FOREST DEGRADATION IN CAMBODIA:

AN ASSESSMENT OF MONITORING OPTIONS IN THE

CENTRAL CARDAMOM PROTECTED FOREST

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Cover photo: deciduous forest in eastern Central Cardamom Protected Forest, May 2012 (photo by J. Halperin).

Preamble

The Lowering Emissions in Asia's Forests (LEAF) Program, a five-year cooperative agreement, is funded by the United States Agency for International Development's (USAID) Regional Development Mission for Asia (RDMA). LEAF is being implemented by Winrock International (Winrock), in partnership with SNV – Netherlands Development Organization, Climate Focus and The Center for People and Forests (RECOFTC). The LEAF program began in January 2011 and will continue until January 2016.

The US Forest Service International Programs (USFS/IP) collaborates with governmental and non-governmental partners to share best practices and act as an advocate for US interests abroad. The USFS/IP draws on the expertise of the entire agency– National Forest Systems, Research and Development and State and Private Forestry – promoting sustainable forest management overseas and bringing important technologies and innovations back to the United States.

The USFS/IP was requested by LEAF and USAID/RDMA to lead in the development of options for identifying and developing forest monitoring methodologies that can estimate greenhouse gas emissions from forest degradation. The key objectives and outcomes of the LEAF/USFS partnership include:

- Assessing forest degradation drivers and monitoring options at the sub-national level in Lao PDR, Vietnam, and Cambodia. The short, one-month field assessments were completed in the first half of 2012;
- Convening a regional forest monitoring experts' workshop to discuss lessons learned from the sub-national assessments and operational aspects of various forest degradation monitoring approaches, highlighting potentially successful approaches given existing drivers. This workshop was held in Bangkok in November 2012; and
- Communicating results of these activities and regional lessons learned to develop forest degradation monitoring demonstration programs and strengthen capacity in partner countries and regional institutions. This report contributes to this objective.

All three country reports have received extensive reviews from a range of technical experts associated with the LEAF project (including Winrock International experts), USFS and subsidiary projects such as SilvaCarbon, USAID country missions (except in Lao PDR) and relevant USAID bilateral projects such as the Vietnam Forests and Deltas project. However any inadvertent errors or omissions remain the responsibility of the authors and do not reflect the views or comments of the reviewers.

While every effort was made to collaborate with Government counterparts in the design, implementation and reporting of this work, this report does not constitute endorsement or a reflection of the host government's perceptions or opinions on the technically and politically difficult task of monitoring forest degradation. The country reports were produced as part of LEAF's early in-country scoping efforts to help design LEAF's field interventions as well as collectively contributing to the expanding regional knowledge base on forest degradation monitoring options.

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Acknowledgements

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Acronyms

ASEAN	Association of Southeast Asian Nations
BAF	Basal area factor
CCPF	Central Cardamom Protected Forest
CI	Conservation International
CLASLite	Carnegie Landsat Analysis System
CO2	Carbon dioxide
FA	Forestry Administration
FAO	Food and Agriculture Organization of the United Nations
FCPF-RPP	Forest Carbon Partnership Fund – Readiness Preparation Proposal
GIS	Geographic Information Systems
IPCC	Intergovernmental Panel on Climate Change
LEAF	Lowering Emissions in Asia's Forests
MAFF	Ministry of Agriculture, Forests and Fisheries
MoE	Ministry of Environment
MoP	Ministry of Planning
MRV	Monitoring, Reporting and Verification
NDFI	Normalized Differential Fraction Index
NTFP	Non-Timber Forest Product
PFM	Participatory Forest Monitoring
PSP	Permanent Sample Plot
REDD+	Reducing Emissions from Deforestation and Forest Degradation, and conservation and sustainable management of forests and enhancement of carbon stocks
SNV	The Netherlands Development Organization
SPOT	Système Pour l'Observation de la Terre
UNFCCC	United Nations Framework Convention on Climate Change
UNREDD	United Nations collaboration initiative on REDD+
USAID/RDMA	United States Agency for International Development / Regional Development Mission for Asia
USFS	United States Forest Service
WI ECO	Winrock International Ecosystem Services Unit

Executive Summary

Techniques for monitoring deforestation and associated changes to forest carbon stocks are widespread and well-published. In contrast, techniques for monitoring forest degradation are relatively untested in developing countries, despite the inclusion of degradation in UNFCCC REDD+ negotiations. The lack of a definition of forest degradation and the broad variety of forest management objectives further complicate forest degradation monitoring. The Lowering Emissions in Asia's Forests (LEAF) program of the United State Agency for International Development/Regional Development Mission for Asia (USAID/RDMA) is working to build institutional technical capacity for monitoring changes in forest carbon stocks in the Asia-Pacific region, including changes due to human-caused forest degradation.

The United States Forest Service (USFS) was asked by LEAF and its partner organizations to assess options for monitoring forest degradation at sub-national levels in three Mekong countries: Cambodia, Lao PDR, and Viet Nam. This assessment focuses on our assessment of the Central Cardamom Protected Forest (CCPF) in Cambodia, conducted in May 2012.The CCPF was established in 2002 under the jurisdiction of the Forestry Administration (FA) of the Cambodian government. It is jointly managed through a cooperative agreement between FA and Conservation International (CI). The CCPF occupies an area of 401,313 ha located in portions of Koh Kong, Pursat, and Kampong Speu provinces. It encompasses a large portion of the Cardamom Mountain range, and elevations vary from 200 m to over 1700 m. The natural vegetation consists predominantly of evergreen forests at higher elevations, semi-evergreen forests at lower elevations, and deciduous forests located in drier areas of the monsoonal rainshadow. Seven communes are located near the borders of CCPF; however, only the communes of O'Som and Tatai Lieu, with a combined population of approximately 1,600, are located inside the CCPF.

