the difficulties which developing countries have experienced in upgrading their forest monitoring capacity to establish MRVs that meet the information needs of REDD+. This is part of a wider gap in our understandings of the sociology of remote sensing systems, especially in developing countries.

Technology adoption models have much to contribute to this, and various models were reviewed in this section, which were devised to explain the factors affecting technology adoption and/or predicting adoption decisions by either individuals or organisations levels. The predominant TAM and UTAUT models have fundamental limitations to apply to organizational adoption, whereas, the DOI, TOE and Refined Induced Innovation model shed important light on how adoption is socially influenced. However, all types of technology adoption cannot be explained by one specific model or theory since the factors affecting adoption vary by task characteristics, national/cultural contexts and types of technology adopted (Baker, 2011). Some models also simplified the adoption process and interactions between adoption components. However, on balance, the TOE framework seems to offer the best foundation for a framework for evaluating the adoption of technologies for REDD+.

Developing countries have developed considerably since the 1960s, but the need for appropriate technology remains, as does research into its design, distribution and utilisation. Today developing countries need appropriate technology for REDD+ MRV systems as urgently as they needed appropriate technology for other purposes in the 1960s. The reason for this urgency is their vulnerability to climate change, and in extending technology adoption models to evaluate how developing countries are adopting technologies for REDD+ MRV systems. This thesis will also fill a key gap in the technology adoption literature – how adoption is influenced by international policy on climate change.

Chapter 4
Methodology and Methods

4.1 Introduction

This chapter describes the methodology and methods which will be used in this research. In the first part of the chapter, two conceptual frameworks are presented. The Conceptual Framework for Information Production is a macro-framework to show how different organizations and their technologies can combine to provide end-users, such as governments or the UNFCCC, with the forest information which they need. Various technologies could be used to fill the gap between the demand for forest information and the current capacity of the organization to supply it. The Technology Adoption System framework can explain how technologies are actually adopted, and can be used to evaluate present forest information production capacity and identify the socially optimal technology choice to enhance this capacity to fill the information gap.

4.2 The Conceptual Framework for Information Production

The ability of the national forestry department of any country to supply national forest information to meet demand by national or international bodies can be represented by using a knowledge exchange chain framework (Grainger, 2010) (Fig. 4.1).

Every national forestry department in the world is currently structured to supply information on forest area and timber stocks to its government. It produces a national forest area map, by using remote sensing or other methods, and then adds to this information on the distribution of timber stocks, derived from data collected by national forest inventory methods.

The Information Production (IP) Framework proposes that ideally the supply of information by government departments in any country is in balance with the actual demand for information by the government. This explains why in developing countries national forest area maps have often been produced at a frequency of only once every 10-20 years, or even longer. National forest inventories have been undertaken much less frequently (Grainger, 2007). Despite the written commitments of governments in stated policies, actual policies are often less ambitious.

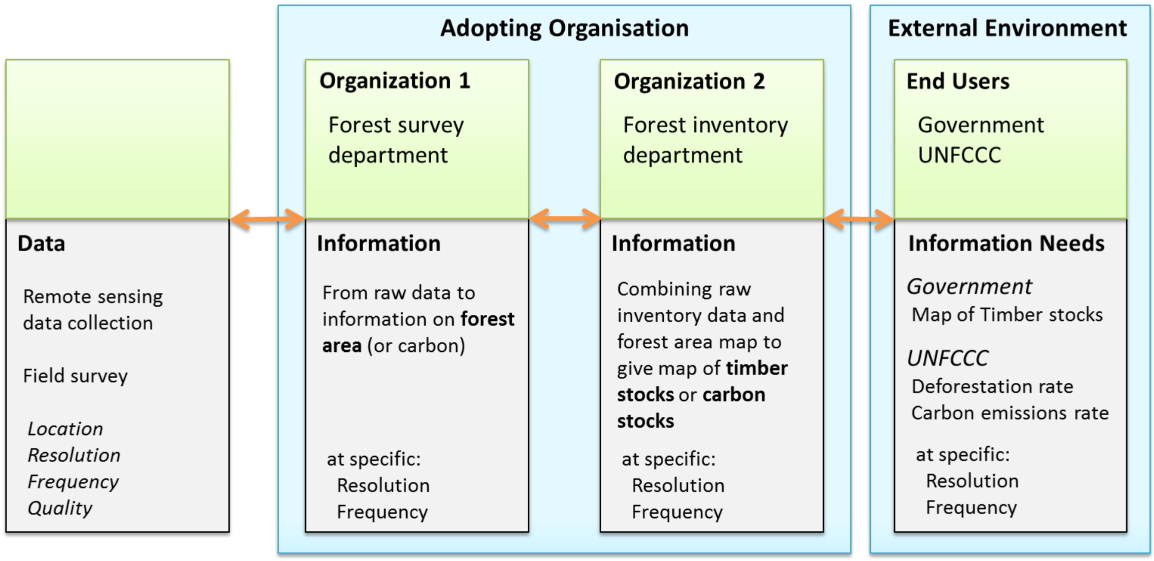

Figure 4.1 The Conceptual Framework for Information Production (IP)

(This framework drew on the Knowledge Exchange Chain framework (Grainger, 2010).)

International demand for forest information is usually much greater than national demand. If a country wishes to participate in the UNFCCC's REDD+ mechanism, it will need to modify the system by which it produces forest information, in order to deliver information on forest area and carbon stocks (not timber stocks) at a resolution and frequency required by the UNFCCC. In this new system, a national forestry department may now have to use satellite data to produce information on forest area at, for example, a resolution ranging from 30 m (or less) to 1 km, and a frequency of five years, in order to estimate the rate of deforestation. Information on carbon stocks may be gained by intensifying national forest inventory data collection, by using non-optical remote sensing methods, e.g. LIDAR, or by a combination of the two.

This conceptual framework can therefore be used to evaluate the gap between the current capacity of a national forestry department to produce national forest information at the resolution and frequency required by the government, and the resolution and frequency required by the UNFCCC. It assumes, for convenience of application to all countries, that surveys of forest area and national forest inventories are undertaken by different divisions of the national forestry department.

After evaluating current forest survey designs, various technological options which may appear to fill the gap can be presented. However, if the new design is to be acceptable to the government it will have to satisfy other criteria, which can be predicted using the technology adoption literature reviewed in Chapter 3. The conceptual framework for identifying the *socially* optimal design to supply information needs is described in the next section.

4.3 The Technology Adoption System Framework

To complement the Conceptual Framework for Information Production, this section describes a Technology Adoption System Framework to explain how technologies are adopted to meet demand for forest information.

4.3.1 The Origin of the Conceptual Framework

Based on the literature review chapter, organizational models seem more appropriate than individual models for evaluating the adoption of new technologies for REDD+ MRV systems. Of the various organizational models reviewed in the literature review chapter, the TOE framework (Depietro, et al., 1990) appears to have most potential to provide a foundation for a conceptual framework in this thesis, as it includes the adopting organization, the external environment and the characteristics of technologies. Thus, the basic structure of the conceptual framework for this research is built on the principles of the TOE framework.

However, even the TOE framework has gaps that need filling, which include not only the provision of a more robust conceptual framework, but also the explanation of: (a) the selective adoption of one technology from a group of potential technologies; (b) the compatibility between a new technology and existing practices, technologies and human capital in the organization, and how they are joined together to enhance information production capacity; (c) the role of scale in the external environment (e.g. inducements for national commitments to an international environmental convention), and in the use of the technology (e.g. how it is combined with ground data collection of the kind that is fundamental to national forest inventories).

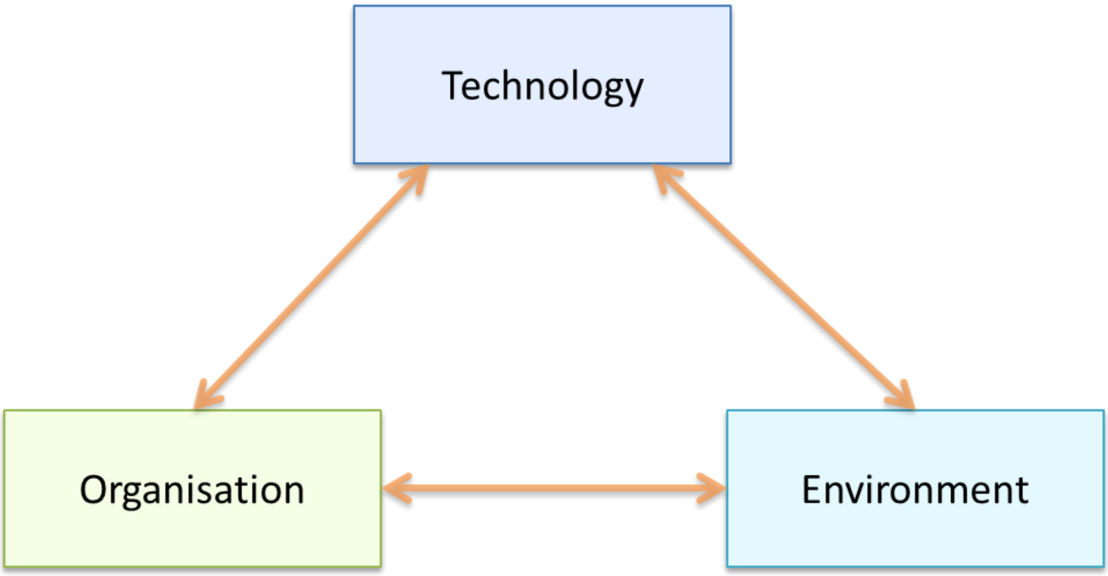

Figure 4.2 Structure of the Technology, Organization and Environment (TOE) Framework

(The structure of the TOE framework that was presented by Depietro, et al. (1990), in Tornatsky and Fleischer (1990), shows the basic structure of the Technology Adoption System (TAS) framework.)

4.3.2 The Basic Structure of the Technology Adoption System Framework

In this research, a Technology Adoption System (TAS) framework is used to explain adoption decisions in terms of the results of reciprocal interactions between three main modules: Available Technologies, the Adopting Organization and its External Environment, structured as in the TOE Framework (Fig. 4.2). The Adopting Organization corresponds to Organizations 1 and 2 in Figure 4.1, and the External Environment refers to End Users in Figure 4.1.

The TAS has unique features compared with the TOE. In particular, instead of a single technology, the framework is customised for the selection of an optimum technology from a number of potentially available technologies, and for considering organizational capacity, including existing practices or institutions, with which the new technology to be selected needs to be compatible. Unlike the TOE, the TAS Framework will not predict adoption decisions, but it provides a framework for (a) explaining actual adoption decisions; (b) evaluating present information production capacity; and (c) ranking available technologies according to their suitability for a particular purpose, in this case REDD+ MRV systems.

For explaining actual adoption decisions and socially optimal technologies, all three TAS modules will be used. For evaluating present information production capacity, only the Adopting Organization module and the External Environment module will be used.

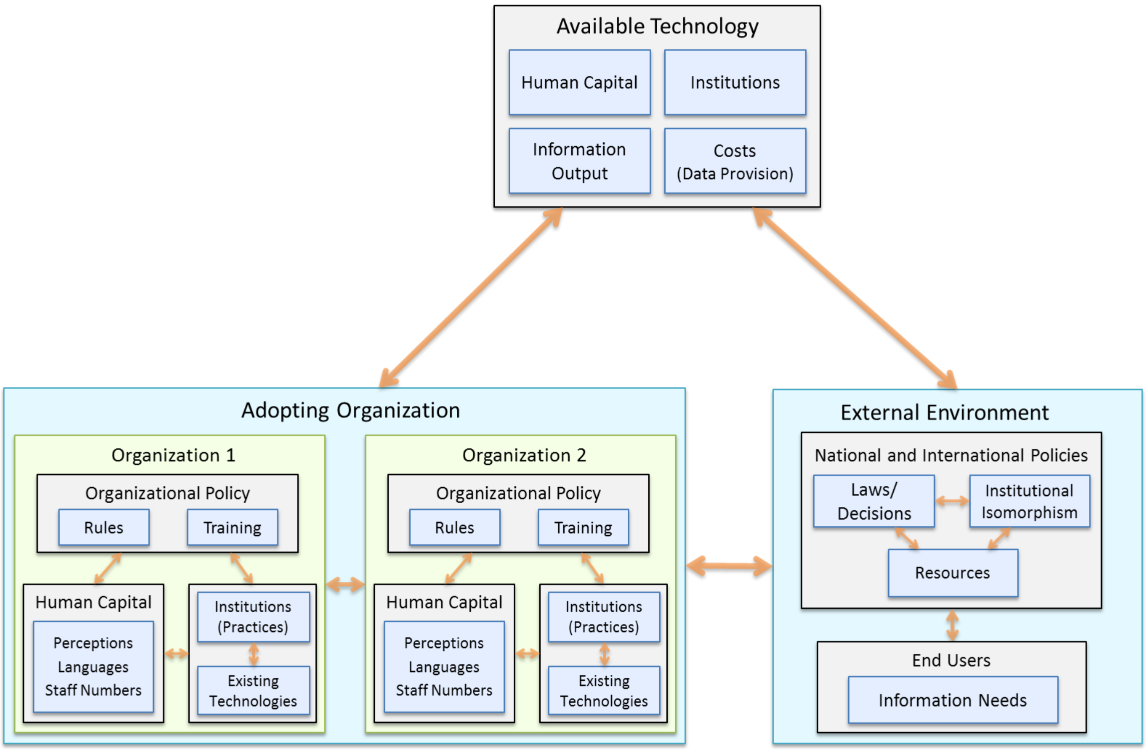

Figure 4.3 The Technology Adoption System (TAS) Framework with the Adopting Organizations Module, Available Technologies Module and External Environment Module

(Arrows show communication links between components, which indicate different types of interactions and relationships between components, such as compatibility, suitability, synergistic links, or various implications of other components that affect technology adoption processes.)

Figure 4.3 provides more detail on the key components in the three modules. It can show interactions between the components, and processes within each component which in turn affect interactions between the modules that help to explain the adoption process at the inter-organizational situation and the selection of a particular technology package. It also shows communication links which depend on processes within more than one component. The rest of this section outlines the modules, and how their expected roles, and interactions between them, influence the adoption process.

4.3.3 Adopting Organization Module

Organizational features have an important influence on successful technology adoption (Choi, 2009). In the TAS, key features of the Adopting Organization are: (a) Organizational Policy, (b) Institutions, (c) Existing Technologies, and (d) Human Capital (Fig. 4.3).

4.3.3.1 Organizational Structure

The Adopting Organization module allows for multiple parts of the same organization to be identified. (It may also encompass a separate body if this is involved in adopting a particular package of technologies.) So in Figure 4.3 the Adopting Organization module includes two organizations: here Organization 1 represents a typical forest survey division and Organization 2 a forest inventory division. This allows for the fact that in some countries, the characteristics of different divisions of the same forestry department can be an obstacle to providing end users with their information needs.

4.3.3.2 Organizational Policy

Centralized innovation diffusion or induced adoption may be decided and controlled by top administrators in an organization, and adoption decisions may be taken by the top level of the adopting organization for the entire organization, or one or more divisions. These decisions are affected by the policy of the organization which is also affected by national and international policies or laws.

Organizational policy is implemented by using rules to determine the formal institutions in the organization. Compulsion by top management will affect individual adopters' decisions.

The opportunities and quality of training for personnel in the adopting organization can also be determined by organisational policy. Awareness of technology can be spread by training or by trained personnel, and the use of new technologies, i.e. technology adoption, can be promoted by training, since adequate training can improve both individual and organizational capacity to assimilate, adapt, modify, and use technology (IPCC, 2000).

4.3.3.3 Institutional Component

The behaviour of an organization is determined by the repeated practices, or ‘Institutions’, of all the actors in an organization. Institutions are formally defined as "enduring regularities of human action in situations structured by rules, norms and shared strategies, as well as by the physical world" (Crawford and Ostrom, 1995, p.582).

The institutions of any actor in an organization can be divided into: (a) formal institutions associated with the organization as a whole or the specific niche which the actor occupies; and (b) informal institutions which have developed within the organization or which have been generated by the actor concerned. Formal institutions within the organization are influenced by its policy, but informal institutions are not. The ease of communication within an organization, and between organizations, both of which can influence technology adoption, is influenced by formal institutions, e.g. through well-defined lines of command, and by informal institutions developed using social connections.

The TAS assumes that there are synergistic links between the institutions of an organization/division and the technologies which are employed by the organization/division. Technologies substitute for practices previously undertaken by human beings, and many of the everyday practices of human beings are inseparable from the technologies they use, and the skills needed to operate these technologies. Changing institutions could therefore affect the technologies employed, and changing technologies will affect the institutions which are reproduced. Consistency with existing institutions will influence adoption decisions as it determines "ease of use" (Rogers, 1995), and every new technology will have associated with its institutions, or practices, required for its effective operation.

4.3.3.4 Human Capital Component

However, whereas the operation of mechanical technologies merely required people to press levers or buttons, the skills needed to operate digital technologies include the ability to speak particular languages, including the language in which training materials are written, the language in which instructions are given to the computer in command line or menu-driven software, and (for technical support staff) the language in which the software is programmed.

The ability of a forest monitoring organization to perform effectively is therefore determined by the technologies at its disposal, the ability of its staff to operate these technologies by having the skills to perform the required practices, *and* the linguistic ability to (a) communicate with computer software and hardware; (b) design the processing of data in a scientific way; and (c) interpret the resulting information in accordance with best scientific theory and practice.

Thus, the adoption, and subsequent use, of new technologies is affected by its human capital, which includes perceptions and linguistic skills in talking to computers as well as fellow employees. Overall capacity is also affected by staff numbers, since even with the help of computers there is a limit to how much one person can do.

According to Hajer (1995), the reproduction of discourse (perceptions and language in this context), is inseparable from the reproduction of institutions. This provides an intellectual justification for the common sense conclusion that staff will not be able to operate a piece of computer software unless they can actually speak to the software. It also justifies the assumption that perceptual and linguistic characteristics in Human Capital, combined with repeated practices in Institutions, can represent the totality of human behaviour when considering technology adoption.

The ability of staff to fulfil these functions will be determined by their previous training in the science of remote sensing and in the use of existing technologies. It will also be determined by the way in which the implementation of the institutions required for the use of existing technologies is influenced by the institutions of the organization as a whole.

The perceptions of new technology will vary by the knowledge and skills of staff and can be changed by training determined by organizational policy. Having sufficient staff in the adopting organization is essential to accomplish their given task for responding to information needs, and trained staff in the organization can provide knowledge and experience to overcome the obstacles in operating existing or new technologies. Organizations are more likely to adopt new technology, if they have human resources with sufficient knowledge and capabilities.

4.3.3.5 Existing Technologies Component

The Existing Technologies component refers to the technologies currently used by the organization. Existing technologies can be any hardware and software used for personnel to complete given tasks. It also includes information technology infrastructure such as networks, facilities, and internet connection.

Existing technologies are linked to the *Institutions* in an organization, since organizations have practices based on existing technologies. Different technologies have different routines for their operation. The routines for existing technology are formed by the accumulated features and actions of personnel in the organization. Existing technology is also linked to perceptual and linguistic skills in *Human Capital*.

The level of existing technology can also affect adoption of new technology, since organizations may not be able to adopt new technology without a prior technological base. An organization's ability to switch from an existing technology to new technology can also be affected by the time that existing technology has been used.

4.3.4 Available Technologies Module

The Available Technologies module includes the full range of technologies from which the organization may select a new technology for adoption. Associated with each technology are certain requirements for institutions and human capital, and for data inputs and information outputs. Consequently, it is argued here that apart from the costs of a given technology package, consistency between these requirements and an organization's existing institutions, human capital and technologies will play a crucial role in the adoption process.

4.3.5 External Environment Module

The effectiveness of adoption of new technology will be affected by an organization's external (operating) environment (Utterback, 1971). The External Environment can affect adopting organizations in different ways, e.g. through external pressures, support, training etc. (Sahay and Walsham, 1996). In this context, the external environment module includes: (a) National and International Policies, and (b) End Users.

4.3.5.1 National and International Policies

The information needs of End Users will be determined by their policies, which include national forest policy at the moment, and international policies, e.g. on REDD+, in the future. The adoption of technologies to meet information needs of national governments or UN conventions will be influenced by the policies of these bodies, and by institutional isomorphism among bodies at the corresponding spatial scale. Institutional isomorphism involves the tendency to imitate the practices of other organizations, e.g. by other government departments when supplying information to the same government, and by the national forestry departments of other countries when supplying information to a UN convention, in this case the UNFCCC. Institutional isomorphism is motivated by a variety of factors, including the adoption of technologies successfully used by others; a desire not to be ‘different’; and in the case of information technology the ease of transfer of digital data and information between computers running the same, or compatible, software (see DiMaggio and Powell, 1983; Hasmath and Hsu, 2014). The amount of resources available for technology adoption is also determined and allocated by national and international policies. Institutional isomorphism could be constrained by available resources for technology adoption, which include financial resources.

4.3.5.2 End Users

As well as receiving information from their ministries and departments for their own purposes, governments are obliged to comply with requests for information from end user organizations outside the country. These organizations include national aid agencies (e.g. the UK Department for International Development); international aid agencies (e.g. the UN Development Programme); other international organizations (e.g. the UN Food and Agriculture Organization) and international conventions (e.g. the UN Framework Convention on Climate Change). Standards for communicating information on climate change are published by IPCC. This information is required to either justify or determine the amount of funding allocated to countries in return for participating in certain projects or schemes (Zorn et al., 2011).

4.3.6 Using the Technology Adoption System Framework

The TAS Framework can be used to: (a) evaluate the capacity of existing organizations, e.g. in the present case the likely success of changes in organization and technologies that have already taken place in the study countries, as part of "REDD+ Readiness" projects, to meet REDD+ requirements for national MRV systems; (b) explain the adoption decisions previously made in REDD+ Readiness projects; (c) evaluate the advantages and disadvantages of alternative design options to enhance existing capacity by adopting new technologies; and (d) identify the socially optimal design for a given country.

4.3.6.1 Evaluating the effectiveness of existing forest monitoring designs

The effectiveness of existing designs for producing forest information, either those designed to produce information on forest area and timber stocks for government purposes, or designs that have been recently introduced to produce information on changes in forest area and carbon stocks for UNFCCC purposes, can be evaluated using two of the modules of the TAS Framework: the Adopting Organization module and the External Environment module.

The Adopting Organization module can produce *outputs* in terms of information on forest change at particular frequencies and resolutions. Information on forest area change is produced by Organization 1 in Figure 4.3 and information on forest carbon change relies on combining this information with information on national forest inventory change produced by Organization 2. The External Environment module requires as *inputs* information on forest change at particular frequencies and resolutions, as specified by international policies.

The gap between planned national outputs with existing technologies and required international inputs can be determined, and explained by reference to the components of the Adopting Organization module, as shown in Table 4.1.

Table 4.1 Matching Information Outputs of the Adopting Organization with Required Information Inputs of the External Environment

Adopting Organization Module
A. Information Outputs 1. Frequency of mapping 2. Resolution of mapping
B. Institutions (Practices) 3. Institutions required to produce current frequency of mapping 4. Institutions required to produce current resolution of mapping 5. Institutions for communicating within and outside the organization
C. Human Capital 6. Staff a. Number of staff b. Number of trained staff 7. Languages a. Computer language(s) used b. Human languages used 8. Perceptions of monitoring
D. Existing Technologies 9. Aerial surveys 10. Optical satellite sensor type 11. Non-optical satellite sensor type 12. Data processing (manual/digital) 13. Operating system and hardware 14. Ground measurement
External Environment Module
E. Complying with National and International Policies 15. Information resolution required 16. Information frequency required 17. National and international isomorphism constraints 18. Resources available for information production 19. Rules on responding to gaps between information demand and supply

The current frequency of mapping and the current resolution of mapping are both determined by the institutions prescribed in each organization for this purpose. For example, the use of digital classification of satellite images can, other things being equal, allow a high frequency of mapping at a high resolution. The manual classification of satellite images can lead to a reasonable frequency of mapping at a lower resolution but is preferred by many developing countries. The composition of the Institutions module is specified here in a generic way to allow for the mapping of forest area using remote sensing techniques in Organization 1, and the mapping of forest timber volume/carbon density using ground measurements in Organization 2. The effectiveness of mapping in each organization, and the capability for combining area information with carbon information, both depend on the existing institutions for communicating within each organization and with the other organization.

The frequency and resolution of mapping at national scale is also influenced by the characteristics of an organization's Human Capital. These include the total number of staff and the number of trained staff, the facility of staff in human languages and computer languages, and the overall perceptions of the monitoring process.

The existing technologies in an organization also influence the frequency and resolution of national mapping. Some countries may still rely on aerial surveys for forest area mapping, although the majority now use data from different satellite sensors. Data is processed either manually or digitally using different operating systems and hardware. Ground measurement is fundamental to national forest inventories and is vital for proper ground truthing in satellite image classification. The current set of technologies may be influenced by national and international constraints (here included in the External Environment module).

The External Environment module also allows for the fact that the current state of national forest monitoring capacity in developing countries will have been influenced by the resources already made available for "REDD+ Readiness" and by anticipation of the much larger resources which will be provided in exchange for required information in the REDD+ scheme. International policies also include rules for responding to gaps between the information required for REDD+ and the information supplied, e.g. through adjustment methods for different "Tiers" of information quality.

4.3.6.2 Explaining adoption of current National Forest Monitoring System designs

While the Adopting Organization and External Environment modules of the TAS Framework may be used to evaluate the effectiveness of current designs of national forest monitoring systems, they cannot explain why these designs may still be insufficient to meet REDD+ information needs despite recent upgrades in REDD+ Readiness schemes. This will require the additional use of a well-established model of policy formulation and decision-making. According to Lindblom's (1959) Incremental

Model, which drew on Simon's (1947) concept of bounded rationality, policy never changes radically, only incrementally, few policy options are considered, and there is no intention to search for a perfect solution, merely one that is better than the present situation and minimizes conflict between different groups in the adopting organization, e.g. the Forest Survey Division and Forest Inventory Division.

4.3.6.3 Identifying Socially Optimal Designs

A key weakness of incremental decision making in practice is that only a limited number of options are considered, and so decision makers may never have a chance to evaluate options which could be closer to the one that is optimal for them. This is particularly likely with high technology projects, since top managers often have limited understanding of science and technology. Since the TAS Framework encompasses all crucial processes in the use of forest monitoring technologies, and can include a wider range of options for technology packages, it should be able to identify the package which, when added to existing technologies, will lead to the most socially optimal design for a REDD+ MRV system.

According to the TAS Framework, out of a range of Available Technologies, the socially optimal technology package for an Adopting Organization is the one which meets the information needs of End Users but minimizes the distance between the characteristics of the technology, and the characteristics of the Adopting Organization and its External Environment. To estimate social optimality, all three modules are used, but the characteristics of the Adopting Organization and its External Environment can be listed in one column, and the characteristics of the Technology are listed in a second column (Table 4.2).

This 'proximity ranking' approach is a standard application of Multi-Criteria Decision Making (MCDM) methods, which have been widely used to provide solutions to sustainable energy management (Cherni et al., 2007; Amer and Daim, 2011), appropriate technology for developing countries (Lhendup, 2008; Silva and Nakata, 2009; Kishore and Dattakiran, 2011), and selection of technology (Yi et al., 2011). MCDM methods are useful in choosing and ranking technologies from multiple options, and the methods allow the evaluation of social, economic and technological factors for decision-making (Pohekar and Ramachandran, 2004; Kishore and Dattakiran, 2011).

Various criteria and both quantitative and qualitative factors can be evaluated by MCDM methods (Amer and Daim, 2011; Bhattacharyya, 2012).

In the most generic, weighted sum, method (Pohekar and Ramachandran, 2004), for M alternative technology packages and N criteria, the total score of each alternative package A_M is given by:

$$A_M = \sum a_{ij}w_j$$

And the best alternative satisfies:

$$A_M^* = \text{Max} \sum_{ij} a_{ij}w_j, \quad \text{for } i = 1 \ldots M$$

Here, a_{ij} is the value of the i^{th} alternative measured by the j^{th} criterion, and w_j is the weight given to j^{th} criterion. So the technology option with the highest score becomes the basis of the socially optimal design.

Table 4.2 Summary of matching the characteristics of new technologies with existing characteristics of the Adopting Organization and External Environment

Adopting Organization	New Technologies
A. Existing Institutions (Practices) B. Existing Human Capital C. Types of Existing Technologies	A. Required Institutions (Practices) B. Required Human Capital C. Types of Available Technologies
External Environment	
D. Complying with National and International Policies	D. Complying with International Policies

4.4 Research Areas

As the findings of the project need to be widely applicable to establishing feasible forest monitoring systems for REDD+ in tropical countries, it would seem appropriate to undertake studies in at least two countries. For selecting countries to be evaluated for this research, several conditions were considered. For instance, empirical data collected from countries with sufficient potential to participate in REDD+ will be helpful for the purpose of this research, and different levels of forest monitoring capacities were considered to evaluate and compare forest monitoring capacity of forest departments. Other geographical and ecological factors, including the total area of potential countries and deforestation rates, also considered as the factors may have significant effluences on satellite data provision and frequency of monitoring to detect deforestation and regrowth, and thus eventually have significantly implications for spatial resolution of forest area monitoring, and intensity of forest inventory.

The relationship with Republic of Korea (ROK), where the Green Climate Fund (GCF) is located, was also considered, when making contact with forestry departments in developing countries, to identify the possibility of obtaining permits for fieldwork. ROK has been looking for project sites after expressing its strong willingness to participate in REDD+ to mitigate climate change. ROK and tropical countries in Asia have established the ASEAN-ROK Forest Cooperation (AFoCo) to effectively implement forest conservation projects in Asia region. In 2011, ROK signed agreements with four countries in Southeast Asia - Indonesia, Cambodia, Philippines and Myanmar - for forest conservation projects.

After reviewing academic literature and documents from international organizations such as FAO, the Republic of Indonesia and the Kingdom of Cambodia in the Asian region were chosen as the two case study countries. The total area of Indonesia is large, but the area of Cambodia is relatively small, and historical and existing capacities for forest information production of Cambodia and Indonesia are known to be very different. Currently, ROK is conducting REDD+ pilot projects in Cambodia and Indonesia, which started in 2011 and 2013 respectively. The main characteristics of these countries, and other factors related to their forest monitoring systems, are outlined in the following sections.

4.4.1 Kingdom of Cambodia

In 1953, Cambodia gained independence from France, but Cambodia’s political situation was not stable until the mid-1990s, since in the 1970s and the 1980s Cambodia experienced civil wars, insurgencies and the Cambodian genocide. Hence, the Royal Government of Cambodia (RGC) was not able to pay much attention to its forest resources until the beginning of the 1990s. Forestry industry boomed at the middle of the 1990s, and many logging companies from other countries, such as the Grand Atlantic Timber, came to Cambodia, to which Cambodia could sell forest concessions (Le Billon, 2000). Between 1992 and 2005, Cambodia has experienced extreme, and steady, deforestation (FAO, 2010a; 2015a).

In the late 1990s, many external organisations started to worry about deforestation occurring in Cambodia, and thus many of those requested the Cambodia government to frame and enforce forest policies on land use and forest management in order to prevent extreme forest loss in Cambodia. Some external donors tried to intervene in framing forest regulations and law enforcement of Cambodia more directly. Global Witness, which is a NGO based in the U.K., for example, acted as an 'Independent Observer' for monitoring forest loss and enforcement activities in Cambodia after awarding a fund provided by the World Bank's Forest Crimes and Monitoring Project (FCMP) in 1999 (Brown and Luttrell, 2007). Since 1999, the Cambodian government has cancelled 15 forest concessions (FAO, 2015b) and established protected areas. The Cambodian government banned granting forest concessions and established new harvest codes to ensure sustainable forest management in 2002.

The independent forest monitoring system operated by such external donors, however, was not deemed a successful project as primary forests continued to be destroyed by logging companies. There were still illegal forest concessions and logging activities, and even basic regulations were often ignored by logging companies as the legal system in Cambodia was weak (Forest Trends, 2015). The failure of the independent forest monitoring system was mainly due to lack of order, political conflicts and corruption inherent in Cambodia. External pressures were not able to make effective impact on forest loss, and strict law enforcement for forest management was hindered by political conditions and weak governance in Cambodia. Although the Cambodian government began the forestry reform process in 1999 and framed the Forestry Law 2002, the Cambodian government didn't seem to have strong willingness to prevent the over exploitation of forest resource at the time, as the forest concessions changed into the form of economic land concessions by which logging companies, and other third parties, could hold rights for cutting down trees in their business areas for the purpose of agro-industrial development. There were over 160 economic land concessions in Cambodia which represents about 10% of total land area (Kapos et al., 2010). Although sustainable forest management was started to be promoted by Cambodia's stated forest policy, actual policy still remained exploitative, which is described as the ‘ambiguous phase’ of forest policy evolution phases in Grainger and Malayang (2006) and Grainger (2004).

Since the year 2010, Cambodia has prepared for REDD+ by being a member of the World Bank’s Forest Carbon Partnership Facility (FCPF) and UN-REDD (UN-REDD, 2010). Cambodia is supported by Japan in establishing the REDD+ Monitoring System, including technology and infrastructure for MRV system (UN-REDD, 2010). Cambodia is a much smaller country than Indonesia, containing only 9.5 million ha of forest in 2015 (see, Figure 4.4), but this declined at a proportionally much higher rate of 208,000 ha (2%) per annum between 2000 and 2010 (FAO, 2015a). Cambodia is considered to have relatively good forest area change monitoring and remote sensing capacities, but still has a low forest inventory capacity and intermediate carbon pool reporting capacity (Romijn et al., 2015).

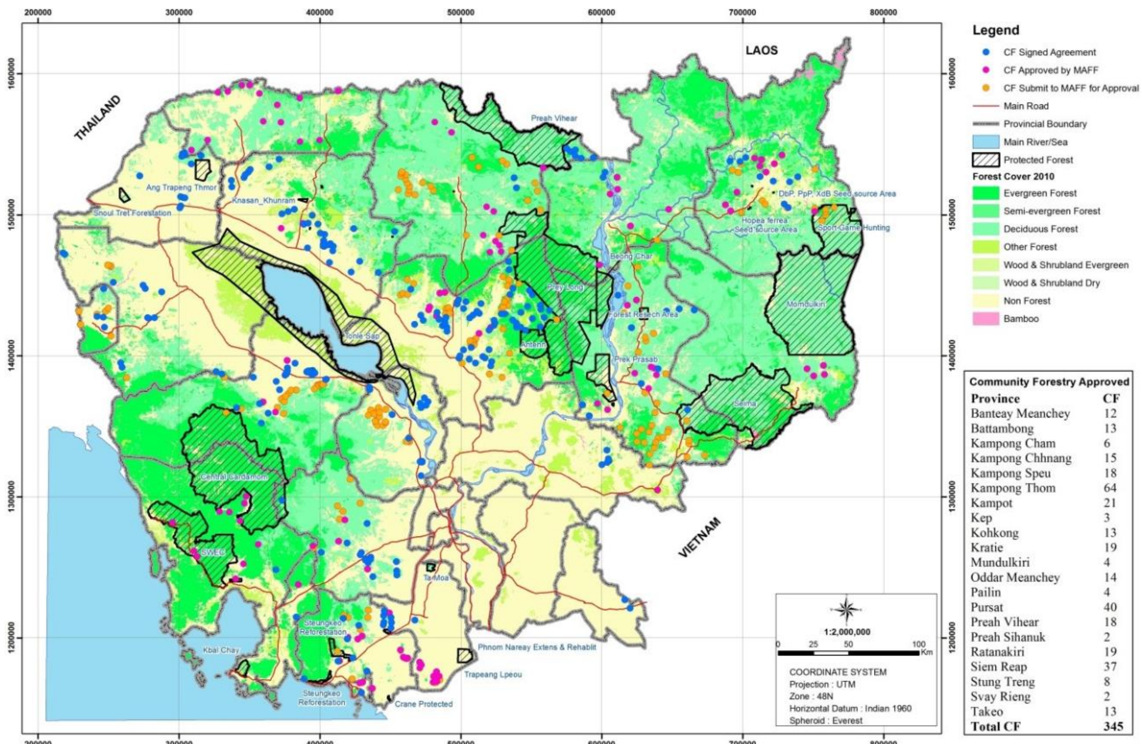

Figure 4.4 Map of Cambodia, showing forest types, community forests and protected forests in Cambodia

(Courtesy of the Forestry Administration of Cambodia)

4.4.2 Republic of Indonesia

To prepare for REDD+, Indonesia has been a member of two REDD+ Readiness schemes: UN-REDD and the World Bank's FCPF. Indonesian REDD+ programme has been financially supported by the Norwegian government through the Indonesia-Norway REDD+ Partnership, which was signed by the Norwegian Minister of Environment and the Indonesian Minister of Foreign Affairs on the 26th of May in 2010 (Caldecott et al., 2011), and the establishment of Indonesia's MRV system has been supported by UN-REDD.

Indonesia has the third largest area of tropical forest in the world – 91 million hectares (ha) in 2015 – and accounts for about a tenth of all tropical moist forest. Between 2000 and 2010 its forest area was declining at 1 million ha (1%) per annum (FAO, 2015a). Some researchers report that annual primary forest loss in Indonesia between 2000 and 2012 was higher than that of Brazil (Margono et al., 2014), and annual total forest loss in Indonesia is still increasing (Hansen et al., 2013).

Indonesia estimated its forest area and changes between 1990 and 2013 by manual-visual interpretation of mosaicked Landsat data. It has a national forest inventory capacity of about 3,000 field plots, but still has low carbon pool reporting capacity (Romijn et al., 2015).

4.5 Methods

To evaluate the evolution of forest information production and technology adoption in Cambodia and Indonesia, this research relies on empirical data collected during fieldwork, and secondary data. Empirical data are collected through direct observations and interviews. These are explained in detail in the following sections.

4.5.1 Activities

The research uses the Technology Adoption System (TAS) framework and the Conceptual Framework for Information Production to analyse empirical data on how pre-existing forest monitoring capacity has been enhanced by REDD+ Readiness activities, as well as how existing capacity can be further enhanced. During the fieldwork, the operations of the national REDD+ MRV centres in Cambodia and Indonesia were observed. The main activities during the fieldwork involved:

1. Evaluating the gap between existing information product and REDD+ needs.
2. Explaining the reason for the gap in terms of organizational and technological factors identified in the Technology Adoption System (TAS) Framework
3. Evaluating progress in filling the gap due to REDD+ Readiness activities
4. Evaluating the new technologies adopted in REDD+ Readiness activities
5. Proposing other new technology packages that might be more socially optimal

The field trip in Cambodia was conducted from the 9th of June to the 31st of August in 2016, and a second visit was conducted to collect additional data from the 20th of July to the 8th of August in 2017. The field trip started by meeting the deputy head of MRV centre, who is in charge of forest monitoring and MRV for REDD+ in Cambodia, and then interviews and observation at the Cambodian MRV centre were conducted for about 12 weeks. The main sites for activities were the national MRV centre under the Forestry Administration (FA) in the Ministry of Agriculture, Forestry and Fisheries (MAFF). I have also visited the Ministry of Environment (MoE), the REDD+ secretariat, the United Nations Development Programme (UNDP) Cambodia and FAO Cambodia in Phnom Penh. The national MRV team mainly produces forest maps using GIS and Remote Sensing technologies by the support from the Japan International Cooperation Agency (JICA), and the FAO Cambodia monitors all the MRV process and proposes new methodologies for National Forest Inventory (NFI) and Satellite Forest Monitoring (SFM).

The field trip in Indonesia was conducted from 6th of June to 29th of September in 2017 (about 16 weeks). After obtaining a foreign research permit from the Ministry of Research, Technology and Higher Education of Indonesia, with support from a research counterpart in Indonesia affiliated in the Faculty of Forestry at Bogor Agricultural University. During this fieldwork, I was based in the Directorate of Forest Resource Inventory and Monitoring in Jakarta, which is the main site for activities. The Directorate of Forest Resource Inventory and Monitoring mainly produces forest information for the Government of Indonesia and the UNFCCC, and is supported by internal, domestic, international organisations and research institutes. The Deputy Director of Forest Resources Inventory and Monitoring in the Ministry of Environment and Forestry, who is in charge of producing forest cover maps of Indonesia, arranged for me to conduct interviews with forestry officers and observations at the Directorate of Forest Resources Inventory and Monitoring.

During this time, I also visited Bogor Agricultural University (IPB), National Institute of Aeronautics and Space (LAPAN), Geospatial Information Agency (BIG) and German Corporation for International Cooperation (GIZ) in Jakarta and Bogor for interviews and observations.

4.5.2 Data Collection

For collecting empirical data in the countries, this research mainly relies on secondary data, direct observations and interviews during the field trip.

4.5.2.1 Secondary data

This research uses a variety of documentary evidence to identify factors linked to the interactions between technological and organizational factors that affect a country's ability to meet the minimum requirements for REDD+. Thus, a wealth of academic literature, as well as documents and guidelines from international conventions and organisations, such as the UNFCCC, IPCC and FAO, were referred to throughout the research. National reports submitted to the UNFCCC for preparations for REDD+, such as ‘National REDD+ Strategies’ and ‘National Forest Reference Emission Level (FREL) for REDD+’, were also referred to throughout the research.

During the fieldwork in Cambodia and Indonesia, less widely available manuals for forest cover mapping, consultancy reports and government reports related to MRV systems and REDD+ projects for Cambodia and Indonesia were collected.

These key unpublished documents for Cambodian REDD+ were obtained during fieldwork: *REDD+ strategy of Cambodia, National Forest Monitoring System of Cambodia*, and *Forest Reference Level in Cambodia*. I also obtained detailed manuals and overall workflow for land use and land cover mapping and forest carbon assessment of Cambodia, which were developed by the JICA technical advisory team for CAM-REDD.

One of the key documents I obtained during fieldwork in Indonesia is '*National Forest Inventory of Indonesia: Final Forest Resources Statistics Report',* which is the only remaining book written in English, explaining the first National Forest Inventories (NFIs) in Indonesia.

4.5.2.2 Direct observations

By conducting direct observations at the MRV centre in Cambodia and the Directorate of Forest Resources Inventory and Monitoring in Indonesia, general practices for forest mapping including current resolution and frequency required by the government to produce national forest information were identified (Figure 4.5). Current forest monitoring technologies, the characteristics of the MRV team of Cambodia and the Directorate of Forest Resources Inventory and Monitoring in Indonesia, and forest information production practices were also observed in order to identify current information gaps caused by existing technologies and organizational characteristics. The lists of variables to be observed are given in Appendix A.

Figure 4.5 Fieldwork in Cambodia and Indonesia

a) Observation of Cambodian forestry officer conducting visual interpretation of satellite data for the 2016 forest cover assessment, the Watershed

Management and Forest Cover Assessment office in the Forestry Administration, Phnom Penh, Cambodia (taken in July 2016)
b) Observation of Cambodian forestry officer and JICA technical advisor conducting visual interpretation, Cambodian REDD+ MRV centre in Phnom Penh, Cambodia (taken in August, 2016)
c) Interview with an Indonesian forestry officer, The Directorate of Forest Resources Inventory and Monitoring in the Ministry of Environment and Forestry, Indonesia (taken in August, 2017)
d) Observation of the process of producing a national forest cover map, The Directorate of Forest Resources Inventory and Monitoring in the Ministry of Environment and Forestry, Indonesia (taken in September, 2017)

4.5.2.2.1 Cambodia

I worked at the MRV centre for about one and a half months, from the 15th of July to the 31st of August in 2016, in order to observe their forest mapping activities, and participated in some official workshops for Cambodian REDD+ and its MRV system in Cambodia, such as the workshop “National Workshop on the REDD+ Strategy” which was held on the 30th of August 2016. I asked the technical advisors from Japan about detailed procedures for producing forest maps in order to find out current forest area monitoring methodologies, and closely worked with the MRV team members together to observe how they actually conduct forest information production. During the time, I had also some informal interviews to identify perceptions, experience and ability of the MRV team members.

4.5.2.2.2 Indonesia

To observe forest monitoring activities in Indonesia, I worked in the Directorate of Forest Inventory and Monitoring under the Ministry of Environment and Forestry from 10th of August to 6th of September. I worked closely with staff in the Directorate of Forest Inventory and Monitoring to observe detailed procedures for producing forest maps, and how they actually conduct forest information production, in order to find out current forest monitoring methodologies. During the time, I had also some informal interviews to identify perceptions, experience and ability of the team members. I participated in a few workshops, held in Bogor, for Indonesian forest monitoring, its MRV system, and communication links.

4.5.2.3 Interviews

Interviews were conducted to collect data related to present forest information production capacity of Cambodia and Indonesia, historical changes of forest monitoring systems, and organizational factors, which are indicated in the key variables identified by the TAS Framework (Figure 4.5).

Key personnel (i.e. managers of divisions and team members) in the forestry departments in Cambodia and Indonesia were first interviewed as they are expected to give valuable information on current forest monitoring systems and progress in collecting forest data resulting from REDD Readiness activities.

To identify current forest monitoring capacity, questions for interviews were focused on obtaining information which cannot be obtained from academic literature and consultancy reports. To identify socially optimal technology, questions for interviews were focused on their experience, perceptions and awareness of new technology. Practical difficulties in collecting forest data and estimating forest carbon stocks were also investigated by interviews with key personnel (see Appendices B and C).

Earlier forest monitoring capacity, i.e. used before starting REDD+ Readiness activities, were also be identified by interviews, as will technological and organizational aspects and technologies adopted after starting these activities.

In short, the interviews were focused on identifying how forest monitoring systems (including remote sensing and NFI) function, and the constraints on their functioning. Identifying how people perceive these systems and how the latter actually operate were the main purpose of the interviews. The type of interviews is Semi-structured open-ended interviews, so based on interview guidelines, the researcher asked interviewees questions in accordance with situations and the levels of experience, knowledge and positions of the interviewees. In most of cases, the length of interviews was around 50 minutes but sometimes interviews lasted for about 2 hours. All interviews were recorded using a mobile phone, and transcribed. The researcher also had several informal interviews with the MRV team members in both Cambodia and Indonesia in order to obtain more detailed information.

Since bodies engaged in forest monitoring in Cambodia and Indonesia have different organizational structures and information production capacities, the type of data collected in the two countries, and the structure of interviews (e.g. interviewees, key questions, procedure for testing, and the use of the information obtained from the interviews) vary accordingly, as explained below and in Appendices B and C.

4.5.2.3.1 Cambodia

The researcher had interviews with key personnel in the Forestry Administration in Cambodia, i.e. the Deputy Head of the Cambodian MRV centre and his team members. Key government officials at the Forestry Administration and the Ministry of Environment of the Cambodian government, who are in charge of the Cambodian MRV system for REDD+ and Greenhouse Gases (GHGs) inventory, are the Deputy Head of the MRV centre and the Deputy Director of the Carbon and Climate Change department. The MRV team members at the National MRV team, technical advisors from JICA and a forestry officer from FAO Cambodia were interviewed. As there is no independent National Forest Inventory team under the MRV centre (i.e. Forest Inventory Division), I had an interview with a forestry official, who is in charge of devising field manuals for Cambodian NFI, and developing emission factors and allometric equations. He has been working on estimating timber stocks in the Forestry Administration for 40 years. The Royal University of Agriculture (RUA) is the main research institute for Cambodian NFI, so I had an interview with a professor, who is conducting research with the Forestry Administration and the Fishery Administration (FiA) to develop Cambodian allometric equations, conversion factors and wood density.

The number of people interviewed was 15, including two forestry officers in the Forestry Administration, two technical advisors in the Wildlife Conservation Society (WCS), and a Director of the Korea-Mekong Forest Cooperation Centre (KMFCC) (see Appendix C-1).

4.5.2.3.2 Indonesia

The main sites for interviews, and observations, were the Directorate of Forestry Resources Inventory and Monitoring, the Directorate General of Climate Change of the Ministry of Environment and Forestry, LAPAN (Indonesian National Institute of

Aeronautics and Space) and BIG (Indonesian Geospatial Information Agency) in Jakarta and Bogor.

National Forest monitoring activities are undertaken by 4 Sub-Directorates, i.e. the Sub-Directorates of Forest Resources Inventory, Forest Resources Monitoring, Forest Thematic Mapping and Spatial Data Networking, under the Directorate of Forestry Resources Inventory and Monitoring. The Directorate of Forestry Resources Inventory and Monitoring is supported by 22 Regional offices in forest are monitoring and national forest inventory (NFI). The Sub-Directorates of Forest Resources Inventory in Jakarta conducts NFIs, and field data surveys are carried out at the regional level (UN-REDD, 2011b). The Sub-Directorates of Spatial Data Networking supports data sharing and data exchange (Sugardiman, 2012), and the Sub-Directorates of Forest Thematic Mapping provides maps for detailing the locations of sample plots. I tried to have interviews with at least 1 person in each key organisation for producing forest information for Indonesia's REDD+ MRV and successfully had interviews with 14 forestry officers in the Directorate of Forestry Resources Inventory and Monitoring.

The number of people interviewed was 24, including the Deputy Head of MRV and Registry for Land-based sector who is in charge of the national MRV system, two researchers in LAPAN and another two researchers in BIG. Two professors at Bogor Agricultural University (IPB), two technical advisors from German Corporation for International Cooperation (GIZ), and a researcher in World Resource Institute (WRI) were also interviewed (see Appendix C-2).

4.5.3 Proposing New Socially Optimal MRV Designs

After completing the field work and evaluating existing forest monitoring capacity, I intended to use the TAS Framework to identify socially optimal MRV designs for satisfying UNFCCC requirements for information on forest carbon emissions in Cambodia and Indonesia. These designs took into account the current procedures for collecting and processing remote sensing and inventory data in the two countries, but also compared these with a menu of possible alternative technology packages, based on the analysis in Chapter 2.

4.5.3.1 Available technologies

These alternative packages include different combinations of remote sensing data and ground data that have possibility of being socially optimal technology for the two countries. All the options for socially optimal MRV designs comply with the Tier 2 or 3 levels in IPCC Guidelines.

The list of Available Technologies only includes technologies that are already available for operational use. Even sensors which are collecting data are not always used operationally at large scale, e.g. Landsat sensors have collected global data since 1972, but the first global forest map based on Landsat data was not produced until 2012. Remote sensing scientists have tended to focus more on testing each new sensor that is launched and so are always anticipating the next sensor. For example, satellite sensors which are scheduled to be launched to estimate global forest biomass, include Tandem-L (L-band SAR to be launched in 2020, providing 4 Dimensional data (vertical 2D and horizontal 2D)), Biomass (P-band, to be launched by ESA in 2020), NASA-ISRO Synthetic Aperture Radar (NISAR: the first dual frequency (L-band and S-band) polarimetric SAR, planned to be launched by NASA and ISRO in 2020), and Global Ecosystem Dynamics Investigation (GEDI) LiDAR (planned to be deployed on the International Space Station (ISS) in 2018, 500 meters footprint and swath width of 6.5 kilometres, accuracy for forest height of about 1 meter). However, while these have potential to monitor forest area and forest carbon stock changes at national level for REDD+ MRV systems in the future, the governments of tropical countries require practical advice on what will operate now.

Convenient technologies for processing satellite images are also required by tropical countries. Google Earth Engine, developed by Google and supported by the US Geological Survey (USGS), the National Aeronautics and Space Administration (NASA) and other bodies, provides access to ready-to-use datasets for forest area monitoring, including Landsat, Sentinel and MODIS data, and also a workspace in the Cloud for classifying satellite data to map land cover/land use change. Although this has advantages, governments are very sensitive to incursions on their national sovereignty by "outside" monitoring, and so perceptions of external interference, which are allowed for in the TAS Framework, will have to be considered when advising on the use of such engines. Governments may already have made arrangements to gain access to satellite data through intergovernmental portals, such as those operated by the Group on Earth Observations (GEO), and these preferences were also identified in field work.