To assess monitoring options in the CCPF, a conceptual framework was developed, which includes three steps: 1) define biomass reference for monitoring in each forest strata of interest, 2) identify and assess the scale and intensity of forest degradation drivers, and 3) identify and assess monitoring approaches based on defined biomass change thresholds (Figure 1). We evaluated three main approaches as monitoring options including: ground-based field measurements, remotely sensed imagery, and predictive modeling. Potential variants of each approach were assessed using a qualitative ranking system. The results were then used to develop an integrated monitoring system combining elements of all three approaches. The monitoring system takes into consideration the important drivers of degradation in the CCPF, the operational circumstances, and the expected capacity for implementation.

The first step in the conceptual assessment framework is to define a biomass reference in each strata of interest. The biomass reference is the average biomass per forest strata at the year in which monitoring begins. During our field assessment we established variable-radius plots in each major forest type to obtain comparative information on biomass in 'less-degraded' and 'more-degraded' stands. Due to time and logistics constraints we were unable to sample undisturbed stands. We determined coarse estimates of differences in volume, basal area, and tree density between less-degraded and more-

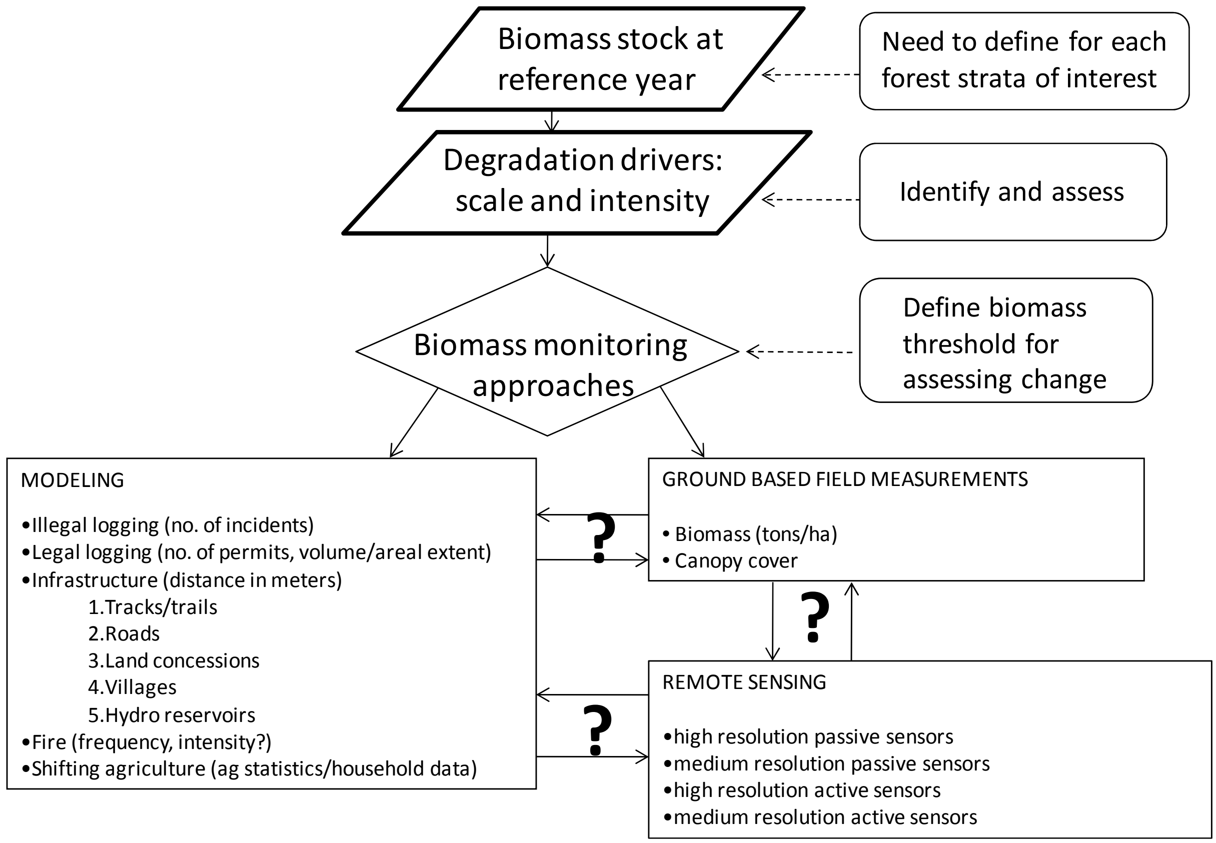

Figure 1. Conceptual framework to assess monitoring options.

degraded forest in the three forest types. The results were generally consistent with other published estimates for degraded examples of these forest types in Cambodia.This assessment did not attempt to develop historical baselines of forest biomass, since data needed are generally unavailable for the study area. In this assessment we focus only on options for monitoring forest degradation into the future from a biomass reference established for each strata of interest at the beginning of each monitoring cycle.

For the second step in the conceptual assessment framework, we identified forest degradation drivers through direct field observations, reviews of data regarding degradation activities, and with interviews of FA and CI staff. Indirect drivers of forest degradation that we identified in the CCPF include: inappropriate large-scale agricultural and hydropower developments, expanding transportation infrastructure, population increase through in-migration, and lack of demarcation of forest areas. The direct drivers of forest degradation include: unsustainable harvesting for timber, harvesting for fuel wood, and possibly modified fire regimes.

For the third step in the conceptual framework, we assessed monitoring approaches by ranking them according to an ordinal scale of indicators across a range of criteria. These criteria were designed to address the suite of issues surrounding monitoring protocol design. We then used the results of the assessment to develop a recommended monitoring system for implementation as a demonstration, or 'proof-of-concept' project for sub-national forest degradation monitoring in Cambodia.

We recommend an integrated system in employing the three main approaches (remote sensing, field inventory, and predictive modeling) in which each approach supports the others to mitigate technical and capacity challenges and reduce uncertainty (Figure 2). The monitoring objective is to quantitatively estimate human-caused loss of at least 30% above-ground biomass (with a 95% confidence interval).

within forest strata as defined by degradation risk and forest type within a monitoring cycle of between two and four years.