4.5.3.2 Ranking available technologies

The ranking of available technologies was to have used the method summarized in Table 4.2 and variables taken from the master list in Table 4.1 (Table 4.3). The comprehensiveness of the components of the three modules of the TAS was justified in Section 4.3, and the list of variables in Table 4.1 is regarded as the minimum set of variables needed to characterize the three modules and the information flows between them. Indicator theory is still embryonic in its ability to define the totality of indicators required for given sets of criteria (Gudmundsson, 2003). This research may also contribute to this literature in providing a robust mechanism for defining the minimum comprehensive set of variables needed for these purposes.

The ranking system for available technologies was to be based on systems used in Multi-Criteria Decision Making (MCDM) methods, described in Section 4.3.6.3. The weighted sum MCDM method will be used to score each variable and to rank technologies (Pohekar and Ramachandran, 2004; Lhendup, 2008; Bhattacharyya, 2012). In this research, all variables would have default weights of 1, unless there is a good reason not to have 1. A participatory approach will be used in the pilot study to get feedback on weightings from key stakeholders (Kocaoglu, 1983). If weightings other than 1 are used they would be determined by either "justifiable reasons with relevant examples and cases" (Lhendup, 2008; Bhattacharyya, 2012) or by the Analytic Hierarchy Process (AHP) (Amer and Daim, 2011).

Table 4.3 Matching the characteristics of new technologies with existing characteristics of the Adopting Organization and External Environment

Adopting Organizations	No.	New Technology
Institutions (Practices)		
▪ Institutions required for mapping at existing frequency	1	▪ Institutions required to map at desirable frequency
▪ Institutions required for mapping at existing accuracy	2	▪ Institutions required to map at desirable accuracy
▪ Existing institutions for communicating inside and outside the organization to gain required data/information	3	▪ Institutions needed to communicate inside and outside the organization to gain required data/information
Human Capital		
▪ Staff Numbers		▪ Staff Numbers Required
o Total staff	4	o Total staff
o Trained staff	5	o Trained staff
▪ Languages		▪ Languages
o Computer languages used	6	o Computer languages required
o Human languages used	7	o Human languages required
▪ Perceptions of monitoring	8	▪ How staff perceive technology
Existing Technology		
▪ Aerial surveys	9	▪ Aerial survey (e.g. for LiDAR)
▪ Optical satellite sensor type	10	▪ Optical satellite sensor type
▪ Non-optical satellite sensor type	11	▪ Non-optical satellite sensor type
▪ Data processing (manual/digital)	12	▪ Data processing type needed
▪ Operating system and hardware	13	▪ Operating system/hardware needed
▪ Ground measurement	14	▪ Ground measurement
External Environment - ***Complying with National and International Policies***		
▪ Information resolution required	15	▪ Information resolution possible
▪ Information frequency required	16	▪ Information frequency possible
▪ UNFCCC isomorphism constraints	17	▪ Adopted by other governments
▪ Resources available	18	▪ Resources needed
▪ Existing rules on responding to gaps between information demand and supply	19	▪ Required rules on responding to gaps between information demand and supply

The score for each variable would be estimated by Similarity Evaluation. The two-way similarity evaluation indicates the distance between two factors. The distance can be indicated by numbers between 1 and 5. The degree of coincidence between the two sets of characteristics would be ranked on a scale of 1-5 for each characteristic (5 meaning highest coincidence, 1 meaning lowest coincidence) (Table 4.4) (Lhendup, 2008; Bhattacharyya, 2012). Each score for estimating similarity would be determined by justifiable reasons, based on information obtained by interviews and direct observation.

Table 4.4 Criteria for scoring variables

Scale of scores
Similarity between Adopting Organizations, or External Environment, and New Technology ▪ 5 – Perfect match ▪ 4 – Good match ▪ 3 – Moderate match ▪ 2 – Slight match ▪ 1 – Zero match
NB. In some cases, the scores may also indicate: ▪ Good/ Bad ▪ Easy/ Difficult ▪ Affordable/Not affordable ▪ Accurate/Inaccurate ▪ Acceptable/Unacceptable

(Source: Developed based on Lhendup, 2008; Kishore and Dattakiran, 2011; Bhattacharyya, 2012)

The variables can be either numerical or qualitative ones (Kishore and Dattakiran, 2011). Therefore, different criteria for each variable can be applied. For example, the frequency of area mapping can be in intervals of 5 years (i.e. 5, 10, 15, 20 and more than 20 years), while the degree of staff computing language ability can be the gap between the present language ability of staff and required language ability for operating an available technology. The gap is a qualitative factor linked to each technology which can be identified by interviews with staff in forest monitoring divisions. Detailed criteria for scoring each variable are given in Appendix D.

Technologies for each organization within the set of Adopting Organizations would be ranked using the approach in Table 4.3. This would enable various technology packages, comprising forest area mapping and forest carbon mapping technologies, to be jointly assessed. After comparing the total scores of alternative technology options by the weighted sum method, the technology option with the highest score becomes the basis of the socially optimal design.

For reasons explained in detail in Chapters 6 and 7, new socially optimal MRV designs were not proposed for either Cambodia or Indonesia, since both countries have optimised their choice of MRV technologies themselves.

Chapter 5
The Evolution of Forest Information Production in Cambodia to Meet International Demand

5.1 Introduction

This chapter examines how the organization of national forest monitoring in Cambodia has evolved over the last 30 years. It looks in particular at how the set of technologies used for national forest monitoring has evolved in response to changes in demand for forest information, technological change, and the ability of the national forest monitoring system to adopt new technologies. After the REDD+ negotiations started, Cambodia implemented its REDD+ Readiness Programme to improve its ability to meet much greater international demand for information. The Cambodian case study described in this chapter reveals how the evolution of Cambodia's forest monitoring system, organisations, and the adoption of new technologies for improving its forest monitoring capacity were affected by the REDD+ Readiness Programme. This analysis is framed by the Technology Adoption System (TAS) Framework described in Chapter 4.

The chapter consists of 6 main parts. The first two parts look at the ability of Cambodia's forest monitoring system to meet national demand for forest information before REDD+ negotiations. The REDD+ Readiness programmes implemented in Cambodia are outlined in the third part. The fourth and fifth parts look at how forest area monitoring and national forest inventory of Cambodia have evolved after the implementation of the REDD+ Readiness Programme. Interactions between forest survey and inventory activities to meet international demand for forest information are presented in the sixth part.

5.2 Forest Area Monitoring before the REDD+ Readiness Programme

The evaluation of forest monitoring before the onset of REDD+ negotiations is divided into two parts. This section looks at forest area monitoring, while the next section looks at the monitoring of forest timber volume.

5.2.1 National and International Policies and Information Needs

5.2.1.1 National policies and information needs

Of all the countries in Southeast Asia, Cambodia has arguably had the least political stability since 1970, and consequently forest management did not have a high political priority for a considerable period. The country gradually stabilized after the formation of the State of Cambodia in 1989 (Öjendal and Lilja, 2009), and the Kingdom of Cambodia in 1993 (following the restoration of the Monarchy). It is therefore understandable that a new Forest Law was not passed until 2002.

Since the main driver of formulating national policies, and a reform programme, was external concerns about severe deforestation, and the Cambodian government did not seem willing to control overexploitation of the country's forest resources, implementation of such policies was not strict, and national demand for forest cover information was not high. Although the duties of the new Forestry Administration for producing forest area data and information for preparing and implementing the National Forest Management Plan were stated in Article 7 of the 2002 Forest Law (RGC, 2002), national information needs for forest management were not stipulated in detail, and so national forest monitoring capacity also remained underdeveloped even after 2002.

5.2.1.2 International policies and information needs

The Government of Cambodia must respond to information requests from overseas bodies. These include the Food and Agriculture Organization of the United Nations (FAO), and the International Tropical Timber Organisation (ITTO) and the United Nations Framework Convention on Climate Change (UNFCCC).

After the year 2000, Cambodia was also required to submit information on greenhouse gas emissions from land-use and land use change, as a part of its National Greenhouse Gas Inventory, and it submitted its first National Communication to the UNFCCC in 2002 (MoE of Cambodia, 2002). Yet none of these requests was compulsory and insufficient information supply was also acceptable. Although Cambodia showed its commitment to such climate change initiatives by ratifying the UNFCCC in 1995 and the Kyoto Protocol in 2002 (FCPF, 2009), the estimates it reported were very uncertain, mainly due to lack of reliable data. They were based on national forest cover statistics produced by the Forestry Administration in 1994 (FCPF, 2009) that were not very accurate. They were the same statistics reported to FAO's Forest Resources Assessments.

5.2.2 Outputs: frequency and resolution of mapping

The occasional mapping of national forest area using Landsat satellite imagery, which began as early as the mid-1970s in other countries in the region, notably the Philippines and Thailand (Grainger, 1984), did not begin in Cambodia until the late 1980s, for reasons linked to the political instability of the country, mentioned above. Maps were produced in 1988-89, 1992-93 and 1996-97 by external organizations, and published in the subsequent years (Table 5.1) (RGC, 2007; Forestry Administration, 2011; Forestry Administration, 2016a).

It was not until after the year 2000 that the Department of Forestry and Wildlife (DFW) began to take an active role in forest mapping. A four-year mapping frequency was achieved with the production of maps for 2002, 2006 and 2010 to respond to demand for information on forest resources by the DFW.

Some improvement in spatial resolution and Minimum Mapping Unit (MMU) of forest area maps was made. Before 1996, the data format of satellite imagery was hard copy, so spatial resolution of the forest cover maps could not be evaluated and accuracies of the maps were not assessed. The MMU of the 1992/3 and 1996/7 maps was 0.5 km^2, which were produced at a 1:250,000 mapping scale. Between 2002 and 2010, spatial resolution of all the forest cover maps was 30m as Landsat TM and ETM+ data were used for the forest cover assessments, and the MMU of the maps was enhanced to 0.25 km^2, which were produced at a 1:50,000 mapping scale. Yet, the MMU of 0.25

km^2 was still low compared with the spatial resolution of Landsat data, and so it could miss a lot of deforestation activities in forested areas.

Table 5.1 Existing major land use/cover and/or forest cover maps of Cambodia, produced by the Forestry Administration and/or external donors before the REDD+ readiness programme

Year	Producer and partner(s)	Satellite data	Resolution	Frequency	Scale/MMU*	Accuracy
1988/9 **	Remote sensing and Mapping unit of the Mekong Secretariat	Landsat MSS/TM	N/A	N/A	1/500,000, 1 km^2 (4x4mm at map scale) (Brun, 2013)	- Accuracy not assessed
1992/3 ***	MRC**** (implemented by GTZ*****)	Landsat TM	N/A	4 years	1/250,000, 0.5 km^2 (2x4mm at map scale) (Brun, 2013)	- Accuracy not assessed
1996/7		Landsat TM	N/A	4 years		- Accuracy not assessed
2002	DFW****** supported by the Government of Denmark	Landsat 7 ETM+	30 m	6 years	1/50,000, 0.5 km^2 (50 ha) (Brun, 2013)	- Accuracy not assessed
2006	Forestry Administration supported by the Government of Denmark	Landsat 7 ETM+ and TM	30 m	4 years	1/50,000, 0.25 km^2 (25 ha) (Forestry Administration, 2016a)	- Accuracy of 74 % for 4 forest types (71 % before grouping)
2010	Forestry Administration supported by the Government of Denmark and ITTO	Landsat 5 TM	30 m	4 years	1/50,000, 0.25 km^2 (25 ha) (Forestry Administration, 2016a)	- Around 85% (Forestry Administration, 2016a)

* Minimum Mapping Unit
** Reconnaissance Land Use Maps of Cambodia project
*** Forest Cover Monitoring Project (FCMP)
**** Mekong River Commission
***** German Technical Cooperation Agency
****** Department of Forestry and Wildlife under the Ministry of Agriculture, Forestry and Fisheries (MAFF)/FRM
- Forest definition for the 1988/9 map is 'Crown cover > 10%'.
- Forest definition for the 1992/3 and 1996/7 maps is 'Crown cover > 20%, Tree height > 10m'.
- Forest definition for the 2002 and 2005/6 maps is 'Crown cover > 20%, Tree height > 5m'.
- Forest definition for the 2010 map is 'Crown cover > 10%, Tree height > 5m, Minimum area

0.5 ha' (Brun, 2013).

- These surveys were carried out in the year(s) mentioned, and most of the maps were published in the following year, e.g. the 2006 and 2010 maps were published in 2007 and 2010 respectively.

(Source: Generated based on information from interviews, FCPF, 2009; Forestry Administration, 2012; Brun, 2013; Forestry Administration, 2014; and Forestry Administration, 2016a)

5.2.3 Organizations

The recent history of forest mapping in Cambodia can be divided into two main organizational periods. In the first period, which began in the late 1980s, overseas organizations not only funded the mapping of forest in Cambodia, they also took responsibility for this. Landsat surveys were undertaken by the Mekong Secretariat in 1988-89, and by the German Technical Cooperation Agency (GTZ) for the Mekong River Commission (MRC) in 1992-93 and 1996-97 (RGC, 2007; Forestry Administration, 2011; Forestry Administration, 2016a). The latter was funded by the Government of Germany.

In the second period, which began in 2002, the Department of Forestry and Wildlife (DFW) of Cambodia, and its successor, the Forestry Administration, has played an active role in mapping. Surveys were funded by overseas aid agencies, such as the Danish International Development Agency (DANIDA) and the International Tropical Timber Organisation (ITTO), and overseas staff also provided technical support during the surveys. The DFW produced the 2002 forest cover map, and the Forestry Administration, which was established in 2003 in accordance with the 2002 Forestry Law (FAO. 2010b), produced the 2006 and the 2010 forest cover maps (Forestry Administration, 2016a), with financial and technical support from those overseas agencies.

Within the Forestry Administration, responsibility was given to the Remote Sensing and Geographic Information System (RS/GIS) unit of the Watershed Management and Forest Land Office (Brun, 2013), which was created in 1998 by merging the two units that had been created in the mid-1990s with the assistance from FAO and GTZ (FCPF, 2009; Wellving, 2010) (Figure 5.1).

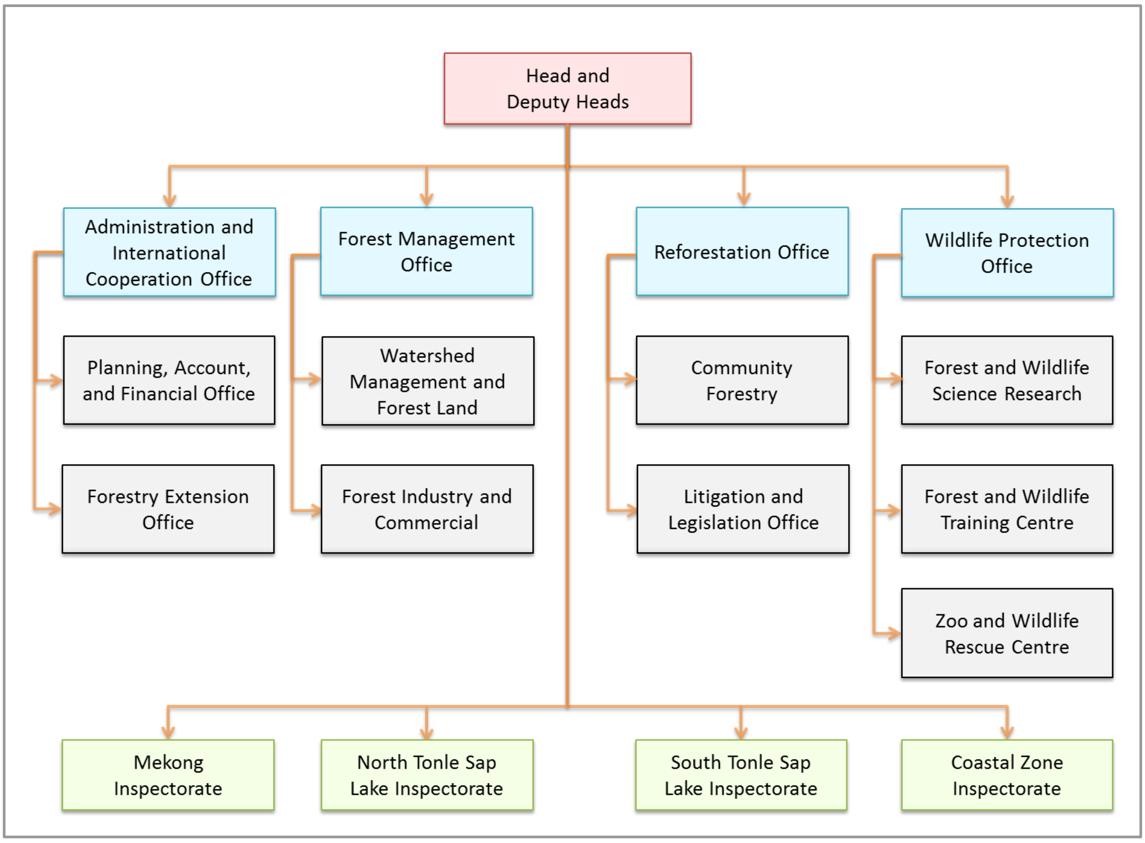

Figure 5.1 Organisational structure of the Forestry Administration

(Watershed Management and Forest Land Office was responsible for forest cover mapping, but there was no independent office for forest inventories, Adapted from Forestry Administration, 2004)

5.2.4 Technologies adopted

The principal technology adopted by overseas organizations which mapped forest area in the 1980s and 1990s was the visual interpretation of hard copy Landsat images, using only limited ground truth data. Boundaries of forest areas were drawn by hand (Table 5.2). Since forest cover assessments by generating forest cover maps were conducted by overseas organisations, Cambodia had only very limited technologies for forest area monitoring.

When the Department of Forestry and Wildlife became involved in mapping in 2002, it adopted a slightly different technology. This involved the visual interpretation of on-screen images, and with the use of Geographical Information Systems (GIS) this speeded up the earlier process.

However, although on-screen manual-visual classification using satellite data in digital format was introduced, and higher resolution images were used as ancillary data, during the 2000s only a little improvement in both forest cover monitoring capacity and technologies was made. The same interpretation methodology that had been applied to the 2002 maps was used for the 2005/06 national forest cover map, which was produced by the RS/GIS unit in 2007 using Landsat ETM+ data. The methodology used for the 2010 map was also similar to that for the 2006 map, and the 2002 map, as a 'dependant interpretation' method was applied to the 2010 map (Brun, 2013). The 2010 forest cover map was produced using 15 Landsat 5 TM images out of 19 scenes obtained from the Geo-Informatics and Space Technology Development Agency (GISTAD) of Thailand (Forestry Administration, 2012), and like the 2006 map, non-forest class in the 2010 map had no sub-classes, since those maps were focused only on forest cover assessment. Accuracy assessments of forest cover monitoring were said to be performed from 2002, but the number of ground truth samples was very small. For the accuracy assessments of the 2002, 2006, and 2010 maps, only 88, 100 and 104 ground truth samples were used, respectively (Brun, 2013). Although classification results could be converted into a data format for GIS, it was still necessary to visually interpret all the polygons in imagery. Thus, the process was still time-consuming and the accuracy of the forest cover maps was low.

Table 5.2 Existing technologies for producing land use/cover and/or forest cover maps of Cambodia before the REDD+ Readiness programme

Year	Producer and partner(s)	Satellite data	Format	Processing methods	Ground truthing	Land cover classes	Remark
1988/9	Remote sensing and Mapping unit of the Mekong secretariat	Landsat TM	Hard copy	Visual Interpretation	Not conducted (Brun, 2013)	20 (of which 9 classes for forest)	- Additional imagery: Aerial photographs
1992/3	MRC* and GTZ	Landsat TM	Hard copy	Visual Interpretation	Minimum field verification (Brun, 2013; FAO, 2010a)	29 (of which 15 classes for forest)	- Additional imagery: SPOT and Aerial photographs
1996/7		Landsat TM	Hard copy	Visual Interpretation			

2002	DFW** supported by the Government of Denmark	Landsat 7 ETM+	Digital format	Manual Classification (Visual Interpretation on screen)	88 samples	8 (of which 4 classes for forest)	- On-screen digitization - Additional imagery: Landsat 5 TM
2005/6	Forestry Administration supported by the Government of Denmark	Landsat 7 ETM+ and TM	Digital format	Manual Classification (Visual Interpretation on screen)	100 samples	5 (8 classes before merging: grouping of 2002 nomenclature)	- First use of digital classification techniques (FCPF, 2009) - Additional imagery: QuickBird and Landsat 5 TM
2010	Forestry Administration supported by the Government of Denmark and ITTO	Landsat 5 TM	Digital format	Manual Classification (Visual Interpretation on screen)	104 samples	5 classes (of which 4 classes for forest types, 10 classes before merging)	- Dependant interpretation - Additional imagery: QuickBird and Landsat 7 ETM+

* Mekong River Commission

** Department of Forestry and Wildlife under the Ministry of Agriculture, Forestry and Fisheries (MAFF)/FRM

- 'The 1988/1989 Reconnaissance Land Use Maps of Cambodia' can be imported in GIS (Brun, 2013).
- Technical and financial support for the 2002, the 2006 and the 2010 map was offered through DANIDA.
- Non-forest class in the 2006 and the 2010 map has no sub-classes, since those maps were focused only on forest cover assessment.
- The methodology used for the 2010 map is similar to that for the 2006 map as the ‘dependant interpretation’ method was applied to the 2010 map (Brun, 2013).
- When the Forestry Administration produced the 2010 map, forest cover changes between 2002 and 2010 and between 2006 and 2010 were evaluated, and after starting the REDD+ readiness, the 2006 and the 2010 map were upgraded to be consistent with the 2014 forest cover map (Forestry Administration, 2016b).

(Source: Generated based on information from interviews, FCPF, 2009; FAO, 2010a; Forestry Administration, 2012; Brun, 2013; and Forestry Administration, 2014)

5.2.5 Explaining Technology Adoption

This section explains the adoption of technologies for forest area monitoring in Cambodia using the Technology Adoption System (TAS) Framework.

5.2.5.1 Financial resources

Forest area mapping before REDD+ Readiness was not only funded by overseas organizations but also involved their staff to varying degrees. So they were able to choose the technologies which they thought would be most effective under Cambodian conditions. It can therefore be assumed that practicality, rather than financial constraints, was the most important consideration in technology adoption.

5.2.5.2 Institutions

The overseas staff employed by the agencies who funded the surveys from the late 1980s were all experienced in manual/visual interpretation of Landsat images and therefore reproduced their long-standing institutions.

From 2002 onwards, these institutions were shared with Cambodian forestry officers who participated in the mapping process. For image interpretation and classification practices, manual-visual classification could be used by Cambodian forestry officers, and so they could have experiences in performing on-screen manual-visual classification, and forest cover mapping at national scale, as stated by two forestry officers:

> *"From 2007 to 2010, I worked as a forestry officer for forest management and forest cover assessment. We generated maps by hand digitizing. We did every process for forest monitoring manually."* (Ms. Sar Sophyra, 20th July 2016)

> *"When we used the previous methodology for 2002 and 2006 maps, we did interpretation for all the areas by visual interpretation for all the polygons. In 2010, we completely relied on visual interpretation, digitized on-screen. We still need to check all the polygons."* (Ms. Hout Naborey, 29th of August 2016)

On the other hand, the short-term nature of forest surveys did limit how these institutions became embedded within the Department of Forestry and Wildlife. Some forestry officers who became skilled in Landsat interpretation subsequently left for other jobs which paid higher wages.

5.2.5.3 Human capital

The low level of human capital in Cambodia has been a significant constraint on national forest monitoring since its inception. This is seen most clearly in how overseas organizations wishing to help Cambodia to map its forests had to use their own staff, or foreigners employed by them, to do this from the late 1980s until 2002. Only a few Cambodian forestry officers participated in forest monitoring activities, and their knowledge and skills for processing and analysing satellite data were embryonic.

From 2002 onwards, forest area mapping has involved a mixture of Cambodian and overseas personnel, enabling an effective sharing of skills and institutions that has allowed indigenous human capital to expand. On the other hand, the limitations of indigenous human capital have also constrained the ability of the Department of Forestry and Wildlife, and its successor the Forestry Administration, to adopt new technologies. This has led to an incremental evolution of visual interpretation of Landsat images.

The quality of human capital was low because most forestry officers' educational backgrounds were not in remote sensing or GIS, and so forestry officers learned skills for forest monitoring from their seniors. Thus, most of them felt that processing satellite data was difficult. None of them could use computer language for processing satellite data, and the majority of them had problems with communication in English when they work with overseas organisations. The Deputy Head of the MRV centre and a forestry officer working on forest cover monitoring and accuracy assessments explained human capital before the REDD+ Readiness programme:

> *"2 or 3 people could analyse satellite data. They had experience in manual classification." (Mr. Leng Chivin, 7th of August 2017)*

> *"When I started working for the Forestry Administration in 2008, I didn't have any experience in remote sensing. I just learned satellite image processing after starting working here." (Ms. Hout Naborey, 29th of August 2016)*

The four year frequency for producing forest cover maps since 2002 allowed forestry officers to have enough time for producing forest cover maps using on-screen manual classification, but it also limited staff's experiences in other technologies. The RS/GIS unit produced national forest cover maps only three times by similar technologies during the 2000s, and they were also assisted by overseas organisations. Two forestry officer at the MRV centre explained forestry officers' incompetence at forest cover classification and mapping in the past, which limited adopting new technology:

> *"When we classified forest types for the assessment, my seniors in the RS/GIS unit determined the type of species in forest stands based on their experience, so the interpretation process caused frequent mistakes, resulting in high uncertainty in forest cover maps."* (Ms. Sar Sophyra, 20th of July 2016)

> *"In 2008, I learned how to use ArcView for forest mapping. It is not for remote sensing, but for forest mapping. In 2010, we started working on remote sensing." (Ms. Hout Naborey, 29th of August 2016)*

Adopting new technology was also limited by lack of training. Training focused on operating existing technologies for implementing given projects, not on new technologies. Training for the RS/GIS team was provided by the Geographic Resource Analysis and Science A/S (GRAS) of the University of Copenhagen in 2007 as part of a capacity building and development programme (FCPF, 2009), but most data processing and analysis processes were still performed manually by on-screen visual interpretation and hand digitization since forestry officers had limited skills and qualifications.

5.2.6 The Gap between Forest Area Information Supply and Demand

The eagerness of overseas aid agencies to help in the reconstruction of Cambodia following the establishment of the State of Cambodia in 1989 resulted in the 1990s in the supply of forest resources information that probably exceeded the official demand for such information by the evolving government. After the new Forest Law was promulgated in 2002, the supply of forest resources information was effectively in balance with the demand for it (Table 5.3).

Table 5.3 The gap between forest area information supply and demand before the REDD+ Readiness

		Information supply before REDD+ readiness	National (and International***) Information demand
Factors in forest area monitoring	Satellite images	Landsat images	Various images possible
	Data format	Hard copy/Digital	Digital format recommended
	Image processing	On-screen manual visual classification	Not specified
	Frequency/ Resolution (MMU)	4 years/30 m (25 ha*)	Not specified but as high as possible
	Forest degradation monitoring	Not monitored	Not compulsory
	Land classes	5 classes of which 4 classes for forest types**	Not specified
	Accuracy	Around 85% for 2010 map (Forestry Administration, 2016a)	Not specified, but as high as possible
	Points for ground truth	Around 300 for 2010 map, of which 104 from field survey (Brun, 2013).	Not specified but accuracy assessment recommended
	Human resources	Insufficient trained forestry officers	Not specified
	Institutions	Practices for manual classification in the central office not routinized	Various but fixed practices recommended

* Best minimum mapping unit for forest area monitoring at national scale was 0.25 km^2 produced at a mapping scale of 1/50,000.
** The number of classes for the 2010 forest cover map, 10 classes before merging.
*** FAO provided guidelines for forest growing stock monitoring for FRA, and IPCC guidelines provide different Tiers for carbon stock reporting in accordance with accuracy of data. Yet, neither of them was compulsory. For more details, see Chapter 2.

This was similar for international demands on forest cover information, as international demand was not high. FAO and the IPCC provided guidelines for forest area monitoring for Forest Resources Assessments (FRA) and National Communications to the UNFCCC respectively, but complying with such guidelines was not compulsory for Cambodia, and accuracy levels of most of the factors for forest area monitoring defined for reporting were not strictly applied to forest area estimates.

Although minimum data and information on forest cover changes to meet national and international needs could be supplied, the quality of information was not high. Forest area monitoring was implemented by manually classifying five land cover classes using Landsat data, and forest degradation was not monitored. Accuracy was estimated, but the number of field samples for ground truth was not sufficient. Frequency and resolution of forest area monitoring remained the same as at 4 years and 30m respectively, since 2002. MMU was enhanced up to 25 ha, but it could still miss a large area of deforestation.

Forest cover information production by repeating forest area monitoring, and adopting new technologies for building better capacity for information supply, was constrained by various factors including existing technologies, institutions, communication links and human capital. Specifically, implementing forest area monitoring at higher frequency and resolution was also limited by existing technology and institutions, i.e. on-screen manual-visual classification, and changing the institutions was limited by human capital, existing technology, and other organisational factors. As the frequency and resolution of forest area monitoring were not clearly specified, and national and international information demands were not high, improving them was limited by rules including those linked to national, and international, policies. There were fixed practices for manual processing in the RS/GIS unit, but they were not fully routinized as practices relied on informal institutions. Monitoring activities were performed during short term projects in collaboration with overseas organisations, and the number of trained forestry officers for forest area monitoring was insufficient for image interpretation, and for adopting new technology.

5.3 Forest Growing Stock Monitoring before the REDD+ Readiness Programme

The monitoring of timber reserves in Cambodia's forests was just as underdeveloped as monitoring of forest area when the process of national reconstruction began in the early 1990s. This section looks at the monitoring of forest timber volume before the

REDD+ Readiness Programme, and explains technology adoption for raising capacity for supplying information on timber stocks.

5.3.1 National and International Policies and Information Needs

5.3.1.1 National policies and information needs

The export of timber became an important source of foreign currency for the new State of Cambodia in the 1990s. However, as seen in other countries in the region in the early stages of the development of their forest economies, tracking the size of timber reserves was less important at this stage than gaining money from forest exploitation. As exporting timber products by granting forest concessions was the mainstay of Cambodia's economy in the late 1990s, the Cambodian government needed to estimate timber stocks to collect royalties from logging companies. Hence, national information needs focused on commercial species, and providing information on non-commercial species was not required. Yet, national policy did not strongly encourage the Forestry Administration to produce growing stock information, and thus frequency and resolution of growing stock monitoring were not clearly defined.

5.3.1.2 International policies and information needs

International demand for information on the volume of timber in Cambodia's forests in the 1990s was basically confined to requests for information from the Food and Agriculture Organization of the United Nations (FAO) and the UN Framework Convention on Climate Change (UNFCCC). Responding to information requests from other international organisations such as the Forest Carbon Partnership Facility (FCPF) of the World Bank and the International Tropical Timber Organisation (ITTO), for producing global statistics for estimating forest resources and timber stocks, was not compulsory.

These requests imposed no minimum quality standards on member states. For estimating global forest resources and carbon stocks, international organisations such as FAO and the IPCC provided guidelines for growing stock reporting, but, when producing and reporting information on the amount of growing stocks, the levels of accuracy defined by data and parameters used for growing stocks monitoring were not strictly applied.

5.3.2 Outputs: frequency and resolution of inventory

Overseas aid agencies provided funds to undertake inventories of Cambodia's forests in the 1990s in parallel with forest area surveys. Between 1996 and 1998, FAO and the UN Development Programme (UNDP), in collaboration with the Department of Forestry and Wildlife (DFW) of Cambodia, surveyed 279,242 ha in Sandan district in Kampong Thom Province (FAO, 2007a; FCPF, 2009). The information on growing stock per hectare for evergreen, mixed and deciduous forests, which are three major forest types in Cambodia, was produced (FAO, 2015b). Yet, as the pilot scale project was carried out with only limited resources, field surveys were focused on forest areas in one district in Kampong Thom, and it was a low-intensity forest sampling survey.

A start was made in establishing a network of Permanent Sample Plots (PSPs) by the Forestry Administration in collaboration with the Ministry of Environment and FAO in 1998. However, Cambodia’s growing stock information production was much poorer than that by overseas organisations. Inventory data were collected from Cambodia’s 120 PSPs, with repeated measuring in 2004 and 2010. That gave a 6 year frequency, but the number of PSPs being measured decreased gradually from 120 in 1998 to 48 in 2010 (Table 5.4).

As seen in other countries in the early stages of the development of their forest economies, mapping the distribution of timber reserves on the ground was of most importance to the companies awarded logging concessions. Consequently, from 1990 onwards inventory data was mainly supplied to the Department of Forestry and Wildlife (DFW) by timber companies. Data were submitted to the DFW from 15 forest concessions after 2002 as part of their Strategic Forest Management Plan (SFMP) (see the bottom of Table 5.4 for more information). During the project, data from 6,940 plots in evergreen, mixed and deciduous forests were compiled by categorising logged or unlogged forests for timber stock estimates for logging.

Table 5.4 Major forest inventories in Cambodia before REDD+, conducted by the Forestry Administration and/or external donors

Year	Tittle	Institution	Frequency	Resolution (Coverage/Plots)
1996 -98	Establishment of a forest resources inventory process in Cambodia.	DFW-FAO/UNDP	26 years	279,242 ha in Sandan district in Kampong Thom Province. Low intensity forest sampling survey (FAO, 2007a). Measured 60 plots (Top et al., 2004)
1998/ 2004 and 2010 *	Permanent Sample Plots	DFW/Forestry Administration with MoE and FAO	6 years	PSPs in five regions (Koh Kong, Siem Reap, Kampong Thom, Ratanakiri and Kratie province). 1998 - 1st measurement 120 plots 2004 - 2nd measurement 104 plots (Walker et al., 2010)
2002	Strategic Forest Management Plans (SFMPs)**	15 Forest Concessions	N/A	Total 6,940 plots in Unlogged Evergreen (2,000 plots), Logged Evergreen (1,760 plots) Unlogged Mixed (1,460 plots), Logged Mixed (300 plots), Unlogged Deciduous (1,360 plots), and Logged Deciduous (60 plots) (Walker et al., 2010)

* 1998 - 1st measurement 120 plots
2004 - 2nd measurement 104 plots
2010 - 4th measurement 48 plots (Walker et al., 2010)

** For forest concession management, all forest concessionaires in Cambodia were required to develop and submit a Strategic Forest Management Plan (SFMP) in line with mandatory compliance requirements introduced by the Cambodian government in 2001 (Savet and Sokhun, 2003; Forestry Administration. 2008).

(Source: Generated based on information from interviews, Top et al., 2004; FAO, 2007a; Forestry Administration, 2010; Walker et al., 2010; Bradley, 2011; Samreth et al., 2012; Sola et al., 2014; and Than, 2014)

5.3.3 Organizations

The actual organization of forest inventory in Cambodia in the 1990s was dominated by overseas organizations who provided technical assistance and personnel (e.g. FAO) and funding (e.g. UNDP).

Official responsibility for forest inventory was in the hands of first the Department of Forestry and Wildlife and then after 2003 the new Forestry Administration. However, their involvement in forest inventory activities was largely confined to collating information produced by inventory projects undertaken by overseas organizations, and by the companies awarded logging concessions (see Figure 5.1 in Section 5.2.3 for organisational structure).

5.3.4 Technologies adopted

The Government of Cambodia did not have a technology for undertaking forest inventory until the Department of Forestry and Wildlife, in collaboration with UNDP and FAO, undertook a pilot scale inventory project between 1996 and 1998. For the 1996-1998 project, a cluster sampling methodology, which uses 60x20 meter sized nine plots in a cluster, was adopted to select field sampling points based on a 4x4 km grid (FAO, 2007a). The project was planned for developing and testing a new methodology and processes for future forest inventories in Cambodia through training Cambodian forestry officers in the Forestry Administration to prepare for conducting NFI in the future (Table 5.5). As a result, the Forestry Administration established a Permanent Sample Plots (PSPs) system in 1998, as part of the FAO project (Samreth et al., 2012).

The technology consisted of a network of PSPs and a methodology for measuring them and analysing the data. Cambodia could have established its own inventory institutions when it set up its PSPs in 1998, and re-measured them in 2004. In compliance with the Forestry Law 2002, the Forestry Administration estimated timber stocks for commercial use from small areas, and also established general procedures for forest survey. For the measurements, nested rectangular plots were selected for the PSPs, which had sizes of 50x50m, 20x20m, and 10x10m (Sola et al., 2014). Although tree height was not measured, trees with DBH>7.5cm were inventoried during each measurement (Sola et al., 2014). Yet, the procedures were not embedded within the Forestry Administration.

Table 5.5 Existing technologies for major forest inventories before the REDD+ readiness programme in Cambodia

Year	Tittle	Institution	Methodology and methods	Remark
1996-98	Establishment of a forest resources inventory process in Cambodia	DFW with FAO/UNDP	- Cluster sampling method, 60x20m sized 9 plots in a cluster, for selecting field sampling points based on 4x4km grids (FAO, 2007a).	- 1:50,000 maps used (FAO, 2007a).
1998/2004 and 2010*	Permanent Sample Plots	DFW/Forestry Administration with MoE and FAO	- Plot shape: Nested rectangular plots, Plot size: 50x50m, 20x20m, 10x10m (Sola et al., 2014) - Trees inventoried: DBH≥30cm in plots and DBH≥7.5cm in sub-plots (Samreth et al., 2012)	- Tree height not measured.
2002*	Strategic Forest Management Plan (SFMP)	15 Forest Concessions	- Forest Concessions used different sampling methods	

* Total 6,940 plots in unlogged and logged evergreen, mixed and deciduous forests (Walker et al., 2010)

- For the 1996-98 inventory, 1:50,000 maps were produced using aerial photographs, and Landsat data for 1996/7 were also used (FAO, 2007a).
- During the 1996-98 inventory, attributes such as Altitude, Topography, Orientation, Slope, Soil type and Geological structure of plots, and Height, classes, Area of forest canopy cover, and Number of trees by different diameter and size classes from each plot were recorded (FAO, 2007a).

(Source: Generated based on information from interviews, FAO, 2007a; Forestry Administration, 2010; Walker et al., 2010; Bradley, 2011; Samreth et al., 2012; Sola et al., 2014; and Than, 2014)

5.3.5 Explaining Technology Adoption

5.3.5.1 Financial resources

Cambodia adopted a technology that was recommended by FAO and for which funding was supplied by the United Nations Development Programme (UNDP). However, the pilot scale inventory project was both short-term and limited in area, and the Government of Cambodia did not have the resources to extend the use of this technology to national scale and sustain it over the long term.

5.3.5.2 Institutions

The short-term nature of the pilot scale inventory project also prevented the procedures for undertaking forest inventories from being converted into sustainable national institutions. The Department of Forestry and Wildlife continued to rely on timber companies for inventory information and so it was this procedure which became institutionalized.

5.3.5.3 Human capital

As part of the pilot scale inventory project, forestry officers in Cambodia were trained in inventory techniques. Training was mainly provided by external organisations such as FAO and UNDP during the ‘Establishment of a Forest Resources Inventory Process in Cambodia’ project in 1996-98, which was a pilot scale inventory for building Cambodia’s forest inventory capacity by training staff (FAO, 2007a).

However, since Cambodian forestry officers were not able to continue using these techniques after the project ended the associated human capital declined over time. As forest inventories continued to rely on timber companies, and forest inventories by Cambodian forestry officers were undertaken irregularly, they had limited skills and experiences in field surveys. As the scale of forest inventories was small, they were not qualified for forest inventory activities at national scale.

5.3.6 The information gap between information supply and demand in growing stock monitoring

During the 1990s and the first half of the 2000s it can be assumed that the Government of Cambodia obtained the information on timber reserves in the country's forests which it required, and from the source that it had designated - timber companies operating logging concessions. This information did not enable it to form an independent view of the quality of logging and the sustainability of forest management in concessions, but it is likely that this was not a high priority for the government in this period, most of which predated the Forest Law of 2002. National information needs were not clearly defined by national policies.

5.4 The REDD+ Readiness Programme

In the 1990s and 2000s, information supplied to the Government of Cambodia on forest area and timber reserves was generally in balance with the information that the government required. However, after the Bali Road Map was agreed by the UN Framework Convention on Climate Change (UNFCCC) in 2007, the government became aware that the quality of its national forest monitoring system would not be sufficient to provide the information required as part of its participation in the Reducing Emissions from Deforestation and Degradation (REDD+) mechanism of the UNFCCC. In 2008, it therefore laid plans for implementing REDD+ Readiness activities to upgrade its system in cooperation with overseas agencies.

The REDD+ Readiness Programme provides an interesting case study of how overseas bodies offered a range of new forest monitoring technologies to a developing country, and how the developing country selected those which it felt best matched its future needs and present capacities. This section outlines the technologies that were offered to Cambodia in its REDD+ Readiness Programme. The following section describes which technologies were adopted by Cambodia and uses the Technology Adoption System (TAS) Framework to explain how the Government of Cambodia effectively selected the socially optimum mix of technologies.

5.4.1 The History of Cambodia's REDD+ Readiness Programme

Cambodia's REDD+ Readiness Programme began in 2011. It involved technical and financial support from a number of overseas aid agencies, as well as from UN-REDD, the body established by the United Nations to coordinate the activities of a number of UN agencies with expertise in increasing the capacity of developing countries in forest monitoring. UN-REDD provided US $ 4,201,350 for Cambodia's capacity building (UN-REDD, 2010), which was planned to be completed by 2013. Cambodia continued to be supported by the Forest Carbon Partnership Facility (FCPF) of the World Bank's REDD+ Readiness programme from December 2013 to December 2017 with a total budget of US $ 3,800,000. During this whole period, Cambodia was also financially and technically supported by the Japan International Cooperation Agency (JICA) in its REDD+ Readiness programme, by establishing CAM-REDD in 2010 based on a bilateral agreement, which is a project for facilitating the implementation of REDD+

Strategy and Policy in Cambodia (Winrock International, 2011). The JICA project was undertaken from the 1st of June in 2011 to the 30th of November in 2017 (JICA, 2017).

The REDD+ Readiness programme assessed existing methodology, data, and human capital to advance existing forest monitoring system, and provided outlines for establishing Cambodia's forest monitoring system (UN-REDD, 2013c; UNDP, 2013). UN-REDD focused on national strategy, implementation mechanisms and evaluating existing policy. Establishing an MRV system and a reference emission level, and designing a national forest inventory, was led by FAO, while technical aspects of capacity building for forest area monitoring were implemented by JICA.

Cambodia started its Phase 2, Results-based demonstrations activities after completing its REDD+ Readiness Programme in 2017, and plans to start its Phase 3, Results-Based Payments, in 2021 (Forestry Administration, 2016b).

5.4.2 REDD+ Readiness Programme for Forest Area Monitoring

Cambodia was offered a number of new forest area monitoring technologies in its REDD+ Readiness Programme. They were designed to enable the country to establish a Measuring, Reporting and Verification (MRV) centre that could supply information required by the UNFCCC once the rules for REDD+ had been decided. This information was likely to consist of historical forest cover changes, forest area by forest types, and forest carbon density for establishing a reference emission level by a forward projection of forest carbon stocks. The technologies offered to Cambodia for forest area monitoring included Landsat-based enhanced on-screen manual-visual classification and digital classification, ALOS-PALSAR based forest area monitoring, and LiDAR sampling.

Landsat-based enhanced on-screen visual classification and digital classification for forest area monitoring were proposed after the MRV team had discussions with the JICA technical assistance team and FAO staff. Landsat based forest area monitoring was proposed because Cambodia had relied on on-screen manual visual classification of the imagery, so it ensures compatibility with historical data, and with other countries in data format. Free data acquisition was also guaranteed by the new US Geological Survey (USGS) satellite data provision policy for Landsat. It also guaranteed obtaining historical data.

Adopting ALOS-PALSAR data was also offered to improve Cambodia's forest area monitoring capacity. It was envisaged that the use of the L-band SAR data could improve the frequency of monitoring forest area changes in responding to external information requests, as ALOS-PALSAR signal could penetrate through cloud and forest canopies, and can be operated at night. ALOS-PALSAR's L-band was demonstrated to have strong relationships with forest attributes and vertical structure such as height, diameter and above ground biomass of trees.

5.4.3 The REDD+ Readiness Programme for Forest Carbon Stock Monitoring

Cambodia was offered a number of new technologies that were intended to enhance the ability of its current national forest monitoring system to supply information on trends in forest growing stock, and expand the scope of this system to report on trends in carbon stocks and fluxes too. The technologies offered to Cambodia included developing new National Forest Inventory design and allometric equations, and OpenForis for inventory data management in addition to LiDAR sampling.

Designing a system for Cambodia's National Forest Inventory was planned by the REDD+ Readiness programme to provide emissions and removals factors that are necessary for REDD+ related activities (UN-REDD, 2013c), as Cambodia had never undertaken a national forest inventory, and existing Permanent Sample Plots (PSPs) were destroyed by forest cover changes, land use conversion, and illegal logging. The number of PSPs in Cambodia measured in 1998 and 2004 was 120 and 104 plots respectively, but only 48 plots were left in 2010, apart from 15 plots for forest regrowth monitoring (Walker et al., 2010). FAO and the MRV team members consolidated existing forest inventory data produced by overseas organisations and timber companies, but most of them were biased, because they were produced using different methodologies and differed from each other in forest variables. As part of developing new National Forest Inventory design, using OpenForis was recommended by FAO to facilitate Cambodia to collect, input, analyse and report inventory data efficiently. Open Foris is a set of free and open-source forestry software tools, including Collect, Collect Earth, Calc, and SEPAL, presented by FAO, by which inventory data can be entered, managed and analysed for forest inventories, conservation, monitoring and reporting purposes. It can also be used for land use, land use change, and deforestation monitoring using various satellite data.

Developing allometric equations was also proposed by FAO. As previous forest inventories were focused on timber stocks, Cambodia hadn't developed allometric equations and carbon factors that were essential for carbon stock estimations. Existing allometric equations, and available models (including soil organic carbon models) produced by overseas organisations, were only for specific areas, so they could not be used for developing country-specific emissions and removals factors.

LiDAR sampling technology was also proposed, and tested by the JICA air-survey team. LiDAR was proposed as Cambodia did not have the capacity to collect National Forest Inventory data on the ground. It was expected to provide forest carbon data for selected locations by its capability of three-dimensional spatial metrics of forest structure, stem volume, and canopy cover. Costs for implementing forest inventory were also expected to be reduced by using LiDAR data.

5.5 Forest Area Monitoring after the REDD+ Readiness Programme

The technologies and practices which were adopted after the REDD+ Readiness Programme are now described, and the Technology Adoption System framework is used to explain why new technologies were or were not adopted. Cambodia offers a good case study of how a government can identify the socially optimum set of technologies that balance the information needs of key actors and the limitations imposed by current national forest monitoring capacity and other relevant national conditions. Our analysis begins by looking at changes to forest area monitoring.

5.5.1 National and International Policies and Information Needs

5.5.1.1 International policies and information needs

Compared with the situation in the 1990s and 2000s, the big difference in international demand for Cambodian forest information after 2010 is for information on changes in forest area and carbon stocks to feed into regular reports to the UN Framework Convention on Climate Change now that developing countries will join developed countries in reducing their emissions of greenhouse gases as part of the successor to the Kyoto Protocol. The Reducing Emissions from Deforestation and Degradation (REDD+) mechanism was intended to be a central element of this contribution.

Cambodia had participated in negotiations on the new Protocol and on the design of REDD+ since 2007. The National Assembly of Cambodia ratified the Paris Agreement on Climate Change in 2016. It followed up its second National Communication to the UNFCCC in 2015 with a document that specified its Intended National Contribution to implementing the Paris Agreement (GSSD, 2015).

To meet international demand for forest area and changes information, Cambodia will have to report its forest monitoring statistics, which include forest area and carbon stock changes, to the UNFCCC every four years in National Communications (NCs). Cambodia's MRV team also needs to update the statistics every two years for Biennial Update Reports (BURs). For the purpose, monitoring is needed at much higher frequency.

5.5.1.2 National policies and information needs

Demand for forest information by the Government of Cambodia had not changed greatly since the new Forest Law was promulgated in 2002. However, the government was aware of the potential for utilizing for national purposes the information that would be produced for the UNFCCC by the new Measuring, Reporting and Verification (MRV) centre that it had established within the Forestry Administration.

For national use, Cambodia needs forest cover information for forest demarcation, forest classification and registration for forest management activities that include the development of forest resource and conservation of wildlife and biodiversity in forested areas (RGC, 2010). However, national demand for forest cover information is still not high, and Cambodia seems to focus more on meeting international information needs.

5.5.2 Outputs: frequency and resolution of mapping

Since starting the REDD+ Readiness Programme, Cambodia has increased the frequency of national forest cover mapping from once every four years (2010, 2014) to once every two years (2016). National scale forest cover maps have been produced for

2010, 2014 and 2016, and historical data have been reanalysed by the MRV team with support from JICA and FAO in order to develop Cambodia's Forest Reference Emission Level (FREL) that is subject to submitting to the UNFCCC for technical assessment (Table 5.6).

The spatial resolution of satellite images used for mapping has stayed the same at 30 m, since Landsat images are the main source of data, but the Minimum Mapping Unit (MMU) of forest area maps is enhanced. From 2010 to 2016, the spatial resolution of all the forest cover maps was 30m as the MRV team relied continuously on Landsat data for forest area monitoring, but the MMU of the maps was enhanced to 0.05 km^2, which corresponds to 5 ha.

Using Landsat 8 images has increased classification accuracy by moving from 8 bit radiometric resolution (256 brightness levels) to 16 bit resolution (63,536 brightness levels). Accuracies of the maps were assessed based on more intensive ground data collection, though it is still not very great.

Forest types within land cover classes were determined using the Land-Cover Classification System (LCCS) software version 3.0 developed and provided by the FAO. Thus, the number of land cover classes increased by 22, from 10 classes for the 2010 map, of which 11 classes are for forest cover.

Forest cover assessment and forest cover map generation were conducted using ArcGIS and QGIS, and verification and accuracy assessment were performed using ground data and very high resolution images available through Google Earth, in addition to RapidEye and SPOT images donated by JICA. In the process, several vector datasets such as 'boundary of forest plantation', 'social land concession', 'economic land concession', and 'locations of hydropower dams' were used as ancillary data to improve classification accuracy (Forestry Administration, 2016a). The overall accuracy of the 2014 map that was calculated by R, R-shiny application and Collect Earth is 81.23%.

Table 5.6 Existing official land use/cover and/or forest cover maps of Cambodia, produced by the Forestry Administration and/or external donors after starting the REDD+ readiness programme

Year	Producer and partner(s)	Satellite data	Resolution	Frequency	Scale/MMU*	Accuracy	Ground truthing
2010**	Forestry Administration supported by the Government of Denmark and ITTO	Landsat 5 TM	30 m	4 years	1/50,000, 0.25 km² (25 ha) (Forestry Administration, 2016a)	- Around 85% (Forestry Administration, 2016a)	104 samples
2014	Forestry Administration supported by UN-REDD and JICA	Landsat 8 OLI	30 m	4 years	1/50,000, 0.05 km² (5 ha)	- Accuracy 81.23%	212 samples (201 samples were actually visited***)
2016	Forestry Administration supported by UN-REDD and JICA	Landsat 8 OLI	30 m	2 years	1/50,000, 0.05 km² (5 ha)	- Accuracy being assessed.	Ongoing

* Minimum Mapping Unit
** The 2010 map is included in both before and after starting the REDD+ Readiness Programme, because it is produced during the transition period.
*** The number of total sample points for accuracy assessment of the 2014 map was 1,252, of which 1,040 points were checked using satellite images, such as RapidEye (165 points), Google Earth (527 points), and Landsat 8 (348 points) images (Forestry Administration, 2016a).
- Forest definition for the 2010 map is ‘Crown cover > 10%, Tree height > 5m, Minimum area 0.5 ha’ (Brun, 2013).
- Overall accuracy of the 2014 map is 81.23%, User’s accuracy is 78.70, Producer’s accuracy is 82.17%, Kappa coefficient is 79.49% (Forestry Administration, 2016a).
- Forest definition for the 2014 and 20016 maps is ‘Crown cover > 10%, Tree height > 5m and Minimum area > 0.5 ha’.
- As of 2016, the MRV team produced the 2014 forest cover map in 2015 for forest cover assessment and is working for generating the 2016 forest cover map. The 2014 map is not publicly available yet.

(Source: Generated based on information from interviews, Forestry Administration, 2012; Brun, 2013; and Forestry Administration, 2014)

However, although accuracy assessment for the Cambodia's 2014 map was based on the methodology and theory presented by Congalton and Green (2009), and the number of samples for ground truthing increased from 300 points for the 2010 map to

1,252 for the 2014 map, the number of sample points for ground truthing is still not sufficient for reliable accuracy assessment, because only about 16 % of the data used for ground truthing (201 sample points) was collected by actual field surveys. The remaining points for ground truthing were verified by Google Earth images (527 points), RapidEye images (165 points), and Landsat 8 images (around 350 points) (Forestry Administration, 2016a).

5.5.3 Organizational Structure

5.5.3.1 Internal organizations

Two major organizational changes have occurred as a result of the REDD+ Readiness Programme. First, in 2012 the government established a Measuring, Reporting and Verification (MRV) centre as a single point of contact for reporting to the UNFCCC (Figure 5.2). The MRV team is an inter-ministerial agency, but it is in fact a different name for the Watershed Management and Forest Cover Assessment office under the Forestry Administration. The MRV team is in charge of both forest area monitoring and forest inventory, and most forest monitoring practices for REDD+ MRV, including producing forest cover maps, estimating forest carbon stocks, collecting field data and planning MRV processes, are conducted by the RS/GIS unit in the Watershed Management and Forest Cover Assessment office under the Forestry Administration.

Second, the wider organizational position of the MRV centre with the Government of Cambodia has been changed. The MRV team has relocated and been affiliated to the General Department of Administration for Nature Conservation and Protection (GDANCP) of the Ministry of Environment since 2017. This organisational change made monitoring, and managing, protected forests in Cambodia easier, as the Ministry of Environment has jurisdiction over the areas. Although the Forestry Administration is the main agency of the Cambodia’s REDD+ Task Force, and provincial offices under the Forestry Administration support forest monitoring activities such as collecting field data for ground truthing, it only has jurisdiction over upland forests. In addition, by the change, the MRV centre can be more actively involved in international climate change initiatives as reporting GHGs emissions is the responsibility of the Ministry of Environment.

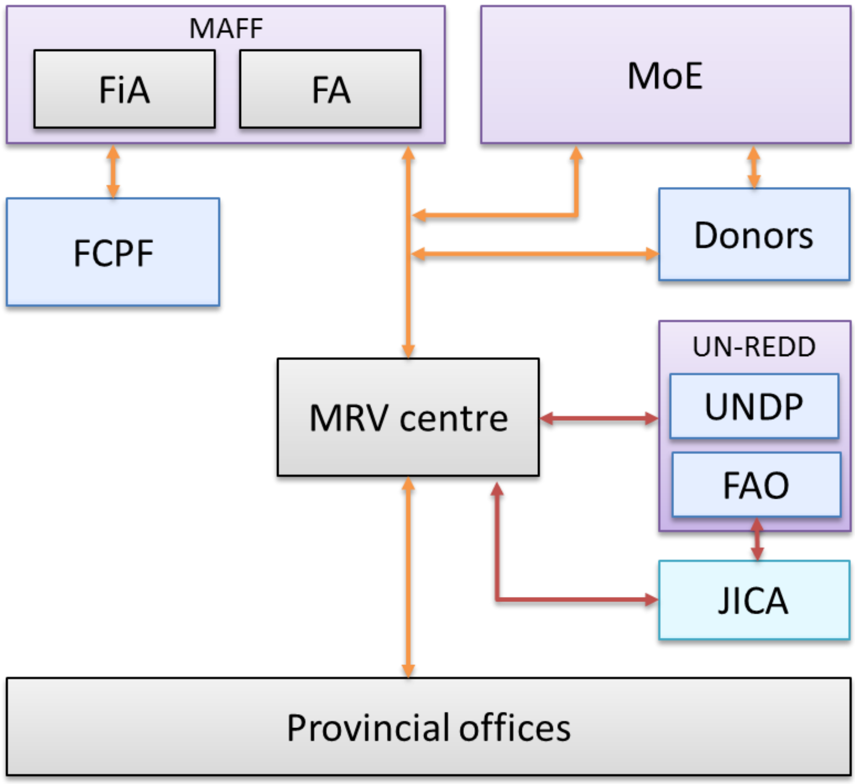

Figure 5.2 Key organizations for forest area monitoring for REDD+ MRV in Cambodia

(Arrows indicate communication links for forest data/information production/sharing for forest area monitoring, and red arrows indicate key communication links for forest area monitoring, JICA is supported by the Forestry and Forest Products Research Institute (FFPRI) in processing satellite data.)

5.5.3.2 External organizations

The MRV centre continues to be strongly supported by the overseas bodies which are providing technical and financial support for its REDD+ Readiness Programme. Such organisations include the Japan International Cooperation Agency (JICA), the United Nations REDD (UN-REDD) programme, the United States Agency for International Development (USAID), the World Bank and some other donors in monitoring forest area and establishing national forest monitoring system for Cambodia's national REDD+ MRV (Figure 5.2).

Of these organisations, UN-REDD, FAO, and JICA are key partners. JICA and FAO have been closely working with the MRV team since 2012, and plan and check all forest monitoring activities with the MRV team. The MRV team and FAO cover all the MRV components of the REDD+ Readiness Programme and capacity building, whereas JICA focuses mainly on satellite forest monitoring. Technical advisors from JICA support planning and implementing forest area monitoring and building a national forest monitoring system. They were also involved in developing Cambodia's reference emission level and producing reports submitted to the UNFCCC.

5.5.3.3 Communication links

Detailed examination of the potential advantages and disadvantages of new technologies has been helped by good communication links between the Forestry Administration and the overseas bodies engaged in Cambodia's REDD+ Readiness Programme. The MRV team works closely with JICA and FAO for forest area monitoring. The Forestry Administration has a 'Data Sharing Agreement' with FAO and JICA by which FAO and JICA use forest data and report analysis results derived from the data. Research for testing new technologies is conducted by the Forestry and Forest Products Research Institute (FFPRI) and a few universities in Japan that are linked to JICA (e.g. Hirata et al., 2018; Langner et al., 2014).

While there are strong communication links with JICA and FAO, the MRV team seldom work with other organisations as commented by an MRV team member and a technical advisor in JICA:

> *For forest area monitoring, I don't often work with people in other organisations. (Mr. Net Norint, 25th of July 2016)*

> *Data collection was quite difficult. Between government agencies, cooperation between them, for example between MoE and MAFF, is very difficult, and donor agencies are doing some duplicated jobs in some extant. This is not a unique situation of Cambodia. These kind of bureaucratic problems exist in any country. This is also a big obstacle in constructing database. (Mr. Shigeru Ono, 19th of August 2016)*

As the MRV team seldom communicates with other government agencies, the MRV team still has difficulties in obtaining permissions from other sister organisations for field campaigns and collecting existing historical field data, because forest areas in Cambodia are managed by three government agencies. The MRV team is a sub-division of the Ministry of Environment, so the MRV team members need permission from the Ministry of Agriculture, Forestry and Fisheries (MAFF) and the Fisheries Administration (FiA) to collect ground data, and to compile existing field data and historical data. These three different departments have produced statistics for forest resources which can be used as reference data. Although existing data that belong to different government agencies are now being integrated into a single NFI database, processes for collaboration take much time. This situation is explained by an MRV team member:

> *"Collecting field data is difficult. I did field survey about 10 times. One field survey for 1 week to 3 weeks… It takes more than 1 month to get data from other departments; sometimes it takes several months and sometimes the MRV team doesn't get response to the requests from sister organisations. So, we normally work with our own data." (Mr. Net Norint, 25th of July 2016)*

5.5.4 Technologies after REDD+ Readiness

The Government of Cambodia has retained on-screen manual-visual interpretation of satellite images as its main classification technology, but has adopted new technologies for satellite image processing such as image segmentation, tile-based manual mosaicking, and Principal Component Analysis (PCA) for change detection (Table 5.7). Although these new technologies were adopted by the MRV team, the actual methodology for forest area monitoring remained the same as before the REDD+ Readiness programme, i.e. on-screen manual-visual interpretation.

Table 5.7 Existing technologies for producing land use/cover and/or forest cover maps of Cambodia after starting the REDD+ readiness programme.

Year	Producer and partner(s)	Satellite data	Format	Methods	Land cover classes	Remark
2010 *	Forestry Administration supported by the Government of Denmark and ITTO	Landsat 5 TM	Digital format	Manual Classification	5 classes (of which 4 classes for forest types, 10 classes before merging)	- Additional imagery: QuickBird and Landsat 7 ETM+

2014	Forestry Administration supported by UN-REDD and JICA	Landsat 8 OLI	Digital format	Enhanced visual interpretation**	Total 22 classes of which 11 for forest	- Visual interpretation and verification supported by SPOT, RapidEye and GeoEye - Object-based classification using eCognition - Fishnet tool in ArcGIS for image mosaicking - Google Earth for verification and accuracy assessment
2016	Forestry Administration supported by UN-REDD and JICA	Landsat 8 OLI	Digital format	Enhanced visual interpretation	Total 22 classes of which 11 for forest	- Google Earth for verification and accuracy assessment - PCA for change detection - Fishnet tool in ArcGIS for image mosaicking

* The 2010 map is included in both before and after starting the REDD+ Readiness Programme, because it is produced during the transition period.

** Enhanced visual interpretation is called Semi-Automatic Classification by the MRV team and technical advisors from JICA and FAO.

- Technical and financial support for the 2010 map was offered through DANIDA.
- The methodology used for the 2010 map is similar to that for the 2006 map as the 'dependant interpretation' method was applied to the 2010 map (Brun, 2013).
- When the Forestry Administration produced the 2010 map, forest cover changes between 2002 and 2010 and between 2006 and 2010 were evaluated.
- Non-forest class in the 2010 has no sub-classes, since those maps were focused only on forest cover assessment.

(Source: Generated based on information from interviews, Brun, 2013; Forestry Administration, 2014; and Forestry Administration, 2016a)

Image segmentation was adopted in 2014 to produce a vector wall-to-wall map for the 2014 forest cover map (Figure 5.3 and Figure 5.4). It was done with eCognition using red-band Landsat images to perform visual land cover classification by identifying the type of objects (i.e. polygons) generated.

Tile-based manual mosaicking was adopted in 2015 to generate cloud-free satellite imagery for the 2016 forest cover map (Figure 5.3 and Figure 5.4). The whole

Cambodian territory can be covered by 15 scenes of Landsat L1T images, if there is no cloud cover in the images, but the MRV team used 54 scenes for the 2016 forest cover map due to persistent cloud cover in Landsat images. To generate cloud-free imagery, and to reduce the number of images, the fishnet tool in ArcGIS was used, by which a 10x10 km grid can be produced for the tile-based manual mosaicking.

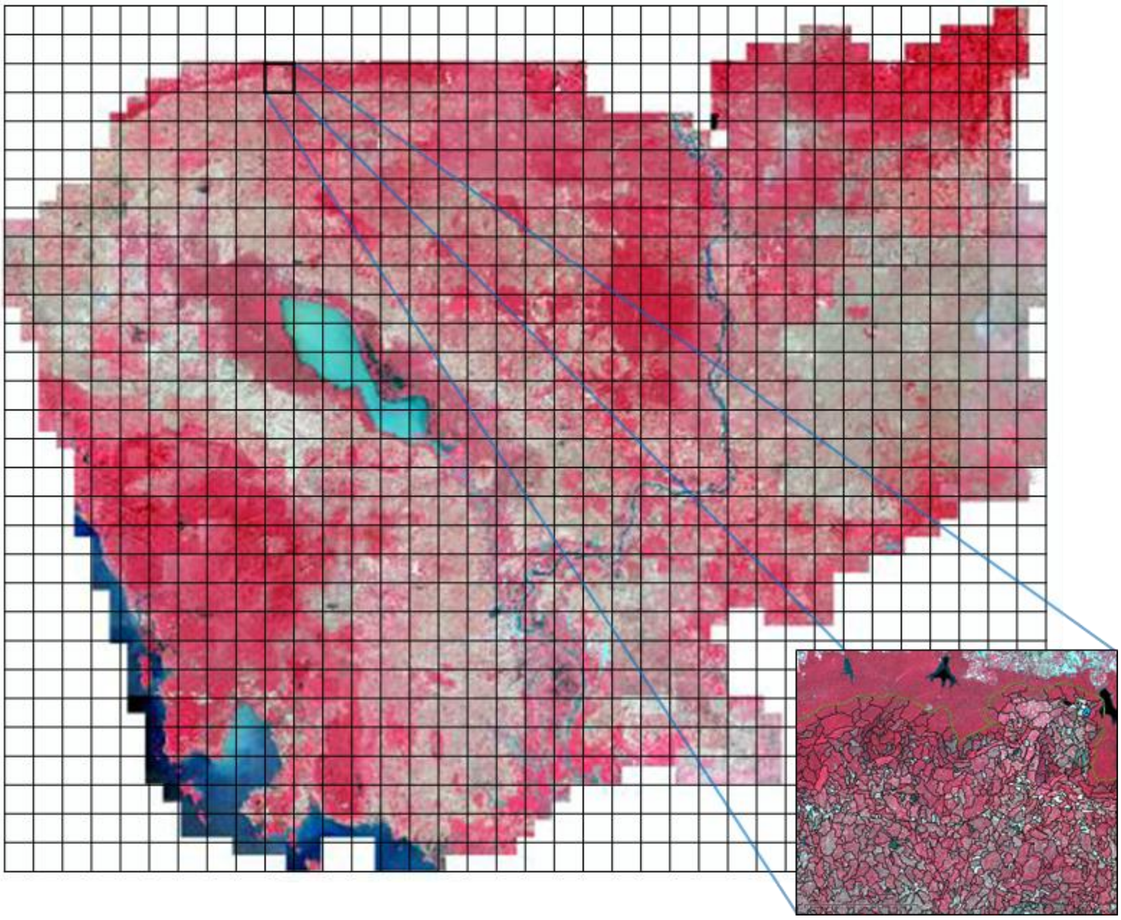

Figure 5.3 Mosaicked Landsat 8 images for the 2016 forest cover map, and image segmentation

(Tile-based manual mosaicking was performed using the fishnet tool in ArcGIS, Image segmentation was performed with eCognition for the 2014 forest cover map (bottom right, Krong Samraong area in Oddar Meanchey Province, Cambodia), Produced using images provided by the Forestry Administration of Cambodia)

To detect and extract deforested areas, and changes in land cover, between 2014 and 2016, the Principal Component Analysis (PCA) tool in ArcGIS was adopted in 2016, by which the MRV team can extract only changed areas using the 2014 and 2016 red-band Landsat images by setting threshold of the PCA data. It is, thus, much easier and saving time than using previous methodologies as the MRV team members can concentrate more on changed areas than unchanged areas. The 2016 surface reflectance image for the 2016 forest cover map was overlaid with binary imagery produced using the PCA threshold data to extract changed areas by visual interpretation.

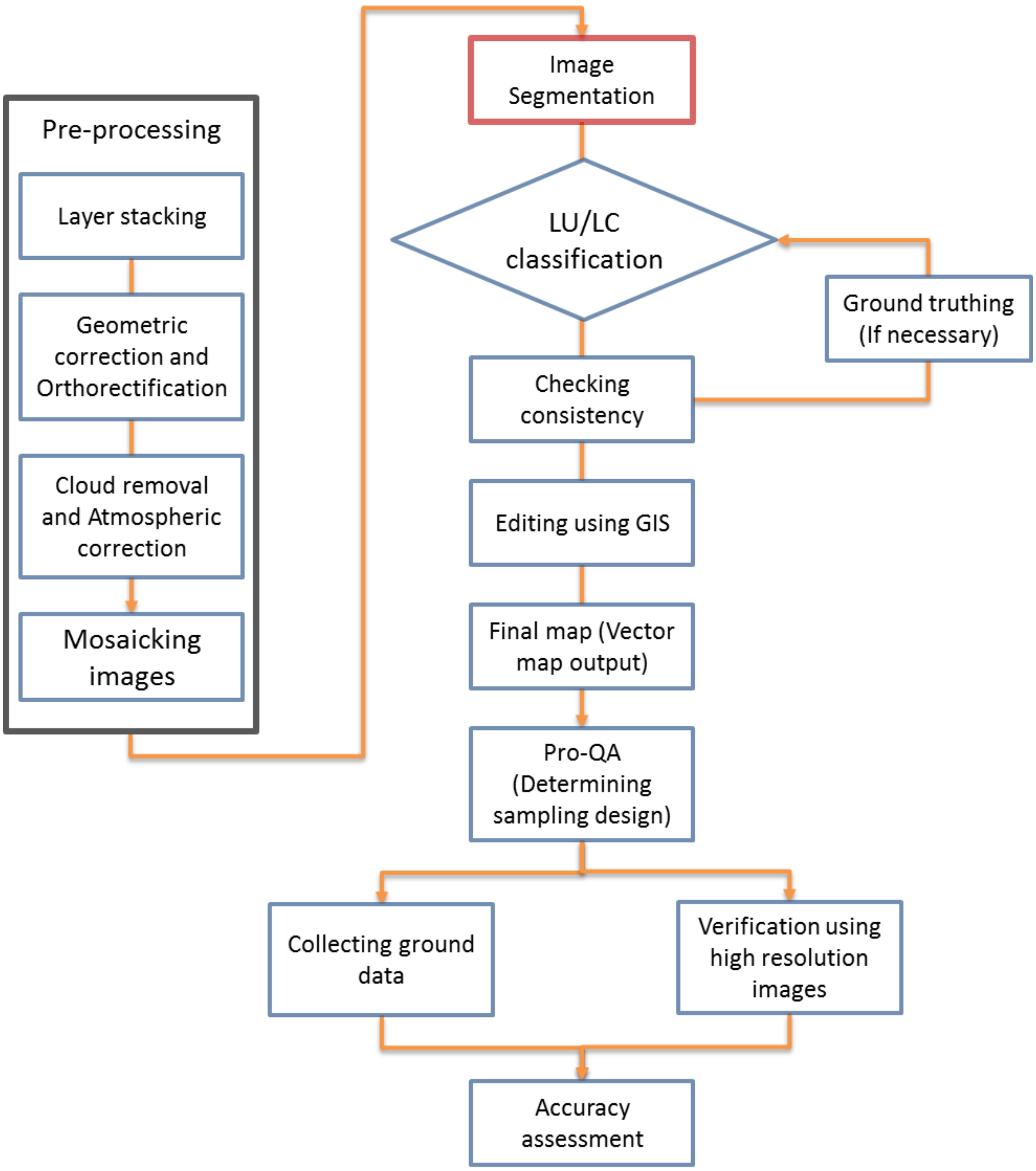

Figure 5.4 Workflow for producing the 2014 forest cover map

(Pre-processing processes in the black box (upper left) are performed by the Forestry and Forest Products Research Institute (FFPRI) in Japan, and the red box shows the major new technology adopted by the MRV team, which is also mainly performed by JICA. For the 2016 map, Principal Component Analysis (PCA) was used for change detection after image segmentation, Adapted from Forestry Administration, 2016a)

Some new technologies for forest area monitoring are operated by overseas organisations. Data acquisition and general procedures for pre-processing of the images, including atmospheric and topographic correction, and image mosaicking, are still performed by the Forestry and Forest Products Research Institute (FFPRI) to produce Landsat surface reflectance images (see, Figure 5.2 for organisational structure).

5.5.5 Decisions on Adopting New Technologies

Decisions by the Government of Cambodia on retaining existing technologies and adopting new technologies were made by means of a series of meetings between the MRV team, the Minister of Environment, overseas organizations (e.g. JICA and FAO) and other technical consultants.

These decisions were made by considering not only the need to provide information in future to the UNFCCC, but also the future needs of the Forestry Administration. To participate in REDD+, Cambodia has established a satellite forest monitoring system, and methodologies for forest cover assessment and forest cover classification, for MRV activities in accordance with the IPCC 2006 guidelines since 2014. The system is planned and designed not only for REDD+, but also for the whole forestry sector.

The MRV team could make decisions and adopted a few new technologies for forest area monitoring because there has been enduring leadership (see, Glied, et al., 2007), support from overseas organisations, and relationships relying heavily on personalised communications. As the Minister of Environment, and some other high ranking government officials, show strong commitment to participate in the national REDD+ programme, their political will and leadership provide sustaining impetus to change forest information production which could be promoted by changing rules. They are also the basis of strategic direction in forest area monitoring for its MRV system. Since the establishment of the MRV team, the manager, in addition to the Minister of Environment, has been continuously in charge of forest area monitoring, and the MRV team members also have not changed. Overseas organisations have been working with those government officials, including the MRV team, from the beginning of the REDD+ Readiness Programme in Cambodia. Such relationships could last due to personalised communications between government officials and people working for overseas aid agencies that enabled overseas aid agencies to renew and extend supporting projects, e.g. JICA programme and FCPF Readiness programme.

Decisions could be made in consultation with overseas organisations involved, but decisions on which technology to be adopted were, on the other hand, limited by them. As ‘harmonisation of past and current forest cover change based on available satellite images and aerial photographs’ was one main goal of the REDD+ Readiness Programme (UN-REDD, 2010), new technologies were recommended from this perspective, and based on the existing technology and system. For this reason, SAR and LiDAR were later excluded from alternative technologies for forest area monitoring. Completely new technology was not recommended by overseas technical advisors, hampering radical changes. This is evident in the statement made by a FAO’s forestry officer in Cambodia:

> *“We make recommendations, but we try to do that, based on what is already there. We are not going to recommend something which is completely new and which is not sustainable.” (Mr. Mathieu Van Rijn, 24th of August 2016)*

A few new technologies have been adopted by the MRV team to improve on-screen manual-visual classification, but adopting other more advanced technologies has been limited by various constraints. Such constraints are explained in detail in the following sections.

5.5.6 Explaining Technology Adoption

5.5.6.1 Human capital

One major consideration in adopting new technologies has been the need for compatibility with existing human capital and constraints on enhancing this.

5.5.6.1.1 Number of staff and trained staff

Two major constraints are the small number of staff and their limited qualifications. The present MRV team members started to work together for MRV activities from 2012.

Officials from different government agencies (i.e. the Ministry of Agriculture, Forestry and Fisheries, the Ministry of Environment, the Ministry of Mines and Energy, and the Ministry of Interior) started to work together in the MRV centre, but most of them returned to their original agencies. In 2017, at the MRV centre, five forestry officers are working for forest cover assessment for MRV activities. They are responsible for Cambodian MRV activities and forest cover assessment, including producing historical forest cover maps for the Cambodia's forest reference emission level, accuracy assessment, and field data collection for ground truthing and verification (Table 5.8). All the members studied forestry science during their undergraduate degrees, and attended only one module for RS/GIS during this time. Two of them were recruited after starting the REDD+ Readiness programme.

Table 5.8 Demographic features including main duties, experience and educational backgrounds, of the Cambodian MRV team members

No.	Position at the MRV centre	Main duty	Duties for MRV	Experience in forest monitoring	Educational background	Remarks (Ability in image processing)
Forestry officer 1	Deputy Head of the MRV centre	Planning MRV processes, and managing forest monitoring practices, FREL and Forest cover assessment for REDD+ MRV	Managing producing forest cover maps, estimating forest carbon stocks and collecting field data	Since 2005 (11 years)*	BSc in forest science and MSc degree in RS/GIS from AIT**	One of the Authors of FRA 2010 and 2015 Cambodia, and responsible for MRV activities in Cambodia.
Forestry officer 2	Deputy Chief of the MRV centre	Managing FREL and Forest monitoring	Producing forest cover maps for establishing a FREL	From 2007 (9 years)	BSc in forest science and MSc in RS/GIS from AIT	Responsible for establishing a FREL in Cambodia
Forestry officer 3	Deputy Chief of the MRV centre	Satellite Forest Monitoring and NFIs for REDD+ and forest management plan	Verification and accuracy assessment and collecting ground truth data by combining time-series images	From 2008 (8 years)	BSc in forest science, attended a module for RS, GIS and GPS	Learned ArcView for forest mapping in 2008 and started working on RS in 2010

Forestry officer 4	Forestry officer	Assistant to the deputy head of the MRV centre and forest cover assessment	Satellite Forest Monitoring and NFI for producing land use/cover maps for 2014 and 2016	From 2012 (4 years)	BSc in forest science, attended a module for RS, GIS and GPS	Worked for NGO from 2008-2012; Wild Life Conservation - Bird Life Institution
Forestry officer 5	Forestry officer	Administration	Technical assistance for producing forest cover assessment	From 2013 (3 years)	BSc in forest science	No other previous experience, but attended a module for RS, GIS and GPS

* Before 2005, forestry officer 1 worked as a forestry administrator in the Forestry Administration
** AIT is the Asian Institute of Technology (AIT) in Thailand
- The MRV team members started working together in 2013, as an MRV team
- All the members studied forest science during their undergraduate course
- Most of them attended only one module for remote sensing, GIS and GPS for forest monitoring during their undergraduate courses

The MRV team could adopt a few new technologies, i.e. image segmentation and Principal Component Analysis (PCA), as the quality of human capital was enhanced. The Deputy Head and the Deputy Chief of the MRV centre obtained master degrees from Asian Institute of Technology (AIT) in Thailand. During their master degrees, they studied remote sensing and GIS, focusing on digital classification of optical satellite data, and tried to adopt digital classification after completing their degrees. This is stated by the Deputy Head of the MRV centre:

> *"Me and Sophyra got MSc degrees from AIT in 2008 and 2009. So we tried to introduce automatic classification methods. Until 2014, we tried to apply semi-automatic classification."* (Mr. Leng Chivin, 7th of August 2017)

However, adopting other new technologies, e.g. radar and LiDAR, was limited by human capital, as the MRV team members still have limited skills and knowledge on other sensors. More specifically, technology adoption is hampered by operating existing technology, training and the MRV team members' educational backgrounds, languages and perceptions, which are related to human capital. This is explained in more detail in the following sections.

5.5.6.1.2 Operating existing technologies and training

The limited skills of present staff are clear from interviews carried out with them. The MRV team members normally deal with optical images, so all of them can analyse Landsat data for land and forest cover maps. Senior staff can analyse RapidEye, SPOT, ALOS images for forest cover assessment, while two juniors can only analyse Landsat data for forest cover assessment and use SPOT and RapidEye data for accuracy assessment by visual checking. All of them use Erdas imagine, eCognition and ArcGIS for forest monitoring and producing forest maps, and most of them have minimum knowledge of Google Earth Engine. The Deputy Chief has basic minimum knowledge about R and Matlab, and only one of them uses ENVI sometimes.

Although the MRV team members are used to analysing optical data, adopting new technology is limited by operating existing technology. It is because the MRV team members analyse optical satellite data by on-screen manual-visual interpretation and have limited educational backgrounds in remote sensing, GIS and spatial data analysis. For this reason, they are used to handling data in vector format but have difficulties in converting and processing data in other data formats. This is an obstacle to adopting other technologies such as digital classification, SAR and LiDAR.

Using computing languages is also affected by operating existing technology, eventually hampering adopting other technologies. Analysing raster data for national forest area monitoring is extremely difficult without using computing languages because of the size of data. Although they have attended several training courses for R, Python, Matlab, and Google Earth Engine, most of the MRV team members cannot use computing languages for forest area monitoring as they do not use computing languages for their day-to-day work. The Deputy Head of the MRV centre commented that:

> *"They don't use computing languages for land cover maps, so they can't use computing languages. They don't have any difficulties caused by computing languages during their work because they don't need to use computing languages for their duties. They could learn new computing languages to operate new*

> *technologies to be adopted, but now we don't have a plan for using other images or software."* (Mr. Leng Chivin, 15th of July 2016)

For junior staff, operating existing technologies is limited also by human languages. It is the same for testing and adopting new technology, because most manuals and training for new technologies are given in English, as stated by an MRV team member:

> *"When I worked and attended training courses, I had some problems with English, and normally the Deputy Chief translates English to Khmer for us when we have training in English in our building."* (Mr. Net Norint, 25th of July 2016)

Almost all staff in the MRV centre have limited abilities in image processing, including computing and human languages, except those for on-screen visual classification and modifying vector data. It may be because the MRV team members' educational backgrounds are not for analysing spatial data, and they learned skills by conducting their tasks, in addition to attending short-term training courses. Junior staff had much less experience and pre-education.

As it is well known that to analyse satellite data, a basic knowledge of key principles is very important, the MRV team, and overseas aid agencies, tried to raise the quality of human capital by attending short-term training courses, but it was not effective. Training on forest area monitoring using satellite data, REDD+, MRV and IPCC guidelines was provided during the Readiness programme (UN-REDD, 2013c), as taking regular education courses was difficult without long-term plans. For remote sensing, in 2015 and 2016, all the team members have attended training courses on various sensors and different pieces of software for collecting and analysing data for forest monitoring; some of the MRV team members, for instance, attended training courses such as 3 training courses for LiDAR, 1 training course for SAR for 3 days, ENVI for 3 days, Google Earth Engine for 15 days, QGIS for 7 Days, eCognition for 7 days and OpenForis for 7 days. FAO's remote sensing specialists have also provided training for accuracy assessment, and the MRV team members learned 'Terra Amazon' for producing forest maps. Yet most training courses were just for introduction, and were not very effective in raising capacity for analysing satellite data using more advanced approaches, and for adopting new technology, although they were effective for operating existing technologies. Despite the training, the MRV team members cannot process higher level input data by operating appropriate software for the processes, and understanding the rudiments of geographical information science and remote sensing technology is not much improved. Most junior members have difficulties in processing and analysing other satellite data, other than Landsat data. Training for capacity building and technology adoption is limited by prior qualifications as stated by a JICA technical advisor:

> *"Japanese institutes proposed to use R and 3 Japanese professors visited to teach R. But they didn't check how many people have ever used scripting and they didn't understand what kind of education they received at university and high school. It was completely failed." (Mr. Shigeru Ono, 19th of August 2016)*

The MRV team members' actual image processing skills after attending training courses were explained in the statement made by the Deputy Head of the MRV centre who is responsible for producing activity data:

> *"Only Ms. Sophyra and I have MSc degree in RS and GIS, but the others just attended training courses after finishing their undergraduate courses. Some of them can analyse optical data, such as Landsat and RapidEye, but I don't think we can analyse LiDAR data. SAR such as ALOS-PALSAR data might be possible to be used by a few of us."* (Mr. Leng Chivin, 15th of July 2016)

The quality of human capital in *provincial* offices is much lower than that of staff in the MRV centre, and raising their capacity was also limited by their education. Provincial offices may not need to produce forest maps, but lack of provincial offices' forest monitoring capacity may cause some issues in producing forest information as provincial offices are important in providing ground truth data for classification and verification, establishing sub-national FRELs, and ensuring the accuracy of forest area maps. Human capital in the provincial offices is low, and training them was difficult, as explained by the Deputy Head of the MRV centre and a member of the MRV team:

> *"Staff in provincial officials cannot collect ground truth data by themselves. We go there and request them to join us because they very well know about the specific areas … We produced random points so we know where we have to go and how much data we have to collect. We are working together. We prepare everything and then we request them to join when we go to the field."* (Mr. Leng Chivin, 7th of August 2017)

> *"We tried to teach local forestry administration staff, buy they couldn't learn how to analyse satellite data. So we stopped teaching them. We just taught them how to use GIS and GPS, but not Remote Sensing techniques." (Ms. Hout Naborey, 29th of August 2016)*

Interestingly, actual forest monitoring capacity for MRV activities in the MRV centre has been raised by interactive and personalised communication outside formal training sessions (see Palacpac, 2009), as stated by a member of the MRV team:

> *"When I have questions regarding script methods, I ask the questions to the person who taught me, working for the US survey. I keep contact with the trainer… We all attended the training courses together, but I don't know why they [the other MRV team members] are not interested in using Google Earth Engine. It takes time to use it. I think I can use Google Earth Engine."* (Ms. Hout Naborey, 29th of August 2016)

This is 'learning through personalised communication'. When JICA proposed new technology for producing the 2014 forest cover map, it provided personal training many times and checked the MRV team members' progress. The MRV team members can now perform all the mapping processes for forest cover assessment by themselves, except pre-processing. The MRV team members closely work together with JICA in the same office, and they use the technologies for their work repeatedly. The MRV team members take some benefits from other training, but existing capacity for forest cover assessment seems to be the result of close long-term cooperation with JICA, as an MRV team member and a technical advisor from JICA commented:

> *"We can do all the mapping process but JICA provides some new methods such as PCA … When JICA adopt new technology, they teach us, and check progress. That is why we know how to do this. We don't have backgrounds and degrees on this."* (Ms. Hout Naborey, 29th of August 2016)

> *"We are not only proposing new methodology, but test it together and then together side by side we make a map … We are still here, like Mr. Furuya. So if there is this kind of long term commitment from donor agencies, it is good because they simply come here and submit proposals, but we take care of the rest. Long term care is very important in order for them to understand new technology for capacity building and adaptation … We installed software and trained people to*

> *run ... Our duty is supporting, but sometimes we implement. The most important thing is we stay together to be implemented by government officials." (Mr. Shigeru Ono, 19th of August 2016)*

5.5.6.1.3 Awareness and Perceptions

Decisions on adopting new technologies are not made in a mechanistic way, but also depend on the awareness and perceptions of staff involved. Two senior officers at the MRV centre are well aware of information needs, required forest information resolution and frequency and reporting cycles, while other members have only little knowledge of required forest information resolution and frequency. Information on MRV activities is obtained through overseas aid agencies, as the MRV team members check and discuss all their work with technical advisors from JICA and FAO. Thus, the MRV team members don't think they have problems in responding to information needs from international conventions although they think they need more staff for forest information production as forest area monitoring by visual interpretation takes much time.

The MRV team members have not much information on how other MRV centres in surrounding countries produce forest information and what kind of technologies they are using for their duties, as commented by the Deputy Head of the MRV centre:

> *"We don't have this network system sharing together, even Mekong countries. In Mekong region, there are 5 countries, and Vietnam has the best capacity ... We don't have proper network with Mekong countries but are working with a research centre under European Commission. They are going to establish regional network on sharing database."* (Mr. Leng Chivin, 7^{th} of August 2017)

This kind of lack of information, and awareness, can hamper adopting new technologies and establishing a robust MRV system. Senior forestry officers think Cambodia is developing its own forest monitoring system for MRV, and so the MRV team is not trying to follow other countries in establishing Cambodia's MRV system. This is evident in the statements made by an MRV team member:

> *"I have only little knowledge about other MRV teams ... But we are developing our own forest monitoring system for MRV, so sometimes just consider and refer to the situations of other MRV centres. We are not trying to follow them in establishing*

> *MRV system. We develop our MRV system by working with international organizations [FAO and UNDP] and organizations from Japan [JICA and FFPRI]."* (Ms. Sar Sophyra, 20th of July 2016)

For this reason, the MRV team members also think at this stage that existing technologies are sufficient for their work and information production although they are willing to learn and adopt new technologies to make their tasks easier.

Despite the perceived usefulness of adopting new technologies, such as improving their work performance and information production, adopting such technology is limited by awareness and perception that are affected by organisational policy, obtaining information, and educational backgrounds. Although the existing technology cannot fully meet national and international information needs, the MRV team members feel that existing technology is sufficient for forest area monitoring and MRV activities for REDD+, and do not feel they need more advanced technology, because existing technology that were improved through the REDD+ Readiness programme was already determined by organisational policy for information production.

Decisions on not adopting SAR and LiDAR data were also limited by perceptions that are formed based on the MRV team members' educational backgrounds, abilities and awareness. The MRV team members feel that they cannot analyse active sensor data, although they have attended training courses on SAR and LiDAR provided by the Japan Aerospace Exploration Agency (JAXA) and the SilvaCarbon programme, which is a capacity building programme of the US Government to enable tropical countries to measure forest and terrestrial carbon. Such perceptions of SAR and LiDAR are explained by a member of the MRV team:

> *"Even if Mr Chivin decided to adopt LiDAR, we would not be able to use it because we don't have any knowledge and information about that. We can analyse only optical data. In 2016, we tried to use Sentinel-1 data but that was difficult. Our country has no enough ability to do that."* (Ms. Hout Naborey, 29th of August 2016)

This has influence on making decisions on new technologies to be adopted because when making decisions, seniors and technical advisors from overseas aid agencies take account of how the MRV team members perceive new technologies, and whether they can use alternatives.

This is the same for scripting methods, such as Google Earth Engine. The MRV team members think they don't need computer languages for their work as they use medium resolution optical images only. All of them feel that scripting methods are very difficult and that they may not be able to use them although they are willing to learn more computing languages. At the moment, only one MRV team member uses Google Earth Engine (GEE) for generating historical data and sample points for verification and accuracy assessment of changes from 2006 to 2014.

Such perceptions of active sensors are not only for the MRV team members but also for JICA technical advisors who have significant influence on making decisions on technology adoption. The technical advisors also feel analysing active sensors data is extremely difficult, and also think the MRV team may not be able to analyse the data acquired by active sensors, as stated by a technical advisor from JICA:

> *"Processing raw SAR data is very difficult that is why JAXA provides pre-processed L-band SAR data. Sugarcane and Cassava have very strong backscatter signals. Using SAR data for tropical forest monitoring is very different to use them for monitoring urban areas or other earth surface. In Indonesia, they partly use SAR data for land cover and forest monitoring but they check one by one using Landsat data. LiDAR looks like easy, but clean up LiDAR data is difficult."* (Mr. Shigeru Ono, 19th of August 2016)

5.5.6.1.4 Institutional change

The Government of Cambodia, in consultation with key organizations providing the REDD+ Readiness Programme, e.g. FAO and JICA, also decided that the technologies used by the new MRV centre should involve as little change as possible in existing institutions. Before producing the 2014 forest cover map, technical advisors from JICA evaluated existing forest monitoring capacity to recommend advanced technology for forest area monitoring since Cambodia needed to meet international information needs for REDD+. After having a series of discussions and workshops, new technologies to be adopted were decided. As participants are aware of their capabilities, decisions were made based on the evaluation of existing resources, including human capital, budget and existing technologies. The leader of the technical assistance team from

JICA explained how existing technologies for forest area monitoring and verification were selected:

> *"We have analysed what they have done and what is necessary in the immediate future, then we together decided we should use eCognition system to upgrade the historical method a little bit, not dramatic change. And also we provided opportunities for capacity building. This is where we are. So, the mapping method of the MRV team is visual interpretation, eCognition for segmentation and visual identification. It is not automatic. This is our system." (Mr. Shigeru Ono, 19th of August 2016)*

As Cambodia had limited resources, especially human capital, they had to minimise changing existing institutions. Without considering such constraints, adopting new technology including institutionalising new technologies would have been limited by such factors, as the Forestry Administration of Cambodia kept repeating producing new forest cover maps and updating existing maps by relying on on-screen manual-visual interpretation since 2002.

Institutional changes were minimised by overseas aid agencies' participation in national forest area monitoring. Instead of the MRV team, image mosaicking, image segmentation and Principal Component Analysis (PCA) for change detection are performed by JICA and the Forestry and Forest Products Research Institute (FFPRI) in Japan. This is why new satellite image processing methods are implemented by overseas organisations, while only visual interpretation parts are performed by the MRV team manually.

> *"We had experience in manual classification from 2002 to 2006. In 2014, from the experience, we had to update our technical perspective for REDD+ mechanism ... In 2013, we discussed with our international experts and they said that Cambodia should use semi-automatic classification."* (Mr. Leng Chivin, 7th of August 2017)

In view of these limitations on human capital, it was understandable that a decision was taken that expanding the type of satellite images processed from the optical sensors used at present to also include non-optical sensors, such as radar and LiDAR, would not be compatible with existing human capital in Cambodia.

5.5.6.2 Existing technology

A major constraint imposed by existing technology on the adoption of new technologies was the very slow Internet speed available to government agencies in Cambodia. This has prevented adoption of new technologies that rely on cloud-based processing. All new data processing technologies that require Internet access, including cloud-based geodatabase systems, and downloading satellite images were excluded from the list of available technologies by this reason. Google Earth Engine is often recommended by FAO for forest area monitoring, for example, but was not adopted due to limited internet connection, and electricity supply. In Cambodia, Internet connection is not stable and blackout happens frequently, as explained by the technical advisor from JICA:

> *"When donors tried to provide a good system, they asked what happened to the Internet. Donors have to provide some special fund for this, like FAO does. It is because their system depends upon high speed Internet. JICA knew about this problem, so usually we do not recommend Internet-dependent system … In Phnom Penh, there are so many high speed internet shops available, but it is not true in government agencies. That is why we had difficulties in using Google Earth, because it uses quite wide signals which are often very inefficient." (Mr. Shigeru Ono, 19th of August 2016)*

Adopting other new technologies, such as digital classification, SAR and LiDAR for satellite data processing was also limited by existing technology, including methodology, software, hardware, and information technology infrastructure in addition to other technical reasons. Supervised classification was not compatible with existing technology, as existing image processing methods for forest area monitoring had completely relied on dealing with vector data from Landsat images. Existing technologies for data collection and analysis are not compatible with those for other technologies that need to process raster format digital data. In addition, digital classification was also not possible because the existing 22 land cover classes that were decided to be used for both national and international purposes is not compatible with automatic and semi-automatic digital classification. SAR or LiDAR were not adopted, as processing such data require more specialised and advanced software, hardware and facilities, as well as expertise.

5.5.6.3 Financial resources

Although overseas organizations have provided generous financial support for the purchase of new hardware, software and satellite images, and for training Cambodian staff, there have necessarily been limits to the funds available to the MRV centre from these organizations and from the Government of Cambodia. If unlimited funds had been available, it would have been possible to circumvent the limitations imposed by poor Internet access by installing new high speed and high capacity server computers, but this has not been possible.

Some improvements were made, but financial resources for more advanced technologies, such as digital classification, radar and LiDAR are still not sufficient. Digital classification and analysing radar data for national forest cover maps, for example, requires higher computing power, bigger data storage and recruiting new forestry officers with appropriate expertise. Analysing radar and LiDAR data requires purchasing satellite, or airborne, data and software optimised for analysing the data. Air survey facilities including aircraft and sensors that can be used for LiDAR do not exist in Cambodia. The need for financial, and technical, assistance was partly met by overseas bodies such as UN-REDD, FCPF and JICA, but they are focusing on subtle improvements in existing technology.

National contributions to forest area monitoring are still not sufficient. Although the Ministry of Environment shows its will to implement REDD+, national policy does not seem supportive enough, as evident from financial support. To commence the result-based payments phase of REDD+, monitoring forest area changes by producing forest cover maps for supplying activity data at greater accuracy is required. However, unlike stated policy, financial support from the government remained the same as before, and political decisions to increase budget for forest cover monitoring activities and capacity building have not been made yet, though the needs of financial and technical assistance were expressed by the Cambodian government at the General Debate of the 68th and 70th sessions of the UN General Assembly in 2013 and 2015.

Financial constrains also limit training in new technologies. Even if the MRV team members want to attend training courses, they are limited as stated by an MRV team member:

> *"I have attended 1 or 2 days training from FAO and requested more training. There would be no training planed. No funding." (Ms. Hout Naborey, 29th of August 2016)*

Since the MRV team members have limited opportunities to improve their abilities, this is another obstacle to adopting new technology.

5.5.7 The Gap between Forest Area Information Supply and Demand

Improvements made to forest monitoring in Cambodia as a result of the REDD+ Readiness Programme have gone some way to meeting the future needs of the UNFCCC in REDD+ reporting (Table 5.9). A good example of this is the ability to establish a 12 year historical baseline. Using the existing maps from 2002 to 2014, Cambodia can establish a 12 year historical baseline for reporting, giving 4 year frequency, and it will be intensified up to 2 year basis soon. Current data format and land classes for activity data match UNFCCC recommendations for reporting. Cambodia's methodology is consistent with Approach 3 in the IPCC guidelines, which uses spatially explicit land cover data (Forestry Administration, 2010).

Table 5.9 The gap between forest area information supply and demand after the REDD+ readiness

		Information supply after starting REDD+ readiness	Information demand (UNFCCC recommendations)**
Factors in forest area monitoring	Satellite images	Landsat images	Various
	Data format	Digital	Digital
	Image processing	Semi-automatic (Enhanced visual interpretation)	Recommendations provided
	Frequency/ Resolution	4 years*/30m, but minimum mapping unit is 5 ha at best (Frequency is improving up to 2 years)	Reporting: 4 years for NCs, and 2 years for BURs***/as high as possible. Measurements require higher frequency and resolution.
	Small scale deforestation (Near real-time monitoring)	Planned but not monitored	Small scale deforestation monitoring recommended

	Forest degradation monitoring	Planned but not monitored	Degradation monitoring recommended
	Drivers of deforestation (Human activities)	Planned but not monitored, patterns of deforestation and land use changes not analysed	Recommended
	Forest regrowth	Measured (1 class for regrowth)	Forest regrowth monitoring recommended
	Land classes	22 classes of which 11 for forests	Recommendations provided (6 classes for LULUCF with sub-classes)
	Accuracy	Accuracy of 2014 map 81.23%	As high as possible/necessary for results-based payments
	Points for ground truth	2014 map 1,252 of which 212 from field survey (Forestry Administration, 2016a)	Not specified but uncertainty assessment and QA/QC**** needed
	Human resources	Minimum trained staff (2 MSc, 3 BSc) and very limited human capital in provincial offices	Not specified
	Institutions	Existing established practices and progressing	Various but fixed practices needed*****

* working on improving frequency from 4years to 2 years by producing the 2016 forest cover map
** IPCC guidelines provide different approaches for forest area monitoring in accordance with accuracy of data.
*** To comply with the UNFCCC decisions, Annex I nations are required to submit their National Inventory Report (NIR) every year, which includes emission from forests, but at the moment, it is not for developing countries.
**** Quality Assurance and Quality Control
***** Digital classification is recommended for frequent monitoring and updates
- International policies recommend tropical countries to measure and report their forest carbon stocks and changes in accordance with the UNFCCC reporting requirements and the most recent IPCC guidelines for the Agriculture, Forestry and Other Land Use (AFOLU) sector (GFOI, 2016; UNFCCC, 2010).

On the other hand, gaps between information demand and supply still exist. The first is the quality of forest area information. While visual interpretation and change detection has been enhanced by the adoption of image segmentation and principal component analysis, the spatial resolution of monitoring is still not small enough. For REDD+, resolution of forest area mapping is not specified by the UNFCCC, but the current resolution of forest area monitoring is still not sufficient for producing activity data that shows ‘the extent of human activity causing emissions and removals’, as the minimum mapping unit of 5 ha could still miss a lot of deforestation caused by illegal logging, forest fires and encroachment. Moreover, for Cambodia's reference emission level, the minimum mapping unit is 25 ha because of compatibility with historical data. Improving resolution of forest area monitoring is limited by existing technology, i.e. enhanced on-screen manual-visual classification, institutions, and human capital. For monitoring forest degradation, the MRV team will have to use higher spatial resolution images unless forestry officers at provincial offices conduct intensive field surveys and regular patrols.

The quality of forest area information is also shown by the accuracy of forest cover maps. Improving accuracy of forest area monitoring is limited by existing technology, i.e. minimum mapping unit and image interpretation methodology, institutions, and political support from the Cambodian government, due to the inherent limitation of manual visual interpretation. Collecting field data for accuracy assessment is not fully supported by provincial offices.

Finally, the ability to supply information on more complicated aspects of forest change, such as forest regrowth and forest degradation, is still not sufficient. Although the UNFCCC provides only rough recommendations for MRVs instead of detailed operational methods (FCPF, 2016), there are activities and elements that need to be monitored and reported for REDD+. Those include forest regrowth, forest degradation, leakage and monitoring negative drivers of deforestation. Monitoring such elements is also limited by existing technology, institutions, human capital, and financial resources. A system for monitoring negative drivers of deforestation and forest degradation, which could be caused by 'leakage' and accelerate forest carbon emission from 'forest remaining forest' is yet to be established as stated by a forestry officer:

> *"Currently, we don't have any capacity for monitoring forest loss such as illegal logging, selective cutting, fuel wood collection, and forest fires. For REDD+, we need a clear and obvious MRV system, but currently we only monitor deforestation."*
> (Mr. Chhun Delux, 1st of August 2016)

The identified gap between information supply and demand indicates the need for further improvements in forest area monitoring, yet improving information supply by adopting new technology is hampered by institutional, organizational, technological, financial and human capital constraints on changing institutions, in addition to national policy, as mentioned above.

5.6 Forest Growing Stock Monitoring after the REDD+ Readiness Programme

For Cambodia, as for many tropical countries, the biggest challenge in making the transition to REDD+ reporting involves reporting on changes in forest carbon stocks. This is because two main improvements are required. First, undertaking regular National Forest Inventories to measure changes in forest timber volume, or growing stock. Second, developing methods to convert changes in forest growing stock into changes in forest carbon stocks. As was reported in Section 5.3, the quality of forest inventory information in Cambodia before the start of the REDD+ Readiness Programme was very low, and the country had limited capacity to convert estimates of growing stock into accurate carbon equivalents.

5.6.1 National and International Policies and Information Needs

5.6.1.1 International policies and information needs

Even if a National Forest Inventory (NFI) can be undertaken, to comply with UNFCCC requirements Cambodia will need to develop the capacity to convert estimates of changes in growing stock into changes in carbon stocks. Cambodia is required to estimate changes in biomass and carbon quantities in forests between two points in time by conducting NFIs. For estimating forest carbon stocks, Cambodia has relied on inventory data produced by government agencies and overseas donors implementing forest conservation projects. It will also have to provide reports on changes in carbon stocks every two years for Biennial Update Reports and National Communications (NCs) to the UNFCCC.

5.6.1.2 National policies and information needs

Although passage of the Forest Law 2002 raised government expectations of the quality of forest management, gaining more reliable information on forest growing stock is still not a major government priority. Consequently, international demand for information is the major driver of change in this part of the national forest monitoring system.

5.6.2 Outputs: frequency and resolution of inventory

As shown in Section 5.3, a good foundation for a NFI was laid in 1996-98 in a pilot inventory covering 279,242 ha in Kampong Thong province with the support of FAO and UNDP. Based on this, the Forestry Administration, in collaboration with the Ministry of Environment and FAO, established 120 permanent sample plots by 2010. Unfortunately, only 48 were actively measured (Table 5.10).

The only change in forest inventory activities since the start of REDD+ negotiations in 2007 is that there have been a number of small-scale measurements in community forests and REDD+ pilot projects. These were intended to be integrated into the national forestry monitoring, and to provide information on forest carbon stocks and changes, and biomass conversion factors. Since 2009, the Oddar Meanchey Carbon Stock Survey, which is a pilot and subnational inventory, has been conducted by PACT, which is a non-profit international development organization, in collaboration with Community Forest International (CFI), Terra Global Capital (TGC) and the Forestry Administration (Mahanty et al., 2015). The area for the survey is wider than 67,853 ha and the sample size for the project is 126 plots in Oddar Meanchey province. The Wildlife Conservation Society (WCS) has been conducting the Seima protection forest REDD+ project and the Preah Vihear Pilot Stock Survey since 2009 and 2011 respectively. During the two projects, 225 plots located in Mondulkiri province (Inventoried area = 187,698ha), and 72 plots in Preah Vihear province, have been measured. The Preah Vihear Pilot Stock Survey is conducted in collaboration with the Forestry Administration and the Ministry of Environment of Cambodia. Since 2010, the Southern Cardamom carbon stock survey has been being conducted by Wildlife Alliance (WA). The project also a pilot and subnational inventory, for which 124 plots in Koh Kong province were measured.