Analysis of remotely sensed imagery is recommended to quantify the amount and location of canopy disturbance in the study area. This will form the basis for identifying biomass loss due to canopy-

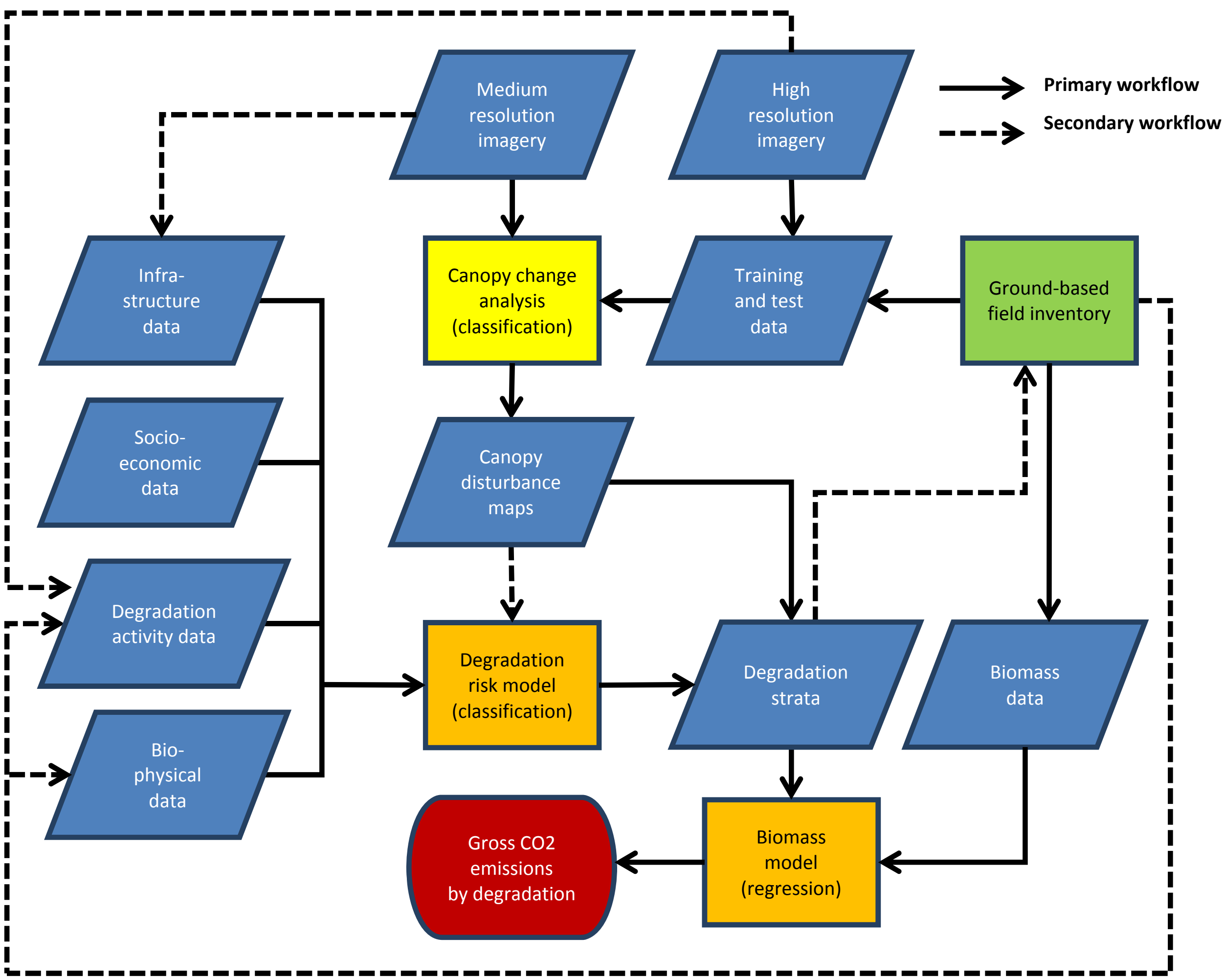

Figure 2. Workflow model of the integrated monitoring system to assess biomass/carbon stock change resulting from forest degradation in the Central Cardamom Protected Forest, Cambodia.

disturbing activities such as timber harvest. Because of the ephemeral nature of canopy gaps, the time frame for change analysis will require acquisition of imagery at intervals of 2 to 4 years. We recommend medium-resolution (5 to 30 m pixel size) imagery as the source data for the analysis. The monitoring objective would be to detect changes in canopy cover of at least 30% with a 95% confidence interval. Accuracy of the canopy disturbance map would be assessed using a combination of ground-based sample plots and high-resolution (< 5 m pixel size) imagery. The recommended minimum mapping unit for analysis is one hectare.

Predictive models are central to the CCPF monitoring recommendation, since they provide the framework within which the other approaches are applied. The two recommended predictive models are degradation risk stratification and biomass change estimation. Degradation risk stratification is based on a classification algorithm, such as Random Forests or Maxent that stratifies the landscape according to probability thresholds for occurrence of degradation activities. It is based on the spatial relationships between known occurrences of degradation activities and the predictor variables such as distance from population centers, transportation infrastructure, forest type, slope, and/or elevation. The resulting landscape stratification is used to interpret the source of canopy disturbance identified by remote sensing analysis of satellite imagery. The model is evaluated by generating an error estimate using reference data. We recommend an overall misclassification error rate of less than 20 percent. The model-based stratification can also be used to ensure efficient and representative sampling of ground-based field data. The biomass change model extrapolates ground-based field inventory data to estimate changes in biomass values within each forest strata. Decision-tree regression analysis (e.g., Random Forests) is recommended to predict the target variable (biomass value) at a given location in a spatial grid within a stratum based on relationships between biomass measurements from available forest inventory data and a set of predictor variables similar to those used in the degradation risk model.