Table 5.10 Forest inventories in Cambodia after the onset of REDD+ negotiations, undertaken by the Forestry Administration and/or external donors

Year	Tittle	Institution	Frequency	Resolution (Country Coverage/Plots)
2010	Permanent Sample Plots	Forestry Administration and MoE with WCS, Kyushu University and FFPRI (Samreth et al., 2012)	6 years	PSPs in five regions (Koh Kong, Siem Reap, Kampong Thom, Ratanakiri and Kratie province). 2010 - 3rd measurement, 15 PSPs for regrowth forest monitoring. 2010 - 4th measurement, 48 PSPs (Walker et al., 2010).
2008~	Oddar Meanchey Carbon Stock Survey - Pilot/subnational inventories	PACT with CFI*, TGC** and Forestry Administration	N/A	Oddar Mean Chey province Inventoried area: >67,853 ha Sample size: 126 plots (Walker et al., 2010)
2009~	Seima protection forest REDD+ project	WCS	N/A	Mondulkiri province. All dryland types, Inventoried area = 187,698ha, 225plots (Walker et al., 2010)
2010~	Preah Vihear Pilot Stock Survey	WCS/Forestry Administration/MoE	N/A	Preah Vihear province, All dryland Types, Sample size: 72 plots (Walker et al., 2010)
2010~	Southern Cardamom carbon stock survey	Wildlife Alliance (WA)	N/A	Southern Cardamoms in Koh Kong province, Sample size: 124 plots. Pilot/subnational inventories, All dryland types (Walker et al., 2010)
2011~	Cambodia's first National Forest Inventory*	Forestry Administration and FAO	N/A	- Field manual tested in the fields: Semi-Evergreen and Deciduous forests in Siem Reap Province, and Mangroves in Koh Rong Province (Cambodia REDD+ Taskforce Secretariat, 2016)

- Most of the inventories are pilot and subnational inventories based on voluntary carbon projects, except for the PSPs measured in 2010.
- Cambodia's UN-REDD REDD+ Readiness programme officially started in 2011, but this list includes forest inventories conducted before starting the Readiness programme because REDD+ pilot projects in Cambodia have already started in 2008.

* Community Forest International

** Terra Global Capital

*** As of 2016, after completing NFI design, a field manual and datasheets (field forms) for the NFI were produced, and Large scale NFI trails are planned to commence in 2017 (Cambodia REDD+ Taskforce Secretariat, 2016; Leng, 2016; Than, 2014).

(Source: Generated based on information from interviews, FAO, 2007a; Forestry Administration, 2010; Walker et al., 2010; Bradley, 2011; Samreth et al., 2012;

Sola et al., 2014; Than, 2014; Cambodia REDD+ Taskforce Secretariat, 2016; and Leng, 2016)

Despite having implemented two different types of inventories, data produced through the projects could not be used for estimating forest carbon stocks and changes, as the amount data was insufficient, and inventory data were collected for different purposes, using different methodologies. For the same reason, such small-scale measurements, which were intended to provide forest carbon stock information, could not become part of Cambodia's national sampling scheme. This suggested the need of a new national forest inventory design that will be explained in the following section.

5.6.3 Existing Technologies

As shown in section 5.6.2, two different types of inventories have been undertaken, and a new NFI, and developing allometric equations and carbon factors, are in planning stage. Different technologies have been, and are planned to be, used for such inventories.

5.6.3.1 Inventories undertaken

Two main types of inventory technologies are currently in use in Cambodia. The first type of technology was that used for Cambodia's Permanent Sample Plots (PSPs). To measure the PSPs, three different sizes (50x50m, 20x20m, 10x10m) of nested rectangle plots were used (Sola et al., 2014), and minimum size of DBH greater than 7.5 cm was measured, yet the PSPs measured in 2010 are now being measured by overseas organisations (e.g. WCS, the Forestry and Forest Products Research Institute (FFPRI) and Kyushu University) (Table 5.11). Forest carbon stocks and changes at national scale cannot be accurately estimated using country-specific data, as stated by a forestry officer:

> *"Currently, those permanent sample plots are measured by NGOs that work in the area. If they conduct REDD+ project in the area, they measure sample plots, for example, every 2 years or every 5 years, depending on their REDD+ methodology ... Currently we don't have any capacity, or technology, to monitoring carbon*

stock changes, unless we are able to conduct national inventory." (Mr. Chhun Delux, 4th of August 2017)

Table 5.11 Existing technologies for forest inventory after the REDD+ readiness programme in Cambodia, conducted by the Forestry Administration and/or external donors

Year	Tittle	Institution	Methodology and methods	Remark
2010	Permanent Sample Plots	Forestry Administration and MoE with WCS	- Plot shape: Nested rectangle plots, Plot size: 50x50m, 20x20m, 10x10m. (Sola et al., 2014) - Trees inventoried: DBH≥30cm in plots and DBH≥7.5cm in sub-plots (Samreth et al., 2012)	- Measured by Kyushu University and FFPRI (Samreth et al., 2012)
2008~	Oddar Meanchey Carbon Stock Survey - Pilot/subnational inventories	PACT with CFI, TGC and Forestry Administration	Systematic Random Sample (Walker et al., 2010) - Plot shape: Not nested (single) rectangle plots, Plot size: 50x50m. (Sola et al., 2014) - Tree inventoried: DBH≥10cm	- Tree height not measured. - Manual written in English and Khmer for Standard Operating Procedures (SOP) (Bradley, 2011)
2009~	Seima protection forest REDD+ project	WCS	- Systematic Random Sample (Walker et al., 2010) - Plot shape: Nested circle plots, Plot size: Radius=20m, 15m, 5m. (Sola et al., 2014) - Trees inventoried: DBH≥5cm - Species and wood density inventoried.	- Tree height not measured. - Allometric equations developed - Laser rangefinders for measuring trees and distance measuring equipment for plot locations (Bradley, 2011).
2010~	Preah Vihear Pilot Stock Survey	WCS/Forestry Administration/MoE	Systematic Random Sample for trial blocks (Walker et al., 2010) - Plot shape: Three nested circle plots, Plot size: Radius=20m, 15m, 5m (Sola et al., 2014). - Trees inventoried: DBH≥5cm	- Tree height not measured.
2010~	Southern Cardamom carbon stock survey	Wildlife Alliance (WA)	- Systematic Random sample for the project area (Walker et al., 2010) - Plot shape: Nested rectangle plots, Plot size: 200x25m, 10x25m, 10x6m) (Sola et al., 2014) - Tree inventoried: DBH≥5cm	- Tree height sampled.

2011~	Cambodia's first National Forest Inventory	Forestry Administration and FAO	- Systematic sampling, Grids for different sampling intensities for 3 forest strata: uplands (6kmx6km), wetlands (4kmx4km), and mangroves (2 phase sampling: 1st phase 1kmx3km, 2nd phase 3kmx3km) (Leng, 2016; Than, 2014)	- Developing methodology, field manual, and NFI design was technically supported by FAO (Cambodia REDD+ Taskforce Secretariat, 2016).
- Although Cambodia officially started its REDD+ Readiness Programme in 2011, this table includes major forest inventories that have been undertaken since 2008. It is because Cambodia has already started its Readiness programme unofficially, before starting its REDD+ Readiness Programme.				

(Source: Generated based on information from interviews, FAO, 2007a; Forestry Administration, 2010; Walker et al., 2010; Bradley, 2011; Samreth et al., 2012; Sola et al., 2014; Than, 2014; Cambodia REDD+ Taskforce Secretariat, 2016; and Leng, 2016)

Other approaches have been used in the small-scale inventories in community forests and REDD+ pilot projects. Although the Forestry Administration is involved in various REDD+ pilot projects, as most field measurements are undertaken by external organisations, those methodologies are not Cambodia's own methodologies for its NFI. In addition, most other inventories undertaken after starting the REDD+ Readiness Programme are pilot and sub-national inventories based on voluntary carbon projects (Figure 5.5), and so different methodologies and methods were used for them. For the Oddar Meanchey Carbon Stock Survey, a Systematic Random Sample for the project area was used (Walker et al., 2010), and plot shape for the survey was 50x50m Not nested rectangle plots (Sola et al., 2014). For the Survey, a manual was devised in English and Khmer for Standard Operating Procedures (SOP) (Bradley, 2011), and during the survey, trees with DBH≥10cm were inventoried. A Systematic Random Sample for the project area and Nested circle plots were used for the Seima protection forest REDD+ project (Walker et al., 2010), and radius of the circle plots were 20m, 15m and 5m (Sola et al., 2014). During the project, species of trees with DBH≥5cm were recorded and after the field measurement wood density and allometric equations were developed. Laser rangefinders and distance measuring equipment were used for measuring trees and plot locations (Bradley, 2011). For the Preah Vihear Pilot Stock Survey a Systematic Random Sampling method for trial blocks was used to measure trees (DBH≥5cm) in three nested circle plots with radius of 20m, 15m and 5m (Sola et al., 2014; Walker et al., 2010), whereas a Systematic Random sampling method was used for the Southern Cardamom carbon stock survey (Walker et al., 2010). Plot shape for the Southern Cardamom carbon stock survey was nested rectangle plots with sizes of 200x25m, 10x25m and 10x6m (Sola et al., 2014), and diameter of trees larger than 5cm at breast height were inventoried. Height of trees is measured only during the Southern Cardamom carbon stock survey.

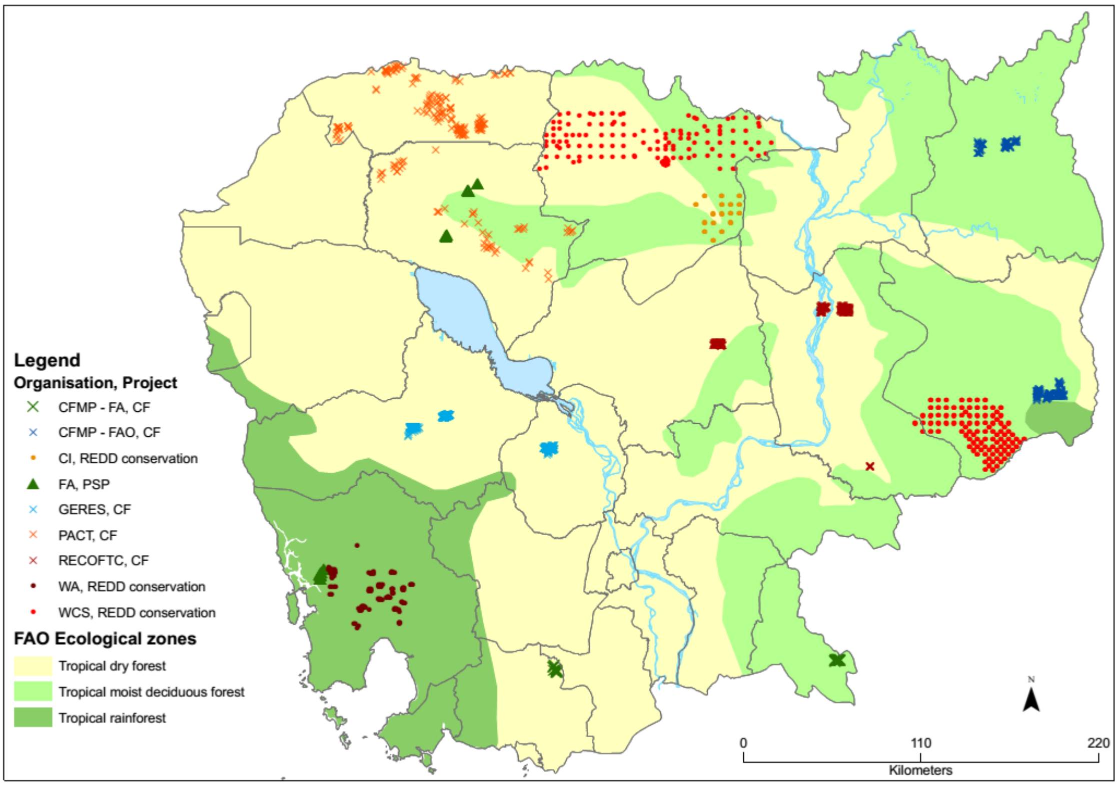

Figure 5.5 Location of sample plots for forest inventories within project areas in Cambodia

Source: Sola et al. (2014)

5.6.3.2 Inventories in the planning stage and developing allometric equations

The Forestry Administration, with the help of FAO, has been working on the design of Cambodia's first National Forest Inventory since 2011 (Figure 5.6). Field manuals devised for the NFI were tested in forested areas in Siem Reap and Koh Rong provinces. For sampling, a systematic sampling method, by which field plots will be measured using grids for different sampling intensities for 3 forest strata - uplands (6kmx6km), wetlands (4kmx4km), and mangroves (2 phase sampling: 1st phase 1kmx3km, 2nd phase 3kmx3km), was decided to be adopted (Than, 2014; Leng, 2016).

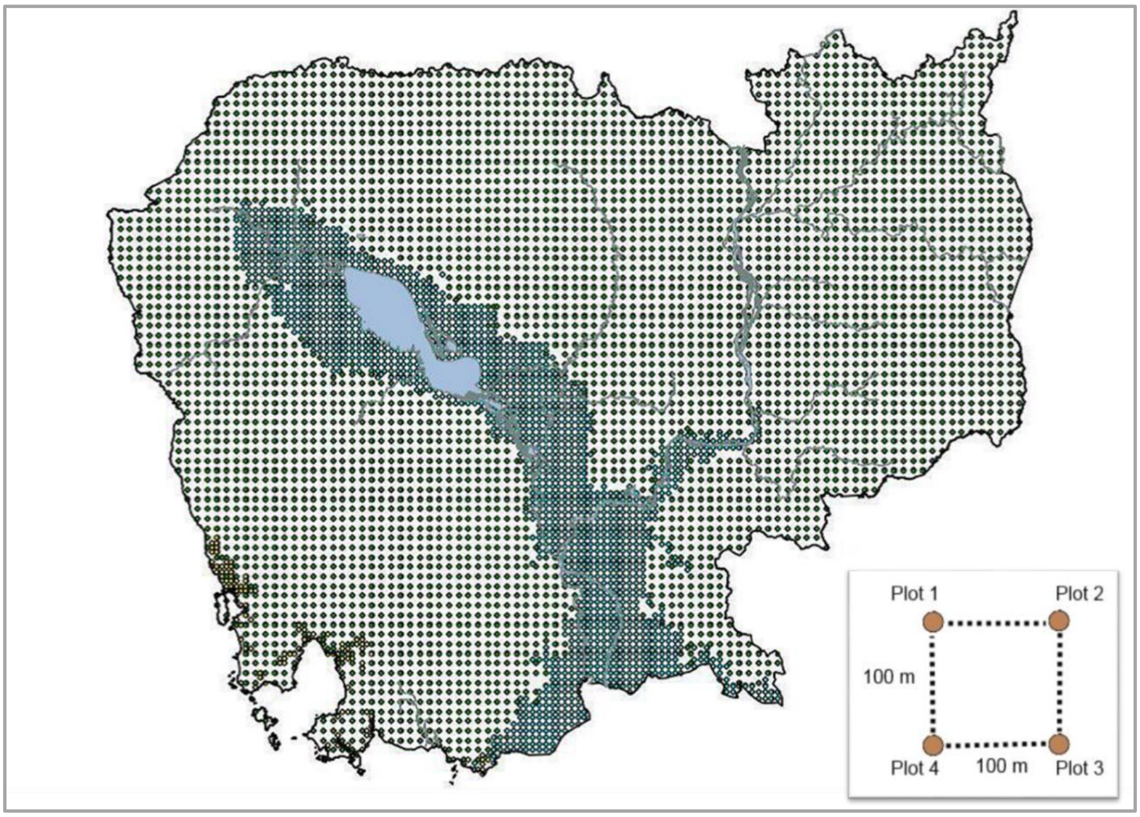

Figure 5.6 Cambodia's new National Forest Inventory design

(Main image shows locations of sample plots on grids sized 6kmx6km for uplands and 4kmx4km for wetlands and mangroves, while inset shows the shape of clustered sample plots, Plots located in flooded forest and protected areas will be measured by the Fisheries Administration and the Ministry of Environment respectively, Source: Courtesy of the Forestry Administration of Cambodia)

In line with the new NFI design, the development of allometric equations, and other carbon factors such as wood density, was begun in 2015, based on short term projects. Allometric equations for only one major species, *Barringtonia*, in flooded forest were developed, and to develop more allometric equations and other parameters, the Royal University of Agriculture (RUA) has set up 29 sample plots in forest areas using the nation forest inventory tool provided by the Forestry Administration. As Cambodia has only one allometric equation, it still relies on allometric equations developed by Vietnam, the US Forest Service and Chave (2005).

5.6.4 Decisions on Adopting New Technologies

Decisions on adopting a design for Cambodia's first national forest inventory were made by the MRV team in conjunction with advisers from FAO and JICA. Adopting a new design was necessary because Cambodia didn't have an NFI design that could be used for estimating forest carbon stocks and changes with low uncertainty. Although Cambodia had inventoried data, most historical data are difficult to be used for estimating carbon stocks and changes, as forestry officers stated:

> *"Historical data are not useful and most of them cannot be used for REDD+ because of different approaches, methodology and purposes."* (Mr. Chhun Delux, 4th of August 2017)

> *"We can use most data collected before REDD+ for the estimation of timber products, but partly estimated only, so not for whole carbon stocks. We have less data for estimate forest carbon stocks."* (Mr. So Than, 29th of August 2016).

Although methodologies were used by REDD+ pilot projects in Cambodia, devising a new methodology was inevitable. When FAO's forestry officers collected existing data from different stakeholders, such as the Forestry Administration and external donors related to REDD+ pilot projects and community forests, and analysed the existing inventory data for estimating forest carbon stocks for reporting, they found that most of them were not suitable for estimating carbon stocks because of different purposes of inventories and diverse methodologies used for such inventories.

Although Cambodia's NFI design is designed to be used for multiple-purposes, i.e. meeting both national and international information needs, for Cambodia, it seems that meeting international demand for information on forest carbon overweighs meeting national demand for information on timber volume. Inventories for MRV requires more detailed measurements than those for timber stocks, but from the beginning, Cambodia's new NFI design was focused on estimating forest carbon stocks and changes. More specifically, as national information needs are not high, the new NFI design could be focused more on meeting international information needs, i.e. reporting requirements for REDD+, by producing forest information that is necessary for estimating forest carbon stocks for implementing national REDD+. Protocols and manuals for implementing NFIs in accordance with the new NFI design were also devised in line with that.

5.6.5 Explaining Technology Adoption

This section explains not only why decisions were made on inventory technologies but also why they have not yet been implemented.

5.6.5.1 Existing technologies

The Government of Cambodia was strongly influenced by existing technologies when deciding how to adopt a technology for its first National Forest inventory (NFI). The only possibility was to continue with the existing technology of manual measurement, even though it had never been applied at national scale before. As described earlier in the chapter, the use of non-optical satellite data was not considered feasible, given limitations on human capital and other factors.

5.6.5.2 Human capital

The technology chosen for the first NFI had to be consistent with present human capital after forestry officers had been trained in inventory procedures in the REDD+ Readiness Programme.

Although during the REDD+ Readiness programme, training was given on implementing NFIs in the field, and on MRV and IPCC guidelines (UN-REDD, 2013c), human capital in Cambodia is still not sufficient to implement forest inventories at national scale, and so implementing the first NFI is hampered by human capital. When implementing NFIs, people are needed to lead the project, analyse data, and lead field surveys, in addition to field crews and local people, but such people are still not sufficient in the Forestry Administration and in other government organisations.

Forestry officers' field experiences on forest inventories were increased during various forest conservation projects and REDD+ demonstration activities (Bradley, 2011), and core groups of staffs from the Forestry Administration, the Fishery Administration and the Ministry of Environment were trained through technical supports provided by DANIDA in 2011, and by the Technical Cooperation Programme (TCP) of the FAO afterwards (Cambodia REDD+ Taskforce Secretariat, 2016), but, forestry officers have limited experience in forest inventory at national scale. In addition, only a few

Cambodian people are able to analyse inventory data and design NFIs, as having sufficient knowledge of statistics is essential for such tasks. This is explained by FAO's forestry officer:

> *"There are a lot of different components for NFI and a few resource people know quite most of them … In terms of real deeper analyses a few people able to do that really need good knowledge of statistics in order to do that. It is really challenging … In terms of field inventory itself, measurement is well understood, but harder part is analysing ... There are 24 provinces in Cambodia but for NFI, we will work with higher level offices, and local people might be involved." (Mr. Mathieu Van Rijn, 24th of August 2016)*

Limitations on human capital continue to constrain progress in implementing the NFI. One key requirement for developing a system for producing estimates of changes in forest carbon stocks is a set of allometric equations suited to Cambodia. Only one person in the MRV centre is qualified to do this and so progress is slow.

5.6.5.3 Organizations and institutions

Undertaking an NFI requires an effective organization on a national scale, comprising a considerable number of trained personnel capable of implementing institutions consistent with the rules of the inventory design produced by the Forestry Administration.

Unfortunately, Cambodia still lacks a sufficiently strong national organization for undertaking its first National Forest inventory (NFI). There is no department within the Forestry Administration that is dedicated to forest inventory. As a consequence of this, any planning of an NFI, or reporting on changes in national forest carbon stocks, will have to be undertaken by the five forestry officers who staff the MRV centre.

In principle, the same external organizations that have been supporting the improvement of forest area monitoring in the MRV centre could also support the initial NFI (Figure 5.7). UN-REDD, JICA and FCPF have been providing financial and technical support. All three organisations are financially supporting the MRV centre, and FAO, in collaboration with JICA, provides technical support with designing NFI, collecting existing data, training and grouping provincial offices. Equipment for field surveys was provided by JICA in 2011 and 2012 (Forestry Administration, 2014). However, without an embryonic national organization such support would be of no use.

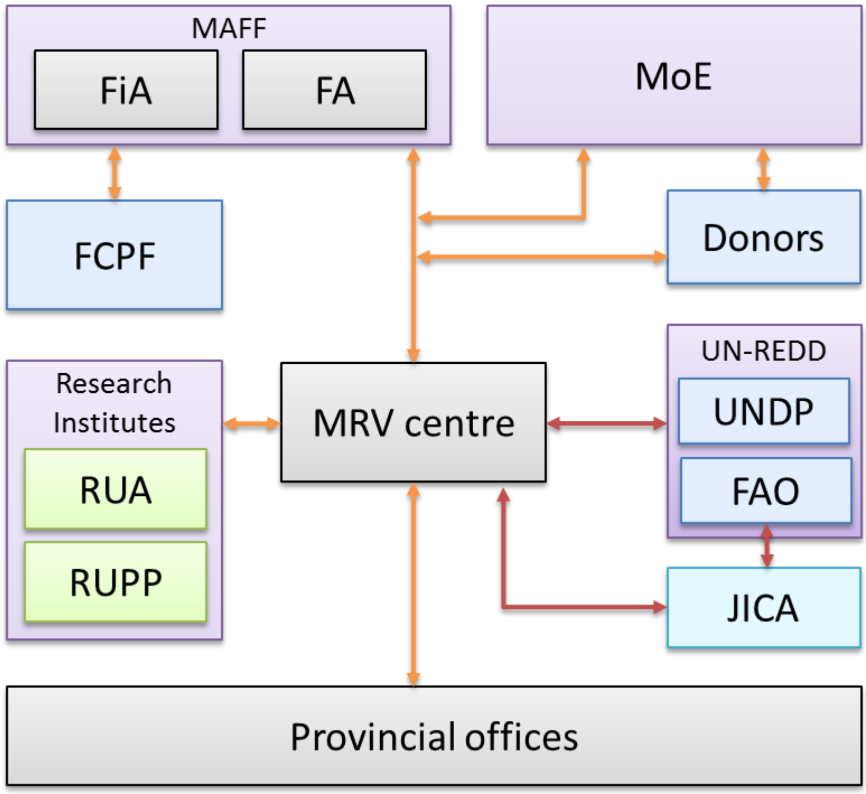

Figure 5.7 Key organizations for forest inventories for REDD+ MRV in Cambodia

(Arrows indicate communication links for forest data/information production/sharing for forest inventory, and red arrows indicate key communication links for Cambodia's first NFI)

It would be possible to establish an organization capable of undertaking an NFI if there were sufficient personnel within the Forestry Administration who had been trained in inventory methods and at previously been reproducing the necessary institutions. Unfortunately, such people do not exist. The last inventory of any scale was the small pilot survey undertaken in the late 1990s, and the experience gained in that survey has long since declined. As Cambodia has never undertaken a forest inventory at national scale, the MRV centre has difficulties in scaling up. The Forestry Administration is not yet qualified for scaling-up forest inventories from local to national levels as Cambodia only has experience in small-scale demonstration projects for REDD+.

Commencing the first NFI, and scaling-up small-scale forest inventories, is also constrained by different institutions in government agencies, i.e. Forestry Administration, Fishery Administration and the Ministry of Environment. Although the

Forestry Administration in cooperation with FAO already developed its own NFI design and determined procedures for field survey, and the Forestry Administration has long term plans for its NFIs, organisations related to forest inventory still rely on different methodologies, as explained by an FAO's forestry officer in Cambodia:

> *"We are working at a national level like UNFCCC. There are many local REDD+ projects which are project scale, and they have different methodologies ... We have national strategy and national data. So the challenge is how to ensure national guidelines are being used at local level and project level. Problem is conducting an NFI rather than having all different methodologies." (Mr. Mathieu Van Rijn, 24th of August 2016)*

They have been relying on their own regulations and practices for a long time. As three different government agencies, and other Cambodian and overseas organisations, are participating in national forest inventories, this require establishing new rules that could define and integrate roles of organisations and practices.

5.6.5.4 Financial resources

Although overseas organizations have provided funds for designing Cambodia's first NFI, and for training staff in inventory methods, they will not be providing the large amount of funds necessary for undertaking the NFI, estimated at about $6 million. For this the government will have to rely on funds from the World Bank Forest Carbon Partnership programme, and since these funds have still not been provided this is delaying the start of work on the NFI. This is explained by a forestry officer at the Forestry Administration and an FAO forestry officer in Cambodia:

> *"In Cambodian REDD+ strategy, we all included our strategies for MRV ... Conducting NFI requires very high costs so we are waiting for funding. It would be about $6,000,000."* (Mr. So Than, 29th of August 2016)

> *"For short term activities we have funds, except for NFI. We are looking for further funding for NFI because it takes 6-7 years for one NFI cycle. We are discussing possible investment through the forest investment programmes. That is for short term. Eventually, it has to be country ownership, so the country has to*

> *allocate resources to implement this kind of activities."* (Mr. Mathieu Van Rijn, 24th of August 2016)

National contributions to growing stock monitoring are still not sufficient. The amount of the budget is determined and allocated by national policy, however, unlike stated policy, actual policy is still not supportive enough, as evident in the above statement made by the forestry officer at FAO in Cambodia.

Developing allometric equations, carbon conversion factors and monitoring forest carbon pools is also constrained by financial resources, as such research has been relying on short term projects. Forestry officers in the Forestry Administration were working to develop allometric equations for one species in deciduous forest, but they were not able to complete it, as the project supported by FAO has finished. To continue to develop allometric equations, the Forestry Administration is now planning to conduct another short term project supported by ITTO. The development of allometric equations has been significantly hindered by continuity of funds for those projects as a professor working for developing allometric equations and carbon conversion factors stated:

> *"Now, the project is finished, so he may not be working now because of funding. We already cut trees and he brought a tree to my laboratory. I have analysed it, and sent him all the data from the tree to developing allometric equation during next projects ... For soil carbon, we collect samples and send it to Thailand to analyse them, because we have no equipment for it. I already talk to my boss to set up a soil laboratory, and we can analyse them even though it is very slow, but it takes much time to analyse them one by one. In Thailand, soil carbon is automatically analysed by using machine."* (Prof. Kim Soben, 30th of August 2016)

For Cambodia, financial support for the NFI and developing allometric equations and other biomass and carbon expansion and conversion factors is discontinuous, and securing funding is still uncertain. It is mainly caused by the ambiguous future of the evolving REDD+ scheme.

5.6.5.5 Communication with other government agencies

Even when the necessary funds have been provided and a forest inventory organization within the Forestry Administration has being established and staffed, the

Forestry Administration will not be able to implement the NFI on its own. It will require strong collaboration with other government agencies whose personnel are active in the field throughout Cambodia and who can provide either ground data they have collected themselves or infrastructure within which Forestry Administration personnel can collect these data. At the moment, such communication links are very limited.

Commencing Cambodia's first NFI is hampered by limited communication links between the central office and provincial offices, between the Forestry Administration and other government agencies, and between Cambodian government agencies and external organisations, as constructing solid communication links and stronger networks between the MRV centre and those organisations is an essential prerequisite for implementing NFIs.

Communication links between the Forestry Administration and other government agencies, which have significant influence not only on implementing the new NFI design, but also on developing allometric equations and carbon factors, have not been established yet either. They are also essential for implementing field measurements, and for consolidating data to be collected during field surveys for analyses, as forest areas in Cambodia, e.g. protected forests and community forests, are under different authorities, i.e. Ministry of Environment (MoE) and Ministry of Agriculture, Forestry and Fisheries (MAFF) of Cambodia, and these government agencies will conduct national forest inventory in three forest strata (uplands, wetlands and mangroves) under their jurisdictions. Yet, such communication links are not formally defined. Thus, government officials and research institutes rely on informal institutions when conducting field surveys and consolidating inventoried data, as stated by a forestry officer and a professor at RUA:

> *"I don't work with other ministries … At provincial level the MRV team is not yet established. We will need to working on who will be a technical person and who will be in charge of collecting data."* (Mr. So Than, 29th of August 2016)

> *"We have different working groups … I normally work with the Fisheries Administration, but for upland forest we work with the Forestry Administration. It is dependent on research and project ... We are all friends." (Prof. Kim Soben, 30th of August 2016)*

Weak communication links are also constraints on integrating existing practices to avoid duplicated works, and consolidating existing data for information production. The Forestry Administration in conjunction with the Fisheries Administration (FiA) and the Ministry of Environment is assessing growing stock changes in upland, flooded and protected forests, and MoE and MAFF conduct forest conservation projects with the World Wide Fund for Nature (WWF), Conservation International (CI), USAID and other donors based on Memorandum of Understanding (MOU), but mechanisms for regular communication, and information exchange, are not established yet.

Communication links between Cambodian government agencies and external organisations that are conducting various forest conservation projects such as the Oddar Meanchey community forest REDD+ demonstration project and the Keo Seima Wildlife Sanctuary (KSWS) REDD+ demonstration project are also very weak. By refining government policies on the management of forest carbon stocks in order to support implementing REDD+ pilot projects in 2008, Cambodia allowed external organizations to implement sub-national REDD+ pilot projects in several forest areas in Cambodia. To establish a national forest monitoring system in accordance with UNFCCC decisions, ongoing subnational REDD+ pilot projects need to be part of national forest monitoring system for MRV. However, for forest inventories, the MRV team does not have strong communication links with such pilot projects.

5.6.6 The Gap between Forest Carbon Stock Information Supply and Demand

At the moment there are major gaps between the information required by the UN Framework Convention on Climate Change (UNFCCC) for reporting in National Communications and as part of the REDD+ mechanism and that which the Government of Cambodia can provide (Table 5.12). The principal gaps include the quality of data and information on growing stocks, allometric equations, carbon conversion factors for estimating forest carbon stocks and changes, and for developing emissions and removals factors. As Cambodia's first NFI has not been implemented, key carbon pools that are essential for estimating forest carbon stocks with low uncertainties have not been measured yet. As Cambodia has only a few country-specific emission factors for evergreen, semi-evergreen and deciduous forests, the MRV team relied on emission factors from published literature and from neighbouring countries, i.e. Thailand and Vietnam (Kapos et al., 2010; Forestry Administration, 2016a). The Forestry Administration still uses allometric equations presented by Chave et al. (2005), Brown (1997), and FAO for Atlantic Forest. There are no available national data on estimating forest biomass and carbon stocks, except for the old forest inventory data produced by FAO (FAO, 2015b). For estimating growing stocks and growth rates, biomass conversion and expansion factors (BCEF) from FRA guidelines were used. The Forestry Administration has not estimated carbon factors for each species yet, although it is planning to measure 3 carbon pools, i.e. AGB, dead wood, and litter, during its first NFI. Cambodia has much less data for estimating soil carbon.

To supplement existing carbon factors, the Forestry Administration already collected some existing data from different project sites, but most of the data are biased ones as donors collected data for different purposes using different methodologies. Furthermore, most of projects sites are located in protected areas, so forest inventory data can be biased toward the areas where the projects are implemented as field plots in protected areas are not appropriate to capture changes outside of the protected areas or different forest types. For this reason, emission/removal factors for AGB and BGB by forest types are derived from existing values in literature, and missing values are complemented by emission factors provided by IPCC (Forestry Administration, 2016a).

To produce unbiased growing stock data by implementing national forest inventories, Cambodia already finalized developing a new sampling design for NFIs, and manuals for field surveys. The frequency and resolution of the planned first NFI well match IPCC recommendations, as national scale systematic sampling is planned to be repeated every 5 years. If it could be successfully implemented, Cambodia might be able to report changes in forest carbon stocks at Tier 2 or Tier 3 levels to the UNFCCC.

Table 5.12 The gap between carbon stock information supply and demand after the REDD+ Readiness

<table>
<tr><th colspan="2"></th><th>Information supply after REDD+ readiness</th><th>Information demand (UNFCCC recommendations)</th></tr>
<tr><td rowspan="10">Factors in NFI and Carbon reporting capacity</td><td>Frequency/Resolution</td><td>5 years planned/Developed national scale systematic sampling but not operational</td><td>Various, but ideally 5 years (Reporting: 4 years for NCs, and 2 years for BURs/as high as possible, Measurements require higher frequency and resolution)</td></tr>
<tr><td>Emission factors*</td><td>Developed using AGB and BGB by forest types by collating emission factors from literature (Forestry Administration, 2016a)</td><td rowspan="6">Tier 2 or Tier 3 level recommended**

Tier 1: Default values (Continental scale)
Tier 2: Country-specific data (National scale)
Tier 3: Actual inventories with repeated measures (Local scale)</td></tr>
<tr><td>Allometric equations</td><td>1 species developed and developing 2 more species (Chave's equation and H-DBH model from Sola et al. (2014) were used for FREL)</td></tr>
<tr><td>BCEF***</td><td>Not developed yet, but developing, used default value provided by IPCC for FREL for BGB</td></tr>
<tr><td>Carbon conversion factors</td><td>Not developed yet but developing (used default value provided by IPCC for FREL)</td></tr>
<tr><td>Wood density</td><td>Developing, used Sola et al. (2014) for FREL</td></tr>
<tr><td>Carbon pools</td><td>Not estimated yet but planned</td></tr>
<tr><td>Human resources</td><td>Basic minimum trained forestry officers for field survey</td><td>Not specified</td></tr>
<tr><td>Institutions for NFI</td><td>Still establishing but NFI designed and manuals for field survey generated</td><td>Various but fixed practices and manuals needed</td></tr>
<tr><td>Uncertainty assessment</td><td>Impossible but planned to assess uncertainty</td><td>Accuracy assessment recommended/necessary for results-based payments</td></tr>
</table>

* Cambodia estimated AGB by forest types by collating emission factors from literature, and found available forest inventory data (Forestry Administration, 2016a).

** IPCC guidelines provide different Tiers for carbon stock reporting in accordance with accuracy of data.

*** Biomass Conversion and Expansion Factors

- International policies recommend tropical countries to measure and report their forest carbon stocks and changes in accordance with the UNFCCC reporting requirements and the most recent IPCC guidelines for the Agriculture, Forestry and Other Land Use (AFOLU) sector (GFOI, 2016; UNFCCC, 2010).

However, estimating changes in forest carbon stocks requires at least two cycles of NFIs, and implementing NFIs and routinizing practices for forest information production is limited by institutional, financial and human capital constraints. Financial support has been given by overseas organisations, but those are not for implementing NFIs. National contributions are needed to implement NFIs, but budgets have not increased, reflecting national policy. Institutionalising the new NFI design for producing information on growing stocks and changes is constrained by institutional challenges. Such challenges include lack of formal and informal institutions, inter-organisation cooperation, and strong communication links between the central office and provincial offices, between the Forestry Administration and other government agencies, and between Cambodian government agencies and external organisations. Scaling-up existing practices at project levels, and collecting existing data, are limited by such institutional challenges. Training was given by international organisations, but Cambodia still has only a basic minimum of trained forestry officers for field surveys, and limited human capital for analysing inventoried data, and for calculating standard deviations and errors for uncertainty analysis. Moreover, Cambodian forestry officers don’t have experience in forest inventory at national scale, so they are having difficulties in scaling-up their practices. Such insufficient human capital hampers producing information on forest carbon stocks by undertaking NFIs too.

5.7 Interactions between Forest Survey and Inventory Activities

If Cambodia's MRV centre is to function efficiently there will need to be close integration between forest area monitoring and forest carbon stock monitoring. Estimates of forest carbon stocks require a good base map of forest area, and ground data collected during inventory activities will also be invaluable for satellite image classification.

In Cambodia, in the MRV centre the same people are responsible for forest area monitoring as for forest inventory. On the one hand, such integration is beneficial, but on the other, the absence of an independent NFI division under the MRV centre indicates major constraints on estimating reductions in forest carbon stocks to respond to information demand from end users. As the NFI system in Cambodia is yet to be operational, no interactions for producing forest information exist. For this reason, forest carbon stocks and changes are not estimated by the MRV centre, except for Cambodia’s initial reference emission level. Forest degradation is not monitored either as to monitor forest degradation intensive interactions between forest survey and inventory divisions are required. Key inventory data for developing country-specific emission and removal factors such as DBH, tree height and wood density may not be able to be supplied to the MRV team until at least one cycle of NFI has been completed.

5.8 Conclusions

This chapter has shown how the Government of Cambodia has selected optimal technologies to meet its demand for forest information and demand for information by international organizations. It has also shown how the Technology Adoption System (TAS) Framework can explain how this optimization occurs, and how the Information Production (IP) Framework can identify the gap between information supply and demand.

As a result of the REDD+ Readiness programme, Cambodia showed improvements in both forest area monitoring and growing stock monitoring. The frequency of forest area monitoring was enhanced from once every four years to once every two years, and for forest carbon stock monitoring, a new NFI design for estimating forest carbon stocks has been developed. Considering the dependence of Cambodia's forest monitoring activities on overseas organisations before the REDD+ Readiness programme, and the fact that it never implemented forest inventories at national scale, these seem distinct improvements.

Adopting new technologies, i.e. methods for forest area monitoring and a new NFI design, was enabled by assistance from overseas organisations and organisational changes. Cambodia's technology adoption and operating new technologies were supported significantly by overseas organisations. The technology adoption processes for both forest area and growing stock monitoring were accompanied with two major organizational changes, i.e. the establishment of the MRV centre and its wider organizational position with the Government of Cambodia. Thus, Cambodia's technology adoption for raising its forest area and growing stock monitoring capacity can be featured as incremental evolution with support from overseas bodies, and with organisational changes.

In addition, the decisions on adopting new technologies could be made because the MRV centre could focus more on meeting international information needs, while national demand for forest information is still low. A new NFI design could be developed because meeting international demand for information on forest carbon overweighs meeting national demand for information on timber volume. From the beginning, Cambodia's new NFI design was focused on estimating forest carbon stocks and changes.

However, although some improvements were made in both forest area and growing stock monitoring, further improvements by adopting more advanced technologies and institutionalising the new NFI design were constrained by various factors described in the TAS Framework. The actual methodology for forest area monitoring remained the same as before the REDD+ Readiness programme, i.e. on-screen manual-visual interpretation, and the first Cambodia's NFI is yet to be implemented. Adopting new technologies for forest area monitoring was limited by technological, institutional, organizational, and financial constraints on changing institutions in addition to human capital and national policy. It was also limited by lack of training, which focused on improving the operation of existing technologies for implementing given projects, not on new technologies. Implementing Cambodia's first NFI, and developing allometric equations and other carbon factors, has been hampered by human capital, existing technologies, financial resources, other organisational and institutional constraints, and poor communication with other government agencies. This has led to an incremental evolution of visual interpretation of Landsat images, and developing a new NFI design. When adopting new technology, institutional changes had to be minimised because although overseas organisations have been supporting Cambodia's forest monitoring capacity building, adopting new technologies is constrained by the ability of the Cambodian forest monitoring organisation.

As technology adoption was limited by these factors, the gap between forest area and carbon stock information supply and demand still exists. The quality of forest area information, including the spatial resolution and accuracy of monitoring, the frequency of forest area monitoring, and the ability to supply information on forest regrowth and forest degradation are still not sufficient. Since starting the REDD+ Readiness Programme, Cambodia has increased the frequency of national forest cover mapping from four years to two years, but the number of sample points for ground truthing collected by actual field surveys is still not sufficient for reliable accuracy assessment. The quality of forest area information is still in doubt. Implementing forest area monitoring at higher frequency and resolution was also limited by existing technology and institutions, i.e. on-screen manual-visual classification, and changing the institutions were limited by human capital, existing technology, and other organisational factors. As the first NFI has not yet been implemented, Cambodia cannot supply sufficient information on changes in forest carbon stocks for REDD+ purposes. Forest carbon information production is limited by institutional, financial and human capital constraints. In addition, estimates of forest carbon stocks require close integration between forest area monitoring and forest carbon stock monitoring. In principle, such integration is possible since the same people in the Cambodian MRV centre are responsible both for forest area monitoring and for forest inventory. However, these people are too few in number.

This chapter has demonstrated the ability of the Technology Adoption System (TAS) Framework, in combination with the Information Production (IP) Framework, to explain technology adoption for better information supply in a small country with the basic minimum of forest monitoring capacity before the REDD+ negotiations. The next chapter will be devoted to examining how forest monitoring has evolved in a much larger country in which forest monitoring capacity was more advanced before REDD+ Readiness.

Chapter 6
The Evolution of Forest Information Production in Indonesia to Meet International Demand

6.1 Introduction

Negotiations on the Reducing Emissions from Deforestation and Forest Degradation (REDD+) mechanisms of the UN Convention on Climate Change (UNFCCC), as part of the wider negotiations on the 2015 UNFCCC Paris Agreement, have prompted developing countries to increase their limited forest monitoring capacity in order to be able to supply the information that is required for countries participating in REDD+. In line with this, Indonesia, a large country with a basic minimum level of forest monitoring capacity before REDD+ negotiations began in 2007, had to raise its forest monitoring capacity to meet much greater international demand for forest information for REDD+. For that, it was offered new technologies through the REDD+ Readiness programme. This process, raising forest monitoring capacity by adopting new technologies, was influenced by overseas organisations on the growth in monitoring capacity, and also by a number of different government organisations involved in forest monitoring and REDD+ reporting.

This Indonesian case study discusses what kind of new technologies for forest monitoring were offered, and why they were offered, and why some of the new technologies were adopted, or not adopted, by Indonesia. Specifically, the case study identifies major constraints on adopting new technologies for forest area and growing stock monitoring, the influence of government and overseas organisations related to forest monitoring and adopting new technologies, and whether the upgraded Indonesia’s forest monitoring system could meet the international demand for information on forest carbon stocks and changes. Constraints on the evolution of the organisation of forest monitoring, and the adoption of available new technologies, are analysed with reference to key variables in the Technology Adoption System (TAS) Framework described in Chapter 4, including technologies, organisational structure, institutions, human capital, financial resources, and interactions between various organisations.

The main body of this chapter is divided into six main parts. The first and second parts look in turn at the ability of Indonesia's forest monitoring system to track changes in area and timber volume before REDD+ negotiations. The REDD+ Readiness programme in Indonesia is outlined in the third part. The fourth and fifth parts look at how the monitoring of forest area and timber volume changed to meet the much greater international demand for information after REDD+ negotiations began. Interactions between forest area and timber volume monitoring are discussed in the last part.

6.2 Forest Area Monitoring before the REDD+ Readiness Programme

The evaluation of forest monitoring before the onset of REDD+ negotiations is divided into two parts. This section looks at forest area monitoring, while the next section looks at the monitoring of forest timber volume.

6.2.1 National and International Policies and Information Needs

6.2.1.1 National policies and information needs

Indonesia contains about a tenth of tropical moist forest area and since the 1960s it has been one of the leading producers and exporters of tropical hardwoods. Although it introduced a log export ban in 1980, this was not accompanied by an increase in the priority given to forest monitoring to ensure that forests were properly managed. From the 1970s to the early 1990s, information available to the Ministry of Forestry on the state of the country's forest resources was based on a few aerial photographic surveys and Landsat studies that were not comprehensive or particularly accurate.

The need for providing forest cover information to exploit and manage forest resources was specified in Forestry Laws passed in 1967 and 1994. Article 15 of Law No. 41 of 1999, regarding forestry, stipulated the needs of forest area designation, forest area boundary management, forest area mapping, and forest area stipulation for "Forest

Area Affirmation”. Yet, although the needs of forest resources monitoring activities were stipulated in Indonesia’s stated policy, and other government agencies needed forest cover information, it seems that those were still not the Indonesia government’s top priority. The frequency and resolution of forest area information that should be provided was not clearly defined.

6.2.1.2 International policies and information needs

Indonesia also needed to respond to two types of international demands for forest cover information, but both of which were not compulsory. The first was responding to information requests from overseas bodies for global forest resources statistics. These include the Food and Agriculture Organization of the United Nations (FAO), the International Tropical Timber Organization (ITTO), and some other organisations. However, responding to such information requests was not compulsory or legally binding.

The second was responding to international climate change mitigation initiatives. Indonesia submitted its first National Communication to the UNFCCC in 1999, in which information on greenhouse gas emissions from Land-Use and Land-Use Change and Forestry (LULUCF) was included, since the President of the Republic of Indonesia approved the Ratification of UNFCCC in 1994 by establishing the Act Number 6/1994 (MoE of Indonesia, 1999). However, this was a token voluntary submission, and estimated using existing national forest cover statistics of 1990 (MoE of Indonesia, 1999). Indonesia later also ratified the Kyoto Protocol through Act Number 17/2004, but Indonesia was classified as Non-annex 1 Parties that had no obligation to reduce GHGs emissions.

6.2.2 Outputs: frequency and resolution of mapping

To respond to national (and international) information demand, Indonesia has produced forest cover information at the national scale since 1989 (Table 6.1). Indonesia produced forest cover information with overseas organisations until 1999 and by itself from 2000.

In the 1990s, two major forest cover monitoring projects at national scale were undertaken, which were supported by overseas organisations. The first was for the post-stratification of the first Indonesian National Forest Inventory (NFI) data (FAO, 1996). The second was to respond to the World Bank's Second Policy Support Reform Loan II to the government of Indonesia in 1999 (Holmes, 2002).

Table 6.1 Existing major land use/cover and/or forest cover maps of Indonesia, produced by the Indonesian forestry department before the REDD+ readiness programme

Year	Producer and partner(s)	Satellite data (Years acquired)	Resolution	Frequency	Scale/MMU*	Accuracy
1989-1996	Directorate General of Forest Inventory and Land Use Planning, with FAO	Landsat 4 MSS and 5 TM (1986-1991; FAO, 1996)**	60 m	N/A	1/250,000, 25 km² (best resolution when published)	Accuracy not assessed
1999	Mapping and Inventory Division of the Directorate General of Forestry Planning	Landsat (1996-1998; Holmes, 2002)***	60 m	N/A****	1:500,000	Accuracy not assessed (Holmes, 2002)
2000	Directorate General of Forestry Planning	Landsat 5 TM (1999-2000; FAO, 2007b)	30 m	4 years*****	1/250,000******	Accuracy not assessed
2003	Directorate General of Forestry Planning	Landsat 5 TM (2002-2003; FAO, 2007b)	30 m	3 years	1/250,000 (MoF, 2005)	Accuracy not assessed
2006	Directorate General of Forestry Planning	Landsat 5 TM and 7 ETM+ (2005-2006; FAO, 2015c)	30 m	3 years	1/250,000	Accuracy not assessed
2000-2005	Directorate General of Forestry Planning	MODIS	500 m	N/A		Accuracy not assessed

* Minimum Mapping Unit

** Only about 60 Landsat MSS scenes, out of 131 scenes obtained, were available for 1972-1982 (FAO, 2007b).

*** Landsat images acquired between 1996 and 1998, and images from 1994 or 1995 were also used in some instances (Holmes, 2002).

**** Actual frequency is 12 years (Holmes, 2002), but it is not included because only forest cover was estimated and there were no sub-classes for land cover or forest types (Holmes, 2002).

***** As predominant Landsat images for the NFI were acquired in 1989, actual frequency is longer than this.

****** Mapping scales of 1:100,000 for multispectral bands and 1:50,000 for panchromatic imagery are recommended for classification. Minimum mapping units for the map are 6.25 ha at 1:50.000 scale, and 25 ha at 1:100.000 scale (Margono et al., 2016).

- The 1999 monitoring results was published in 2002 (Holmes, 2002), and the 2000 and the 2003 monitoring results, “Recalculation of Indonesia forest cover”, were published in 2003 and 2005 (FAO, 2007b).
- “Recalculation of Indonesia forest cover” was published in 2003, 2005, 2008, 2011, and 2012, and used for FAO’s FRA 2005 and 2010 (Margono et al., 2016).
- Before 2000, there were two nationwide mapping programs in Indonesia, i.e. the Regional Physical Planning Program for Transmigration (RePPProT) in the 1980s and for the first NFI program in the early 1990s. For the RePPProT program, a nationwide forest cover map was produced, using aerial photographs and satellite imagery from 1984 to 1986, with very limited field checks (Holmes, 2002).

(Source: Generated based on information from interviews, FAO, 1996; Holmes, 2002; MoF, 2005; FAO, 2007b; FAO, 2010c; FAO, 2015c; and Margono et al., 2016)

Although these projects were technically, and financially, supported by overseas organisations, the resolution, quality and spatial coverage of outputs were considered to be not high standards. The 1996 and the 1999 maps were produced using Landsat MSS and TM imagery at scales of 1:250,000 and 1:500,000 respectively, and the quality of satellite imagery was poor. There were also problems in interpretation of satellite imagery (see FAO 1996; Holmes, 2002). As there are many islands in Indonesia territory, monitoring did not completely cover all the islands. For the 1996 map, Java was excluded (FAO, 1996). Forest cover monitoring in 1999 covered only Sumatra, Kalimantan, Sulawesi, Irian Jaya and Maluku (Holmes, 2002). The accuracy of classification was not assessed.

During the 2000s, some improvements were made in both the resolution and frequency of mapping. The biggest improvement was regular production of forest cover maps at national scale. As mentioned earlier, national forest cover mapping was undertaken in the 1990s, but it did not cover the whole country. The first national forest cover map that covered the whole country was produced in 2000, and Indonesia continued to produce national forest cover maps triennially by itself – maps were produced in 2000, 2003 and 2006. The frequency of forest cover mapping was exceptional, compared to other tropical countries.

The resolution of mapping was also enhanced, although mapping scale and accuracy assessment remained unchanged. Spatial resolution of forest cover maps enhanced to 30 m since Landsat 5 TM and 7 ETM+ data were used as the main satellite data for forest mapping, instead of Landsat 4 MSS that has 60 m spatial resolution. On the other hand, the scale of the forest cover maps was remained the same as 1:250,000, and some low resolution images such as MODIS and SPOT vegetation were also used. As the 1990s, the accuracy of the maps was not assessed, and ground truth data for classification and verification were rarely collected from the field.

6.2.3 Organizations

Indonesia's forest mapping history can be divided into two main organizational periods, before and after 2000, by the relationships with overseas and Indonesian organisations. Before 2000, Indonesia's forest cover monitoring was technically and financially supported by overseas organisations. The assistance from overseas organisations in the 1990s was mainly for implementing the first National Forest Inventory (NFI) Project. For the project, financial support was provided by the Forestry Institutions and Conservation Project of the World Bank, and technical support for establishing Indonesia's initial national forest monitoring system and capacity building for forest area monitoring activities was provided by FAO (FAO, 1996; 2007b).

On the other hand, after 2000, national forest cover maps have been produced by the Sub-Directorate of Forest Resources Monitoring, without assistance from overseas organisations. Even though forest area monitoring was occasionally supported by overseas organisations through small projects, Indonesia produced forest cover maps independently for its own use.

During both of the periods, the Directorate of the Ministry of Forestry responsible for providing this information was the Directorate of Forest Resources Inventory and Monitoring under the Directorate General (DG) of Forestry Planning. It was divided into the Sub-Directorate of Forest Resources Monitoring, the Sub-Directorate of Forest Resources Inventory, the Sub-Directorate of Forest Thematic Mapping, and the Sub-

Directorate of Spatial Data Networking, which evolved from four units, under the Mapping and Inventory Division in the Directorate General of Forest Inventory and Land Use Planning, that had been created for the first NFI project (Figure 6.1). Of the four Sub-Directorates, the Sub-Directorate of Forest Resources Monitoring, which was the Remote Sensing unit for the first NFI project, has produced forest cover information for the Ministry of Forestry and other government agencies with its regional offices in accordance with Article 4 of the Forestry Law Number 41/1999.

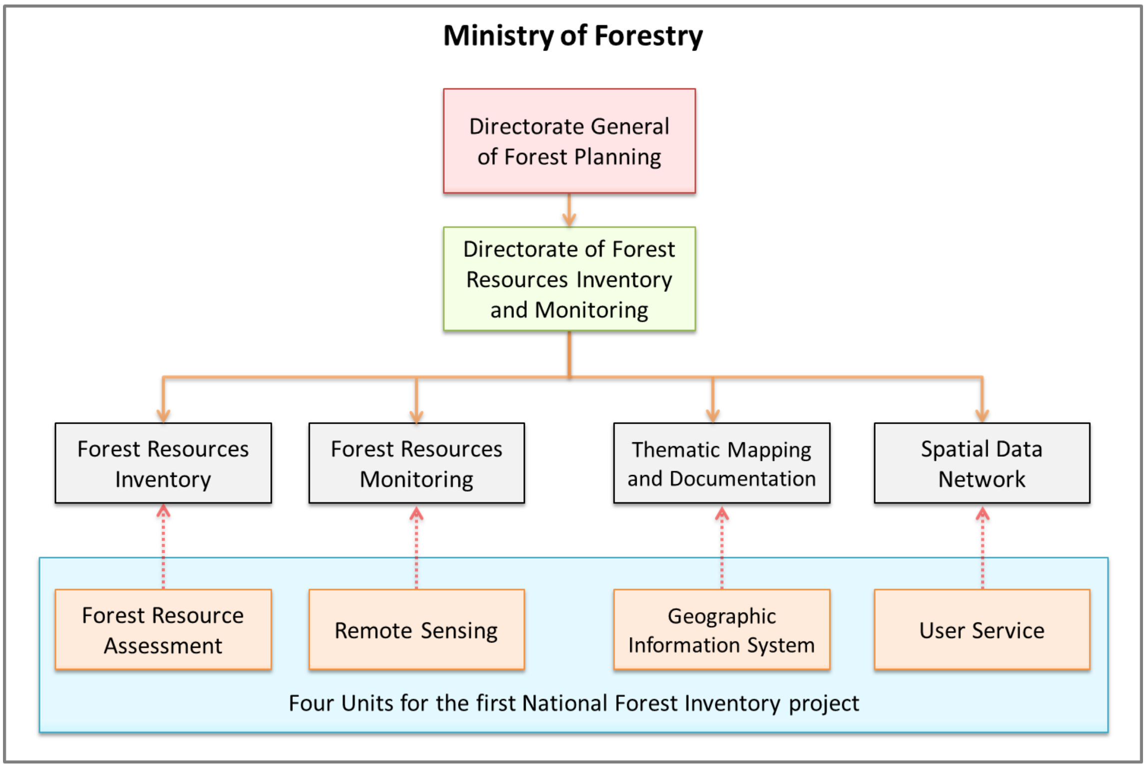

Figure 6.1 Sub-Directorates of the Directorate of Forest Resource Inventory and Monitoring under the Directorate General of Forest Planning of the Ministry of Forestry

(Four Sub-Directorates in grey boxes evolved from the four units, under the Mapping and Inventory Division, used for the first National Forest inventory project in Indonesia between 1989 and 1996)

Since the early 2000s, these forest area monitoring activities have been supported by Indonesian organisations outside the Ministry of Forestry. The National Institute of Aeronautics and Space (LAPAN) has provided satellite data to the Ministry of Forestry since 2003 in accordance with an MOU for satellite data provision (Margono et al., 2016). Base maps and standard for map generation have been provided by BAKOSURTANAL (National Mapping Agency). LAPAN and BAKOSURTANAL supported training forestry offices in the regional offices as for the triennial forest monitoring activities, the role of forestry offices in the regional offices was important in land cover classification.

6.2.4 Technologies adopted

The Sub-Directorate of Forest Resources Monitoring produced national forest cover maps with its in-house technologies for forest area monitoring. The technologies for forest mapping in Indonesia could be divided into three different types by data processing methods, data formats and the number of classes. The three technologies were manual-visual classification on hard copy, digital classification with other processing methods, and on-screen manual-visual classification (Table 6.2).

The principal technology used by Indonesia before the first NFI project was manual-visual interpretation on hard copy of aerial photographs or Landsat images. This technology relied on manual delineation of boundaries with tracing films.

The first opportunity for adopting digital classification occurred for the first NFI project undertaken between 1989 and 1996, when the Ministry of Forestry decided to test the use of digital classification. Digital classification was tested and temporarily used for forest area monitoring between 1992 and 1999, as part of the mixed use of different processing methods. Supervised classification of Landsat images was used for the post-classification of inventoried data collected during the first NFI project, and for land cover classification (Nugroho, 2006), although vegetation cover was delineated mainly by visual interpretation of Landsat MSS images. As digital classification was used, the area of forest strata in the maps, which were produced by combining forest classes, was also calculated digitally (FAO, 1996). For generating the 1999 deforestation map, digital classification was more intensively used, but it was only for forest and non-forest classification at low resolution (Holmes, 2002).

Table 6.2 Existing technologies for producing land use/cover and/or forest cover maps of Indonesia before the REDD+ readiness programme

Year	Producer and partner(s)	Satellite data	Format	Processing methods	Ground truthing	Land cover classes	Remark
1989-1996	Directorate General of Forest Inventory and Land Use Planning, with FAO*	Landsat 4 MSS and 5 TM	Digital format and hard copy	Mixed use of manual, on-screen manual and digital Classification	Not conducted	14 classes	- First use of Landsat data and digital classification - Additional imagery: SPOT image and aerial photograph (FAO, 2007b)
1999	Mapping and Inventory division of the Directorate General of Forestry Planning **	Landsat	Digital format	Interpretation of digital data (Holmes, 2002)	Field checking not conducted (Holmes, 2002)	- Forest cover only (Holmes, 2002)	- No sub-classes for forest or nonforest cover
2000	Directorate General of Forestry Planning	Landsat 5 TM and 7 ETM+	Digital format	Manual Classification (Visual Interpretation and on-screen digitization)	Ground check from 2000 to 2001 (FAO, 2007b)	23 classes, of which 6 for natural forest	- Additional imagery: SPOT Vegetation 1000 m and MODIS 250 m (MoEF, 2016)
2003	Directorate General of Forestry Planning	Landsat 5 TM and 7 ETM+	Digital format	Manual Classification (Visual Interpretation and on-screen digitization)	Ground check from 2003 to 2004 (FAO, 2007b)	23 classes, of which 6 for natural forest	- Same method and additional imagery used for 2000
2006	Directorate General of Forestry Planning	Landsat 5 TM and 7 ETM+	Digital format	Manual Classification (Visual Interpretation and on-screen digitization)	Field checking conducted (FAO, 2010c)	23 classes, of which 6 for natural forest	- Same method and additional imagery used for 2000

2000-2005***	Directorate General of Forestry Planning	MODIS and SPOT Vegetation	Digital format	Digital classification	Field checking not conducted	Forest-nonforest only	- Corrected with Landsat ETM+ data (MoF, 2008)

* As part of the first Indonesian NFI
** Without coordination with the regional offices of the Ministry of Forestry (Holmes, 2002).
*** For immediate deforestation monitoring and reporting (MoF, 2008).
- The map of 1999 and the map from the NFI were available at the Ministry of Forestry website (Holmes, 2002).
- The 2000 and 2003 mapping was conducted by national budget (FAO, 2007b).

(Source: Generated based on information from interviews, FAO, 1996; Holmes, 2002; MoF, 2005; FAO, 2007b; FAO, 2010c; FAO, 2015c; Margono et al., 2016; and MoEF, 2016)

After the period of mixed use of different processing methods, in 2000, on-screen manual-visual classification became the main technology for national forest cover mapping. Indonesia decided to return to on-screen manual-visual classification of digital format Landsat data for producing national forest cover maps because of limited satellite data, existing technologies and institutions in the Sub-Directorate of Forest Resources Monitoring. (This is discussed in more detail below.) A forestry officer who has been working in the Sub-Directorate of Forest Resources Monitoring since 1996 explained changes in technologies:

> *"We started using [on-screen] manual classification in 2000. Before that we used digital classification. But we had many problems in digital classification, especially haze and cloud. So in 2000, we made pivotal decision to change digital classification to manual classification. [Before 2000] We used supervised classification, but we could not cover the whole county at one time." (Mr. Usman, 21st of August 2017)*

The reversal was accompanied with the more intensive use of Geographical Information Systems (GIS) and the participation of people outside the Sub-Directorate of Forest Resources Monitoring. On-screen manual-visual classification was performed using GIS, and as the process was time-consuming and labour-intensive, external consultants participated in the production of the 2000 map. They were later replaced by forestry officers in regional offices after capacity building in regional offices for on-screen manual-visual classification, and since then, forestry officers in regional offices have performed visual interpretation, scene by scene. The influence of these changes on adopting new technologies is explained in Section 6.5.

6.2.5 Explaining Technology Adoption and Reversal

This section uses the Technology Adoption System (TAS) Framework to explain the adoption and reversal of technologies before REDD+ Readiness.

6.2.5.1 Material constraints

As shown in the previous section, digital classification was used between 1992 and 1999, but it was not adopted. One constraint on adopting digital classification was data provision, caused mainly by cloud and haze cover in addition to limited budget (Figure 6.2). As Indonesia has no cloud-free season and the total area of the country is large, many images were required to give complete low cloud coverage. Using digital classification was difficult because it requires far more satellite images than manual visual classification. Even if forest areas were covered by clouds, forestry officers were able to performed visual classification with their experience and local knowledge with minimum field data.

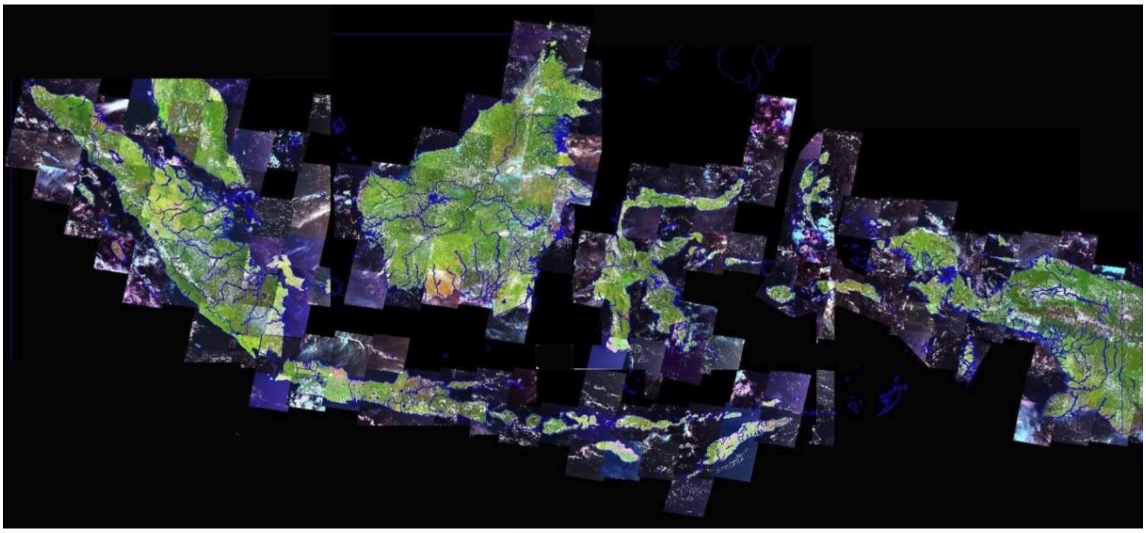

Figure 6.2 217 Landsat 7 ETM+ images mosaicked for the 2009 forest cover map of Indonesia

(Source: Ministry of Environment and Forestry of Indonesia)

Limited Landsat data, and limited time for annual deforestation monitoring and reporting, resulted in national forest cover monitoring using low resolution satellite data in the mid-2000s. Indonesia was not able to secure sufficient satellite images even for visual interpretation, and so difficulties in obtaining Landsat images with low cloud were countered by using SPOT 4 images and other low spatial resolution satellite data such as MODIS. In 2006, deforestation at national scale from 2000 to 2005 was estimated by digital classification of SPOT Vegetation 1000 m and MODIS 500 m in collaboration with South Dakota State University (MoF, 2008) (see Table 6.1 and 6.2).

6.2.5.2 Existing technology

Another constraint on adopting digital classification for national forest area monitoring was existing technologies. This included software and hardware such as data storage and server capacity. Although digital processing was used as part of the mixed use different satellite data processing methods, capacity for full implementation of digital classification was still not operational and software for the full implementation of digital classification of satellite data was not in place. Due to the lack of computing power, and data storage, even executing supervised classification scene by scene was not easy. Digital classification that is performed using raster datasets requires higher computing power, more satellite data and bigger data storage and server capacity, compared to manual classification that deals with spatial data in vector format. Merging the classification results in raster format and converting the raster data to vector data for further analysis was even more difficult as the converting process caused the staircase effect.

6.2.5.3 Financial resources

Adopting digital classification for forest area monitoring was constrained by limited materials and existing technology, and this was caused by limited financial resources. The availability of financial resources was a constraint on forest area monitoring in this period in terms of limiting the number of satellite images, and hardware and software purchased for satellite data processing. Covering the whole Indonesia territory using Landsat data requires at least 217 scenes, but Landsat data were not free at the time. On-screen manual classification was possible as funds for purchasing hardware and software were provided through the first NFI project. Yet, after the end of the NFI project, software licence for digital classification could not be maintained due to limited financial resources.

6.2.5.4 Institutions

Digital classification for forest area monitoring had been used, and reversed, as explained in the previous section, and these were accompanied with changes in institutions linked to them. Technology adoption was related to not only physical factors mentioned above, but also social factors such as institutions, and human capital.

The Indonesian case study showed that the decision on technology adoption was affected by institutional similarity, i.e. similarity between the practices for operating existing and new technologies. This enabled forest area to be mapped every three years from 2000 onwards. Technology was reversed as forestry officers were more familiar with manual-visual classification. The origins of present practices, or institutions, for satellite image classification can be traced to delineating boundaries of forests by hand drawing on aerial photographs in the 1960s and 1970s, and later it was applied to Landsat images. Institutions for manual-visual interpretation on hard copy and on a computer screen were similar, although the form and type of data in addition to the use of computers were different. A professor explained Indonesian forestry officers' experience in visual interpretation and the adoption of new technologies for forest area monitoring in the past:

> *"They used paper-printed Landsat data, and then covered by plastic for delineation ... After that they developed [on-screen] manual visual interpretation. The Ministry of Forestry spent time and money to train forestry officers. Now, the system is done by their officers and officers in regional offices. This is why they use visual interpretation." (Prof. Saleh, 18th of August 2017)*

After the period of mixed use of different classification methods (i.e. manual classification on hard copy, on-screen manual classification, and digital classification) under the first NFI project, on-screen manual classification was institutionalised from 2000. The adoption of on-screen manual-visual classification occurred after the temporary shift to digital classification. Manual classification on hard copy could be switched to on-screen manual classification as practices for those were similar while provision of satellite data in digital format was increasing. On-screen manual-visual classification was a new hybrid technology between manual and digital classification.

On the other hand, embedding institutions for digital classification within the Sub-Directorate of Forest Resources Monitoring was difficult, as they were less consistent with existing institutions. Supervised classification was used for about 8 years, from 1992 to 1999. However, routinizing practices for supervised classification was difficult, as it required additional procedures such as intensive and exhaustive pre-processing including radiometric and topographic correction, noise removal and image mosaicking in addition to converting data format. Forest officers were not familiar with such processes, and spectral features of satellite data.

This also suggests that without complete institutionalisation, reproduction of institutions by adopters is difficult. Institutions for digital classification were introduced by technical staff from overseas organisations, and shared with Indonesian forestry officers. However, the degree of sharing and implementing institutions were not sufficient to be implement, and repeat, forest area monitoring at national scale. Digital classification was performed scene by scene based on data availability, and so was never performed for the whole country. As an example, during the first NFI project, only 34 percent of the country could be covered by Landsat TM images acquired for 1986-1990 (FAO, 2007b).

6.2.5.5 Human capital

People could not adapt to new institutions, and human capital that operates technologies was poor too. The quality of human capital in the Sub-Directorate of Forest Resources Monitoring was a constraint on adopting digital classification. Between 1986 and 1990, training for interpretation and analysis of remote sensing data had been provided by FAO for the first NFI (FAO, 1996; P3SEKPI, 2017), and a basic minimum number of forestry officers for national forest cover mapping have been available since then. By the year 2000, the number of staff who could undertake satellite data analysis in the central office of the Sub-Directorate of Forest Resources Monitoring was about seven, including the Director, and another 10 people worked on GIS analysis. However, they had limited knowledge of remote sensing and other methods for analysis that could have been used. Thus, accuracy of forest cover maps was not assessed, and ground truthing was not used for accuracy assessment, because of limited knowledge of remote sensing. Forestry officers were used to performing forest cover monitoring using existing technology, but they were not flexible enough to accommodate to new institutions. The quality of human capital in the past was stated by the Deputy Director of the Sub-Directorate of MRV and Registry for land-based sectors in the Directorate of Climate Change, who worked in the Sub-Directorate of Forest Resources Monitoring until 2015:

> *"In the past, we didn't know anything. It was like "do we need to have the accuracy? really? why?" Something like that."* (Dr. Margono, 23rd of August 2017)

To meet enhanced mapping frequency, forestry officers in regional offices began to participate in national forest area monitoring as substitutes for external consultants, but they had more limited knowledge on satellite data processing than those in the central office.

6.2.6 The Gap between Forest Area Information Supply and Demand

From the early 1990s Indonesia made a massive leap in national forest area monitoring. So clearly a sound organisation had been established, as had the necessary institutions. This occurred despite constraints on finance and human capital. The Sub-Directorate of Forest Resources Monitoring provided national forest cover information triennially from 2000 to 2009, which was exceptional in the tropics, and so it can be assumed that information supply was sufficient to meet national demand for information on forest area change (Table 6.3).

Indonesia's forest monitoring system still had limitations, however. They are the quality of forest area information, including resolution and accuracy, limited by various factors. Although Landsat data were the main satellite data, mapping scale was only 1:250,000 because of the reliance on existing institutions and technology, i.e. on-screen manual-visual classification. Accuracy of classification was not assessed, and collecting field data for ground truthing was rarely conducted because of limited human capital, financial resources, and existing institutions.

Table 6.3 The gap between forest area information supply and demand before the REDD+ Readiness

		Information supply before REDD+ readiness	National (and International***) Information demand
Factors in forest area monitoring	Satellite images	Landsat images	Various images possible
	Data format	Hard copy/Digital before 2000 and digital after 2000	Digital format recommended
	Image processing	On-screen manual-visual classification since 2000	Not specified
	Frequency/ Resolution	3 years after 2000/30m*	Not specified, but as high as possible
	Forest degradation monitoring	Not monitored	Not compulsory
	Land classes	23 classes of which 6 classes for natural forest**	Not specified
	Accuracy	Not assessed	Not specified, but as high as possible
	Points for ground truth	None	Not specified, but accuracy assessment recommended
	Human resources	Minimum number of trained forestry officers for manual classification	Not specified
	Institutions	Fixed practices for manual classification in central and regional offices.	Various but fixed practices recommended

* Spatial resolution was 30 m but mapping scale was 1:250,000.
** Since 2000.
*** FAO provided guidelines for forest growing stock monitoring for FRA, and IPCC guidelines provide different Tiers for carbon stock reporting in accordance with accuracy of data. Yet, neither of them was compulsory. For more details, see Chapter 2.

6.3 Forest Growing Stock Monitoring before the REDD+ Readiness Programme

Governments also need reliable information on timber volume (or ‘growing stock’) in their forests if they are to manage these forests sustainably. This information is usually supplied by National Forest Inventories (NFIs) which ideally are updated on a regular basis. The information provides a crucial starting point for producing information on changes in carbon stocks, but in this period such information was not required.

6.3.1 National and International Policies and Information Needs

6.3.1.1 National policies and information needs

Supplying growing stock information was encouraged by national policies although it was not the Indonesia government’s top priority. After the enactment of the Act of the Republic of Indonesia Number 5/1967, concerning the management and conservation of state and private forests, Indonesia started its forest inventory in the early 1970s. The Government needed forest inventory data and information for forest area affirmation, forest resources balance, forestry plan preparation and forestry information system (Article 13 of Law no. 41/1999 regarding Forestry). Yet, although national information needs were stipulated in forestry laws, e.g. Government Regulation Number 44/2004 regarding Forestry Planning, none of them define the frequency and resolution of forest inventory in detail.

6.3.1.2 International policies and information needs

National policies also encouraged supplying growing stock information to meet international demand, but most international demands for forest information were not compulsory. The only source of major international demand for information on national forest growing stock before 2009 came from the Food and Agriculture Organization of the United Nations (FAO) for its Forest Resources Assessments (FRAs). Indonesia was also requested to supply information periodically to the International Tropical Timber Organization (ITTO), though neither request required a compulsory response. Indonesia was required to submit its National Communication to the UNFCCC, but it was also a voluntary submission.

6.3.2 Outputs: frequency and resolution of inventory

Indonesia’s growing stock data production at national scale begun, when it commenced a project entitled “Forestry Institution and Conservation Project” with support from FAO. It is Indonesia’s first National Forest Inventory (NFI) that lasted for 8 years from 1989 to

1996. During the project, Indonesia’s first official permanent sample plot clusters were established in collaboration with FAO, and as a result of the project, 2,735 sample plot clusters systematically distributed over the country were measured.

After completing the first NFI project, Indonesia continued to measure its permanent sample plots without support from overseas organisations, but the number of permanent sample plots measured every year has gradually declined. Although the frequency of NFIs has been said to be five years, Indonesia measured only 1,145 and 485 sample plots between 1996 and 2000, and between 2000 and 2006 respectively (IGES, 2012). Given the number of permanent sample plots measured during the first NFI project, this is an extreme decline.

6.3.3 Organizations

Indonesia’s forest inventory history can be divided into two main organizational periods, before and after 1996, when Indonesia’s first NFI was completed. Indonesia’s NFI was financially and technically supported by overseas organisations for the first NFI project, but after that, it produced growing stock information by itself. For the first NFI project, a total budget of US$ 14.1 million was provided by the World Bank (FAO, 1996), and technical assistance was given by FAO. FAO helped designing the NFI, implementing field surveys, and training forestry offices in both central and regional offices (FAO, 1996). Subsequent field surveys implemented after completing the first NFI were funded by the Government.

Over the two organizational periods, the Sub-Directorate of Forest Resources Inventory has been responsible for implementing forest inventory at national, regional, watershed, and management unit levels for surveying the status and physical condition of forest, flora and fauna, human resources as well as community social condition in and around forest (Article 13 of Law no. 41/1999), which originated from the Forest Resources Assessment unit created for the first NFI project (see Figure 6.1 in section 6.2.1.1). After the first NFI, the Sub-Directorate of Forest Resources Inventory continued to coordinate field inventory activities and operated the field data processing system using GIS and other software. Field surveys are supported by regional offices in accordance with Article 4 of the Forestry Law 41/1999 that gave the Sub-Directorate of Forest Resources Inventory the authority to supervise regional offices for undertaking forest inventories.

6.3.4 Technologies adopted

Indonesia's technology for its National Forest Inventory (NFI) did not change after the adoption of the technology for its first NFI. Indonesia employed the technologies recommended by FAO, and protocols and field instructions for inventorying in the field were provided by its Sub-Directorate in collaboration with FAO.

The technology for Indonesia's first NFI was a package of a network of permanent sample plots and a methodology for measuring them and analysing the data. The NFI design was a systematic stratified sampling design with post-stratification. In a systematic grid of 20x20 km, plot clusters were distributed in forested and non-forested areas below 1,000 m altitude. The size of a plot cluster was 1,300 m x 1,300 m, which consisted of a 1 ha square Permanent Sample Plot (PSP) at the centre and surrounding eight Temporary Sample Plots (TSPs) (FAO, 1996). During field surveys, site information on PSPs was recorded, and trees in the PSPs were classified for measuring trees lager than diameter at breast height (dbh) of 5 cm (MoEF, 2016). The inventoried data were entered into a computer and then validated (FAO, 1996) (Figure 6.3).

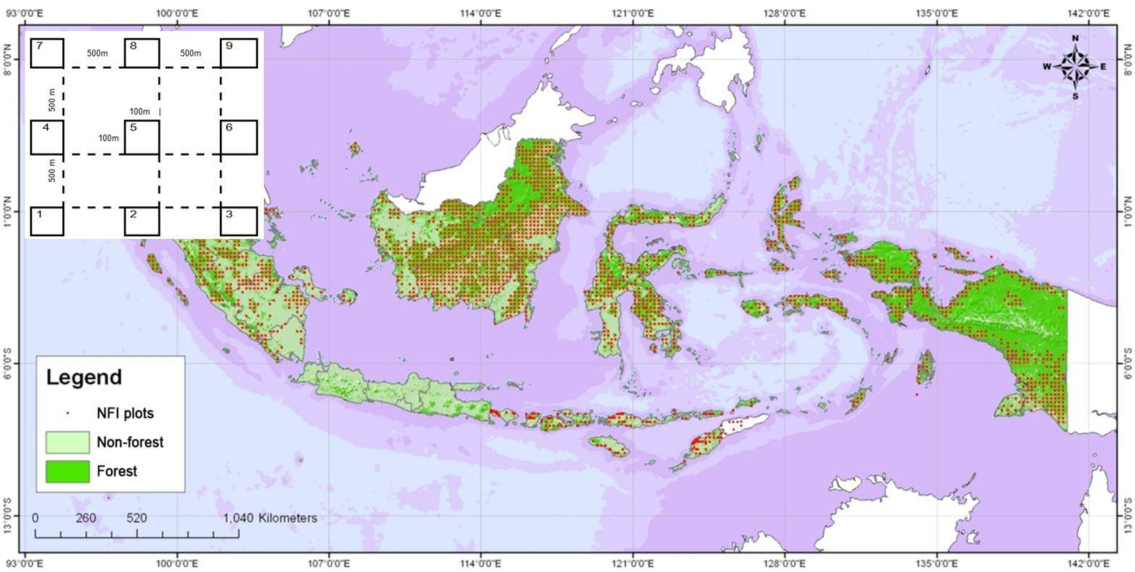

Figure 6.3 Stratified systematic sampling design for Indonesian NFIs

(The figure shows locations of plot-clusters in a 20 km x 20 km grid within the Universal Transverse Mercator (UTM) coordinate system, and the structure of the plot-cluster (white box at upper left corner). Source: Directorate of Forest

Resources Inventory and Monitoring of the Ministry of Environment and Forestry, Indonesia)

The technology for Indonesia's first NFI also included methodology for estimating timber volume. Total volume of trees by species groups was calculated on the basis of dbh and tree height using a set of field data storage and processing systems, and a single allometric equation. A custom-made field data processing system was developed and used, and plot-cluster and strata information in the system was integrated into a GIS database to stratify the sample, analyse the data by stratum, and produce thematic maps using spatial strata information from the GIS (FAO, 1996). Only one generic allometric equation was used for estimating trees volume, since after analysing volume data from 2,932 trees during the first NFI, forestry officers concluded that there were no significant differences in tree allometry between locations and species groups (FAO, 1996).

This technology remained in use for a long time, but capacity for operating the system was gradually degraded during the 2000s. As of 2008, right before starting Indonesia's REDD+ readiness programme, the number of plot clusters remaining in Indonesian was only 1,197 (MoF, 2008) in spite of sampling density for NFIs enhanced up to 10 km in 2006 (FAO, 2007b).

6.3.5 Explaining Technology Adoption

Technology for growing stock monitoring had adopted as described, but the intensity of measurements has degraded since then. This section explains the adoption of the forest inventory technology using the Technology Adoption System (TAS) Framework.

6.3.5.1 Institutions

Indonesia could implement within a Sub-Directorate of the Ministry of Forestry internationally recognised technologies and rules for conducting its first National Forest Inventory (NFI) between 1989 and 1996, because the overseas staff employed for the first NFI reproduced institutions based on their experiences and knowledge, and such institutions were shared with Indonesian staff in the central and regional offices who actually implemented the practices.

However, after completing the project, the rules for the NFI were not institutionalised in the Ministry of Forestry because of the one-off nature of the project planned and led by overseas organisations, national policy, standing information needs and other reasons. Field measurements, including establishing sample plots, measuring the plots and field data entry, were implemented by Indonesian staff in the regional offices, but such activities became substantially degraded. Institutionalising the rules for NFI introduced as part of the externally funded project was not supported by national policy as national information needs after the completion of the project were not as high as the outputs that could be produced by implementing practices for the first NFI.

6.3.5.2 Financial resources

Lack of funding was another reason for this shift. After the end of the NFI project, financial support from overseas organisations was terminated, and the Indonesian government was unable to provide funding for its NFIs due to the financial crisis between 1997 and 1999. Lack of government funding meant that the NFI rules could not be converted into institutions in the Ministry of Forestry to ensure that measurements continued to be made on the scale and frequency that these rules require.

6.3.5.3 Human capital

Another reason for the unsuccessful institutionalisation was human capital. Although the first NFI project provided a good foundation for further training, the quality of human capital was not sufficient to fully reproduce the institutions introduced for NFIs. During the project, field crew leaders were trained by FAO staff to lead teams for collecting inventory data in the field using GPS and GIS (FAO, 1996). Some forestry officers in the central office, and regional office were educated at Bogor Agricultural University (IPB) or Gadjah Mada University, which had faculties of forestry since the beginning of the 1960s. From the 1980s onwards, some forestry officers started to study for MSc or PhD degrees in forestry in European countries, especially Germany and the Netherlands (MoF, 2006). However, it seems that the quality of human capital was still not sufficient to keep the NFI system fully running.

6.3.6 The Information Gap between Information Supply and Demand in Growing Stock Monitoring

Growing stock data collected during the first NFI were sufficient to provide information that its government needed for forest management and planning (Table 6.4). The government could also use its information to report to FAO for its FRAs, and to the UNFCCC for its first National Communication submitted in 1999. Indonesia, however, did not have other biomass and carbon parameters, such as allometric equations, biomass and carbon expansion and conversion factors including wood density, as information provision was focused on responding to national demand for timber volume estimation.

Table 6.4 The gap between growing stock information supply and demand before the REDD+ Readiness

		Information supply before REDD+ readiness	National (and International***) Information demand
Factors in NFI and growing stock reporting capacity	Frequency/ Resolution	5 years/National scale sampling but intensity decreased	Not specified, but ideally 5 years
	Emission factors*	Not developed	Not compulsory
	Allometric equations	Not developed (used a single generic equation)	Not compulsory
	BCEF**	Not developed	Not compulsory
	Carbon conversion factors	Not developed	Not compulsory
	Wood density	Not developed	Not compulsory
	Carbon pools	Not estimated	Not compulsory
	Human resources	Minimum number of trained forestry officers for field survey	Not specified
	Institutions for NFI	Rules for practices existed	Various methodologies proposed and fixed practices recommended
	Uncertainty assessment	Possible	Accuracy assessment recommended

* Indonesia estimated AGB for forest types as emission factors by analysing existing data and literature survey to find available data and collecting existing forest inventory data (MoEF, 2016).
** Biomass Conversion and Expansion Factors
*** FAO provided guidelines for forest growing stock monitoring for FRA, and IPCC guidelines provide different Tiers for carbon stock reporting in accordance with accuracy of data. Yet, neither of them was compulsory. For more details, see Chapter 2.

6.4 The REDD+ Readiness Programme

As shown in the previous sections, before REDD+ negotiations, Indonesia's forest information supply and demand was generally in balance. However, to meet increasing internal and external demand on forest information, in accordance with evolving international climate change mitigation actions, Indonesia had to raise its capacity to produce such information by adopting new technologies. New opportunities for adopting new technologies occurred with the REDD Readiness Programme that began in 2009 with funding from UN-REDD and the Forest Carbon Partnership Facility (FCPF) of the World Bank. Indonesia's experiences during these programmes provide additional insights into whether or not new technologies are adopted.

6.4.1 The History of Indonesia's REDD+ Readiness Programme

To participate in REDD+, Indonesia has implemented its REDD+ Readiness programme with financial and technical assistance from overseas organisations. Later, after becoming a partner country of UN-REDD in 2008, Indonesia officially commenced Phase 1 of the REDD+ Readiness programme, Capacity Building, in 2009 (UN-REDD, 2009), and completed it in 2012. UN-REDD is an inter-agency construction involving several UN organisation dedicated to implementing REDD+ Readiness (see 2.2.4 for more information on REDD+ Readiness programme). For this activity, the Norwegian government provided US$ 5,644,250 as part of the UN-REDD programme (UN-REDD, 2009). Shortly after completion of Phase 1, Indonesia started Phase 2 of the REDD+ Readiness programme. This involved a Results-Based Demonstrations project in accordance with the Indonesia-Norway REDD+ Partnership, which is still ongoing. In addition to UN-REDD, Indonesia's REDD+ Readiness programme has been financially and technically supported by the World Bank's Forest Carbon Partnership Facility (FCPF) project since 2011. FCPF provided US$ 3.6 million for REDD+ Readiness activities between 20011 and 2016 (RoI, 2013), and continues to support Indonesia's REDD+ Readiness programme. The forest area monitoring component for REDD+ was also supported by the Japan International Cooperation Agency (JICA).

6.4.2 The REDD+ Readiness Programme and the JICA Project for Forest Area Monitoring

During the REDD+ Readiness Programme, UN-REDD focused mainly on the improvement of the existing forest monitoring system, capacity building for data analysis, establishing a Forest Reference Emission Level (FREL), and implementing sub-national pilot projects (UN-REDD, 2009), since the Ministry of Forestry already had an operational National Forest Monitoring System that consisted of remote sensing and forest inventory components. To transform the existing system for forest area monitoring into a system for producing better information on forest area and changes for estimating forest carbon stocks, new forest area monitoring technologies were offered by UN-REDD, FCPF and JICA.

The new forest area monitoring technologies proposed during the REDD+ Readiness Programme included MODIS, SPOT and ALOS-PALSAR. MODIS was tested because it could offer greater more frequent forest area monitoring by digital analysis. MODIS was also expected to provide satellite data for early detection of deforestation. SPOT 4 data was offered for land cover classification, and tested for Central Sulawesi. This was for forest cover monitoring at higher spatial resolution (UN-REDD, 2013b). More detailed forest cover classification and multi-level forest area monitoring was expected to be performed by using SPOT 4 imagery.

Meanwhile, Indonesia also examined the possibility of using ALOS-PALSAR data to complement the existing Landsat-based monitoring system. This arose as part of cooperation with the Japan International Cooperation Agency (JICA) and the Japanese Forest Agency from 2008 to 2011. As the main purpose of the project was building capacity to use the PALSAR data in national forest cover mapping, during the project, training was provided for forestry officers in the central office, technical instruction on Synthetic Aperture Radar (SAR) data interpretation was provided, and interpretation manuals and guidelines for analysing the data were developed for activities for forest resources monitoring and REDD+. ALOS-PALSAR data was recommended and tested because radar data could provide cloud-free satellite data, which was one of the biggest constraints on forest area monitoring in Indonesia. In addition, ALOS PALSAR L-band was deemed to be useful for differentiating grass land from forest area, which is very difficult to be classified in tropical countries due to fast vegetation regrowth, as vertical structure of trees can be derived for return signals that penetrate into forest canopy cover. Primary and disturbed forests can be discriminated by backscatter values affected by soil moisture.

For the same reasons mentioned above, FCPF also recommended the Ministry of Forestry of Indonesia to use high resolution satellite data, radar, and LiDAR data as additional inputs, or as ancillary data sets (RoI, 2013).

When Indonesia tested new technologies such as digital classification, MODIS and SAR under its REDD+ Readiness Programme between 2006 and 2011, regional offices were excluded from forest cover monitoring at national scale as their capacity were much lower than that of the central office, i.e. the Sub-Directorate of Forest Resources Monitoring. The Ministry of Forestry devoted a great deal of effort to testing these new technologies, and forestry officers in the central office had to change their daily operations and tasks.

As an outcome of the REDD+ Readiness Programme (UN-REDD, 2013b), the Ministry of Forestry officially launched Indonesia's National Forest Monitoring System (NFMS) on the 29th of October 2012, which provides data and information on forest area and changes for Indonesia's REDD+ Measurement, Reporting and Verification (MRV). Landsat-based forest area monitoring by on-screen manual-visual classification remains as the remote sensing component of the system. The reasons for this will be examined in section 6.5.

6.4.3 The REDD+ Readiness Programme for Forest Carbon Stock Monitoring

The National Forest Inventory (NFI) part of the REDD+ Readiness Programme in Indonesia was led by the Food and Agriculture Organization of the United Nations (FAO), and the Forest Carbon Partnership Facility (FCPF) of the World Bank. FAO focused mainly on upgrading Indonesia's existing national forest inventory methodology for forest carbon estimates since Indonesia already had its NFI design and field sample plots, while FCPF focused on establishing new sample plots for carbon purposes. The REDD+ Readiness Programme was accompanied with capacity building for estimating forest carbon stocks and developing emission and removal factors, and implementing sub-national pilot projects.

To transform the existing system for national forest inventories, new technologies were proposed during the REDD+ Readiness Programme, after reviewing existing methodologies and standards. The new technologies proposed included a new sampling design, developing allometric equations and carbon factors, and adding sample plots and parameters for carbon stock estimates. This was because Indonesia's first National Forest Inventory (NFI) data collected between 1989 and 1997 were already outdated and the first NFI design was not for carbon purposes. The new methodology for Indonesia's NFI was offered because it was expected to enable estimating forest carbon stocks with lower uncertainty, and enhance reporting and verification capacity.

To collect and analyse NFI data, OpenForis was also offed by FAO, and installed for testing in 18 computers in the Ministry of Forestry (UN-REDD, 2013b) (see 5.4.3 for OpenForis). Adopting OpenForis was proposed because the existing NFI data management and analysis system had been developed and used for estimating timber volume. To promote using OpenForis for data collection and analysis, training was provided to 18 forestry officers from the central and regional offices.

6.5 Forest Area Monitoring after the REDD+ Readiness Programme

Indonesia had to raise its capacity for monitoring forest area and changes to supply more reliable information for implementing REDD+, and for the purpose, new technologies were offered by overseas organisations. This section describes the technologies and practices employed after the REDD+ Readiness Programme, and explains why new technologies were or were not adopted using the Technology Adoption System (TAS) framework.

6.5.1 National and International Policies and Information Needs

6.5.1.1 International policies and information needs

While information demands from FAO and ITTO remain the same as before, as international negotiations on climate change mitigation have progressed, this has led to new international demand for information from the UNFCCC. In response, in 2010 Indonesia submitted its Second National Communication to the UNFCCC to report greenhouse gases emissions in Indonesia for the years 2000 to 2005 (MoE of Indonesia, 2010). The Indonesian government ratified the Paris Agreement in October 2016 (Law No. 16/2016), after submitting its national Forest Reference Emission Level (FREL) for deforestation and forest degradation in 2015 (MoEF, 2016).

National political support for these actions was provided through implementing new stated policies. Indonesia's national policies on climate change are stated in the law on Environmental Protection and Management (Law No. 32/2009), the National Action Plan for reducing GHG emissions (Presidential Decree No. 61/2011), and the Inventory of GHG (Presidential Decree No. 71/2011). To support enforcement of the laws, the Indonesian government published the 'National Action Plan on Adaptation of Climate Change 2012'.

To meet international demand for forest area information, Indonesia will have to report its forest monitoring statistics, which include forest area and carbon stock changes, to the UNFCCC every four years for National Communications, and the Sub-Directorate of Forest Resources Monitoring needs to update the statistics at least every two years for Biennial Update Reports. For the purpose, monitoring is needed at much higher frequency.

6.5.1.2 National policies and information needs

Whereas demand for forest information by international organisations has increased, although there were subtle changes, national demand for forest area information remained similar to that before the REDD+ Readiness programme. The latest national requirements for forest cover information production and provision are formally defined by the regulation of the Ministry of Environment and Forestry No: P.18/MenLHK-II/2015

(MoEF, 2015), which states its organizational structure, duties, functions and working procedure of Directorates under the Ministry of Environment and Forestry. Implementation of forest area monitoring to respond to the information needs by the Sub-Directorate of Forest Resources Monitoring is stated in the Articles 189-192 of the same regulation. However, it does not specify the resolution and frequency of information production and supply for national use.

6.5.2 Outputs: frequency and resolution of mapping

After the REDD+ Readiness programme, the frequency of forest area monitoring increased from every three years to annually. By the end of the 2000s, the frequency of national forest cover mapping had risen to once every two years: national forest cover maps were produced in 2009 and 2011. Subsequently the frequency of forest area monitoring rose to one map every year (Table 6.5).

In contrast to the frequency of forest area monitoring, there was no improvement in spatial resolution compared to before the REDD+ Readiness Programme, since the Sub-Directorate of Forest Resources Monitoring continued to rely on Landsat data for forest area monitoring. Spatial resolution of all the forest cover maps and mapping scale remained the same as 30m and 1:250,000 respectively, although for Indonesia's Forest Reference Emission Level (FREL), Minimum Mapping Unit (MMU) of the maps was enhanced up to 0.0625 km^2, which corresponds to 6.25 ha.

After the REDD+ Readiness Programme, the overall quality of historical data was enhanced, while the accuracy assessment for forest area mapping remained of less concern. The improved Landsat data provision made it possible to reassess historical trends in the distribution of forest cover in Indonesia by producing new national forest cover maps for the 1990s and the 2000s. Previous maps had poor quality because of missing data caused mainly by poor data acquisition and high cloud cover. The forest cover maps for the year 2000-2005 produced using MODIS data were also replaced by new Landsat maps (MoEF, 2016). However, even after starting the REDD+ readiness programme, the accuracy of classification was not evaluated, except for the 2011 map. The overall accuracy of that map was stated to be 88% (MoEF, 2016). The use of Landsat 8 imagery for the 2014 and 2016 forest cover maps enhanced the radiometric resolution of imagery, from 8-bits (256 brightness levels) to 16-bits (65,536 brightness levels), but it did not result in more detailed classification or higher classification accuracy because Indonesia continued to use on-screen manual-visual interpretation.

Table 6.5 Existing official land use/cover maps, and forest fires monitoring of Indonesia, produced by the National Forestry Department of Indonesia after starting the REDD+ Readiness Programme

Year	Producer	Satellite data	Resolution	Frequency	Scale/MMU*	Accuracy
2009	Directorate General of Forestry Planning	Landsat 5 TM and 7 ETM+ (2009-2010; FAO, 2015c)	30 m	3 years	1:250,000	- Accuracy not assessed
2011 onwards	Sub-Directorate of Forest Resources Monitoring of the Directorate General of Forestry Planning	Landsat 5 TM, 7 ETM+, and 8 OLI (2013 onwards)	30 m	2 years between 2009 and 2011, 1 year from 2011	1:250,000 (Margono et al., 2016), but for FREL 1/50,000, 0.0625 km² (6.25 ha) (MoEF, 2016)**	- Accuracy assessed only for the 2011 map. - Overall accuracy of 2011 map 87.63% (MoEF, 2016) ***
2017 onwards****	Sub-Directorate of Forest Resources Monitoring	MODIS (MCD45A1) and Landsat	500m for forest fire hotspot analysis, and 30 m for burnt scar area estimates	1 year, up to 1 month	Raster maps with 1×1 km grid (MoEF, 2016)	- Accuracy not assessed.

* Minimum Mapping Unit
** 1/250,000 for annual "Recalculation of Indonesia forest cover" (MoF, 2015, 2014, 2013, 2012).
*** The number of points for the 2011 map is 857, of which 181 for forest.
**** For forest fires monitoring by hotspot analysis.
- After starting the REDD+ readiness programme, the Sub-Directorate updated land cover maps for the 1990s, and as outputs, land cover maps for 1990 and 1996 were produced (MoEF, 2016).
- For the FREL of Indonesia, land cover maps that were reproduced for the year 1990, 1996, 2000, 2003, 2006, 2009, 2011 and 2012. (MoEF, 2016) were used.
- Apart from the land cover maps mentioned above, LAPAN also produced nationwide land cover maps from 2000 to 2012, using a semi-automated matching process. The work was for the Land Cover Change Analysis program (LCCA), which is the remote sensing monitoring component of Indonesia's National Carbon Accounting System (INCAS), and was supported by the Commonwealth Scientific and Industrial Research Organisation

(CSIRO) Australia (MoEF, 2016; LAPAN, 2014).

(Source: Generated based on information from interviews, MoF, 2012; 2013; 2014; 2015; Margono et al., 2016; and MoEF, 2016)

6.5.3 Organizational Structure

Although forest monitoring activities are now implemented solely by the Sub-Directorate of Forest Resources Monitoring, this depends on collaboration with organizations inside and outside Indonesia (Fig. 6.4).

6.5.3.1 Internal organizations

The organisational structure of the Directorate of Forest Resources Inventory and Monitoring remained the same as before the REDD+ Readiness programme, as its four Sub-Directorates' roles was thought to match the activities for REDD+ MRVs. Of the four Sub-Directorates, forest cover monitoring is conducted by the Sub-Directorate of Forest Resources Monitoring, which consists of a National Forest Resources Monitoring Section and a Management Unit Forest Resources Monitoring Section, with support from its 22 regional offices (Figure 6.4).

The wider relationships of the Directorate of Forest Resources Inventory and Monitoring with Indonesian organisations outside the Ministry of Forestry remained unchanged, except for the new interaction with the Directorate General of Climate Change. The Sub-Directorate of Forest Resources Monitoring is supported by the same Indonesian organisations outside the Ministry of Forestry in forest area monitoring, as was before the REDD+ Readiness programme, though their interactions are strengthened. Forest area monitoring activities are assisted by the National Institute of Aeronautics and Space (LAPAN), the Geospatial Information Agency (BIG, National Mapping Agency, formerly BAKOSURTANAL), and Bogor Agricultural University (IPB) (Figure 6.5). LAPAN provides all pre-processed, and mosaicked, satellite data for forest area monitoring, and annual forest map generation and analysis of forest cover area changes are supported by BIG. IPB, as a research institution, conducts research for developing and improving methodologies for forest area and change monitoring. The Sub-Directorate of Forest Resources Monitoring now communicates with the Directorate General of Climate Change for MRV activities. The effectiveness of communications between all these organizations, and their influence on technology adoption, is evaluated in Section 6.5.6.4.

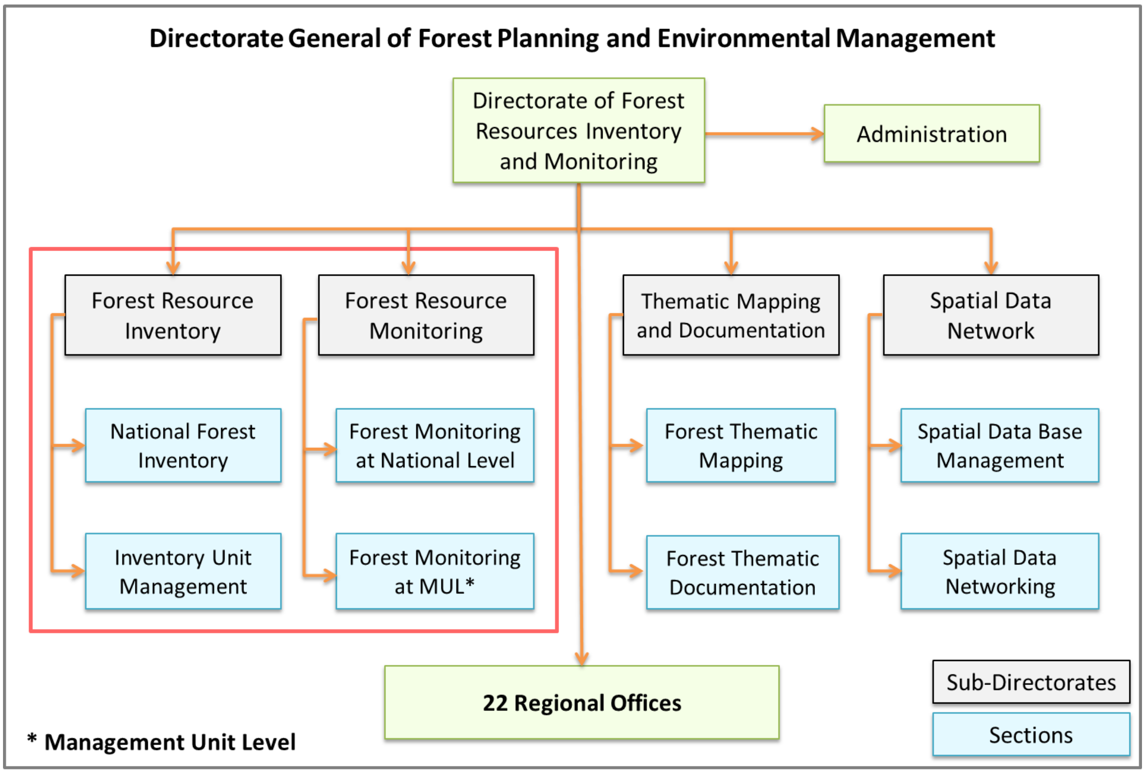

Figure 6.4 Organisational structure of the Directorate of Forest Resource Inventory and Monitoring under the Directorate General of Forest Planning

(Two Sub-Directorates in the red box are key divisions in producing forest area and inventory information)

6.5.3.1 External organizations

For forest area monitoring, the Directorate of Forest Resources Inventory and Monitoring is related to external organisations, though most relationships with overseas organisations are indirect. International organisations and national aid agencies provide project-based technical and financial assistance for Indonesian MRV activities. FAO provides training sessions and occasionally holds meetings and workshops for technical support. The German Corporation for International Cooperation (GIZ) continues to provide advice on the development of guidelines or regulations for national forest monitoring activities by dispatching technical advisors for its Forest and Climate Change programme. The World Resources Institute (WRI) and the University of Maryland (UMD) also support the Sub-Directorate of Forest Resources Monitoring by providing technical advice on forest area monitoring (Figure 6.5). The development of

Indonesia's national GHGs accounting platform for Measurement, Reporting and Verification (MRV) activities has been supported by the Australian Government through the Indonesia-Australia Forest Carbon Partnership (IAFCP) since 2009, and it is now operational. However, these organisations are not directly involved in national forest monitoring activities.