We recommend that ground-based reference data is collected both for accuracy assessment of canopy disturbance maps and for estimating biomass change related to specific activities driving forest degradation. Two types of ground-based field data should be collected: forest inventory plot data, and degradation activity data. Forest inventory plot data will be used in modeling biomass change in forest areas due to degradation activities during a monitoring period. Either permanent or temporary sample plots may be established based on logistics and capacity. Data collection should follow protocols from Winrock International's "Standard Operating Procedures for Terrestrial Carbon Measurement." Degradation activity data are used to model degradation risk for stratification of the study area for sampling and analysis. Degradation activity data should be collected during CCPF ranger patrols when evidence of current or past activities are encountered. Additional activity data could be collected through participatory forest monitoring (PFM) in cooperation with commune forest councils. PFM could also potentially provide data on socio-economic variables (income levels, farming practices) that may be correlated to the occurrence of degradation activities.

The next steps for implementation of these recommendations begin with building technical capacity to implement and evaluate the monitoring system. The assistance of a technical specialist is vital to developing useful predictive models and training local staff in their use. Resources and personnel for developing disturbance maps from imagery must be identified. We recommend the bulk of ground-based field data collection be conducted using CCPF FA personnel, who can be tasked to efficiently collect relevant data for carbon stock change modeling and remote sensing training and evaluation. This will require training forest rangers in collecting accurate field data using standard protocols for terrestrial carbon measurement. Additional personnel may need to be provided to the FA staff complement to avoid impacts on the ranger's existing law enforcement duties. Additional data may be collected in limited areas using Participatory Forest Monitoring in cooperation with commune forest councils.

This monitoring system should be implemented in an iterative fashion with full consultation of relevant stakeholders. The recommendations here are meant to be used as a starting point from which refined protocols and methods are developed according to circumstances and conditions. This assessment should be considered a living document that has the potential to guide strategies for monitoring forest degradation at the sub-national level in Cambodia and other parts of the Mekong region.

1. Introduction

Techniques for monitoring deforestation and changes to forest carbon stocks are widespread and well-published. However, techniques for monitoring forest degradation are relatively untested in developing countries despite their inclusion in UNFCCC REDD+ negotiations. The lack of a definition of forest degradation, and the broad variety of forest management objectives, and societal expectations of what forests should provide, further complicate forest degradation monitoring.

The Lowering Emissions in Asia's Forests (LEAF) program of the United States Agency for International Development/Regional Development Mission for Asia (USAID/RDMA) is being managed by Winrock International in collaboration with Climate Focus and The Netherlands Development Organization (SNV), targeting 6 countries in the Asia-Pacific region (Cambodia, Lao PDR, Thailand, Vietnam, Malaysia, and Papua New Guinea). Two of LEAF's main objectives include building institutional technical capacity for monitoring changes in forest carbon stocks and demonstrating innovation in sustainable land management.

In LEAF countries across the Asia-Pacific region, many recent assessments for developing REDD+ capacity have noted the need for addressing issues surrounding forest degradation monitoring (Romijin et al. 2012, RECOFTC 2012, UNREDD 2012). For example, the 2010 USAID/RDMA Asia Regional REDD Program Planning Assessment Report identified a strong need for increased human resource technical capacity in development of comprehensive forest monitoring systems (Winrock International 2010). Accurate information on land use trends, forest carbon dynamics, and drivers of forest degradation at local levels is needed for improving land management and limiting future degradation. Deforestation is often preceded by forest degradation (Asner 2002, DeFries 2007). Conversely, policies to reduce deforestation may lead to increased forest degradation as timber supplies from land clearing are reduced.

While Cambodia does not currently have a program to specifically monitor forest degradation, the Forest Administration (FA) within the Ministry of Agriculture, Forestry, and Fisheries (MAFF) does have a history of assessing forest cover change. Forest cover in Cambodia has steadily decreased between 1992 and 2005(FAO 2010). However, forest cover statistics for the 1990's in Cambodia are not reliable due to the unstable political and financial situation at the time (FAO 2010). For the period between 2002 – 2006, the FA reports a deforestation rate of 0.8% per year (FA 2007, 2011). The Association of Southeast Asian Nations (ASEAN) average forest loss by country, as reported to FAO, for this same time period, is 0.77% per year. In terms of a forest transition curve, Cambodia could be considered to have 'high forest cover, high deforestation rate' (FA 2011, Griscom et al. 2009). Contrastingly, the Initial National Communication to UNFCCC estimated that in 1994, Cambodia was a net sink for greenhouse gasses in the Land Use Change and Forestry sector (MoE 2002). The amount of CO_2 removed in 1994 was estimated to be greater than CO_2 emitted by more than 17 thousand tons (73,122 versus 53,486 Gt, respectively). As a country with a high deforestation rate, Cambodia may be more interested in the development of deforestation monitoring programs. However, as Murdiyarso (2008) points out, not including monitoring of forest degradation could lead to substantial domestic leakage, or increased loss of forest carbon in 'forest remaining forest'.

Degradation of forests in Cambodia is a complex issue. From a national perspective, forest carbon stock is estimated to have declined by 145 million tons between 1990 and 2010 (FAO 2010). This estimate is likely a result of the loss of forests through deforestation, not including activities in forests that remain forests. CO_2 emissions resulting from losses of forest carbon stock within forests in Cambodia have not been well studied (FA 2011). The Cambodian government initiative under the Forest Carbon Partnership Facility Readiness Preparation Proposal (FCPF R-PP) has noted that this is a key area for research in order to better understand forest degradation and its contribution to the country's overall Greenhouse Gas (GHG) emissions profile. Suggested research activities within the FCPF R-PP include a quantitative assessment of forest degradation drivers and consultation with key stakeholders concerning the results.