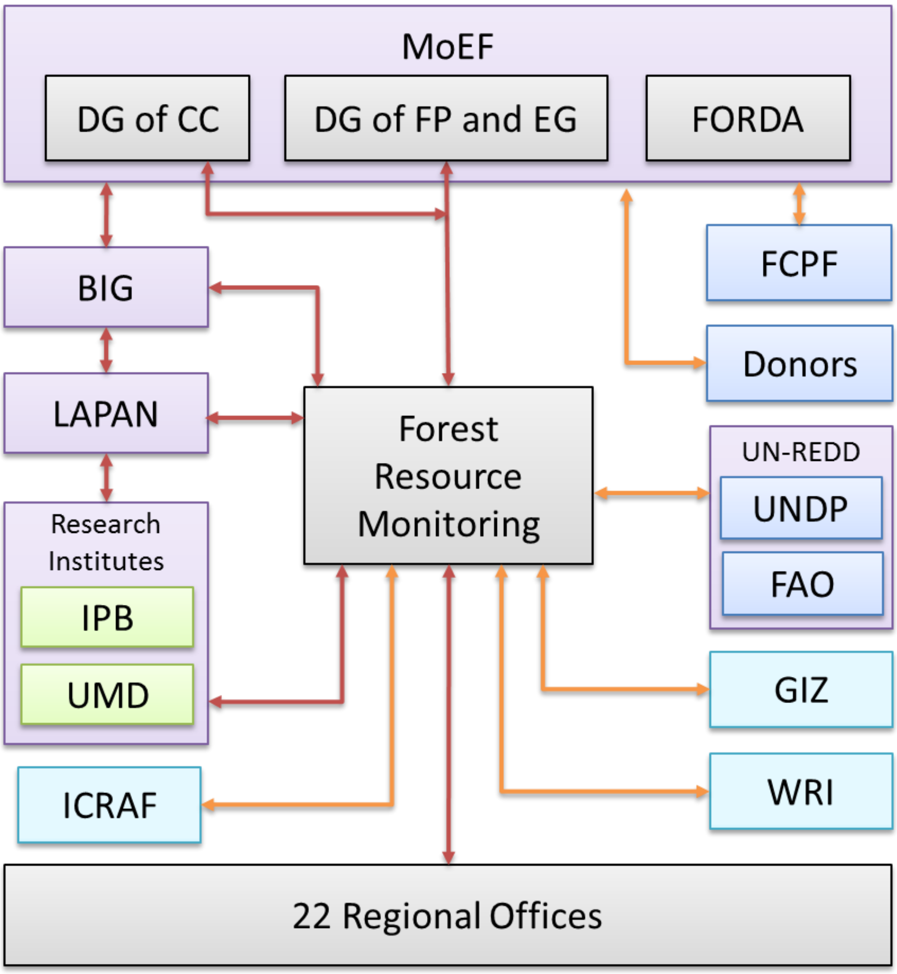

Figure 6.5 Key organizations for forest area monitoring for REDD+ MRV in Indonesia

(Arrows indicate communication links for forest data/information production/sharing for forest area monitoring, and red arrows indicate key communication links for forest area monitoring)

6.5.4 Technologies after REDD+ Readiness

After the REDD+ Readiness Programme ended, technology for national forest cover mapping of the Sub-Directorate of Forest Resources Monitoring remains exactly the same as before (Table 6.6). Indonesia still relies on Landsat-based on-screen manual-visual interpretation for classifying 23 land cover classes. The only exception is that 1.5m SPOT data is used at the management unit level, and MODIS and Landsat data have been used for early detection of forest fires, since January 2017.

Table 6.6 Existing technologies for producing land use/cover maps and forest fires monitoring of Indonesia after starting the REDD+ Readiness Programme

Year	Producer and partner(s)	Satellite data	Format	Methods	Ground truthing	Land cover classes	Remark
2009	Directorate General of Forestry Planning	Landsat 5 TM and 7 ETM+	Digital format	Manual Classification	Field checking conducted (FAO, 2015c)	23 classes, of which 6 for natural forest	- Visual Interpretation and on-screen digitization
2011 onwards	Sub-Directorate of Forest Resources Monitoring of the Directorate General of Forestry Planning	Landsat 5 TM, 7 ETM+, and 8 OLI (2013 onwards)	Digital format	Manual Classification	Not conducted*	Total 23 classes of which 6 for natural forest**	- Visual interpretation and on-screen digitization, and verification supported by SPOT - Additional imagery: SPOT 6 and 7 and MODIS
2017 onwards	Sub-Directorate of Forest Resources Monitoring	MODIS (MCD45 A1) and Landsat	Digital format	Semi-Automatic Classification	Not conducted	N/A	- For forest fires monitoring by hotspot analysis

* The 2011 map was verified afterwards using 857 field data for FREL (MoEF, 2016).
** Total 23 classes for land cover maps of Indonesia, of which 6 classes for natural forest, 1 class for plantation forest, 15 classes for non-forest, and 1 class for clouds/no data" (MoEF, 2016).

(Source: Generated based on information from interviews, MoF, 2012; 2013; 2014; 2015; FAO, 2015c; Margono et al., 2016; and MoEF, 2016)

For the 2011 forest cover map, accuracy assessment was performed for the first and last time, but field data for ground truthing, and verification, is still insufficient as the amount of required data for ground truthing is large. The number of total ground truth samples is 857, of which 181 samples for natural forests, were used (MoEF, 2016), but given the area of Indonesia, and the number of classes and islands, this was too small to perform reliable accuracy assessment. Standards for accuracy assessment of forest cover maps are not developed yet.

6.5.5 Decisions on Adopting New Technologies

Decisions on retaining existing technologies were made by the Director and Deputy Director of Forest Resources Monitoring during their preliminary evaluation, because making decisions on adopting new technologies was restricted by various factors. Although they are in the position where they can make adoption decisions and select new technology for improving forest cover information provision, discussions with them revealed that decisions to change forest monitoring technologies after the REDD+ Readiness Programme had to take account of national as well as international information needs, in addition to other factors such as available resources and organisational constraints.

The Sub-Directorate of Forest Resources Monitoring did not adopt a new system that is optimised for meeting information requests from external bodies as the two officials could frame organisational policy on forest area information supply. They can make decisions on the degree of information supply to the Government, and international conventions and organisations, by taking account of various factors, and by negotiating with other government agencies. As the Sub-Directorate of Forest Resources Monitoring has limited resources and capacity for forest monitoring, compromised forest cover information supply is understandable. Although they are obliged to take actions to respond to both national and international information policies, this situation caused resistance to change to avoid unintended consequences and unknown future political risks (see Ford and King, 2015).

Such decision making processes were also affected by national information demand. Specifically, focusing more on responding to national demand for forest cover information is one reason for having retained existing technology and institutions. Although national and international informational demands are mutually supportive to some extent, the purposes of producing forest cover information are different. Different protocols, variables and analysis are needed to produce forest data and information for national and international demands. Some national forest information can be used for both purposes, e.g. forest fires monitoring, but considering national demand, international information demands require more intensive analysis on land cover changes at higher frequency, e.g. small scale clearing or regrowth, leakage, and forest degradation. 23 land cover classes that were adopted and optimised for visual interpretation of Landsat data (Margono et al., 2016; MoF, 2003), was decided to remain to provide consistent forest area and change information to other government agencies. They have been a significant obstacle to adopting digital classification. Improved forest fires monitoring, for example, was requested by the government for national purposes after experiencing a devastating forest fire in 2015, and it can also be used for REDD+ purposes. Existing data for national use are used to respond to international demand for forest area information without collecting additional data.

The ALOS-PALSAR based forest monitoring system recommended by JICA was also not adopted because of the same reason. It was thought to be inconsistent with national information needs as it could differentiate only 5 or 6 land cover classes, not the 23 land cover classes used in Indonesia. ALOS-PALSAR could have solved the shortage of satellite images for forest area monitoring that is one of Indonesia's main problems, as its signal, L-band, can penetrate through cloud and enables image acquisition at night. However, it seems that supplying information on forest area and changes with 23 classes was more important than obtaining more satellite images for forest area monitoring.

6.5.6 Constraints on Adopting New Technologies

Adopting new technologies for forest area monitoring was limited by various constraints, including those already mentioned in the previous section. This section explains such constraints in detail using the TAS framework.

6.5.6.1 Material constraints

Although there were alternative automatic or semi-automatic classification methods that could replace existing manual-visual classification with retaining the number and types of land cover classes (see Inglada et al., 2017; Zhang and Roy, 2017), digital classification was not adopted.

Guaranteed data provision was one major reason of having determined not to adopt digital classification, and other satellite data such as SPOT and ALOS-PALSAR, as digital classification requires more satellite data. In Indonesia, the number and quality of available satellite imagery are still the biggest problem in processing Landsat data and producing forest cover maps due to its geographical and biological features, such as the length of the country, the number of islands, and variety of its ecosystem and forest biomes. Even after collecting all available Landsat data from the Geo-Informatics and Space Technology Development Agency (GISTDA) of Thailand, the Geoscience Australia, and the US Geological Survey (USGS), for the period 2000-2012, it was still difficult to generate cloud-free annual satellite imagery at the national scale (LAPAN, 2014).

This problem has been greatly reduced by its adoption of new technology at the National Institute of Aeronautics and Space (LAPAN), not the Ministry of Forestry. LAPAN adopted a pixel-based image mosaicking technology to generate cloud-free imagery, and so the percentage of cloud cover was less than 10% for the 2015 and 2016 maps. However, even with this new technology, cloud covers and hazes on satellite imagery cannot be completely removed, so the quality of imagery is still not regarded as suitable for digital classification (Figure 6.6).

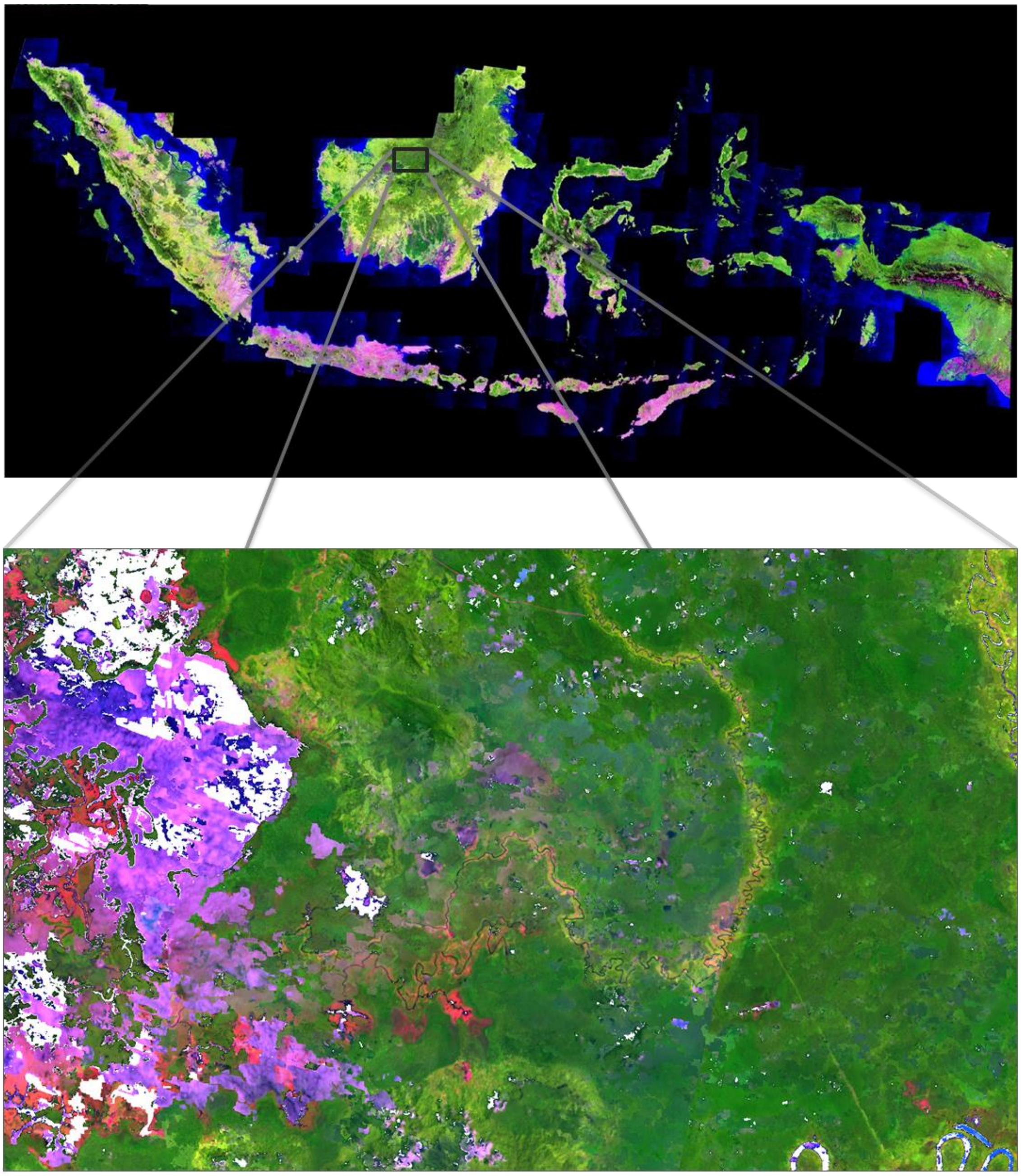

Figure 6.6 Land cover map of 2000 and an image for Danau Sentarum national park area in West Kalimantan, Indonesia

(The upper image is for the whole Indonesia produced by mosaicking 217 Landsat 7 ETM+ scenes, and the lower image shows the quality of a pixel-based Landsat 7 ETM+ Mosaic product (Centred on 112.2698°E, 0.8915°N), Images provided by the Ministry of Environment and Forestry and LAPAN.)

6.5.6.2 Existing technology

Existing technologies optimised for on-screen manual-visual classification of Landsat data became a constraints on adopting new technology. As on-screen manual classification has been the main approach for national forest area monitoring since the decision to return to it was made in 2000, all other technologies, and organisational factors, needed for the central and regional offices for such practices, including hardware and software for satellite data processing, were also purchased and upgraded for the purpose. They are not compatible with digital classification or active sensor data, as stated by the Deputy Director of the Sub-Directorate of MRV and Registry for land-based sectors:

> *"The problem was capacity of server and storage. The University of Maryland has Terabytes server, but the Government of Indonesia is not yet to do that. So, we work together with LAPAN. Our storage is less than one Terabyte. If we have automatic, then we have to run everything in raster format. We don't have enough storage to do that. That is why we have to convert it into vector." (Dr. Margono, 23rd of August 2017)*

6.5.6.3 Financial resources

Another reason why Indonesia could not change its system from the manual one to automatic one, or from medium resolution satellite data to higher resolution satellite data, SAR or LiDAR, is limited financial resources. Financial resources limit materials, equipment, and training for adopting more advanced methods or data, so the Sub-Directorate of Forest Resources Monitoring has only limited software, hardware, data storage, and internet connection in addition to human capital. Despite favourable stated national policy, the amount of budget from the government, or national commitments, has not much increased. This is explained by the Deputy Director of MRV and Registry for land-based sectors and a technical advisor from the German Corporation for International Cooperation (GIZ):

> *"Since Indonesia is a very big country, we have to deal with a huge amount of data. When we have to deal with huge amount of data, we need to have very strong hardware, software, warehouse, space and so on. We are not as rich as the US that they can buy a workstation, server, and everything easily. We are not easy in doing*

that, so we have to know our capacity. This is the amount of money we have." (Dr. Margono, 23rd of August 2017)

"I don't think they can adopt LiDAR. It is too expensive. I mean we did it in our tree project site from FORCLIME, in west, north and east Kalimantan. We did LiDAR study to measure emission factors on a very small scale of course and it is quite expensive." (Ms. Wegscheider, 5th of September 2017)

There has been support from overseas bodies, but financial resources in the Sub-Directorate of Forest Resources Monitoring is still limited because funding from overseas bodies was allocated to LAPAN, and FORDA. Instead of the Sub-Directorate of Forest Resources Monitoring, LAPAN and FORDA adopted new technologies for downloading and processing satellite data and recruited new staff for the new technologies (Ochieng, 2017) with the funding from overseas bodies. This is a result of institutional arrangements for REDD+ in Indonesia that determined the minimised role of the Sub-Directorate of Forest Resources Monitoring, and the expanded roles of LAPAN, and FORDA, in Indonesia's REDD+ MRV activities and national GHG accounting.

6.5.6.4 Human capital

6.5.6.4.1 Staff number and skills

To operate technologies, or change existing technology and institutions, sufficient number of staff and trained staff are required. In the Sub-Directorate of Forest Resources Monitoring, and regional offices, there is a basic minimum number of forestry officers needed for national forest cover mapping by on-screen manual visual classification, and making best use of limited human capital in the country as a whole by decentralizing the classification operation. This is why Indonesia is able to map forest in a large country every year.

However, the quality of human capital is a constraint on adopting new technology. Most forestry officers are experienced in forest cover monitoring and are used to perform forest area monitoring by manual-visual interpretation of optical data. Yet, they have limited knowledge on digital classification including object-based classification. Most forestry officers lack technical competence in computing languages, as forest area monitoring relies on menu-driven software, so they do not need to use computing languages for operating existing technology for their works. Testing different algorithms for supervised and unsupervised classification is limited by such lack of knowledge on digital classification and competence in computing languages. This is same for non-optical satellite data. Most new staff has no experience in LiDAR and radar at all. Almost all the forestry officers in the Sub-Directorate have only limited abilities to process active sensor data, except for the Director, as stated by the technical advisor from GIZ and the Deputy Director of Forest Resources Monitoring:

> *“For SAR, they are definitely missing the expertise here. They don’t have radar experts here. That is one big obstacle of course to even start going into it because there is no one who is familiar or really good in that stuff. (Ms. Wegscheider, 5th of September 2017)*
>
> *To adopt LiDAR or SAR, we must improve our staff’s knowledge and skills before using them because the technologies are very specific. They need some training.” (Dr. Nugroho, 29th of August 2017)*

This is one reason why the Sub-Directorate of Forest Resources Monitoring is focusing on using optical data and trying to use additional higher resolution optical data. Adopting radar data, ALOS-PALSAR, was unsuccessful for this reason.

Technology adoption is also limited by human capital in regional offices. About 15-20 forestry officers in each regional office work on remote sensing and forest inventory, yet the quality of human capital in regional offices for forest area monitoring is much lower than that of the central office. Regional offices are less flexible than the central office in testing and adopting new technology, as they have limited knowledge and skills for other technologies, and various educational backgrounds. Their abilities are still confined to the range of their tasks using manual-visual classification.

6.5.6.4.2 Operating existing technologies and training

As clear from interviews carried out with them, the limited knowledge and skills of forest officers in the Sub-Directorate of Forest Resources Monitoring and regional offices are resulted from institutions linked to existing technology and organisational policy, which are therefore constraints on adopting new technology. Forestry officers' skills for operating existing technologies for satellite image interpretation for national forest monitoring were obtained through experience in the office by implementing assigned tasks and mastering practical use of existing technologies. New forestry officers normally start working in the Ministry after completing their two-year diploma or undergraduate courses, and then learn how to analyse satellite data using ENVI or Erdas in the office. Some new staff does not have educational backgrounds in remote sensing or GIS and have only little prior experiences in forest cover mapping. Due to long dependency on on-screen manual-visual classification and their tasks, forestry officers are more familiar with ArcGIS than other software specialised for analysing satellite data. They are helped by seniors when they have problems, but usually study and practice by themselves in the office, except for attending short term training courses. A professor at IPB who collaborates with the Sub-Directorate commented that:

> *"They are still using visual interpretation because of technical aspect and they are trained from beginning to do visual classification. They are not more related on how to use digital classification. They are not used to." (Prof. Prasetyo, 18th Aug of August 2017)*

Training was provided in accordance with organisational policy, but as the short term training courses are mostly just introductory, they are only for increasing awareness of technologies. Without attending regular educational courses, decisions on adopting new technologies are made against a limited background. This is evident in the statements made by the Director of Forest Resources Inventory and Monitoring and the Section Head of Forest Resources Monitoring at Management Unit Level:

> *"When I have finished my PhD, there was a project with Japan. We used PALSAR at that time to know how we can use radar as a complement to optical data. But the result of the 2 year project, we concluded that it was difficult to use radar because the operators had to change their mind from optical data to radar. Those have very different characteristics and they had to use very different software. The procedures for handling the data are also very different." (Dr. Sugardiman, 28th of August 2017)*

> *"I think for SAR and LiDAR, short training is not enough because of complexity. So I thought if we need to have 1 or 2 staff that have capability in SAR or LiDAR, they have formal education on that, at least master level ... It is difficult for our*

> *staff to understand radar processing using short course. It needs full master or PhD degree." (Mr. Usman, 21st of August 2017)*

FAO provided training for new technologies such as Google Earth Engine, but none of these technologies are now actually used in the office. Such short term training courses do not seem adequate to raise the quality of human capital to the degree to which they can operate the technologies.

6.5.6.4.3 Awareness and Perceptions

Forestry officers at the Sub-Directorate of Forest Resources Monitoring are well aware of the limitations of existing technologies, and of the need to adopting new technologies to improve information production capacity, but they have limited knowledge of new technology and required forest information resolution and frequency, and reporting cycles for REDD+ MRVs.

The lack of awareness has significant influence on perceptions, and adopting new technology is limited by such awareness and perceptions that are affected by existing institutions and experience including pre-education and qualification. More advanced technology can offer better outputs, but forestry officers still think that existing manual-visual classification of Landsat data is the optimal technology for Indonesian forest cover mapping. As revealed by interviews, forestry officers think that as various landscapes, forest types and ecological features of Indonesian islands showed different spectral signatures causing classification errors, misclassification could be minimised by visual interpretation relying on local knowledge, instead of digital classification that relies on a discrete number of spectral bands. This is indicated in statements made by manager-level forestry officers:

> *"I think we can identify everything with manual classification. But it is impossible to do that if we use automatic classification." (Mr. Purwanto, 21st of August 2017)*

> *"I think it is not the best but the most realistic way, because of some problems we cannot overcome, such as haze and cloud condition. If we analyse using digital classification, that will disturb the result. So for us, that is more realistic to analyse using manual classification." (Mr. Usman, 21st of August 2017)*

Interviews also suggested that perceptions and awareness have significant influence on making decisions on adopting new technology for national forest area monitoring. Managers in the Sub-Directorate of Forest Resources Monitoring have limited knowledge on active sensors, so they tend to think their staff will not be able to use SAR or LiDAR data.

Interestingly, perceptions about more advanced technologies, e.g. digital classification, are also a constraint on adopting new technologies for other reasons. The number, and quality, of human capital in central and regional offices is focused on performing on-screen manual classification, so forestry officers and managers feel that adopting digital classification could provoke redundancy of forestry officers. As digital classification or other more advanced technologies for forest area monitoring rely more on computing power, they require less human power, and higher level operating skills. The Deputy Director of MRV and Registry for land-based sectors stated that:

> *"We are still a developing country, so the labour skill is very important for developing countries … We have so many people, so we have to take that true … If you have machine, how are you going to deal with technical staff in the field? They will lose their jobs." (Dr. Margono, 23rd of August 2017)*

6.5.6.5 Institutions

As shown in the previous sections, organisational and technological factors, including human capital, have been gradually optimised for existing technology, i.e. on-screen manual-visual interpretation. During the time, the Sub-Directorate of Forest Resources Monitoring also exhibited path dependency. Synergistic links between technology and institutions were observed, and this is why adopting new technology and changing institutions was difficult.

Path dependency that is a constraint on adopting new technology was caused by Indonesia's long dependency on manual-visual interpretation and the institutions strongly linked to Geographic Information System (GIS) for visual interpretation, classification, and map generation. The decision to make national monitoring the top priority focused on operating existing technologies. In line with this, institutions for on-screen manual-visual interpretation have persisted for at least 30 years in the Sub-Directorate of Forest Resources Monitoring. This led to the heavy reliance on GIS.

Actual forest cover monitoring processes have been performed using GIS that is mainly for dealing with vector data, not other software specialised for Remote Sensing, and processing procedures for satellite data in raster format were minimised. Pre-processing of satellite data was minimised, because visual interpretation did not require intensive pre-processing. Forest cover maps have been digitized, edited and edge-matched through a country-wide GIS database. Existing maps such as land-water, peat land, administrative and forest concession maps, and contours used as ancillary data are also in vector format (FAO, 1996; MoEF, 2016). The decision to reverse Indonesia's main monitoring technology, from supervised classification to adopt on-screen manual classification, resulted in heavier reliance on vector data. To allow annual monitoring, existing institutions, or practices, were rather reinforce by new formal institutions, i.e. rules, for operating the monitoring system. The Ministry of Environment and Forestry enacted regulations on producing annual forest cover monitoring and map generation, including timing, work distribution and roles, and image classification (BSN, 2014). These regulations are focused solely on operating existing technology, i.e. on-screen manual visual classification, as stated by the Deputy Director of the Sub-Directorate of MRV and Registry for land-based sectors:

> *"Now, we are trying to standardise the quality of interpreters. We try to bring the knowledge of LAPAN interpreters into the MOEF interpreters. So we are going to make explanation on how we standardise the knowledge of dealing with visual interpretation because it is not easy. We can sure about one part of mosaic but not sure about the other parts. We are standardising our visual classification." (Dr. Margono, 23rd of August 2017)*

This path dependence has made radical changes in technologies difficult. Existing institutions are entrenched in the Sub-Directorate by accumulated experience in operating the existing Landsat-based system. Institutions for existing technology restricted improving skills, and knowledge, required for other technologies, making adopting other technology difficult.

Technology adoption was also hampered by a phenomenon which we may call "organisational depth", in which path dependency is exacerbated by a decline in skills in proceeding down the hierarchy of multiple layers in an organization that are involved in implementing a programme. The decline in skills means that the entire organisation is less able to respond to changes, e.g. by adopting new technologies. Regional offices under the Directorate General of Forest Planning participated in classification between

2000 and 2006 (MoEF, 2016; Barr et al., 2006), but were excluded when the Sub-Directorate of Forest Resources Monitoring tried to adopt new technologies, such as digital classification, MODIS and SAR, for national forest area monitoring between 2006 and 2009. As forest area monitoring in the regional offices was focused on performing on-screen manual visual classification, and forestry officers in the regional offices was trained to perform on-screen manual-visual classification from the beginning, regional offices' capacity, and practices, did not fit to using more advanced technologies.

6.5.6.6 Internal and external communication

When the decision on retaining on-screen manual-visual classification had to be made, adopting new technology by the Sub-Directorate of Forest Resources Monitoring was limited by communication links that had already existed. Adoption decisions had to be agreed with those organisations, since LAPAN and the Geospatial Information Agency (BIG) have been providing satellite data and base maps, respectively. The communication link with LAPAN is extremely important because it is the only agency that is mandated to provide satellite data to all government agencies. In addition to data provision, general procedures for pre-processing of the images, including atmospheric and topographic correction, and image mosaicking for distributing to regional offices, have been performed by LAPAN to produce Landsat surface reflectance images and MODIS data for early detection of forest area changes caused by forest fires, which account for nearly half of forest cover monitoring activities of the Sub-Directorate of Forest Resources Monitoring.

The communication links with LAPAN and BIG have been more strengthened since the decision on retaining on-screen manual-visual classification was made. As the frequency of mapping had to be enhanced without adopting new technology, the Sub-Directorate of Forest Resources Monitoring had to distribute some tasks to other supporting agencies. External organisations involved included LAPAN, BIG, and IPB, as stated by the Director of Forest Resources Inventory and Monitoring:

> *"First improvement is frequency. The innovation came with regulation re-construction. We also revised budget and network with stakeholders. Previously we worked alone, but now we work in collaboration with LAPAN and BIG. We can*

> *distribute all of our previous activities to them. So, we share the activities, who is doing what in their job description."* (Dr. Sugardiman, 28th of August 2017)

A legal instrument was developed to define and regulate roles, communication links between the organisations for data/information sharing, and responsibilities of each organisation for forest information production. This caused greater interdependency when making decisions on adopting new technology. The Sub-Directorate of Forest Resources Monitoring now exchanges data and information for forest cover monitoring more frequently with LAPAN, and base maps, operational procedure, and standards and regulations for producing forest cover and carbon maps are provided by BIG in accordance with the Law No.4/2011 on Geospatial Information in Indonesia, which also performs quality control of satellite data. However, when making adoption decisions, the Sub-Directorate of Forest Resources Monitoring has to consider the interactions with such organisations and new regulations including One Map policy, one gate policy (Law 21/2013 on Space Activities) and the Presidential Decree No.6/2012 on high resolution satellite data provision, utilisation, quality control processing and distribution.

Technology adoption was limited by communication links in different ways. Communication links for obtaining reliable evidence from research are still limited and ineffective. These information deficits hamper making decisions on technology adoption. LAPAN is also conducting research for improving the forest cover monitoring capacity of Indonesia, but only a few researchers in LAPAN focus on the forestry sector. It is now being supported by research institutes such as Bogor Agricultural University (IPB), the World Resources Institute (WRI) and the University of Maryland (UMD). LAPAN, WRI, UMD and the Sub-Directorate of Forest Resources Monitoring are developing a new methodology for digital image processing and monitoring burnt scar area, and UMD is providing assistance with developing a method for accuracy assessment, for which 10,000 points were generated in SPOT images to identify forest types. Yet, although LAPAN is supported by overseas organisations, the information provided by LAPAN is not sufficient to make decisions on adopting new technology. Adopting semi-automatic classification and LiDAR, in addition to Landsat-based near-real time hotspot detection, are also limited by reliable evidence and communication links for providing the evidence, as stated by a technical advisor in the German Corporation for International Cooperation (GIZ) and the Deputy Director of the Sub-Directorate of MRV and Registry for land-based sectors:

"They are interested to change to semi-automatic, but of course it is a difficult process because they need to be sure that the results from an automatic classification match the quality from what they have now, otherwise it wouldn't be an improvement." (Ms. Wegscheider, 5th of September 2017)

"There is a project for LiDAR for biomass. There is also one data very powerful, maybe the combination of SAR, LiDAR and something else, run by GIZ. It is very powerful for giving information about fires. But the data is not free and they use it only for their own purposes. We just got the report but not the data." (Dr. Margono, 23rd of August 2017)

As LAPAN is the main agency that conducts research with research institutes, the communication links between the Sub-Directorate of Forest Resources Monitoring and such research institutes mentioned are getting weaker. The Sub-Directorate of Forest Resources Monitoring has been getting isolated because communication links with international organisations and national aid agencies are becoming indirect. The Deputy Director of Forest Resources Monitoring outlines the current state of relations with the Japan International Cooperation Agency (JICA), the Food and Agriculture Organization of the United Nations (FAO), the United Nations Development Programme (UNDP), the Forest Research and Development Agency (FORDA), the German Corporation for International Cooperation (GIZ), and the World Agroforestry Centre (ICRAF):

"WRI has cooperation with LAPAN. WRI is not directly work together with us, but we work together. UMD is also working with LAPAN to support us. IPB is working with us and they are also working with LAPAN to conduct research on a new satellite launching … We worked with JICA in the past. We still have cooperation, but not directly. We had cooperation with FAO. We worked with UNDP in the past. Now, they are working with the DG of Climate Change. We also work with GIZ but not directly. They work with another directorate under the DG of Forest Planning … FORDA and ICRAF are not working directly with us but they conduct research. ICRAF updates forest resources monitoring research and they share knowledge and results of the research. FORDA is focussing on carbon stock monitoring." (Dr. Nugroho, 29th of August 2017)

These changes in communication links explained above are results of institutional arrangements, and by such changes, the needs of technology adoption in the Sub-

Directorate of Forest Resources Monitoring, and financial support, are minimised as does its political position. Reinforced communication links with other government agencies, including LAPAN and BIG in addition to the DG of Climate Change, enable annual forest monitoring at national scale, but they also limit the Sub-Directorate of Forest Resources Monitoring's role in Measurement, Reporting and Verification (MRV) activities. This is indicated in the statement made by a Section Head in the Sub-Directorate of Forest Resources Monitoring:

> *"I am not familiar with the REDD+ Readiness because this activity is mostly now in the DG of Climate Change. That was only under the Ministry of Environment before. Our activities are included in general, but we do only specific activities to support these general activities." (Mr. Usman, 21st of August 2017)*

While Indonesia's MRV activities are not governed by a single entity, polycentric governance of such activities has not been effective and fully optimised yet. Organisations' tasks and duties tend to be duplicated. LAPAN, for example, started to produce annual forest area and change maps for Indonesia's national carbon accounting by adopting new technologies, recruiting new staff and conducting research. Most new technologies for forest area monitoring and satellite data processing have been adopted by LAPAN, instead of the Sub-Directorate of Forest Resources Monitoring. However, LAPAN can only classify forest and non-forest without using forest type data provided by the Sub-Directorate of Forest Resources Monitoring. The Sub-Directorate of Forest Resources Monitoring's political leverage is also weakened as its role in MRV activities is reduced. By the same reason, it was inevitable that communication links with international organisations and national aid agencies were weakened, and technology adoption for raising capacity is limited.

The effectiveness of communications, and interactions, between the Directorate of Forest Resources Inventory and Monitoring and the MRV centre, i.e. the Directorate of GHG Inventory and MRV, for estimating forest carbon stocks and changes are explained in detail in Section 6.7.

6.5.7 The Gap between Forest Area Information Supply and Demand

Indonesia has made some improvements in forest area monitoring since starting the REDD+ Readiness Programme. The biggest change has been in the frequency of forest cover monitoring. Using the existing maps from 1990 to 2012, Indonesia established a 22 year historical baseline for reporting. However, despite the annual forest cover monitoring, forest cover information supplied by the Sub-Directorate of Forest Resources Monitoring is still not sufficient to fully meet national information needs requested by the Indonesian government and other internal and external organisations (Table 6.7).

The gap between forest area information supply and demand lies in the resolution and quality of forest area information in addition to providing higher level forest area monitoring results for REDD+.

Current information provision showed insufficient resolution for deforestation and forest degradation monitoring for MRV purposes. For REDD+, the resolution of forest area mapping is not specified by the UNFCCC, and for producing activity dada, Indonesia's methodology is consistent with Approach 3 in the IPCC guidelines, which uses spatially explicit land cover data (MoEF, 2016). However, the minimum mapping unit of 6.25 ha at best could still miss a lot of deforestation activities in forested areas. It is still far lower that spatial resolution of satellite data. Forest degradation is estimated using land cover maps, but only by differentiating secondary natural forest from primary natural forest due to the resolution of mapping. This is because of existing technology and institutions. On-screen manual-visual classification has limitations to not only improving frequency, but also resolution that are linked to institutions. In addition, human resources for the practices are insufficient.

The quality of information seems insufficient as it is not verified. Accuracy assessment should be performed to ensure the quality of forest area information, and for results-based payments, but it is not performed in Indonesia. The accuracy of mapping was estimated only for the 2011 map. Developing ground points for accuracy assessment is not yet completed. Assessing accuracy of forest cover maps is limited by existing technology, institutions, human capital and financial resources.

Table 6.7 The gap between forest area information supply and demand after the REDD+ Readiness

		Information supply after starting REDD+ readiness	Information demand (UNFCCC recommendations)**
Factors in forest area monitoring	Satellite images	Landsat images for forest area monitoring and MODIS for forest fires	Various
	Data format	Digital	Digital
	Image processing	Manual visual classification, on-screen digitization	Recommendations provided
	Frequency/ Resolution	1 year*/30m, but minimum mapping unit is 6.25 ha at best	Reporting: 4 years for NCs, and 2 years for BURs***/as high as possible. Measurements require higher frequency and resolution
	Small scale deforestation (Near real-time monitoring)	Forest fires monitored but others not monitored	Small scale deforestation monitoring recommended
	Forest degradation monitoring	Monitored by classifying primary and secondary forest	Degradation monitoring recommended
	Drivers of deforestation (Human activities)	Not monitored, patterns of deforestation and land use changes not analysed	Recommended
	Forest regrowth	Only forest plantation monitored (Regrowth not included in FREL)	Forest regrowth monitoring recommended
	Land classes (Forest type)	23 classes of which 6 for natural forest	Recommendations provided (6 classes for LULUCF with sub-classes)
	Accuracy	Overall accuracy of 2011 map 87.63% (MoEF, 2016)	As high as possible/necessary for Results-Based Payments
	Points for ground truth	2011 map 857, of which 181 for forest (MoEF, 2016)	Not specified but uncertainty assessment and QA/QC**** needed
	Human resources	Insufficient trained staff for existing technology and institutions in central and regional offices	Not specified

	Institutions	Existing established practices and progressing	Various but fixed practices needed*****

* Frequency of forest fire monitoring is less than 1 year.
** IPCC guidelines provide different approaches for forest area monitoring in accordance with accuracy of data.
*** To comply with the UNFCCC guidance, Annex I nations are required to submit their National Inventory Report (NIR) every year, which includes emissions from forests, but at the moment, it is not for developing countries.
**** Quality Assurance and Quality Control
***** Digital classification is recommended for frequent monitoring and updates
- International policies recommend tropical countries to measure and report their forest carbon stocks and changes in accordance with the UNFCCC reporting requirements and the most recent IPCC guidelines for the Agriculture, Forestry and Other Land Use (AFOLU) sector (GFOI, 2016; UNFCCC, 2010).

In addition, the existing 23 classes for forest cover maps, which have been produced for other government agencies, are also not optimised for carbon purposes, and this hampers supplying higher level forest area monitoring results for REDD+. They are also not suitable for spatial analysis using GIS and modelling for providing higher level activity data as they do not reflect natural and human environmental factors, such as elevation, climate, and management and disturbance history that are related to deforestation, and linking the classes to such factors using auxiliary data is difficult. This is constrained by national and organisational policy that gives priority to national information needs, in addition to institutions.

The frequency of forest area monitoring is sufficient for MRV purposes for the time being, but for result-based payments, more frequent monitoring is required for monitoring small scale deforestation, forest fires, early detection of deforestation, and forest regrowth. The improvement in frequency is not because of organisational, technological and institutional improvements in the Ministry of Environment and Forestry, but because mainly of support from LAPAN and improved Landsat data provision – before 2009, only one scene for one location was available for a specific year, but after 2009, 23 to 25 scenes for same locations could be obtained, because Landsat data were made available free of charge by the US Geological Survey. Thus, improving the frequency of forest area monitoring is extremely difficult, and is limited by existing technology, institutions, and human capital. On-screen manual-visual classification has limitations to improving frequency, and requires many operators to perform practices.

6.6 Forest Growing Stock Monitoring after the REDD+ Readiness Programme

This chapter now looks at growing stock monitoring after the REDD+ Readiness Programme. Before the REDD+ negotiations, the intensity of Indonesia's national forest inventories had gradually decreased, as the technologies and rules for conducting Indonesia's first NFI were not institutionalised. During the REDD+ Readiness Programme, Indonesia was offered new technologies to raise its forest carbon monitoring capacity, as estimating forest carbon stocks and changes requires more intensive field surveys and developing carbon factors, by which trees' attributes can be converted into the amount of forest carbon stocks. This section focuses on why the new technologies offered for forest carbon monitoring during the REDD+ Readiness Programme were not adopted, using the Technology Adoption System (TAS) framework.

6.6.1 National and International Policies and Information Needs

6.6.1.1 International policies and information needs

In addition to longstanding information demands from the Food and Agriculture Organization of the United Nations (FAO) and the International Tropical Timber Organisation (ITTO), Indonesia is now required to report forest area and carbon stock changes to the United Nations Framework Convention on Climate Change (UNFCCC) every four years in its National Communications, and update these statistics every two years in its Biennial Update Reports. To respond to such demands, Indonesia needs to implement National Forest Inventory (NFI), by which carbon fluxes due to changes in growing stock can be estimated, and also allometric equations, wood density and other carbon conversion factors can be determined. For this, Indonesia relies on the Sub-Directorate of Forest Resources Inventory.

Stated policy is designed to support forest information production for such reporting and updating (e.g. Presidential Decree No. 71/2011 regarding the Inventory of GHGs emissions and reductions at different levels) (Sugardiman, 2012). However, it seems that meeting such international demand for forest carbon information is still not a major government priority.

6.6.1.2 National policies and information needs

Growing stock information production and the implementation of forest inventory for various purposes is stated in the Organization and the Working Procedure of the Ministry of Environment and Forestry, included in the Regulation of the Ministry of Environment and Forestry No. P.18/MenLHK-II/2015 (MoEF, 2015). Indonesian government agencies need forest inventory information to exploit forest resources, preserve environment and prevent natural disasters such as forest fires and flood. Although conducting NFIs is encouraged by the Government of Indonesia and its stated policies, political support is not matched by financial support.

6.6.2 Outputs: frequency and resolution of inventory

To respond to national and international demand on growing stock information, after starting the REDD+ Readiness Programme, the Sub-Directorate of Forest Resources Inventory continued to collect inventory data from Permanent Sample Plots (PSPs) in forested areas. Yet, the number of plots being measured has decreased sharply over time (Figure 6.7), as stated by the Director of Forest Resources Inventory and Monitoring:

> *"These are sample plots in 20 x 20km grid. It is about 3,000 plots. To measure all these plots, ideally we need to measure 600 plots to complete NFI with in 5 year. But right now every year we only get data from 60 plots, instead of 600 plots. From that, target is very far behind." (Dr. Sugardiman, 28th of August 2017)*

The reliability of the NFI data has decreased over the years, although 4,450 PSP measurements were made between 1990 and 2013 (MoEF, 2016; Kawai et al., 2017). Most NFI data were collected before starting the REDD+ Readiness Programme, and only about 60 permanent sample plots have been measured every year since then. Most sample plots measured once in the past have not been re-measured yet. The Deputy Director of the Directorate of Forest Resources Inventory and Monitoring explained the number of plots being measured in a year and in the cycle of Indonesia's NFIs:

"We have more than 3,000 plots. We don't measure all the plots every year. This year, we only measured 24-25 plots for re-measurements. Maybe every 5 years, we get inventory data from 200-300 plots because of limited budget." (Dr. Nugroho, 29th of August 2017)

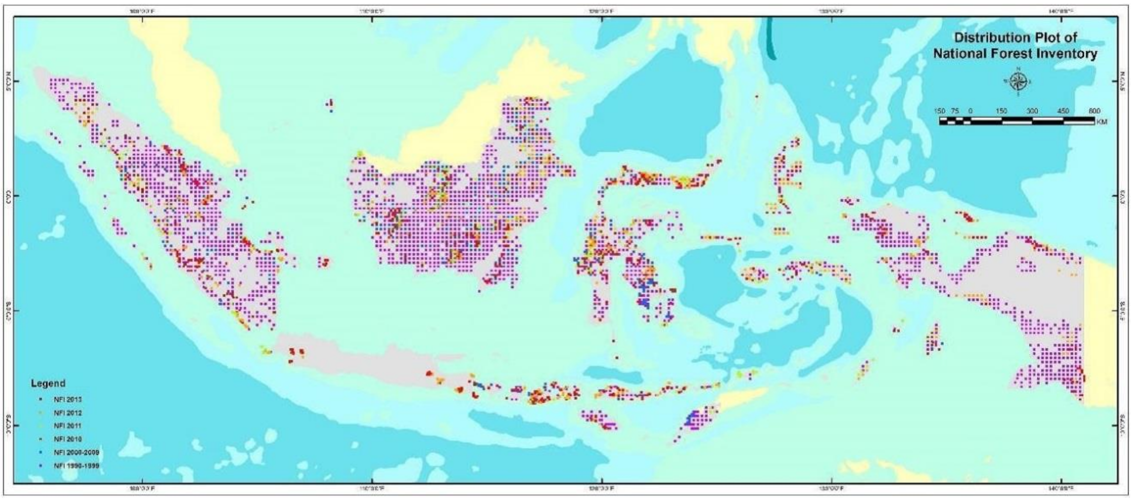

Figure 6.7 Distribution of PSPs and TSPs for NFIs by year

(Purple points indiceate sample plots measured between 1990 and 1999, while blue points are plots measured between 2000 and 2009. Source: MoEF, 2016)

6.6.3 Existing Technologies

Although during the REDD+ Readiness Programme, new methodologies for NFIs were reviewed and offered, and assistance for capacity building was given, the same methodology and sampling design for the first NFI were retained with a little modification. Parameters that should be measured in the field and detailed methods for field surveys were not added. Subtle modifications to the distribution of sample plots to be more efficient in measurements were made. Grid size was enhanced to 5 km to avoid measuring plots located in non-forested areas, and only one plot out of many others located in a same forest class within a region was selected to be measured for efficiency of measurement.

Using existing NFI data, the Ministry of Forestry has set the goal of developing allometric equations, and emission and removal factors for 6 classes – primary and secondary forests for mangrove, dry, and swamp forests – of forest cover, but it is still ongoing. To establish Indonesia's first Forest Reference Emission Level (FREL), the Forest Research and Development Agency (FORDA) consolidated and compiled existing allometric equations and carbon conversion factors for specific species and specific sites developed at local scale from secondary sources. However, it was difficult to use them because all these studies were based on different methodologies and quality, and they could not cover six forest types for all seven main islands of Indonesia (MoEF, 2016). As Indonesia has not completed developing new allometric equations from its NFI data, allometric equations devised by Chave et al. (2005) were used as part of the samples used in that equation was collected in Indonesia. To apply the equations, wood density data compiled from different research was provided by the Ministry of Environment and Forestry, and a carbon conversion factor from the IPCC 2006 Guidelines was used (MoEF, 2016).

To more efficiently collect and analyse inventory data, new technologies such as OpenForis and SEPAL were proposed by FAO, but none of the technologies was actually adopted, since they were regarded as not compatible with existing technology and institutions.

6.6.4 Decisions on Adopting New Technologies

Decisions were made, based on existing technologies, institutions, financial resources and human capital in the Ministry of Forestry, after consultation with other government agencies taking part of MRV activities. The Directorate of Forest Resources Inventory and Monitoring, and other government agencies, deemed that it would be difficult to change the existing system for Indonesia’s national forest inventory due to consistency and compatibility of data, and efficiency of practices. As a result, the Sub-Directorate of Forest Resources Inventory continues to focusing on meeting national demands for growing stock information since new parameters, and carbon pools, that should be measured in the field for estimating forest carbon stocks were not added to existing practices for national forest inventories, while developing emissions and removals factors including developing other carbon parameters is decided to be led by FORDA.

As no significant changes in existing technologies were made, organisational practices, NFI design and parameters for estimating growing stocks remained unchanged. Adopting new technologies offered by overseas organisations were limited by various constraints. In the following sections, such constraints are explained in detail.

6.6.5 Constraints on Adopting New Technologies

This section explains using the TAS framework why the Indonesia's NFI system that was designed for growing stock monitoring could not be transformed into the one for forest carbon monitoring.

6.6.5.1 Human capital

Just as the intensity of NFIs has been decreasing, so human capital for NFIs has also been decreasing. This is a constraint on adopting new technology and changing institutions. Experienced, educated or trained forest officers have retired or been promoted. Although there are 13 forestry officers in the central office, including the Deputy Director and 2 Section Heads, 4 people for the national level and 6 people for the management unit level, the number of experts in the central office for NFIs is not enough, and only a few people in the central office are able to analyse inventory data and design NFIs with knowledge of statistics.

This is the same for regional offices that implement field measurements. Forest officers in these offices are aware of how to conduct field survey for NFIs. Yet, the number of forestry officers who can conduct forest inventory in the field is also not sufficient. There are around 15-20 people in one regional office for forest inventory, but for some regions, it is not sufficient to cover a whole province, considering the area of the regions. As forestry officers' field experiences on forest inventories are decreasing, field experts in regional offices mainly for identifying species also decreased. This is why forestry officers need to be supported by local people, as explained by a forestry officer in the central office:

> *"The big problem in here is we don't have enough people with experiences in identifying species. For example, we make plots and then identify species. But sometimes not all people know what this species is. But maybe local people who live in the area know the species. In the regional offices, we don't have enough people who can identify species of trees. Not all people have their back grounds in forestry. Sometimes, non-forestry people also join the field survey." (Mr. Yogie, 5th of September 2017)*

Limited human capital also hampered developing allometric equations and biomass and carbon conversion factors for carbon stock estimates in addition to other new technologies. The number and quality of human capital for NFIs in the field is decreasing, the Sub-Directorate of Forest Resources Inventory had to be supported by FORDA and IPB in developing emission factors and carbon factors. Training, and financial support, for forestry officers in the Sub-Directorate of Forest Resources Inventory is limited by the situation as the Sub-Directorate of Forest Resources Inventory is no longer the main agency for such tasks. Forestry officers at regional offices receive only occasional training for field surveys, as stated by a Section Head who is working on forest inventory at national scale.

> *"It is too long that we don't conduct training, especially inventory training. No budget. I think the last training was in 2012. We invited 2 forestry officers from each regional office. But after several years, maybe they already move to other provinces. That is the problem. Sometimes we go to regional offices, and give short training for them, about 5 locations in one year." (Mrs. Nurhayah, 5th of September 2017)*

6.6.5.2 Organisations and Institutions

After the REDD+ Readiness programme, new rules, including protocols and guidelines for forest carbon measurement and for Indonesia's national forest inventory, were developed and offered by FAO (UN-REDD, 2013b), and new laws were promulgated accordingly by the Indonesian government (e,g, Presidential Regulation No.71/2011 regarding National GHG Inventory System). This involved national standards for measuring and estimating forest carbon stocks by surveying five carbon pools in the field (SNI 7724: 2011), and developing allometric equations for estimating above ground forest carbon stocks by destructive sampling methods (SNI 7725: 2011) (BSN, 2011a; 2011b). However, none of these are institutionalised within the Sub-directorate of Forest Resources Inventory, and its regional offices. The Deputy Director and a Section Head of Forest Resource Inventory explained the changes in practices:

> *"We have been conducting this since the 1990s. Parameters measured in the field and the methods for the survey are still the same ... Now, we just measure and calculate Above Ground Biomass. Even in regional offices, 5 carbon pools are not*

measured. We use fraction of AGB from research." (Mr. Ubay, 22nd of August 2017)

"We use existing allometric equations. Not developing. We just used equations from Chave. We don't have a plan to develop allometric equations." (Mrs. Nurhayah, 5th of September 2017)

The new rules offered by overseas organisations were not institutionalised because changing institutions in the Sub-Directorate of Forest Resources Inventory was difficult because organisation capacity, including human capital implementing the rules, was too degraded to implement the rules. Only 60 Permanent Sample Plots are measured each year in the entire country. In addition, changing institutions was not strongly promoted by the Indonesian government. Although new rules were established, as current information supply can meet national demand on growing stocks, adopting new technologies or changing institutions for better information production are not strongly promoted by actual policy. The only change in institutions for carbon stock estimation has been the application of biomass and carbon conversion factors to timber volume measurements in the field.

Although the Sub-Directorate of Forest Resources Inventory should be the main agency for Indonesia's REDD+ MRV from long term perspective, the Forest Research and Development Agency (FORDA), in collaboration with Bogor Agricultural University (IPB), the Forest Carbon Partnership Facility (FCPF) of the World Bank, and the World Agroforestry Centre (ICRAF), is trying to institutionalise the new rules to minimise changes to institutions for NFI, and to raise Indonesia's forest carbon information production capacity without adopting new technology (Figure 6.8). However, although FORDA established some research sample plots to add new parameters to be measured in the field and to develop allometric equations and carbon conversion factors by measuring the research sample plots in accordance with new rules, it is still difficult because FORDA also does not have sufficient organisational capacity, including human capital and experience, for the purpose.

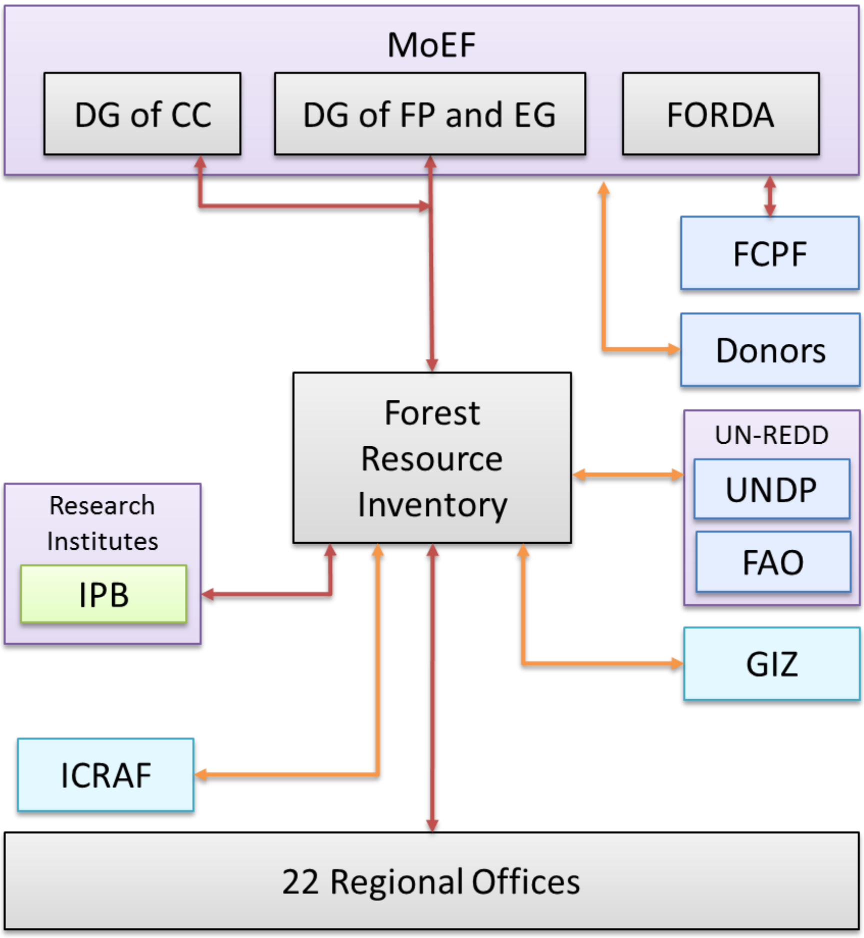

Figure 6.8 Key organizations for forest inventories for REDD+ MRV in Indonesia

(Arrows indicate communication links for forest data/information production/sharing for forest inventory, and red arrows indicate key communication links for Indonesia's NFIs and MRV)

6.6.5.3 Financial resources

Adopting new technology and changing institutions are also restricted by allocation of financial resources that is determined by national and international policies. Sufficient number of Permanent Sample Plots (PSPs) and measurements can provide reliable growing stock data for estimating forest carbon stocks, and new parameters for estimating forest carbon stocks should be measured in the field, but the number of PSPs being measured every year could not be increased and new parameters were not added, due mainly to limited financial resources. Funding from overseas organisations is insufficient as REDD+ Readiness related organisations and initiatives including UN-REDD and FCPF do not provides funding for implementing national forest inventories. Most funding from overseas organisations is for research purposes.

In addition to the lack of funding from international organisations, financial resources are also limited by insufficient national commitment of resources to implementing NFIs. After starting REDD+ negotiations, the budget allocated by the government for NFIs is not much increased. For forest information production for REDD+, the Sub-Directorate of Forest Resources Inventory is politically supported by the Government and the Ministry of Environment and Forestry. However, unlike stated policy, the political interest for forest inventories is not accompanied with sufficient financial support, and so the Sub-Directorate of Forest Resources Inventory had few options to improve its forest monitoring capacity. Organisational policy is determined in line with such circumstances as stated by the Director of the Directorate:

> *"The funding is limited for us, so we have to make some efficiency to make the money more powerful to improvement. So, I have convinced my boss that when I change something I don't use more money and not make inefficiency of our money." (Dr. Sugardiman, 28th of August 2017)*

If the full REDD+ mechanism, as envisaged in 2007, could come into operation, in developing countries received big compensation for reducing emissions from deforestation and degradation, this could provide an incentive to improve inventory activities. Because undertaking national forest inventories is more expensive than mapping forest area change, this is the one activity which has been minimized most through lack of funds.

6.6.6 The Gap between Forest Carbon Stock Information Supply and Demand

By exploiting existing historical forest data, which accumulated since 1990, Indonesia successfully submitted its Forest Reference Emission Level (FREL) to the UNFCCC in 2015. However, although Indonesia was able to report changes in forest carbon stocks at Tier 2 level to the UNFCCC, the supply of carbon stock information is still not sufficient to fully meet international information demands, despite the completion of Indonesia's REDD+ Readiness programme (Table 6.8).

Table 6.8 The gap between carbon stock information supply and demand after the REDD+ Readiness

		Information supply after REDD+ readiness	Information demand (UNFCCC recommendations)
Factors in NFI and Carbon reporting capacity	Frequency/Resolution	5 years /National scale systematic sampling	Various, but ideally 5 years (Reporting: 4 years for NCs, and 2 years for BURs/as high as possible, Measurements require higher frequency and resolution)
	Emission factors*	Estimated AGB by forest types using existing NFI data and equations from Chave (2005) (MoEF, 2016)	Tier 2 or Tier 3 level recommended**** Tier 1: Default values (Continental scale) Tier 2: Country-specific data (National scale) Tier 3: Actual inventories with repeated measures (Local scale)
	Allometric equations**	1 for tree volume/Consolidated existing allometric equations for Indonesia (Chave's equation were used for FREL (MoEF, 2016). H-DBH models were)	
	BCEF***	Not developed	
	Carbon conversion factors	Not developed yet, so used default value provided by IPCC 2006 guidelines (MoEF, 2016).	
	Wood density	Not developed yet, but compiled from various sources by MoEF (MoEF, 2016).	
	Carbon pools	Only AGB measured	
	Human resources	No sufficient experts and trained forestry officers for field survey	Not specified
	Institutions for NFIs	Established	Various but fixed practices and manuals needed
	Uncertainty assessment	Possible by external experts	Accuracy assessment recommended/necessary for results-based payments

* Developed by FORDA

** Indonesia compiled existing allometric equations from literature, but not used for FREL (MoEF, 2016).

*** Biomass Conversion and Expansion Factors

**** IPCC guidelines provide different Tiers for carbon stock reporting in accordance with accuracy of data.

- International policies recommend tropical countries to measure and report their forest carbon stocks and changes in accordance with the UNFCCC reporting requirements and the most recent IPCC guidelines for the Agriculture, Forestry and Other Land Use (AFOLU) sector (GFOI, 2016; UNFCCC, 2010).

The main gap between carbon stock information supply and demand lies in the quantity and quality of information. The quantity of NFI data is insufficient as although the frequency of the NFIs is 5 years, the intensity of the NFIs is very low. Only about 60 plots are measured every year, resulting in irregular and insufficient updates of NFI data. There are limited available data on other carbon pools for calculating carbon emissions and remaining carbon after conversion of forest to non-forest, as only above ground biomass is measured while other carbon pools are not measured. For Indonesia's forest reference emission level, the stock change method to estimate gross emissions from forest was decided to be used, and removals by forest were excluded (FCPF, 2015), as its NFI data could not provide sufficient gains and losses information in carbon pools in various strata. As only limited inventory data are produced every year, forest conditions are excluded from parameters for developing emission factors.

The quality of emission factors is considered to be not good because of the quality of inventory data used, and the methods applied to convert trees' attributes into carbon stocks. Emission factors were developed using historical NFI data that are old and allometric equations and carbon conversion factors from previous studies and IPCC guidelines, which are less accurate. As there have been delays to developing such country-specific factors and other carbon conversion factors, and to measuring 5 carbon pools, Indonesia still relies on the allometric equations presented by Chave (2005), and growth rates, biomass conversion and expansion factors from FRA guidelines and other sources were used for estimating growing stocks. Wood density data and carbon conversion factors for estimating forest biomass and carbon stocks are yet to be developed by destructive methods.

Changing institutions to meet international demand for information on forest carbon stocks, which includes repeating NFIs, adding parameters, measuring carbon pools, and developing local-scale allometric equations and carbon factors, is limited by organisational, technological, institutional and financial constraints explained in the earlier sections. As human capital is insufficient, changing institutions are limited by it too. While negotiations for implementing REDD+ continue and the future of REDD+ has not been determined yet, providing information that should be enhanced for implementing REDD+ by changing institutions is limited also by anticipated returns, i.e. incentives, hampering the investment of resources. Thus, supplying information on forest carbon stocks are limited by national and international policies too.

6.7 Interactions between Forest Survey and Inventory Activities

For estimating forest carbon stocks and changes with low uncertainty, interactions between organisations producing data for activity data and emission and removal factors, and processing, analysing and aggregating those data are crucial. The amount of total forest carbon stocks and changes are accounted by the Directorate of GHG Inventory and MRV under the Directorate General (DG) of Climate Change by manually entering forest area and growing stock data from the Sub-Directorates of Forest Resources Monitoring and Forest Resources Inventory under the Directorate of Forest Resources Inventory and Monitoring into Indonesia's national GHGs inventory system (Figure 6.9).

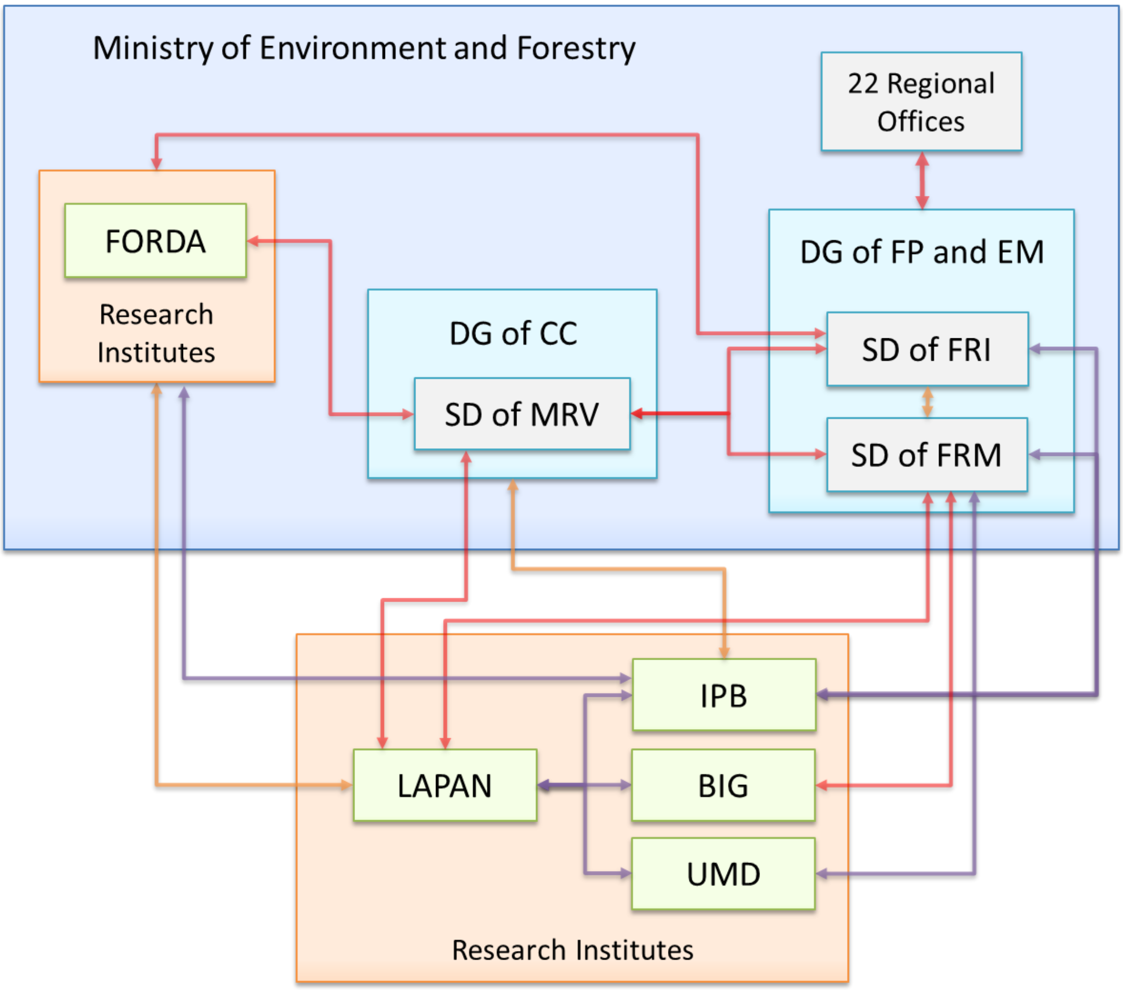

Figure 6.9 Organisations directly involved in Indonesia's Measurement, Reporting and Verification (MRV)

(Directorate of GHG Inventory and MRV, under the Directorate General of Climate Change plays the role as Indonesia's MRV centre. Red arrows show data and information production and provision for MRV, purple arrow show collaboration for research for MRV, and orange arrows show inactive collaboration for MRV)

Since the merge of REDD+ related institutions, the Directorate of GHG Inventory and MRV, where there is the Sub-Directorate of MRV and Registry for Land-Based Sectors, has been playing the role as Indonesia's MRV centre (Ochieng, 2017). Indonesia’s national GHGs emissions and removals from land based sectors, including both forests and peat lands, are estimated by the Forest Research and Development Agency (FORDA) by operating the Indonesian National Carbon Accounting System (INCAS) (see Krisnawati et al., 2015).

After the completion of the REDD+ Readiness Programme, significant changes to the interactions between Indonesian organisations related to MRV activities for estimating forest carbon stocks for MRV purposes occurred, but forest carbon information production is still limited by the interactions. The interaction between the Directorate General (DG) of Climate Change and the Directorate of Forest Resources Inventory and Monitoring is inefficient, and the interactions between the Sub-Directorates under the Directorate of Forest Resources Inventory and Monitoring are limited.

The interaction between the Directorate General (DG) of Climate Change and the Directorate of Forest Resources Inventory and Monitoring is inefficient, because of responsibility of their tasks and roles. The Directorate of GHG Inventory and MRV interacts with both the Sub-Directorate of Forest Resources Monitoring and the Sub-Directorate of Forest Resources Inventory separately. For this reason, the MRV centre cannot control the quality and levels of information provided by the Directorate of Forest Resources Inventory and Monitoring. As an example, the DG of Forest Planning provides the amount of biomass, not emission factors. The format of national forest cover information is converted into the format recommended by IPCC and UNFCCC by the DG of Climate Change for reporting and verification (i.e. converting the amount of biomass into carbon stocks for each stratum to estimate total carbon stocks by applying carbon values to forest/land cover strata), while the DG of Forest Planning produces data and information on forest cover and growing stocks as it has long been doing by existing technology and institutions. Country-specific allometric equations and carbon conversion factors are yet to be provided by FORDA. The quality of final outputs is less concerned when supplying data and information. The MRV centre interacts with the Sub-Directorates under the Directorate of Forest Resources Inventory and Monitoring separately because Sub-Directorates have limited interactions, and so relies on statistical analysis.

The limited interactions between the Sub-Directorates under the Directorate of Forest Resources Inventory and Monitoring hamper better forest carbon information production. The Sub-Directorate of Forest Resources Monitoring doesn't closely work with the Sub-Directorate of Forest Resources Inventory, except when exact timber volume data in natural forests are needed for forest concessions. NFI data are difficult to use for ground truthing due to the number of samples, the timing of field data provision, locations of plots, and the purposes of collecting field data, so NFI data have not been used to assess the accuracy of the 2011 map that was used to submit Indonesia's first FERL, and forestry officers in the Sub-Directorate of Forest Resources Monitoring collect field data for their own use. The Sub-Directorate of Forest Resources Inventory interacts with the Sub-Directorate of Forest Resources Monitoring, only when it needs land cover maps to know the condition of forest cover to identify land cover type of sample plots to be measured, and to estimate timber stocks by land cover classes. Although, forest area is calculated by the Sub-Directorate of Forest Thematic Mapping, the Sub-Directorates of Forest Resources Monitoring and Forest Thematic Mapping have limited collaboration too. Such lack of interactions limits estimates of carbon stocks and changes, as it causes poor spatial analyses of forest area and growing stock data, and carbon stock changes for Measurement, Reporting and Verification (MRV). For this reason, estimating forest carbon stocks and changes for reporting relies on statistical analysis by the Sub-Directorate of MRV and Registry for land-based sectors, rather than spatial analysis by producing carbon maps.

6.8 Conclusions

Using the Technology Adoption System (TAS) Framework and the Information Production (IP) Framework, this chapter has explained the technology adoption process in Indonesia and its information supply capacity. During the REDD+ Readiness programme, various new technologies for estimating forest area and forest carbon stocks were offered, yet none of them was actually adopted. More specifically, Indonesia tried to transform its existing forest monitoring system into the one for carbon purposes, yet technology for national forest cover mapping remains exactly the same as before, and the number of permanent sample plots continued to decline.

Making the decision on adopting new technology for forest area and growing stock monitoring was limited by institutional, technological, financial constraints, in addition to human capital. Human capital was not sufficient to enable adopting new technologies for forest area and growing stock monitoring. Technology adoption was limited by institutional constraints as Indonesia has long relied on manual-visual interpretation and Geographic Information System (GIS) for visual interpretation, classification, and map generation. Institutions for forest area monitoring, thus, showed path dependency that inhibits institutional change for adopting new technologies. Changing institutions for forest area monitoring was limited by a phenomenon called organisational depth that exacerbates path dependency. The decline in skills in proceeding down the hierarchy of multiple layers in an organization that are involved in implementing a programme means that the entire organisation is less able to respond to changes. For the same reason, existing technologies for forest area monitoring were not compatible with new technologies. Financial support for both forest area and growing stock monitoring was also not sufficient.

To raise its forest monitoring capacity, Indonesia changed organisational structure and communication links between organisations, instead of changing technology. The frequency of forest area monitoring increased from once every three years before the REDD+ Readiness programme to annually after the REDD+ Readiness programme. It was enabled by the strengthened communication link with the National Institute of Aeronautics and Space (LAPAN) and the Geospatial Information Agency (BIG). Emission factors could be developed without changing the methodology for national forest inventory, through intensifying the collaboration with the Forest Research and Development Agency (FORDA) and Bogor Agricultural University (IPB).

However, adopting new technology was further limited by the decision that enabled such changes, i.e. organisational constraints and communication links. As institutions for forest area monitoring are shared with LAPAN and BIG, adoption decisions had to be agreed with those organisations. While Indonesia’s MRV activities are not governed by a single entity, polycentric governance of such activities has not been effective and fully optimised yet. Although LAPAN can only classify forest and non-forest without forest type provided by the Sub-Directorate of Forest Resources Monitoring, it started to produce annual forest area and change maps for Indonesia’s national carbon accounting by adopting new technologies, and adopted most new technologies for forest area monitoring and satellite data processing. For forest carbon monitoring, FORDA is trying to institutionalise new rules for Indonesia’s NFI. For this reason, the political leverage of the Sub-Directorates of Forest Resources Monitoring and Forest Resources Inventory is also weakened as its role in MRV activities is reduced, and funding from overseas bodies was allocated to LAPAN and FORDA.

As new technologies were not adopted, and organisational changes introduced other challenges, the gap between information supply and demand still exists. The main gap between forest area information supply and demand lies in the resolution and quality of forest area information in addition to providing higher level forest area monitoring results for REDD+. The quantity and quality of carbon stock information is not sufficient to meet international demand.

The gap between information supply and demand is also caused by the type of the MRV centre in Indonesia, and interactions between organisations related to national forest carbon information production. After completion of the REDD+ Readiness Programme, significant changes to the interactions between Indonesian organisations related to MRV activities for estimating forest carbon stocks for MRV purposes occurred, but forest carbon information production is still limited by such interactions. The interaction between the Directorate General (DG) of Climate Change and the Directorate of Forest Resources Inventory and Monitoring is inefficient as the Directorate of GHG Inventory and MRV interacts with both the Sub-Directorate of Forest Resources Monitoring and the Sub-Directorate of Forest Resources Inventory separately. Thus, the quality of forest information cannot be controlled. In addition, the limited interactions between the Sub-Directorates under the Directorate of Forest Resources Inventory and Monitoring hamper better forest carbon information production.

Chapter 7
Discussion

7.1 Introduction

While previous research has shown that developing countries can only reduce their deforestation rates as they become more developed (Mather, 2007), the Reducing Emissions from Deforestation and Degradation (REDD+) mechanism of the UN Framework Convention on Climate Change (UNFCCC) assumes that this process can be accelerated, if sufficient international incentives are provided. REDD+ Readiness schemes, which have been implemented since the start of REDD+ negotiations, make a similar assumption that the low capacity of most developing countries to monitor changes in their forests can also be rapidly increased if there is sufficient international support. This thesis has reported the findings of an empirical study carried out in two contrasting developing countries, Cambodia and Indonesia, to see if this second assumption is valid.

This research conceptualised in two main ways the problem faced by developing countries wishing to participate in REDD+. It represented the balance between the supply and demand for forest information by national governments and international organisations using the Information Production (IP) Framework, and the ability of existing national forest monitoring systems to evolve into REDD+ Measuring, Reporting and Verification (MRV) centres by adoption of new technologies using the Technology Adoption System (TAS) Framework.

At the start of this research it was that assumed the empirical studies would show that developing countries were not expanding their forest monitoring capacity as fast as the funders of REDD+ Readiness schemes had anticipated. The TAS Framework therefore included a component that would enable developing countries to choose an intermediate set of technologies that could meet international demand for information while at the same time being consistent with their existing capacity. What this research actually discovered is that in the two countries studied some aspects of forest monitoring capacity have evolved more quickly than expected while others have continued to develop relatively slowly, and that in both cases forest monitoring organisations have optimised their choice of new technologies themselves and so do not need external technical advice to do this. This was unexpected, as was the discovery that constrained optimisation has led to both countries reaching ‘technological plateau’. If these plateau persist, it will limit the ability of these countries to further increase the supply of forest information in the future, but this question needs further study.

This chapter consists of four main sections. The first section compares the results of the two case studies, and generalises the main findings of this research, using the TAS and IP frameworks to look in more detail at the processes underlying these very interesting phenomena. Implications of the research are presented in the second section, and relationship with previous research is presented in the third section. In the fourth section, limitations of the research are presented.

7.2 Key Findings

7.2.1 Self-Constrained Optimisation in Technology Adoption

The main finding of this research is that the adoption of new technologies for upgrading forest monitoring systems in Cambodia and Indonesia has been limited by self-constrained optimization. This is an important contribution to the literatures on technology adoption and the sociology of remote sensing, and challenges the assumption in the REDD+ mechanism of the UN Framework Convention on Climate Change that developing countries can continue to increase their forest monitoring capacity if given the right assistance. As discussed below, this research has shown the various internal constraints that lead to technology capacity reaching a plateau, but another crucial finding is that self-constrained optimization is based largely on national factors rather than on the need to meet international demand for information.

Because the fieldwork for this research was framed by the Technology Adoption System (TAS) framework, the data collected were able to identify the main constraints on adopting new technologies as being: human capital, institutions and perceptions, existing technologies, financial resources, and communication between organisations, by which changing institutions is limited. Technology adoption was also limited by national demand for forest information which varies by countries. To offset technological and institutional limitations, and to ease MRV activities, organisational changes occurred, and forest monitoring activities had to be supported by either national or overseas organisations. However, such organisational change created other challenges that hamper technology adoption and forest information production (Table 7.1).

Table 7.1 Constraints on adopting new technologies, other influential factors, and forest information production capacity

Constraints, other influential factors, and information production capacity		Cambodia		Indonesia	
		Forest area monitoring	Growing stock monitoring	Forest area monitoring	Growing stock monitoring
Main constraints	Human capital	Adopting new technologies for forest area and growing stock monitoring is limited by the quality and number of human capital.			
	Institutions & perceptions	Institutions and perceptions hamper adopting new technologies for forest area and growing stock monitoring.			
	Existing technologies	Existing technologies for both forest area and growing stock monitoring are incompatible with new technologies.			
	Financial resources	Financial resources are insufficient to adopt more advanced forest area and growing stock monitoring technologies.			
	Communications between organisations	Adopting a few new forest area monitoring technologies was enabled by the support from overseas aid agencies.	Implementing NFI is constrained by poor communications with provincial offices and other government agencies.	Technology adoption was hampered by the communication links with domestic agencies supporting forest monitoring.	
Other influential factors	Role of international and national demand	As national forest information demand was low, a few new technologies for forest area and growing stock monitoring could be adopted.		Adopting new technologies for forest area and growing stock monitoring was limited by national forest information demand.	
	Organisational substitution	Organisational substitution in the two countries introduced other challenges to adopting new technologies for forest area and growing stock monitoring.			
	New organisational structures	Single entity: Communication links with sister organisations and provincial offices are weak.		Polycentric governance: Communication links with international organisations and national aid agencies have been weakened.	

	Lack of international financial incentives	The international financial incentives are not sufficient to promote capacity building as the amount and mechanism of international compensation are yet to be determined.	
Information production capacity	Relative development of forest area monitoring	Both Cambodia and Indonesia showed relative development of forest area compared to carbon monitoring.	
	Quality of forest information	Still insufficient to meet international demand due to the accuracy and resolution of forest area information, and insufficient growing stock information.	
	Interactions between forest area and carbon monitoring	The absence of an independent NFI division under the MRV centre is major constraints on estimating reductions in forest carbon stocks to respond to information demand from end users.	Forest carbon information production is limited by inefficient and ineffective interactions with the sub-divisions under the forest monitoring organisation, with the MRV centre.

Technology adoption and organisational changes in the two countries showed path dependency. As the two countries had only little options, they continued to rely on existing technologies and institutions. This phenomenon in the two countries resulted in a relatively higher development of forest area monitoring, compared to forest carbon monitoring, as forest carbon monitoring is more significantly affected by communication between organisations, and financial resources that are determined by national and international policies, than forest area monitoring.

Due to the self-constrained optimisation, the succession of improvements has been interrupted, and reached a plateau. The upgraded technologies are considered socially optimal in the two countries, but not technologically optimal solutions that can fully meet international demand for forest information. The main technologies for forest area and carbon monitoring remained much the same as before. The upgraded MRV designs are still insufficient to fully meet international demand for information on forest area and forest carbon stocks that is essential for REDD+ Measurement, Reporting, and Verifications (MRVs). Forest information produced to meet international demand therefore has high uncertainty. In the following sections, constraints on adopting new technologies that lead to technology capacity reaching a plateau are explained in detail.

7.2.2 Human Capital

The findings of an empirical study carried out in the two countries showed that technology adoption, including making decisions on adopting new technologies and institutionalising new technologies, was limited by the number and quality of human capital, its awareness and perceptions. Such lack of human capital is the same for both forest area monitoring and for growing stock monitoring.

The number and quality of human capital for forest area monitoring and growing stock monitoring in Cambodia are insufficient, and this is why the MRV team members are responsible for both forest area monitoring and growing stock monitoring. Forestry officers in Cambodia have skills to operate existing technologies for forest area monitoring, but they don’t have theoretical and technical expertise in processing higher level input data by operating new technologies as their prior qualifications are limited. This is why Cambodia had to be assisted by overseas organisations when it adopted a few new forest area monitoring technologies, and why other advanced technologies, such as digital classification, radar and LiDAR could not be adopted. A new NFI design has been developed, but organizational capability to undertake an NFI, and to develop carbon factors, is limited as Cambodia does not have sufficient personnel who have been trained in inventory methods and had previously been reproducing the necessary institutions.

The human capital situation in Indonesia is similar to that of Cambodia, although the way of making use of human capital is different. There are a few people who are specialised in radar and optical satellite data, but the number and quality of human capital in the central office is insufficient. Both of these forest monitoring activities are supported by regional offices. Indonesia is making best use of limited human capital in the country to implement annual forest area monitoring. Yet the quality of regional human capital is even lower than that of central human capital, and this became a constraint on adopting new technologies for forest area monitoring. Most forestry officers are experienced in performing forest area monitoring by on-screen manual-visual interpretation of Landsat data. Yet, they have limited knowledge on digital classification, and active sensor satellite data. Adopting new technologies, and changing institutions, for NFIs was also constrained by the number and quality of human capital. As the intensity of NFIs in Indonesia decreased, human capital for NFIs also decreased.

7.2.3 Institutions and Perceptions

This research has shown that adopting new technology was difficult because of repeated practices, or institutions, linked to existing technologies for forest area monitoring, and perceptions that have significant influence on adoption decisions.

Changing institutions is constrained by path dependency that inhibits institutional change for adopting new technologies. As Cambodia and Indonesia have long been using their existing technologies, and they have limited organisational capacities, changing institutions for existing technology to those for new technologies was very different and hence a significant obstacle to technology adoption.

As the two countries showed long dependency on manual-visual interpretation, institutions are strongly linked to manual methods for visual interpretation, classification, and map generation. Operating new forest area monitoring technologies adopted by Cambodia is supported by the staff of overseas aid agencies, and in Indonesia, institutions remained the same as before the REDD+ Readiness programme. Compared to Cambodia, Indonesia showed stronger path dependency as organisational depth exacerbated it. Path dependency is exacerbated by a decline in skills in proceeding down the hierarchy of multiple layers in an organization that are involved in implementing a programme. In the two countries, switching institutions for national forest inventories from those for timber volume monitoring to forest carbon stock monitoring, and institutionalising new rules for national forest inventories, was difficult due to limitations on organisational capacity, organisational interactions, human capacity and financial resources.

Path dependency was exacerbated by perceptions, which are affected by awareness and educational backgrounds in addition to organisational policy that determines training. This has influence on making decisions on new technologies to be adopted because when senior staff and technical advisors from overseas aid agencies make decisions they take account of how the MRV team members perceive new technologies, and whether they can use alternatives. This is why the two countries decided that the technologies used by the new MRV centre should involve as little change as possible in existing institutions. Forestry officers showed a strong preference for on-screen manual visual classification, and although more advanced technology can offer more benefits, the decision to retain existing technologies was made. The Cambodian MRV team members think at this stage that existing technologies are sufficient for their work and information production even though they are aware of the fact that new technologies can improve their work performance and information production, and that existing technology cannot fully meet national and international information needs. Indonesian forestry officers still think that existing manual-visual classification of Landsat data is the optimal technology for Indonesian forest cover mapping although more advanced technology can offer better outputs.

7.2.4 Existing Technologies

The TAS can be used to evaluate the compatibility between existing technologies and new technologies in technology adoption, and analyses showed that new technologies were difficult to adopt because they were not compatible with existing technology.

Most new technologies that can improve developing countries' forest area monitoring capacity are not compatible with existing technology, i.e. software, hardware, and information technology infrastructure. For example, adopting digital classification, SAR and LiDAR for satellite data processing was limited by existing technology, and new data processing technologies that require Internet access are constrained by slow Internet speed available to government agencies. Technologies that require processing raster format digital data are not compatible because existing image processing methods are optimised to handling vector data from Landsat images.

This was the same for forest carbon monitoring. Making the decision on how to adopt a technology for Cambodia's first National Forest inventory (NFI) was strongly influenced by existing technologies. Even though it had never been applied at national scale before, the only possibility was to continue with the existing technology of manual measurement. The use of non-optical satellite data for forest carbon monitoring was not considered feasible, given limitations on existing technology, human capital and other factors. Indonesia's existing NFI design and methodologies relies on field measurements to estimate timber volume and it was decided to continue to use them. After consultation with other government agencies taking part in MRV activities, the decision was made to rely on existing technologies. Transforming the existing system for Indonesia's national forest inventory into a new system for forest carbon estimation was deemed difficult and impractical.

7.2.5 Financial Resources

In the two countries, adopting new technologies for forest area and growing stock monitoring was limited by financial resources. Although generous financial support for the purchase of new hardware, software and satellite images, and for training staff has been provided by overseas organizations, there have necessarily been limits to the funds available to the MRV centre in Cambodia and the Directorate General of Forest Resources Inventory and Monitoring in Indonesia from these organizations and from their governments. Financial resources for upgrading existing technologies to more advanced technologies, such as digital classification, radar and LiDAR are still not sufficient. Analysing radar and LiDAR data, for example, requires purchasing satellite, or airborne, data and software optimised for analysing the data. Cambodia and Indonesia do not have air survey facilities including aircraft and sensors that can be used for LiDAR scanning. Analysing radar data and performing digital classification for national forest cover maps requires higher computing power, bigger data storage and recruiting new forestry officers with appropriate expertise. Internet-dependant software or tools for forest area monitoring, such as Google Earth Engine and Collect Earth, are not being used in Cambodia and Indonesia due to poor Internet connection. If unlimited funds had been available in the two countries, it would have been possible to circumvent the limitations imposed by poor Internet access by installing high speed Internet, and new high speed, and high capacity server computers. However, this has not been possible due to limited financial resources.

It is the same for forest carbon monitoring, and developing carbon conversion factors. Cambodia has not been able to commence its first NFI due to limited financial resources. Although funds for designing Cambodia's first NFI, and for training staff in inventory methods, have been provided by overseas organizations during the REDD+ Readiness programme, they don’t provide the large amount of funds necessary for undertaking the NFI. Developing allometric equations and carbon conversion factors, and monitoring forest carbon pools are also constrained by lack of financial resources. Cambodia was working to develop allometric equations for major species in deciduous forest, but it was not able to complete the project due to the discontinuity of such projects funded by overseas organisations.

Transforming Indonesia’s existing NFI design into one for measuring forest carbon stocks, and increasing the number of sample plots being measured every year, are also limited by financial resources. The number of permanent sample plots being measured every year has been decreasing, and new parameters that should be measured in the field for estimating changes in forest carbon stocks were not added, due mainly to insufficient financial resources. Funding from overseas organisations is limited as REDD+ Readiness related organisations and initiatives including UN-REDD and the World Bank's Forest Carbon Partnership Facility (FCPF) do not provide funding for implementing national forest inventories.

7.2.6 Communication between Organisations

Forest monitoring organisations have interactions with external organisations, and the two case studies showed that such interactions could have positive or negative influences on technology adoption. This resulted from the different roles of external organisations, and communications with them, which appeared to have significant implications for technology adoption.

Adopting a few new forest area technologies and developing a new NFI design in Cambodia were enabled by the long-standing communications with overseas aid agencies, but commencing Cambodia’s first NFI is constrained by weak communication links with other government agencies. A few new forest area technologies could be adopted because the Japan International Cooperation Agency (JICA) and the Food and Agriculture Organization of the United Nations (FAO) in Cambodia not only share practices for forest monitoring, but also play roles as intermediaries in technology adoption. JICA has been working with the MRV team from the beginning of the REDD+ Readiness Programme in Cambodia, and personalised communications between them enabled the adoption of new technologies by sharing institutions and training Cambodian staff. In addition, it conducted assessments of advantages and disadvantages of available technologies for Cambodia to provide information on new technologies. For its growing stock monitoring, Cambodia could develop its new NFI design thanks to the communications between the MRV centre and FAO. Yet, commencing Cambodia’s first NFI is constrained by poor communications between the MRV centre, and provincial offices and other government agencies related to forest inventory, due to the weak communication links for implementing field measurements, integrating existing practices, and consolidating data to be collected.

Technology adoption in Indonesia was hampered by the communication links with domestic agencies supporting forest monitoring. The National Institute of Aeronautics and Space (LAPAN) and the Forest Research and Development Agency (FORDA) assist forest monitoring activities, but it seems that they cannot function as intermediaries that can facilitate and accelerate technology adoption. Annual forest area monitoring is enabled by the communication links with LAPAN because it provides satellite images for forest area monitoring, performs pre-processing of satellite data and image mosaicking, and prepares satellite images for distribution. Yet as institutions are shared with LAPAN, the decision on adopting new technologies should be agreed with LAPAN. As the Sub-Directorate of Forest Resources Monitoring and LAPAN become more interdependent by sharing institutions, technology adoption also depends more on each other. In addition, although LAPAN conducts research for improving the forest cover monitoring capacity of Indonesia, it cannot provide reliable evidence from research. As LAPAN is the main agency that conducts research with domestic and overseas research institutes, the communication links between the Sub-Directorate of Forest Resources Monitoring and international organisations and national aid agencies became indirect. Improving growing stock monitoring is limited by new communication links with FORDA. FORDA is assisting forest carbon monitoring by establishing research sample plots for developing allometric equations and carbon conversion factors. Yet, upgrading the existing NFI system is limited by it because FORDA is trying to institutionalise the new rules offered by overseas organisations, instead of the Sub-Directorate of Forest Resources Inventory. As the role of the Sub-Directorate of Forest Resources Inventory in MRV activities is reduced, FORDA communicates with overseas organisations instead of the Sub-Directorate of Forest Resources Inventory, and so funding from overseas organisations is allocated to FORDA.

7.2.7 International Demand versus National Demand

National and international demand for forest information influences technology adoption in the two countries in different ways. National and international information demands are mutually supportive to some extent. However, as the purposes of producing forest cover information are different, different protocols, variables and analysis are needed to produce forest data and information for national and international demands. Generally, international information demand requires more intensive data collection and analysis, but as developing countries' national demand for forest information varies, they have different implication for forest carbon information production.

Cambodia's NFI design is designed to be used for multiple-purposes in order to meet both national and international information needs. However, it seems that meeting international demand for information on changes in forest carbon stocks overweighs meeting national demand for information on timber volume. From the beginning, developing Cambodia's new NFI design was focused on monitoring changes in forest carbon stocks, yet implementing forest inventories for MRV purposes require more detailed measurements than those for timber stock estimates.

Forest carbon information production in Indonesia is constrained by national information needs, as it seems that national policy gives priority to meeting national information needs. Indonesian forest monitoring organisations are focusing more on responding to national demand for forest area and growing stock information. One reason for having retained the existing 23 land cover classes is meeting national demand for forest area information, and this was a significant constraint on adopting more advanced technologies, such as digital classification and radar. As the Sub-Directorate of Forest Resources Inventory continues to focus on meeting national demand for growing stock information, no significant changes in existing technologies were made. Meeting national demand became a constraint on adopting new parameters for forest carbon purposes, and measuring carbon pools. As Indonesian forest monitoring organisations are obliged to provide consistent forest area and change information to other government agencies due to national information demands, they cannot change their existing technologies by themselves, and forest data produced to meet national demand are being used to respond to international demand for forest carbon information.

7.2.8 Organisational Substitution

Forest monitoring activities in Cambodia and Indonesia are supported by other national and overseas organisations to make forest information activities more effective, or to offset technological and institutional limitations. For forest monitoring activities, Cambodia has strong interactions with overseas organisations, while Indonesia has interactions with national organisations. JICA in Cambodia and LAPAN in Indonesia support forest area monitoring, and measuring carbon parameters and developing emission and removal factors in the two countries are supported by FAO and FORDA, respectively.

Operating Cambodia's new technologies adopted for forest area monitoring is still supported by JICA, and commencing its first NFI is delayed by weak communication links with national organisations related to forest inventory. Such weak communication links resulted in difficulties in obtaining permissions from other sister organisations for field surveys and consolidating existing historical field data. The Cambodian MRV centre has weaker communication links with national organisations than those with overseas organisations.

In Indonesia, to raise forest information production capacity without adopting new technologies, and changing institutions, some tasks had to be distributed to other supporting agencies. Image acquisition, pre-processing of satellite data, image mosaicking, and preparation for image distribution are performed by LAPAN, and establishing research sample plots for developing allometric equations and carbon conversion factors are implemented by FORDA. As institutions are shared, instead of the Sub-Directorates of Forest Resources Monitoring and Forest Resources Inventory, LAPAN and FORDA adopted new technologies with the funding from overseas bodies, as practices for forest carbon estimations are conducted by them. As the roles of the Sub-Directorates of Forest Resources Monitoring and Forest Resources Inventory in Indonesia's REDD+ MRV activities and national GHG accounting are minimised, and the roles of LAPAN and FORDA are expanded, the Directorate General of Forest Resources Inventory and Monitoring of Indonesia is getting isolated and has limited financial and technical support from overseas organisations.

7.2.9 The Development of New Organisational Structures

Upgrading forest monitoring systems through the REDD+ Readiness programme is accompanied by organisational changes. Such organisational changes were intended to enable REDD+ activities by establishing a new Measuring, Reporting and Verification (MRV) centre that is an inter-ministerial agency as a single point of contact for reporting to the UNFCCC.

However, there are distinct differences in organisational changes in Cambodia and Indonesia. In Cambodia, a new MRV centre was established in the Forestry Administration, and then relocated to the Ministry of Environment to ease monitoring forest carbon stocks and reporting to the UNFCCC. Significant changes to organisational structure for MRV activities occurred also in Indonesia, but the Indonesian MRV centre is part of the Directorate of GHG Inventory and MRV under the Directorate General (DG) of Climate Change. It focuses on reporting to the UNFCCC by consolidating data from other government agencies, and is affiliated in the Ministry of Environment and Forestry to ease communications with government agencies related to forest data and information production. The organisational structure of the Directorate of Forest Resources Inventory and Monitoring remained the same as before the REDD+ Readiness programme, which conducts measurements, although it requires new interactions with the MRV centre to supply forest data.

Such organisational changes in Cambodia and Indonesia showed limitations in MRV activities. Although the MRV centre is relocated in the Ministry of Environment, the organisational structure in Cambodia includes only weak communication links with other government agencies, and with provincial offices. This is one reason for the delay in implementing the first NFI. Organisational changes in Indonesia created more challenges as measurements and reporting are implemented by different organisations. Indonesia’s organisational structure is inefficient, as shown in section 7.2.2.2. Organisations’ tasks and duties for forest monitoring and reporting tend to be duplicated as Indonesia’s MRV activities are not governed by a single entity. Polycentric governance of such activities has not been effective and fully optimised yet. As an example, LAPAN also produces annual forest area and change maps for the remote sensing monitoring component of Indonesia’s National Carbon Accounting System (INCAS) by adopting new technologies and conducting research, despite the fact that it can only classify forest and non-forest with assistance from the Sub-Directorates of Forest Resources Monitoring. Due to the minimised role of the Sub-Directorates of Forest Resources Monitoring and Forest Resources Inventory in MRV activities, communication links with international organisations and national aid agencies have been weakened, and technology adoption for raising forest monitoring capacity is limited.

7.2.10 International Financial Incentives

Cambodia and Indonesia have limited funding for upgrading their forest monitoring systems, because of international policy, and national policy affected by international policy.

As REDD+ is not still fully operational, results-based financial incentives are still very limited. The fully operational REDD+ mechanism was envisaged to provide sufficient compensation for reducing emissions from deforestation and degradation, and this could provide an incentive to improve forest monitoring capacity. However, the amount and mechanism of international compensation are yet to be determined, and so the international financial incentives are not sufficient to promote capacity building. For this reason, financial support is insufficient for forest monitoring, implementing NFIs and developing carbon conversion factors. The prospects for securing funding for forest information production and further improvements are still uncertain.

Forest monitoring organisations in the two countries still rely on funding from overseas organisations as financial support from the government is limited. Improving forest monitoring capacity to meet international information demand, and adopting new technology, is not strongly encouraged by national policy. Despite favourable stated national policy, actual national policy is not supportive enough. The amount of budget from the government, or national commitments, has not increased much. Political decisions to increase budgets for forest monitoring activities have not been made because of the ambiguous future of the evolving REDD+ scheme. It seems that such policy is affected by the evolving nature of international environmental policy. Unless the carbon price, or other international compensations, is guaranteed to be high enough, developing countries may continue to rely on funding from overseas organisations for upgrading, or implementing, their MRV activities, which are still limited and selective.

7.2.11 Area Monitoring and Carbon Monitoring

In Cambodia and Indonesia, forest area monitoring capacity has improved, but growing stock monitoring capacity has not. While the frequency of forest area monitoring is increasing, little, or no, progress with NFI in both countries was made, as can be seen from the delay in commencing Cambodia's first NFI, and the declining number of permanent sample plots being measured every year in Indonesia. Cambodia's NFI design was developed for carbon purposes from the beginning, but is yet to be implemented. Indonesia's NFI design was developed for estimating timber volume, and the use and purpose of the NFI design are still the same. The number of Permanent Sample Plots being measured each year in the entire country is only about 60.

This is because of lack of organisational capacities, communication between organisations, and financial resources, and because growing stock monitoring by implementing NFIs is more significantly affected by communication between organisations, and financial resources than forest area monitoring. Implementing NFIs requires strong communication links, and cooperation between organisations, for institutionalising rules for field measurements and consolidating inventory data. The amount of funding is determined by national and international policies, yet the budgets from the governments for implementing NFIs have not increased, and international organisations and national aid agencies don't provide funding for implementing national forest inventories. As undertaking national forest inventories is more expensive than monitoring changes in forest areas, growing stock monitoring is minimized due to lack of funds.

Forest information production in Cambodia and Indonesia is constrained by interactions between forest area and forest carbon monitoring. In Cambodia, the absence of an independent NFI division under the MRV centre can be a major constraint on estimating forest carbon stocks and changes, as forestry officers in the MRV centre are responsible for both forest area monitoring and forest inventory. In Indonesia, forest carbon information production is still limited by the inefficient and limited interaction between the Directorate General (DG) of Climate Change and the Directorate of Forest Resources Inventory and Monitoring, and the interactions between the Sub-Directorates under the Directorate of Forest Resources Inventory and Monitoring. Controlling and improving the quality of forest carbon information are constrained by such interactions.

7.2.12 Accuracy of Information

Despite support from domestic and overseas organisations, Cambodia and Indonesia still cannot fully meet international demand for forest carbon information, as the quality of forest information produced in the two countries is not sufficient. Forest information has high uncertainties because of the low accuracy of forest area maps, and the lack of growing stock data and carbon conversion factors.

The accuracy of forest area information is limited by existing technologies, i.e. manual visual classification, as it has limitations in improving the resolution of mapping, and performing accuracy assessments. The current resolution of forest area monitoring is still not sufficient for producing accurate data as the minimum mapping units used in Cambodia and Indonesia could still miss a lot of deforestation. The accuracy of forest cover maps is not fully evaluated due to the methodological limitations and limited field data. For Indonesia, the accuracy of mapping was estimated only for the 2011 map, and Cambodia performs verification using only limited field data.

The accuracy of data and information on forest carbon stock is insufficient because of a lack of reliable allometric equations and carbon conversion factors. As Cambodia's first NFI has not been implemented, it has only a few country-specific emission factors. Indonesia cannot supply sufficient growing stock data due to the declining number of plots measured every year, resulting in irregular and insufficient updates of NFI data. Allometric equations and carbon conversion factors in addition to wood density values are yet to be developed.

7.2.13 Escaping the Plateau

As discussed above, improvements in forest monitoring capacity have reached a plateau, due to constraints on adopting new technologies. If the present situation continues, radical change seems doubtful.

Considering the present situation, it seems that escaping from the plateau may be difficult without great efforts to overcome constraints on adopting new technologies. The main constraints identified by the TAS framework include human capital, institutions and perceptions, existing technologies, financial resources, national demand for forest information, and communication between organisations. The constraints are linked to each other, but limitations could be reduced by relaxing two constraints, i.e. financial resources and human capital.

Escaping from the plateau may be possible with stronger financial incentives, which could emerge if the REDD+ mechanism becomes fully operational, with results-based compensation. Financial incentives can promote not only information production in developing countries, but also upgrading existing technologies to higher level ones that are compatible with more advanced technologies. Better training would also be promoted by financial incentives.

As human capital appears to be a significant constraint on adopting new technologies for forest area and carbon monitoring, increasing human capital could also offer the possibility of escaping from the plateau. Increasing human capital both in number and quality could reduce institutional constraints and constraints caused by perceptions too.

7.3 Implications of the Research

This thesis looked at how two contrasting developing countries adapted to the needs of REDD+ and the opportunities created by REDD+ Readiness by discussing in detail the main constraints on technology adoption processes in the two countries, and other influential factors. The technology adoption processes in developing countries show incremental evolution by self-constrained optimisation of technologies as the evolution of forest monitoring organisations and their capacity has been interrupted by constraining forces.

7.3.1 Improving Forest Monitoring in Developing Countries

The findings of this thesis have significant implications for improving forest monitoring in developing countries generally. If Cambodia and Indonesia are typical of other developing countries that have participated in REDD+ Readiness Programmes then incremental evolution by self-constrained optimisation of remote sensing technologies is likely to be widespread. Consequently, the quality of forest area and carbon information produced by developing countries is likely to remain insufficient to meet international demand by the REDD+ mechanism.

This research also has implications for national policy on forest monitoring in developing countries generally. This research has shown that actual national policy is a constraint on improving forest monitoring to meet REDD+ needs. The managers of forest monitoring organisations in developing countries could make adoption decisions and select new technologies in consultation with overseas organisations, but they cannot implement these decisions until actual national policies give equal priority to meeting national and international demand for forest information.

Given current uncertainty about the future of REDD+, from an economic perspective, the opportunity costs of implementing forest carbon monitoring for REDD+ at national scale are too high in relation to expected income to radically change developing countries' national policy on this matter, and constraints continue to remain. So developing countries are unlikely to give equal priority to meeting national and international demand for forest information until international financial incentives for REDD+ are increased.

7.3.2 Implementing REDD+

The findings of this research also have significant implications for the implementation of the REDD+ mechanism. The question 'is REDD+ feasible or operational?' has increasingly arisen as implementing REDD+ projects turned out to be not as simple as envisaged (see Bayrak and Marafa, 2016; Enrici and Hubacek, 2018; Milbank et al., 2018; Casse et al., 2019; Korhonen-Kurki et al., 2019). Although REDD+ is a prominent means through which deforestation and forest degradation can be reduced at national and global scales, and the amount of anthropogenic CO_2 emissions that causes climate change can cost-effectively offset, criticisms over the implementation of REDD+ as a global climate change mitigation action are also emerging. As Corbera (2012) said, REDD+ may be "the world's largest experiment in payments for ecosystem services". Thus, implementing REDD+ requires reliable evidence that can support the implementation of international environmental policy.

In this context, the findings of this research have significant implications for how to put REDD+ into operation. As developing countries' forest monitoring capacity is not improving as assumed, it implies that the REDD+ mechanism needs to be reformed, and rules and regulations modified. Under the current UNFCCC decisions and developing countries' circumstances, stepwise-approaches through which existing MRV systems could be upgraded by adopting new technologies are not as simple as anticipated. It is the same for establishing realistic Forest Reference Emission Level/Reference Emission Levels (FREL/RELs) (Mertz et al., 2018), and integrating sub-national FREL/RELs into national FREL/RELs that are the one that should be achieved by developing countries for the result-based payments. The findings of this project suggest that these elements may also need to be simplified and reconsidered, and the REDD+ mechanism needs to be more flexible. It should be reminded that Afforestation and Reforestation projects under the Clean Development Mechanism (A/R CDM) that has introduced by the Kyoto Protocol of the UNFCCC failed to be accepted by developing countries, because administrative procedures for registering for the project sites were complicated (Thomas et al., 2010), and regulations on selection criteria were rather strict.

The most important change which could be made to the design of the REDD+ mechanism is to allow developing countries to report progress in terms of reducing deforestation rates alone. The findings of this research imply that, with sufficient support, improving the monitoring of changes in forest area is a realistic objective but in the short-term improving the monitoring of changes in forest carbon stocks is not.

7.4 Relationship with Previous Research

This research presents a better understanding of the evolution of forest monitoring capacity of developing countries, and of the implementation of REDD+ Readiness and REDD+, since it devised and tested a novel methodology that advances existing technology adoption models in order to evaluate the adoption of technologies used to supply environmental information.

It has long been clear that developing countries had limited forest monitoring capacity (Hardcastle et al., 2008; Wertz-Kanounnikoff et al., 2008; Herold, 2009). However, subsequent research argued that developing countries' forest monitoring capacity could be greatly improved through the REDD+ Readiness programme (e.g. Baker et al., 2010; Romijn et al., 2015). In contrast, what this research has showed, using the Technology Adoption System (TAS) Framework in combination with the Information Production (IP) Framework, is that the gap between current national forest area and carbon monitoring capacity in developing countries, and the capacity needed to meet reporting needs of the UNFCCC REDD+ mechanism, could still be very wide, if Cambodia and Indonesia are typical, as the forest monitoring capacity of developing countries may have reached a plateau.