This report describes results of an assessment to increase the knowledge base on forest degradation, consistent with identified needs in the FCPF-RPP. This assessment is consistent with similar work done at sub-national LEAF demonstration sites in Lao PDR and Viet Nam. Specifically, this assessment aims to:

1. Assess data sources and current on-the-ground activities within selected districts that contribute to an expanded knowledge of forest degradation and subsequent carbon stocks; and,

2. Develop and evaluate options for monitoring of forest degradation, with considerations for cost-effectiveness, precision, accuracy, and feasibility.

This assessment focused on the Central Cardamom Protected Forest (CCPF) in southwest Cambodia (Figure 1). The CCPF is a 401,313hectare (ha) area of mainly evergreen forests in the uplands with semi-evergreen and deciduous forests in the lowland margins (FA 2009). Prior to 1994, the area was not under formal management and subject to unregulated activities such as timber harvesting and wildlife hunting. Impacts may have been high during the 1970's and 1980's (FA 2009). In 1994, the Royal Government of Cambodia issued licenses for seven timber harvesting concessions in the area. In 2001, MAFF issued a moratorium on all industrial-scale logging concessions (IFSR 2004, Miller 2004). In 2002, CCPF was established under the jurisdiction of the FA. The CCPF management plan identifies specific threats to forest resources, including illegal harvesting of luxury timber and collection of fuel wood for both small scale and industrial purposes (FA 2009).

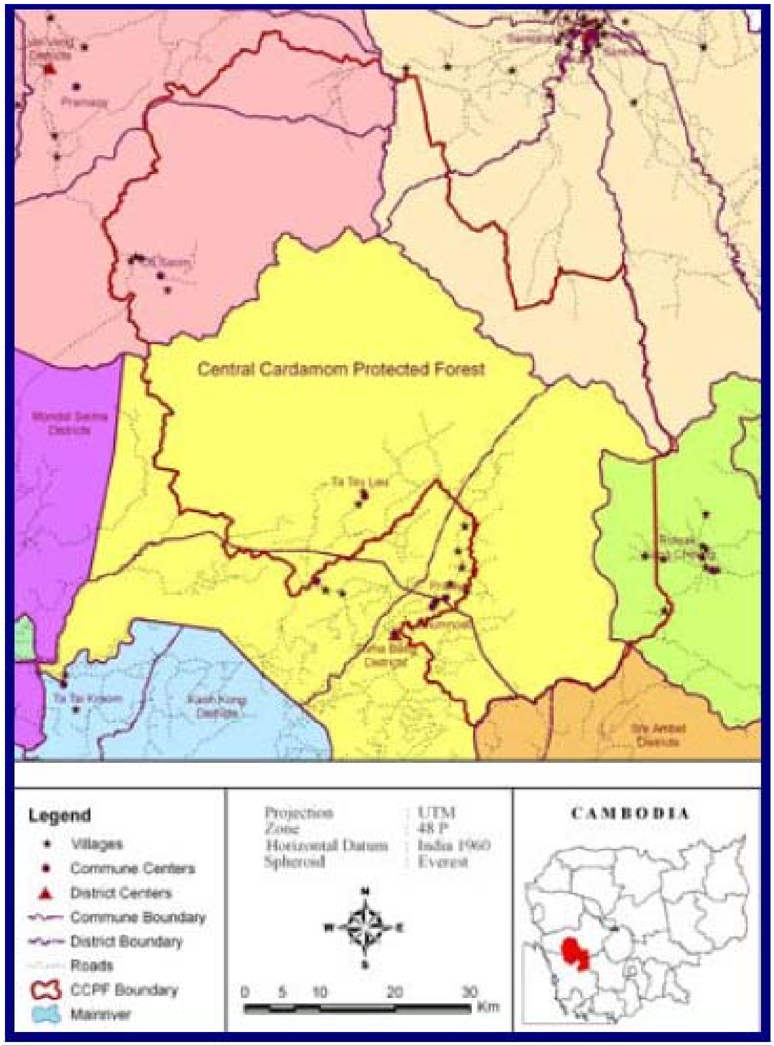

Figure 1. Map of the Central Cardamom Protected Forest. From: FA 2009.

Deforestation in the adjacent Southern Coastal Cardamoms region was analyzed for the Wildlife Alliance using official data from FA, and covering both MAFF and MOE administered lands (Aruna Technologies 2008). This regional analysis looked at three time periods from 1991 – 2005. Results indicate that in 2005 there were 665,556 ha of forest cover. The average annual rate of change in forest cover was estimated to be -0.19%, which is low when compared to the national average annual rate of -1.27% per year. In areas of forest remaining forest where deforestation is low, the need to account for forest degradation is more critical as use of forests for selective timber harvesting and other degradation activities will have a greater impact on GHG emissions than forest clearing.

a. Conceptual framework for monitoring options assessment

In order to assess options for developing a monitoring protocol, it is first necessary to understand the range of information needs that are required. To do this, we designed a conceptual framework to clearly identify information needs and how monitoring options align to fulfill these needs (Figure 2). The first step in the framework concerns development of baselines. Two types of baselines could be considered simultaneously or individually: 1) a baseline of the historical rate of forest degradation, and/or 2) an reference estimate of current biomass, or forest carbon stocks, within a given spatial unit. Within the context of UNFCCC, countries may opt to exclude a baseline for the historical rate of forest degradation within National Communications. Data necessary to estimate historical rates of forest degradation is often lacking, and methods to assess historical forest degradation may not be robust enough for verified REDD+ mechanisms. For this reason, we do not include an assessment of the historical rate of forest degradation in this report. In the conceptual framework, we refer to a baseline as a reference estimate of biomass for each strata of interestin a given area, at the time when monitoring begins. In the case of forest degradation, strata will likely be defined by forest type and degradation activity risk, within the land use category of 'forest remaining forest'. To include forest degradation in a REDD+ mechanism, it will be necessary to form a baseline rate of forest degradation in the future so that mitigation actions addressing the drivers of forest degradation can show additionality. The recommendations from this assessment can form a foundation to create a forest degradation rate after at least one complete cycle of forest degradation monitoring.

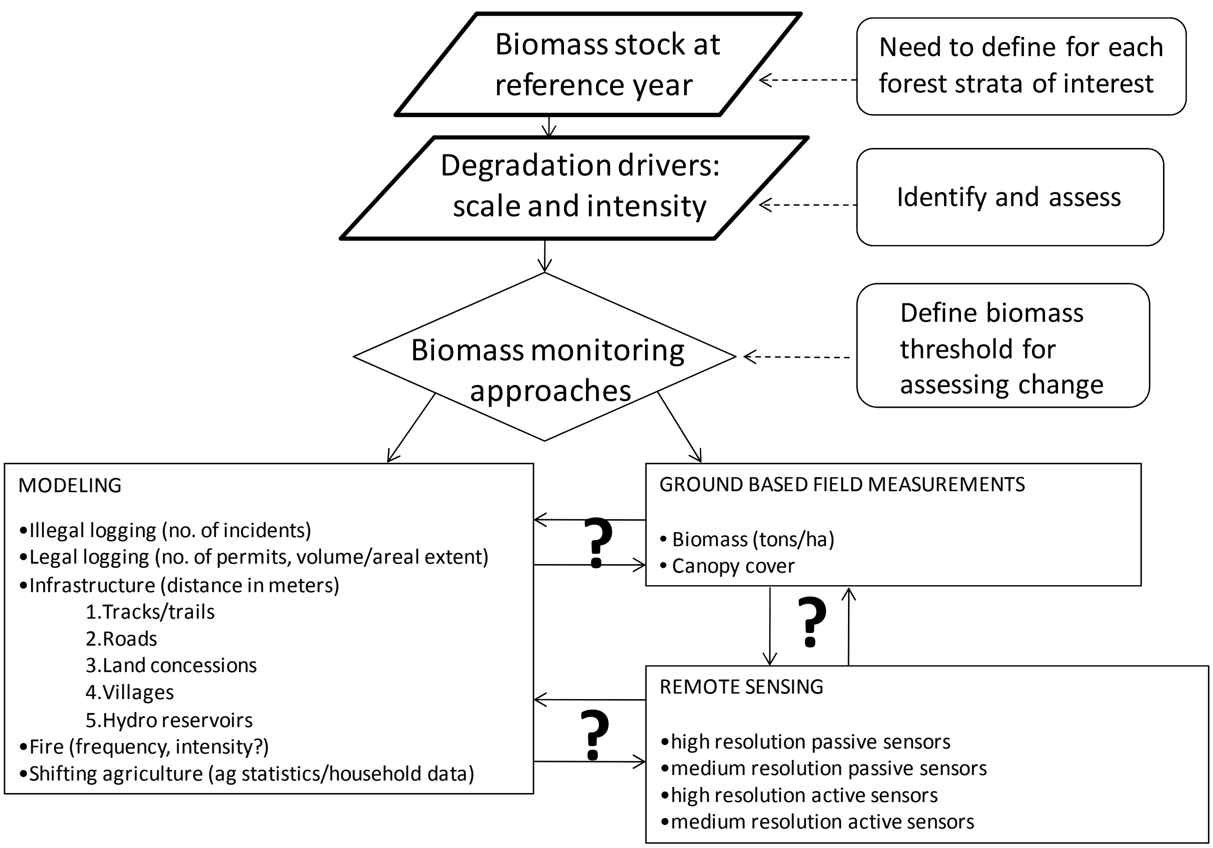

Figure 2. Conceptual framework to assess monitoring options.

Defining the threshold of change in biomass is a critical step. How much change is acceptable? The answer to this question depends on national and sub-national circumstances and country led decision making processes. If acceptable use (i.e., extraction) of timber resources (i.e., biomass) is less than the rate at which forest re-growth occurs, then the use is generally considered sustainable. However, growth and yield information is generally lacking from tropical countries. Section 2 attempts to address this issue in the context of this assessment.

The second step in the framework is to identify and assess the scale and intensity of human activities leading to degradation of forest biomass within the land use category 'forest remaining forest'. The intensity of changes can be subtle or with great impact; the scale of change can be local or widespread. Monitoring options will vary greatly depending on the drivers and their scale and intensity as technical methods vary in their precision to estimate change. Section 3 of this report documents observations and data on forest degradation drivers from a local level in the CCPF.

Approaches to monitoring carbon stock change are addressed in Section 5, which will briefly explore key existing research that has attempted to develop 'best practices' for monitoring, some of which clarifies strengths and weaknesses of individual approaches and the interaction between approaches. We believe that the integration of methods, including ground-based inventory, predictive modeling, and remote sensing, provide the key to sustainable and efficient monitoring.

Assessment of the technical and institutional capacities is crucial to the success and sustainability of a monitoring system. In order to assess the multiple criteria needed for identifying options with potential success, section 5 includes a matrix of monitoring options. These options stem from the 'best practices' identified. Options are ranked according to scores on an ordinal scale for a range of criteria designed to address the suite of issues surrounding monitoring protocol design and implementation. Section 6 then suggests options with the highest level of potential success, and section 7 builds upon these options with recommendations for capacity building.

2. Definitions and Thresholds

Multiple definitions of forest degradation exist (Simula 2009, Cadman 2008, FAO 2011), and several meta-analyses comparing forest degradation definitions have been completed (IPCC 2003, Cadman 2008, Lund 2009, FAO 2011). It is generally accepted that forest degradation results in a reduction of forest ecosystem services which includes globally valued carbon storage, regionally important watershed services, and locally valued goods and services such as Non-Timber Forest Products (NTFP), fuel wood, and timber.

Definitions of forest degradation that encompass a complex suite of attributes concerning forest values are overly complex to operationalize in countries that have short histories of forest monitoring. IPCC (2003) suggests the following definition: "Forest degradation is a direct human-induced long-term loss (persisting for X years or more) of at least Y% of forest carbon stocks (and forest values) since time T and not qualifying as deforestation." This definition may be one measurable approach to initiate monitoring goals that include the biophysical aspects of biomass loss. No matter which definition is adopted, in the context of a REDD+ mechanism a definition of forest degradation implicitly needs to include an indicator (or indicators) of CO_2 emissions, or biomass lost as a committed emission to the atmosphere.