Although REDD+ Readiness schemes have been implemented in developing countries, the capacity to supply forest carbon information is still limited because upgrading forest monitoring systems has been limited by self-constrained optimisation that has led to only incremental evolution. 'Self-constrained optimisation' is a crucial finding, as earlier research did not show that despite the implementation of REDD+ Readiness Programme, developing countries have adopted forest monitoring technologies that they need, not international conventions or other end users need.

Until starting this research, it had been unclear what are the underlying constraining forces hampering increasing forest monitoring capacity of developing countries. For information technologies, critical variables affecting technology adoption were identified by researchers (e.g. Kamal, 2006), but for forest monitoring technologies, they had been remained uncertain. This research presented critical variables, and identified main constrains on adopting new technologies by explaining technology adoption processes in Cambodia and Indonesia. It was known that establishing Monitoring, Reporting and Verification (MRV) systems are hampered by political decisions (Visseren-Hamakers et al., 2012), but the finding that adopting forest monitoring technologies are constrained by national information needs is a new finding.

Given that the sociology of remote sensing systems has been little studied until now (Grainger, 2017), this research has also made an important contribution to the remote sensing literature, and the REDD+ MRV literature. As the sociology of remote sensing is related to global forest monitoring, this research advances the literature on global forest monitoring too. Global forest monitoring has traditionally relied on data and information from governments (e.g. FAO. 2005; FAO. 2010d; FAO. 2015a), which is crucial to modelling land use and land cover change and monitoring global environmental change and biodiversity in addition to assessing sustainable development, formulating international environment policy and monitoring policy implementation (Grainger, 2008; Watmough et al., 2019). Yet, the discipline most directly concerned with satellite monitoring, remote sensing science, has traditionally not examined why global data collected by satellites has not been operationally converted into usable global information (Goward, 2008; Lippitt and Stow, 2015). The advocates for technocentrism and international organisations assume that the quality of global forest information will continue to improve as more governments monitor their forests with increasing accuracy and frequency. Other previous research argued that developing countries' forest monitoring capacity is not improving as fast as expected in spite of international technical and financial assistance offered to developing countries. This research provides a different perspective on developing countries' forest monitoring capacity and global forest monitoring that have been implemented by bottom-up approaches, by discovering that some aspects of forest monitoring capacity have evolved more quickly than expected while others have continued to develop relatively slowly, and by showing that the frequency of national forest area monitoring using satellite data has increased over time in many countries, but there are still critical constraints on the accuracy and frequency of monitoring of forest timber and carbon stocks. Through detailed case studies in Cambodia and Indonesia, it is shown that governments have decided to limit their forest timber and carbon monitoring in spite of opportunities provided by REDD+ Readiness programmes to adopt new technologies, resulting in the poor global forest monitoring, and the reasons for this were explained throughout this thesis.

As well as advancing specific application literatures, like those on REDD+ monitoring and the sociology of remote sensing systems, this research also makes generic advances in the technology adoption literature by proposing and testing a Technology Adoption System (TAS) Framework that can be used to evaluate more complex instances of technology adoption than current frameworks. The TAS Framework advances the earlier Technology, Organization and Environment Framework (TOE) (Tornatsky and Fleischer, 1990) by explaining how suitable a range of new Available Technologies are for a given Adopting Organization by assessing the compatibility between the human capital and institutional requirements of each new technology with the existing human capital, institutions and policies of the organization, and its existing technologies, and how it must respond to the External Environment (e.g. by reporting on REDD+ achievements). The TAS can accommodate interactions between multiple parts of the same Adopting Organization, e.g. the forest area mapping division and the forest inventory division of a government forestry department, and multiple scales in the External Environment. This research also demonstrates the value of the combined use of the Technology Adoption System (TAS) Framework and the Information Production (IP) Framework in evaluating the effectiveness of technology adoption, and identifying constraints on the process, in addition to their ability to evaluate forest monitoring capacities of developing countries.

Previous research has evaluated the forest monitoring capacity of developing countries, and proposed new methodologies and techniques for forest monitoring and MRV activities in developing countries, and available technologies for the purpose (e.g. Herold and Johns, 2007; GOFC-GOLD, 2013). However, previous research focused mainly on technical issues, and social factors were often neglected. By employing an interdisciplinary approach that incorporates technological and social factors, this research sheds light on what causes developing countries' poor forest monitoring capacity in spite of the implementation of the REDD+ Readiness programmes, which had not been clearly explained until this research was presented.

7.5 Limitations of the Research

A structured conceptual framework (the TAS Framework) was selected for this research as it not only identifies constraints on adopting new technologies, but also evaluates existing forest monitoring capacity. In addition, this research was also designed to identify gaps in meeting national and international demand for information through the IP Framework. It was anticipated that achieving such research purposes requires an interdisciplinary approach that bridges remote sensing science and social science. Thus, two conceptual frameworks that are linked to one another were devised and tested. At the beginning of this project, conceptualising technology adoption processes was also deemed to be suitable for this research as this research analysed long term changes happening in organisations, and their technologies, by historical analysis. A conceptual framework is known to be an efficient methodology when evaluating institutions and policy. Thus the technology adoption literature was reviewed, and after analysing technology adoption models at individual and organisation levels, the TAS framework was devised. The TAS framework allows for explaining technology adoption processes, and evaluating individual and organisational factors related to technology adoption.

As explained, devising and applying a conceptual framework seemed suitable for achieving these research purposes and also for making generic advances in the technology adoption literature. However, it appears that the variables identified by the TAS framework could also hamper identifying unexpected constraints on adopting new technologies as questions for interviewees are generated based on the framework. It was known that when employing conceptual frameworks, some variables could be disregarded (Bordage, 2009). To discover unexpected phenomena and variables, semi-structured open-ended interviews were conducted, and a few unanticipated constraints were discovered. Yet, it might still not be enough to fully compensate the nature of the framed approach as approaches and methodologies in the social sciences have their inherent strengths and weaknesses.

An alternative approach would have been to employ grounded theory, that relies totally on systematically collected data and analysis processes to present innovative discoveries, and unexpected findings, when identifying constraints on adopting new technologies (see Glaser and Strauss, 1967; Strauss and Corbin, 1994; Khan, 2014). It is because capturing almost all potentially relevant aspects of phenomena, or research subjects, is enabled by its procedures of data collection and analysis (Corbin and Strauss, 1990). Thus, subsequent studies could consider adopting grounded theory when identifying variables. Nevertheless, it should also be noted that when identifying and categorising possible constraints by evaluating general patterns, and explaining technology adoption processes, theoretical foundation, and explanation, could be weak and congruence could be lacking due to its specific canons and procedures (Thomas and James, 2006). It could have the possibility of misuse due to researchers' epistemological premises (Annells, 1996).

The results of this research are derived from empirical data collected by in-depth interviews and direct observations, and they can be used as valuable reference information. However, it should be noted that the empirical data collected in the two countries could have possibility of bias to some extent. Interviewees in the forest monitoring organisations in the two countries were selected based on language for communication, i.e. competence in English, and were recommended by managers of the organisations at the beginning of each fieldwork. All of the forestry officers in the Cambodian MRV centre were interviewed, but only a third of forestry officers in the Indonesian forest monitoring organisation could be interviewed although all of the manager-level forestry officers were interviewed. During fieldwork, it was also felt that when having interviews, high ranking government officials in both countries tended to focus more on advertising their achievements, rather than providing information related to adopting new technologies, and junior staff tended to hesitate to provide detailed information. In addition, materials used to analyse forest monitoring capacities before the REDD+ Readiness schemes were limited and often inconsistent with one another. To verify such inconsistency, available materials were collected and compared as much as possible before fieldwork, and then verified during interviews. Yet, this may not be enough to clarify all the events in the past. To supplement the data collected through interviews, informal interviews and direct observations were conducted during the fieldwork in the two countries, and a second visit to Cambodia was made to collect any missing data. However, it seems that this may not be sufficient to derive completely unbiased results.

It seems that such possibility of bias is related to the nature of framed approaches that evaluate variables by conducting empirical studies. By employing a conceptual framework as main methodology, hypotheses or research questions can be generated, key variables can be identified, and phenomena can be explained (Potschin-Young et al., 2018). Yet, as examining variables and processes are the focus of empirical study to advance understanding of phenomena, the framed approach is less concerned with how to select interviewees. Although informal interviews were conducted during the fieldwork to supplement formal interviews, it was felt that when adopting and applying the framed approach, researchers should be careful with data collection, especially when selecting interviewees.

Finally, although the TAS framework is devised to explain technology adoption processes, the data collected in Cambodia and Indonesia may not sufficient to fully test all the variables in the TAS framework. Technology adoption at lower scales is limited as this research was confined to capital cities of the two countries. This research presents analyses on interactions between central offices and regional offices in the two countries with limited data and information, as regional offices were not visited for data collection during fieldwork. This was the same for examining the role of External Environment in technology adoption processes, which is a crucial component in the TAS framework, and interactions with external organisations. It is because only a few people affiliated to each external organisation could be interviewed due to difficulties in getting access to the organisations and limited time. When conducting interviews in Cambodia and Indonesia, higher ranking government officials who can actually make political decisions could not be interviewed.

7.6 Conclusions

This chapter presented the generic finding that technology adoption is limited by self-constrained optimisation by comparing the findings from the two case studies in Cambodia and Indonesia. By answering research questions, this research makes crucial contributions to the technology adoption literature, the REDD+ MRV literature, and the sociology of remote sensing literature, and the findings of this research have significant implications for REDD+ MRV systems and implementing forest monitoring in developing countries. They also have wider implications for implementing REDD+ and global forest monitoring. As this research also has some limitations, related mainly to the nature of the TAS framework and data collection, the methodology and methods for this research were discussed in detail. In the next chapter, this research is summarised, and policy recommendations and directions for future research are presented.

Chapter 8
Conclusions and Recommendations

8.1 Introduction

This research was designed to evaluate national forest survey programmes in tropical countries and how they have been upgraded by participating in REDD+ Readiness programmes, identify constraints on adopting new technologies for forest area monitoring and forest carbon monitoring, and propose how to overcome these constraints to improve the supply of information to the REDD+ mechanism. To do this, the research would devise conceptual frameworks to evaluate the gap between current national forest area and carbon monitoring capacity in developing countries and the capacity needed to meet reporting needs of the UNFCCC REDD+ mechanism, and identify the socially optimal technologies which it would be feasible to adopt to raise monitoring capacity to REDD+ reporting standards. These frameworks would be tested through empirical studies in two contrasting developing countries, Cambodia and Indonesia. This chapter summarises the main findings of this research, and the degree to which this research meets the research aims stated at the beginning of this thesis. Based on the generic findings of this research and their implications discussed in Chapter 7, policy recommendations for governments in developing countries, for the UNFCCC, and for overseas organisations are then presented. This chapter ends with suggestions for future research.

8.2 Key Findings and Contributions

To participate in the REDD+ mechanism of the UN Framework Convention on Climate Change (UNFCCC), developing countries must upgrade their national forest monitoring systems to become Measurement, Reporting and Verification (MRV) systems that can monitor changes in forest area and forest carbon stocks. However, despite support from international REDD+ Readiness programmes, most developing countries still have limited forest monitoring capacity.

With the common-sense assumption that to raise forest monitoring capacity, developing countries should adopt new technologies, this research devised and tested a Technology Adoption System (TAS) Framework that could be used to evaluate more complex instances of technology adoption than current frameworks, and an Information Production (IP) Framework that would enable the evaluation of forest information production capacity.

This research found that despite the completion of REDD+ Readiness programmes in Cambodia and Indonesia, their capacity to supply forest information is still low. Technology adoption to upgrade forest monitoring systems has been limited, as self-constrained optimisation has led to only incremental evolution. Improving forest monitoring capacity has been accompanied by organisational changes, but this created other challenges in technology adoption and forest information production.

Technology adoption has involved self-constrained optimisation because adopting new technologies was limited by various factors. Making decisions on adopting new technology has been constrained by organisational and technological factors in addition to national and international policies. Organisational capacities still seem too low to adopt more advanced technologies, owing to limited human capital. Forest monitoring organisations' communications with external organisations have positive and negative influences on technology adoption. Existing technologies and institutions are not compatible with those for some new technologies. Adopting new technology was difficult because of institutions linked to technologies for forest area monitoring, and organisational depth (the deterioration in human capital in moving from national to local scales) exacerbated path dependency. Unlike stated policy, actual policy does not strongly encourage improving forest monitoring capacity to meet international information demand, and gives priority instead to meeting national information demand. This limits financial support from government.

This research has also identified other influential factors affecting technology adoption and information production. It found that national and international demand for forest information influenced technology adoption in different ways in the two countries. In addition, technology adoption was limited by organisational substitution, and interactions between organisations. Organisational changes in Cambodia and Indonesia created new challenges to technology adoption, and showed limitations in MRV activities. Cambodia and Indonesia, however, have shown relative improvements in forest area monitoring capacity, compared to forest growing stock monitoring capacity.

In both countries, improving forest area monitoring has reached a plateau due to self-constrained optimisation and path dependency. As the upgraded MRV designs are insufficient to fully meet international demand for information on changes in forest carbon stocks, the quality of forest area and carbon information produced by the two countries is still insufficient to meet international demand. Forest carbon information production is also limited by interactions between organisations for forest area monitoring and forest inventory.

This research argues that escaping from the plateau may be difficult without greater efforts to overcome constraints on adopting new technologies and without stronger financial incentives. Nevertheless, as constraints on adopting new technologies were identified by the TAS framework, this research provides opportunities for developing countries to escape from the plateau.

By devising a new technology adoption framework that improves on previous frameworks and applying this to historical forest monitoring activities and capacity in developing countries, this research makes novel contributions to the technology adoption literature by presenting a better understanding of the capacity gap that exists between the current ability of developing countries to monitor forest cover/carbon stocks, and how the gap can be filled to operationalise MRV systems for REDD+. As this research presents the findings on why technology adoption is limited, and how the existing forest monitoring systems can be improved are presented, by evaluating how Cambodia and Indonesia adapted to the needs of REDD+, it makes substantial contributions to the REDD+ MRV literature, and the sociology of remote sensing literature.

The findings of this research therefore have significant implications for implementing forest monitoring in developing countries, and establishing REDD+ MRV systems. They also have wider implications for implementing REDD+ and for global forest monitoring.

8.3 Meeting Research Aims

This research had five Aims:

1. Evaluate tropical countries' existing national forest survey programmes and the programmes which have been upgraded by participating in the REDD+ Readiness programmes.

2. Identify constraints on adopting new technologies for forest area monitoring and forest carbon monitoring.

3. Propose solutions to the problem that developing countries still have limited forest monitoring capacity by identifying constraints on adopting new technologies for forest area and carbon monitoring.

4. Devise frameworks to evaluate the gap between current national forest area and carbon monitoring capacity in developing countries and the capacity needed to meet reporting needs of the UNFCCC REDD+ mechanism, and identify the socially optimal technologies which it would be feasible to adopt to raise monitoring capacity to REDD+ reporting standards.

5. Test these frameworks in two developing countries, Cambodia and Indonesia, for the purposes mentioned above.

To tackle Aims 1-3, this project adopted an innovative interdisciplinary approach to tackling Aim 4 that bridges remote sensing science and various social sciences. Instead of assuming that developing countries must adopt the most advanced remote sensing technologies to monitor their forests, an Information Production (IP) Framework and a new Technology Adoption System (TAS) Framework that can evaluate a country's current forest monitoring capacity, and also can propose a "socially optimal" mix of technologies to upgrade this to meet REDD+ reporting needs, were devised.

By testing the two conceptual frameworks in Cambodia and Indonesia (Aim 5), this research fully answered Aims 1-3 above. In Chapters 5 and 6, the exact levels of forest area, forest growing stock, and forest carbon monitoring capacities in these two countries are presented (Aim 1). Using the two conceptual frameworks, Chapters 5 and 6 explain the constraints on upgrading developing countries' current forest information supply capacity by participating in various REDD+ Readiness programmes (Aim 2). The unexpected generic finding that technology adoption has involved self-constrained optimisation explains why developing countries still have poor forest monitoring capacity. Constraints on adopting new technologies are identified and explained in detail throughout Chapters 5 and 6. Socially optimal technologies that can be identified by the TAS framework are not presented as forest monitoring organisations in Cambodia and Indonesia have already optimised their choice of new technologies themselves. Instead, policy recommendations that include organisational and technological aspects are presented in the next section to help developing countries to escape the plateau of self-optimisation.

8.4 Policy Recommendations

This research showed some possibilities of escaping from the plateau caused by constraints on adopting new technologies, and on forest information production. As actions to overcome constraints on adopting new technologies need to be taken by various bodies related to REDD+, this section presents recommendations for governments in developing countries, the UNFCCC, and overseas organisations.

8.4.1 Recommendations for Governments in Developing Countries

8.4.1.1 Organisational aspects

Cambodia needs stronger communication links with provincial offices and other government agencies for better forest monitoring. The quality of forest area information is still in doubt, because the volume of ground data used for accuracy assessments is still limited. Collecting field data is limited by lack of communications with provincial offices. As commencing Cambodia's first NFI is limited by the lack of communications with provincial offices and other government agencies, these communication links need to be strengthened too.

Indonesia needs better communications with overseas organisations and more centralised MRV activities for forest information production. Indonesia’s adoption of technologies for forest area monitoring is constrained by lack of reliable research. Existing communication links for growing stock monitoring are biased towards domestic research institutes, so overseas organisations may be able to assist in transforming and implementing Indonesia’s national forest inventory and developing carbon conversion factors. As producing forest information is limited by ineffective interactions between government organisations related to MRV activities, more centralised MRV activities may be able to improve current information production.

Both countries need to strengthen the organisations of their forestry departments considerably if sufficient ground data on changes in forest growing stocks is to be collected.

8.4.1.2 Technological aspects

Through their REDD+ Readiness programmes, forest area monitoring capacities in Cambodia and Indonesia were improved, but growing stock monitoring and developing carbon conversion factors, and the accuracy of forest area information, are still limited. The gaps between information supply and demand in the two countries indicate the need for further improvements in forest area and forest growing stock monitoring. It is likely that the same is true for other developing countries.

If governments wish to meet UNFCCC demand for changes in national forest carbon stocks, but do not wish to spend money on hiring a lot of new staff to collect inventory data, and regard the use of LiDAR technology as inconsistent with their present forest monitoring systems, they need to identify an alternative technology. One possible option would be to use optical satellite data to measure both forest area and the distribution of biomass, based on the Normalized Difference Vegetation Index (NDVI). This is less accurate than the other options but has been successfully demonstrated in the peer-reviewed literature (e.g. Myneni et al., 2001; Dong et al., 2003).

8.4.1.3 Recommendations for governments in other countries

This research showed that technology adoption is limited by lack of human capital, and this may be a common problem in any developing country. As one solution to escaping from the plateau suggested by this research is increasing human capital, this research recommends that developing countries invest in human capital with long-term plans. Institutional constraints and constraints caused by perceptions could be reduced by the increased human capital.

As this research found that technology adoption, and information production, is constrained also by national information needs, organisational structure for MRV activities, and communications between organisations related to forest information production and reporting, it would be beneficial for developing countries to carefully reassess such factors. To do this, they could use the components of the TAS Framework as a simple checklist by determining:

1. How national demand for forest information, and the resources required to provide this, relate to international demand for forest information, and the resources required to provide this. Making the transition from monitoring forest area to monitoring forest carbon is proving difficult and this needs serious discussion at national level to align national policies with international commitments.

2. How the possibilities for adopting new technologies are constrained by existing technologies, limitations on human capital, and available financial resources.

3. How improvements in forest monitoring are constrained by organisational structures and communication between the various organisations involved. Every country will wish to establish a REDD+ MRV Centre that best fits the existing structures of government organisations, and the different approaches taken by Cambodia and Indonesia on this matter may be helpful case studies.

8.4.2 Recommendations for the UNFCCC

The REDD+ mechanism of the UN Framework Convention on Climate Change is already very ambitious in seeking to rapidly reduce rates of deforestation and forest degradation in the tropics. This research has shown that it is also ambitious in expecting developing countries to quickly upgrade their existing forest monitoring systems to become MRV centres that can monitor the effectiveness of these actions. This research has many implications for the future of the REDD+ mechanism, but two policy changes could have a great impact on the effectiveness of REDD+ monitoring:

1. Only require developing countries to report trends in their forest area and deforestation rate. As shown in this research, there are critical gaps between national forest information supply and international demand for forest information. It seems that developing countries may not be able to meet international demand for forest carbon information in the near future. As obtaining accurate information on forest carbon stocks and changes for implementing REDD+ appears to be difficult, the reporting burden on developing countries may need to be reduced. If monitoring forest degradation and measuring forest carbon pools are impractical for developing countries then it is logical to limit the focus to monitoring forest area instead.

2. Provide stronger financial incentives. This research showed that incentives to increase forest monitoring capacity are too small, since financial support from international organisations is still limited. One way to overcome this constraint would be for the UNFCCC to introduce the results-based compensation scheme that was promised when the REDD+ negotiations began.

8.4.3 Recommendations for Overseas Organisations

Since starting the REDD+ negotiations, there have been various REDD+ Readiness programmes supported by international organisations and national aid agencies, and other capacity building projects. However, the quality of human capital in developing countries is still insufficient to upgrade existing forest monitoring systems substantially.

Despite the various achievements of REDD+ Readiness schemes in Indonesia and Cambodia, the adoption of new technologies has been limited. Three modifications could make a great difference in future:

1. Introduce more sustained and regular training courses. This would help to solve problems arising from the short-term nature of training courses.

2. Plan training more carefully. Cambodia and Indonesia made decisions on adopting new technology after evaluating existing organisational and technological factors, and available resources. Yet, when making decisions on adopting new technologies, it would be better to more carefully plan in advance how to improve technological and organisational capacity, in addition to financial resources, to fit those aspects for new technologies. When making decisions to upgrade existing forest monitoring systems by adopting new technologies, more comprehensive and long term master plans are required.

3. Evaluate the benefits of overseas staff continuing to occupy key technical positions after training ends. Overseas technical advisers continue to be involved in forest monitoring in both Cambodia and Indonesia. There is nothing wrong in this, but giving such experts added responsibilities for planning long-term training could help to implement Recommendation 2.

8.5 Recommendations for Future Research

This research has presented crucial findings on improvements in national forest monitoring, and made important generic advances to the literatures on REDD+ MRV, technology adoption, and the sociology of remote sensing systems. Yet, the need for additional research still exists. This includes:

1. Refining the TAS Framework. The TAS needs to be modified and improved to accommodate factors less concerned in this research. After completing the first fieldwork in Cambodia, the TAS framework was modified to accommodate a few more variables that had not been included, but it seems that this could not make the TAS framework perfect as technology adoption processes are related to various factors, and such factors have interactions with more than one factor. Although the TAS framework includes factors related to adoption by individuals, e.g. awareness and perceptions, it revealed that social capital such as personal networks should be more stressed. For this reason, leadership and personal networks that could make technology adoption possible are mentioned only briefly as this research focuses more on organisational aspects, and on upgrading existing forest monitoring systems by identifying constraints.

2. Study trends in forest monitoring capacity in a wider range of countries. The results were generalised based on just two case studies, but this may not be enough to

represent all developing countries. Other countries in Southeast Asia and developing countries in Africa or Latin America may be in different situations, and they have different forest monitoring capacities and organisational structures. There could be different technology adoption processes and constraints on them. Additional research on experiences and information production of other developing countries could show if plateau in technology adoption and forest monitoring capacity occur in other developing countries too. Additional research using data and information on developing countries' historical forest monitoring capacities, the situations in developing countries, and their technology adoption processes, should be conducted to present more generic findings. In the process, socially optimal technology could be evaluated to present more detailed solutions to forest monitoring in developing countries, which is an important function of the TAS framework.

3. Investigate the economic relationships between the costs of improving the accuracy of REDD+ monitoring and the benefits involved. To accelerate implementing REDD+ MRVs and operationalising REDD+, further research is needed. Since establishing reference emission levels turned out to be not easy (Mertz et al., 2018), to reduce reporting burden, the minimum accuracy of forest information required to implement the REDD+ phase 3, i.e. result-based payments, needs to be evaluated. This research recommended that to increase developing countries' forest monitoring capacity, incentives should be provided. Although it was suggested that by providing incentives to investors, monitoring errors can be reduced and the performance of REDD+ projects can be improved (Sheng et al., 2018), the role of incentives for developing counties to raise their forest monitoring capacity, and the relationships between incentives and forest monitoring capacity needs to be examined. This could evaluate all possible options, from continuing to focus only on forest area monitoring, to upgrading to full forest carbon monitoring.

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List of Abbreviations/Acronyms

AD	Activity Data
AFoCo	ASEAN-ROK Forest Cooperation
AGB	Above Ground Biomass
AHP	Analytic Hierarchy Process
AIT	Asian Institute of Technology in Thailand
ANT	Actor Network Theory
A/R CDM	Afforestation and Reforestation Clean Development Mechanism
AT	Appropriate Technology
BAPPENAS	National Planning Agency of Indonesia
BCEF	Biomass Conversion and Expansion Factors
BFS	Brazilian Forest Service
BIG	National Mapping Agency of Indonesia, formerly BAKOSURTANAL
BURs	Biennial Update Reports
CAM-REDD	JICA project for Facilitating the Implementation of REDD+ Strategy and Policy in Cambodia
CART	Classification and Regression Tree Analysis
CCCA	Cambodian Climate Change Alliance
CDM	Clean Development Mechanism
CFI	Community Forest International
CI	Conservation International
COP (or CP)	Conference of the Parties
DANIDA	Danish International Development Agency
DBH	Diameter at Breast Height
DFW	Department of Forestry and Wildlife of Cambodia
DG of CC	Directorate General of Climate Change of Indonesia
DG of FP	Directorate General of Forest Planning of Indonesia
DOI	Diffusion of Innovations
EDI	Electronic Data Interchange

EFs	Emission Factors
ESA	European Space Agency
ETM+	Enhanced Thematic Mapper Plus
EVI	Enhanced Vegetation Index
FA	Forestry Administration of the Ministry of Agriculture, Forestry and Fisheries of Cambodia
FAO	Food and Agriculture Organization of the United Nations
FCPF	Forest Carbon Partnership Facility of the World Bank
FFPRI	Japanese Forestry and Forest Products Research Institute
FiA	Fisheries Administration of the Ministry of Agriculture, Forestry and Fisheries of Cambodia
FIA	Forest Inventory and Analysis
FORDA	Forest Research and Development Agency of Indonesia
FRA	Forest Resources Assessments
FREL/FRLs	Forest Reference Emission Level/Forest Reference Levels
GCF	Green Climate Fund
GDANCP	General Department of Administration for Nature Conservation and Protection of the Ministry of Environment of Cambodia
GEDI	Global Ecosystem Dynamics Investigation
GEE	Google Earth Engine
GEO	Group on Earth Observations
GFOI	Global Forest Observation Initiative
GHGs	Greenhouse Gases
GIS	Geographic Information System
GIZ	German Corporation for International Cooperation
GOFC-GOLD	Global Observation for Forest Cover and Land Dynamics
GPS	Global Positioning System
GRAS	Geographic Resource Analysis and Science A/S of the University of Copenhagen
GTZ	German Technical Cooperation Agency
IAFCP	Indonesia- Australia Forest Carbon Partnership

ICRAF	World Agroforestry Centre
INCAS	Indonesian National Carbon Accounting System
IP	Information Production
IPB	Bogor Agricultural University in Indonesia
IPCC	Intergovernmental Panel on Climate Change
ITTO	International Tropical Timber Organisation
JAXA	Japan Aerospace Exploration Agency
JICA	Japan International Cooperation Agency
KMFCC	Korea-Mekong Forest Cooperation Centre
k-NN	k-Nearest Neighbour
KSWS	Keo Seima Wildlife Sanctuary
LAPAN	National Institute of Aeronautics and Space of Indonesia
LiDAR	Light Detection and Ranging
LULC	Land Use and Land Cover
LULUCF	Land Use, Land Use Change and Forestry
MAFF	Ministry of Agriculture, Forestry and Fisheries of Cambodia
MCDM	Multi-Criteria Decision Making
MODIS	Moderate Resolution Imaging Spectroradiometer
MoE	Ministry of Environment of Cambodia
MOU	Memorandum of Understanding
MRC	Mekong River Commission
MRV	Measurement, Reporting and Verification
MSI	Multi-Spectral Instrument
NAMAs	Nationally Appropriate Mitigation Actions
NAPA	National Adaptation Program of Action on Climate Change
NASA	National Aeronautics and Space Administration
NCs	National Communications
NDVI	Normalized Difference Vegetation Index
NFI	National Forest inventory
NFMS	National Forest Monitoring System
NFP	National Forest Programme

NIR	National Inventory Report
NRS	National REDD+ Strategy
NSDP	National Strategic Development Plan
PCA	Principal Component Analysis
PSPs	Permanent Sample Plots
Radar	Radio Detection and Ranging
REDD+	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
RGC	Royal Government of Cambodia
RS	Remote Sensing
RS/GIS	Remote Sensing and Geographic Information System
RUA	Royal University of Agriculture in Cambodia
RUPP	Royal University of Phnom Penh in Cambodia
SAR	Synthetic Aperture Radar
SFM	Satellite Forest Monitoring
SPOT	Satellite Probatoire d'Observation de la Terre
TAM	Technology Acceptance Model
TAM-TPB	Technology Acceptance Model and Theory of Planned Behaviour Model
TAS	Technology Adoption System
TCP	Technical Cooperation Programme
TGC	Terra Global Capital
TM	Thematic Mapper
TOE	Technology, Organization and Environmental framework
TPB	Theory of Planned Behaviour
TRA	Theory of Reasoned Action
TSPs	Temporary Sample Plots
TWG-F&E	Technical Working Group on Forestry and Environment of Cambodia

UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UMD	University of Maryland
USAID	United States Agency for International Development
USDA FS	U.S. Department of Agriculture Forest Service
USGS	US Geological Survey
UTAUT	Unified Theory of Acceptance and Use of Technology
WCS	Wildlife Conservation Society
WRI	World Resources Institute
WWF	World Wide Fund for Nature

Appendix A
Direct Observation Guide

A.1 Data to be collected in Direct Observations of Forest Survey Divisions

Organizations

- Organizational structure - hierarchical and vertical structure of the division
- Formal and informal social networks in the divisions
- Interaction between forest survey division and forest inventory division

Human Capital

- Expertise of spatial data processing and analysis
- Number of staff and trained staff in forest survey division
- Former human capital
- Project management experience
- Technical knowledge of forest survey

Institutions/Practices

- Outline of current forest information producing systems
- Frequency and resolution of forest information producing
- Type of area mapping (manual/digital)
- Frequency and resolution of forest area mapping
- Frequency of area mapping and Information production
- Map production
- Data and information flow
- General practices for estimating forest area
- The aims of forest information production in frequency and resolution
- General practices for monitoring forest area
- Producing forest area information practices
- Methods for estimating forest carbon stocks
- Data and information sharing with other adopting organizations
- Collaboration with other adopting organizations
- Estimating forest area and carbon stocks
- Quality or accuracy of forest area monitoring

- Data processing (manual/digital)

Technologies

- Aerial surveys
- Optical satellite sensor type
- Satellite sensor resolution
- Image processing methods or algorithms
- Carbon sensor type
- Technologies adopted after starting the REDD+ readiness programme
- Database management
- Computer languages and software used
- Operating system, hardware and software for forest monitoring
- Source of images for forest area monitoring
- Types of images for forest area monitoring
- Manuals for forest area monitoring

NB. Data will be collected on status before and after REDD+ Readiness activities.

A.2 Data to be collected in Direct Observations of Forest Inventory Divisions

Organizations

- Organizational structure - hierarchical and vertical structure of the division
- Formal and informal social networks in the divisions
- Interaction between forest survey division and forest inventory division

Human Capital

- Number of staff and trained staff for forest inventory
- Personnel's skills in forest inventory
- Project management experience
- Technical knowledge of forest inventories and plot sampling
- Expertise of field data collection, processing and analysis

Institutions/Practices

- Outline of current forest inventory data producing systems
- Database management
- Data and information flow
- Collecting and processing field data
- General practices for estimating timber volume
- Process of producing forest inventory data
- Producing emission factors
- Developing allometric equations
- Measuring five carbon pools
- Sampling methods
- Land use/land cover classification
- Forest stratification
- Field measurement
- Permanent and temporary field plots
- Intensity of forest inventory
- Frequency and resolution of forest inventory
- Data and information sharing with other adopting organizations
- Collaboration with other adopting organizations

Technologies

- Manuals for forest inventory
- Type of forest inventory sampling
- Hardware and software for forest inventory data
- Devices for field measurement

NB. Data will be collected on status before and after REDD+ Readiness activities.

Appendix B
Interview Guides

Interview Guides for managers and staffs of the Forest Survey and Inventory Divisions in Cambodia and Indonesia are provided here. Adapted versions of these interview guides were used for interviewees working for national government agencies (i.e. the Ministry of Environment of Cambodia, and the Ministry of Environment and Forestry of Indonesia), international organisations (i.e. the Food and Agriculture Organization of the United Nations (FAO), the United Nations Development Programme (UNDP) and the Wildlife Conservation Society (WCS) in Cambodia, and the World Resources Institute (WRI) in Indonesia), research institutes (i.e. the Royal University of Agriculture (RUA) in Cambodia, and the National Institute of Aeronautics and Space (LAPAN), Bogor Agricultural University (IPB) and the National Mapping Agency (BIG) in Indonesia) and national aid agencies (i.e. the Japan International Cooperation Agency (JICA) and the Korea-Mekong Forest Cooperation Centre (KMFCC) in Cambodia and the German Corporation for International Cooperation (GIZ) in Indonesia).

B.1 Interview Guide for Managers of Forest Survey and Inventory Divisions

School of Geography

Faculty of Environment

UNIVERSITY OF LEEDS

Date and Place of Interview:
Name:
Division:
Position:

- What is your main duty?
- How many years have you been working for forest monitoring?
- What is your educational background?

Adopting Organization

Existing Technology

- What kind of new technologies has your organization adopted after starting REDD+ readiness programme?
- What do you think about the technologies adopted after starting REDD+ readiness programme?
- What are the improvements in collecting forest data after starting REDD+ readiness programme?
- What kind of NFI data and carbon factors will your country use for FREL?
- Why was your country unable to adopt more advanced technologies?

Human Capital

Perceptions

- Do you need to adopt further new technologies? And do you have any preferences?
- Are you willing to introduce new technologies?
- Do you think your staff can use these new technologies?

Languages

- Has your staff had any problem caused by human languages during their work or operating new technologies?
- What kind of computing languages can your staff use?
- Have they had any difficulty caused by computing languages during your work or operating technology?
- Do you think they can learn new computing languages to operate new technologies to be adopted?
- What kind of new training for collecting and analysing data for forest monitoring has your staff attended?
- What kind of software can they use?
- What kind of images can they analyse?

Institutions (Practices)

- What do you do with existing technology for producing forest information?
- What have been changed in practices after starting REDD+ readiness programme?
- What do you think about the changes?

- What are remaining difficulties in producing forest information (Timber volume and Carbon stocks)?
- What kinds of communications between forest monitoring and inventory division are needed for MRV?
- What are the differences before and after REDD+ readiness in interactions between forest monitoring and inventory divisions?
- How good is communication within your division or section?
- Is there any difficulty in collaboration or communication within your organization?
- Which other organizations do you depend on for data/information?
- What are you exchanging data or sharing information with other organizations for?
- What are the difficulties in collaboration or communication with other organizations?
- What are the differences before and after REDD+ readiness in establishing institutions, and how did you establish them?

External Environment

National and International Policy - Laws, Institutional Isomorphism

- How do you feel about your national policies about to respond to information needs of international conventions?
- What are the differences before and after REDD+ readiness in national international policies?
- Do you know technologies adopted by other MRV organizations and what do you think about that?
- What are difficulties in following other MRV organizations?

End Users - Information Needs

- Do you know what information resolution and frequency are required?
- What do you think about it?
- What are difficulties in responding the external requirements?
- What are the differences in information requests from international organisations and your government before and after REDD+ readiness?

B.2 Interview Guide for Staff in Forest Survey Divisions

School of Geography

Faculty of Environment

UNIVERSITY OF LEEDS

Date and Place of Interview:

Name:

Division:

Position:

- What is your main duty?
- How many years have you been working for forest monitoring?
- What is your educational background?

Adopting Organization

Existing Technology

- What kind of technologies do you use for your duty?
- What kind of technologies has your organization adopted after starting REDD+ readiness programme?
- What do you think about the technologies adopted after starting REDD+ readiness programme?
- What are the improvements in collecting forest data after starting REDD+ readiness programme?
- Do you have any difficulty in operating existing technologies?
- Do you have any difficulty in obtaining satellite images?

Human Capital

- What kind of training for collecting and analysing data for forest area monitoring have you attended?
- What kind of software can you use?
- What kind of images can you process and analyse?

Perceptions

- What do you know about new technologies and their advantages?
- Are you willing to use new technologies?

- Do you think what kind of new technologies you can use?
- Have you ever tried to use other sensors for forest area monitoring?
  - What did you feel when use other sensors?
- Have you ever analysed LiDAR data?
  - What did you feel when you analyse LiDAR data?
- Have you ever analysed SAR data?
  - What did you feel when you analyse SAR data?
- Have you ever analysed Hyperspectral data?
  - What did you feel when you analyse Hyperspectral data?

Languages

- What kind of languages can you speak?
- Do you have any problem caused by languages during your work or operating technology?
- What kind of computing languages can you use?
- Do have any difficulty caused by computing languages during your work or operating technology?
- Do you think you can learn new computing languages?
- What do you think of computing languages for new technologies?

Institutions (Practices)

- What do you do with existing technology for producing forest information?
- What have been changed in practices after starting REDD+ readiness programme?
- What do you think about the changes?
- What are difficulties in producing forest area or carbon stocks information?
- Do you have any practical difficulties in collecting forest data and estimating forest carbon stocks?
- How often do you collaborate with staff in your organization? And for what?
- What are the difficulties in collaboration or communication with staff in your organization?
- What kinds of communications between forest monitoring and inventory division are needed for MRV?
- What are the differences before and after REDD+ readiness in interactions between forest monitoring and inventory divisions?
- What are the differences before and after REDD+ readiness in establishing institutions, and how did you establish them?

External Environment

National and International Policy - Laws, Institutional Isomorphism

- What are the difficulties in following manager's requests?
- Do you know technologies adopted by other MRV organizations and what do you think about that?
- What are difficulties in following other MRV organizations?
- What are the differences before and after REDD+ readiness in national international policies?

End Users - Information Needs

- Do you know what information resolution and frequency are required?
- What do you think about it to respond?
- What are difficulties in responding the external requirements?
- What are the differences in information requests from international organisations and your government before and after REDD+ readiness?

B.3 Interview Guide for Staff in Forest Inventory Divisions

School of Geography

Faculty of Environment

UNIVERSITY OF LEEDS

Date and Place of Interview:

Name:

Division:

Position:

- What is your main duty?
- How many years have you been working for forest monitoring?
- What is your educational background?

Adopting Organization

Existing Technology

- What kind of technologies do you use for your duty?
- What kind of technologies has your organization adopted after starting REDD+ readiness programme?
- What kind of NFI data and carbon factors will your country use for FREL?
- What do you think about the technologies adopted after starting REDD+ readiness programme?
- What are the improvements in collecting forest inventory data after starting REDD+ readiness programme?
- Do you have any difficulty in operating existing technologies?

Human Capital

- What kind of training for collecting field-based data and analysing forest inventory data for forest monitoring have you attended?
- What kind of forest inventory methods do you know?
- What kind of devices for field survey can you use?

Perceptions

- What do you know about new technologies and their advantages?
- Are you willing to use new technologies?

- What kind of new technologies would be optimal for your duty?

Languages

- What kind of languages can you speak?
- Do you have any problem caused by languages during your work or operating technology?
- What kind of computing languages can you use?
- Do have any difficulty caused by computing languages during your work or operating technology?
- Do you think you can learn new computing languages? And what do you think of computing languages for your duty?

Institutions (Practices)

- What do you do with existing technology for producing forest information?
- What have been changed in practices after starting REDD+ readiness programme?
- What do you think about the changes?
- What are the difficulties in producing forest inventory data or emission factors?
- What are the practical difficulties in conducting NFI?
- How often do you collaborate with staff in your organization? And for what?
- What are the difficulties in collaboration or communication with staff in your organization?
- Which other organizations do you depend on for data/information?
- What are you exchanging data or sharing information with other organizations for?
- What are the difficulties in collaboration or communication with the forest survey division and other organizations (e.g. regional offices)?
- What kinds of communications between forest monitoring and inventory division are needed for MRV?
- What are the differences before and after REDD+ readiness in interactions between forest monitoring and inventory divisions?
- What are the differences before and after REDD+ readiness in establishing institutions, and how did you establish them?

External Environment

National and International Policy - Laws, Institutional Isomorphism

- What are the difficulties in following manager's requests?
- Do you know technologies adopted by other MRV organizations and what do you think about that?
- What are difficulties in following other MRV organizations?
- What are the differences before and after REDD+ readiness in national international policies?

End Users - Information Needs

- Do you know what information resolution and frequency are required?
- What do you think about it to respond?
- What are difficulties in responding the external requirements?
- What are the differences in information requests from international organisations and your government before and after REDD+ readiness?

Appendix C
List of Interviewees

C.1 List of Interviewees in Cambodia

No.	Affiliation	Name	Position	Main duty/Remark	Date of Interview
C-01	The MRV centre, and the Watershed management and Forest cover assessment office of the Forestry Administration	Mr. Leng Chivin	Deputy Head of the MRV centre	MRV, FREL and Forest area monitoring and NFI	15 Jul 2016 and 7 Aug 2017
C-02		Ms. Sar Sophyra	Deputy Chief of the MRV centre	MRV, FREL and Forest monitoring	20 Jul 2016
C-03		Ms. Hout Naborey	Deputy Chief of the MRV centre	Satellite Forest Monitoring and NFI	29 Aug 2016
C-04		Mr. Net Norint	Forestry officer	Satellite Forest Monitoring and NFI	25 Jul 2016
C-05		Mr. Menh Keidorang	Forestry officer	Satellite Forest Monitoring and NFI	22 Jul 2016
C-06	Forestry Administration	Mr. So Than	National consultant of forest inventory and Forestry officer	Field manual for NFI and Allometric Equations	29 Aug 2016
C-07	The MoE and the MRV centre	Mr. Uy Kamal	Deputy Director of the Ministry of Environment, and Deputy Head of the MRV centre	GHG inventory and MRV	5 Aug 2016
C-08	JICA	Mr. Shigeru Ono	Team Leader of the JICA TA Team	Technical advisor to the FA, and Satellite Forest Monitoring	19 Aug 2016
C-09		Mr. Toru Furuya	Consultant at the JICA TA Team	Technical advisor on Satellite Forest Monitoring	25 Jul 2016
C-10	FAO	Mr. Mathieu Van rijn	Forestry officer, FAO representative in Cambodia	MRV, NFI and Forest monitoring	24 Aug 2016
C-11	Forestry Administration	Mr. Chhun Delux	Deputy Director of the Forest carbon credits and climate change division	REDD+ strategy, safeguards and finance	1 Aug 2016 and 4 Aug 2017

C-12	WCS (NGO)	Mr. Donal Yeang	REDD+ specialist and National REDD+ policy advisor	REDD+ strategy and Policy	19 Aug 2016
C-13		Mr. Jeff Silverman	Senior technical advisor	Forest monitoring and estimating forest carbon stocks	19 Aug 2016
C-14	RUA (Research institute)	Mr. Kim Soben	Professor at the RUA	NFI, Carbon pools and Allometric Equations	30 Aug 2016
C-15	Korea-Mekong Forest Cooperation Centre (KMFCC)	Dr. Se-Kyung Chong	Director	Director of the Korea-Mekong Forest Cooperation Centre	31 Jul 2017

Total Interviewees: 15 people

- MRV centre and Forestry Administration (GDANCP of the MoE*) – 5
- Forestry Administration – 2
- MoE and MRV centre – 1
- JICA – 2
- FAO – 1
- WCS (NGO) – 2
- RUA (Research institute) – 1
- KMFCC – 1

* This team has been affiliated in the General Department of Administration for Nature Conservation and Protection (GDANCP) of the Ministry of Environment since 2017.

C.2 List of Interviewees in Indonesia

No.	Affiliation		Name	Position	Main duty/Remark	Date of Interview
I-01	Directorate of Forest Resource Inventory and Monitoring	Directorate	Dr. Ruandha Agung Sugardiman	Director	Managing 4 Sub-Directorates under the directorate	28 Aug 2017
I-02		Forest resources monitoring	Mr. Sigit Nugroho	Deputy Director	Producing forest cover maps	29 Aug 2017
I-03			Mr. Ahmad Basyirudin Usman	Section Head	Forest Monitoring at Management Unit Level	21 Aug 2017
I-04			Mr. Judin Purwanto	Section Head	Forest monitoring at national level	21 Aug 2017
I-05			Ms. Anna Tosiani	RS analyst (Staff)	Forest monitoring at national level	22 Aug 2017
I-06			Ms. Melisa Elisabeth	Staff in national monitoring section	Forest monitoring at national level	16 Aug 2017
I-07			Ms. Endrawati	Staff in the section	Forest Monitoring at Management Unit Level	16 Aug 2017
I-08		Forest Resources Inventory	Mr. Ubay	Deputy Director	Managing Forest Inventory	22 Aug 2017
I-09			Mrs. Nurhayah	Section Head	Forest Inventory	5 Sep 2017
I-10			Mr. Anjar Yogie	Forestry officer	Forest Inventory	5 Sep 2017
I-11		Thematic Mapping and Documentation	Mrs. Rossi	Deputy Director	Thematic mapping and documentation	28 Aug 2017
I-12			Mr. Mursid	Section Head	Thematic mapping and documentation	28 Aug 2017
I-13		Spatial Data Networking	Mrs. Tuti	Section Head		5 Oct 2017
I-14			Mr. Ferri Martin	Staff	Distributing and disseminating forest data and information	5 Oct 2017

I-15	Sub-Directorate of MRV and Registry for land-based sectors under Directorate of GHG Inventory and MRV	Dr. Belinda Arunarwati Margono	Deputy Director	Author of Indonesia's FREL, Directorate General of Climate Change	23 Aug 2017
I-16	National Institute of Aeronautics and Space (LAPAN)	Mr. Kustiyo	Senior researcher in Remote Sensing Technology		18 Aug 2017
I-17		Mr. Kuncoro	Researcher in Remote Sensing Technology		29 Aug 2017
I-18	Geospatial Information Agency (BIG: National Mapping Agency, Formerly BAKOSURTANAL)	Mr. Muhammad Haidar	Mapping surveyor in Disaster and Climate Change Department		31 Aug 2017
I-19		Mr. Habib Subagio	Head of Resources Dynamic Division		31 Aug 2017
I-20	Bogor Agricultural University (IPB)	Prof. Lilik Budi Prasetyo	Prof. of Spatial Analysis in Forestry Faculty	Conducting forests 2020 project with ESA	18 Aug 2017
I-21		Prof. Buce Saleh	Professor in IT for Natural Resources Management		18 Aug 2017
I-22	WRI Indonesia (World Resource Institute)	Dr. Arief Wijaya	Forest and Climate Senior Manager	Technical team of MoEF for preparing Indonesian FREL	18 Aug 2017
I-23	German Corporation for International Cooperation (GIZ)	Mr. Wandojo Siswanto	Strategic Area Manager on Forest and Climate Change Policy		25 Aug 2017
I-24		Ms. Stephanie Wegscheider	Development advisor GIS/Remote sensing	FORCLIME (Forests and Climate Change Programme, TC-Module)	5 Sep 2017

Total Interviewees: 24 people

- Director of the Directorate of Forest Resources Inventory and Monitoring – 1
    - Sub-Directorate of Forest Resources Monitoring – 6
    - Sub-Directorate of Forest Resources Inventory – 3
    - Sub-Directorate of Forest Thematic Mapping – 2
    - Sub-Directorate of Spatial Data Network – 2
- Directorate General of Climate Change (Sub-Directorate of MRV and Registry for Land-based sectors) – 1
- National Institute of Aeronautics and Space (LAPAN) – 2
- Geospatial Information Agency (BIG) – 2
- World Resource Institute (WRI) – 1
- Bogor Agricultural University (IPB) – 2
- German Corporation for International Cooperation (GIZ) – 2

Appendix D
Criteria for Scoring Variables

Variables assessed		Scale-Type	Criteria for Scoring	Score*	
				5	1
Institutions (Practices)					
1	Institutions required for mapping at specified frequency	Qualitative-Similarity	Similarity between existing technology and new technology in institutions required to map at specified frequency	Perfect match	Zero match
2	Institutions required for mapping at specified accuracy	Qualitative-Similarity	Similarity between existing technology and new technology in institutions required to map at specified accuracy	Perfect match	Zero match
3	Institutions for communicating inside and outside the organization to gain required data/information	Qualitative-Similarity	Similarity between existing technology and new technology in institution needed to communicate inside and outside the organization to gain required data/information	Perfect match	Zero match
Human Capital					
4	Total staff	Numerical-Gap	Gap between the number of total staff and the number of staff required for new technology	Perfect match	Zero match
5	Trained staff	Numerical and Qualitative - Gap	Gap between the number of trained staff and the number of trained staff required for new technology	Perfect match	Zero match
6	Computing language used	Qualitative-Gap	Gap between actual staff language ability and required language ability for operating new technology	Perfect match	Zero match
7	Human language used	Qualitative-Gap	Gap between human language used (actual human language ability) and human language required for operating new technology	Perfect match	Zero match
8	Perceptions of monitoring	Qualitative-Similarity	How staff perceive new technology for forest monitoring	Perfect match	Zero match

Existing Technology					
9	Aerial surveys	Qualitative-Similarity	Gap between possibility and ability of aerial surveys and aerial surveys required for new technology	Perfect match	Zero match
10	Optical satellite sensor type	Qualitative-Similarity	Similarity between existing and new technology in Optical satellite sensor type for forest area monitoring	Perfect match	Zero match
11	Non-optical satellite sensor type	Qualitative-Similarity	Similarity between existing and new technology in Non-optical satellite sensor type for forest area monitoring	Perfect match	Zero match
12	Data processing (manual/digital)	Qualitative-Similarity	Similarity between existing and new technology in Data processing and analysing procedure	Perfect match	Zero match
13	Operating system and hardware	Qualitative-Similarity	Similarity between existing and new technology in operating system and hardware	Perfect match	Zero match
14	Ground measurement	Qualitative-Similarity	Similarity between current ground measurement and ground measurement required	Perfect match	Zero match
External Environment – Complying with National and International Policies					
15	Information resolution required by UNFCCC	Qualitative-Degree	Information resolution possible to meet international policy	Perfect match	Zero match
16	Information frequency required by UNFCCC	Qualitative-Degree	Information frequency possible to meet international policy	Perfect match	Zero match
17	UNFCCC isomorphism constraints	Qualitative-Degree	Adopted by other governments	Perfect match	Zero match
18	Resources available	Qualitative-Degree	Resources needed for new technology	Perfect match	Zero match

* Scale of score	In some cases, the scores may also indicate:
5 – Perfect match 4 – Good match 3 – Moderate match 2 – Slight match 1 – Zero match	Good/ Bad Easy/ Difficult Affordable/Not affordable Accurate/Inaccurate Acceptable/Unacceptable

Source: Developed based on Bhattacharyya, 2012; Kishore and Dattakiran, 2011; Lhendup, 2008