Currently, there are no generally accepted definitions of degraded forest or forest degradation in Cambodia. The structural definition of forest in Cambodia follows the FAO definition: land covering an area greater than 0.5 ha and occupied by trees greater than 5 m in height and with greater than 10% canopy cover, or that are able to reach these thresholds *in situ* (FAO 2010). In the 2010 FAO Forest Resource Assessment report for Cambodia (FAO 2010), the FA reported 3 classes of forest cover density. However there seems to be confusion over definitions between forest cover and crown cover as these have separate thresholds. These variables could be interpreted and assessed differently, and without clear explanation in the report it is challenging to use the forest cover classes in an operational context.

Monitoring objective statement

In the development of any monitoring program, there are fundamental issues that need to be addressed in order to be able to assess change. This current report does not discuss monitoring principles as they are well documented elsewhere (Elzinga et al. 1998). However, it is important to establish the framework for specific monitoring objectives which are interlinked with management and project goals.

We suggest forming a definition of forest degradation following IPCC (2003), whereby the IPCC suggested definition is:

> ***A direct human-induced long-term loss (persisting for X years or more) of at least Y% of forest carbon stocks (and forest values) since time T and not qualifying as deforestation.***

It is difficult, but not impossible, to substitute the X and the Y in the statement above for several reasons:

- Activities resulting in forest degradation have different intensities, therefore different X years of persistence.
- Activities implemented in different forest types have varying impacts on Y carbon stocks, relevant to the natural stocking, or forest carbon carrying capacity.
- No country has tested the above definition and no country is making any efforts within UNFCCC to establish a framework for defining the X and Y.

In this assessment, we collected preliminary data to assess the range of detectable threshold values for Y, and we make recommendations on this threshold in Section 4. Current UNFCCC negotiations consider a National Communication reporting timeframe of four years for Non-Annex I countries, with updates every two years.

Regarding this assessment, the objective for monitoring forest degradation could then be stated as:

> **To quantitatively estimate human caused loss of at least Y% forest biomass from 'forest remaining forest' within the Central Cardamoms Protected Forest beginning from at a baseline year and monitored at an interval between 2 – 4 years.**

Enhancement of sequestration, reforestation/afforestation, and sustainable management of forests are also objectives of REDD+. Achieving clarity on the net balance of forest carbon dynamics, and the net CO_2emissions to the atmosphere, is the ultimate goal of a REDD+ monitoring program (Skutsch 2011). However, this assessment did not have the time and resources to investigate net changes in forest biomass.

3. Rapid Assessment Results in Selected Districts of CCPF

This assessment visited two areas of the Central Cardamoms Protected Forest: the Rolak Ranger Station in Aoral District, Kampong Speu Province, and the O Som Ranger Station, Veal Veng District, Pursat Province (Figure 3; see also with forest cover map of CCPF in Annex). The Rolak Ranger Station is a 5-hour drive from Phnom Penh, on improved road surface for 90% of the distance. The O Som Ranger Station is a 4-hour drive from Pursat, the capital of Pursat Province.

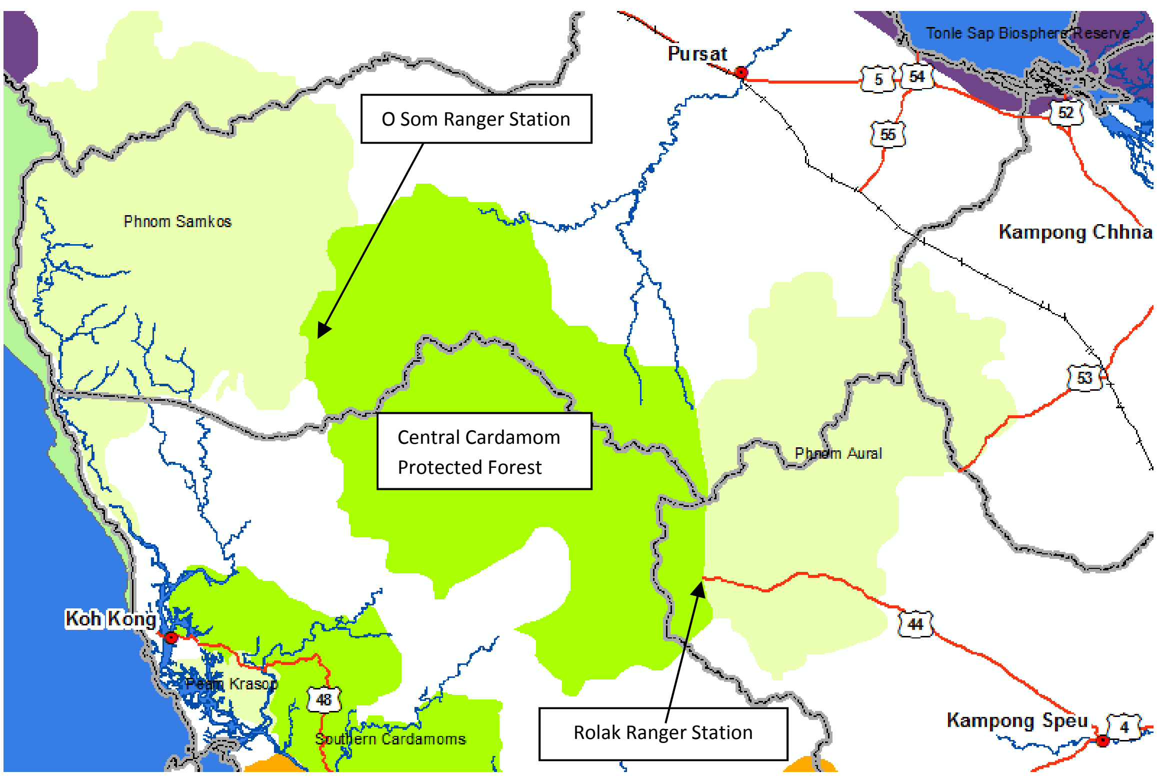

Figure 3. Location of site visits for the forest degradation monitoring options assessment in the Central Cardamoms Protected Forest, May 2012.

Conservation International – Cambodia (CI) works cooperatively with the Forest Administration in managing CCPF. CI provides financial and technical support to forest rangers working from the six ranger stations. Each station has one manager and 6-10staff (including military police and a local expert) that go on daily patrols using motor bikes as transportation. When rangers encounter people engaged in illegal activities, they will record notes and collect a GPS coordinate at the point of encounter. This assessment was conducted in partnership with CI-Cambodia and FA ranger staff.

a. Forest degradation drivers

The FCPF R-PP for Cambodia provides a thorough overview of the direct and indirect drivers of deforestation and forest degradation at the national level (FA 2011). The R-PP accounts for 25 separate direct and indirect drivers, both within and outside the forest sector.

- Direct drivers of deforestation include illegal expansion of agriculture, infrastructure, and settlements.
- Direct drivers of forest degradation include unsustainable and illegal logging, fuel wood collection, and fire.

In this section, we describe indirect and direct drivers of forest degradation based on observations from field visits to CCPF and interviews with FA and CI staff. We only describe the indirect drivers we could attribute to the direct drivers we observed. Overall, our findings on drivers correspond with the direct and indirect drivers that are outlined in the CCPF Management Plan (FA 2009) and in the FCPF R-PP (FA 2011).Other indirect drivers may also contribute to the direct drivers that exist in the CCPF. However, we were not able to link all of the indirect drivers from these documents to our observations.

Indirect driver: Lack of demarcation and awareness of local people of protected area boundaries

Boundaries around the CCPF are not delineated on the ground. A 2009 assessment of REDD+ potential in the Cardamom Region also noted this as a significant challenge (Grogan 2009). In general, CCPF forest protection rangers may not be aware of their location in relation to the boundary during forest patrols. Without clear recognition or clear delineation of the boundary, local people may also not be specifically aware of the location of the CCPF and when they enter into the protected area. In Aoral District, CCPF land is flat to gently sloping with an open forest structure and is easily accessible by foot, motorbike, and carts (motorized and ox driven). Poorly demarcated boundaries provide an opportunity for those engaged in illegal wood extraction to claim ignorance of their location or help them to evade authorities.

Indirect drivers: Large scale development, increasing transportation infrastructure and in-migration

When the CCPF was established in 2002, it became one of many protected forests in Cambodia without full support to enable a full suite of conservation activities to take place, such as the implementation and monitoring of a management plan (Corbett 2008). The CCPF management plan was not finalized until 2009, and has led to a lack of proper planning at the management unit and broader landscape levels. For example, in 2008 the Stung-Attay dam project was initiated in O Som District for development of electricity to feed into the national grid. The Stung-Attay dam project has legal basis to clear just over 5,900 ha adjacent to CCPF, and clearing of forest was contracted to a local firm (Opendevelopmentcambodia 2012). At the time of this assessment in May 2012, clearing was complete. During construction and clearing, there was an influx of Cambodian and foreign migrant workers to the site that more than doubled the local population in O Som. Improved transportation infrastructure was put in place to facilitate delivery of large equipment, heavy machinery, and large quantities of materials and supplies. Two other dam construction projects are planned in or adjacent to CCPF, totaling over 24,000 ha (Opendevelopmentcambodia 2012). Woodland areas that previously provided access to timber and fuel wood have been cleared for large scale plantations, causing a shift in supply for timber products from the remaining intact forests in CCPF. The demand for these resources is likely to increase with a growing population and improved access to markets in Phnom Penh.

Direct driver: harvesting for timber

With the onset of the Stung Attay dam construction in O Som District on the western boundary of CCPF, there were reports of illegal logging in the area. The focus of these reports was on rosewood (*Dalbergia cochinchinensis)*, a species of evergreen forest types. Rosewood is considered as 'vulnerable' by the International Union for the Conservation of Nature (ARW 1998). It is highly prized as a 'luxury' wood and can be worth over 5,000 USD per $m^3$when processed into unfinished products (Lam Hai Co. 2012).

Illegal logging has resulted in a highly degraded forest structure (Figure 4). Regional and international demand for luxury timber has been cited as one factor in illegal logging in Cambodian protected forests (FA 2011).We spoke with several O Som residents who had been gathering rosewood inside CCPF. These informants recalled walking inside the CCPF boundary for up to two days before beginning to search for rosewood. They indicated that rosewood was now so difficult to find that other income-generating activities were now required. Recent demand for rosewood may have declined; however other tropical hardwoods within the evergreen forests could replace this species in regional and international markets. In the deciduous and semi-evergreen forests within CCPF, other hardwoods are also being currently extracted. Timber from these forest types is used for personal home and farm construction and for income generation.

The CCPF Management Plan clearly states that there is no legal basis for extraction of timber from CCPF for commercial use. However, the CCPF Management Plan is not clear how much timber extraction for local use is permitted under Article 40 of the Law on Forestry. The plan estimates local demand of timber resources based on current and estimated population growth. Current total demand of timber for local use is estimated to be between 345 – 477 $m^3$and is projected to increase to between 371 – 500 m^3 per year by 2015 (FA 2009). While these figures seem small, they indicate that planned extraction for local use may not be considered an illegal activity and could be considered to be planned degradation.

Direct driver: harvesting for fuel wood

The demand for fuel wood is driven by local and regional markets. Fuel wood can be processed into charcoal and is often used as a power generation source in brick and garment factories (FA 2011). The demand for charcoal as a fuel source in homes is also high, as the majority of Cambodian households still rely on traditional methods for cooking (MoP 2010). The CCPF management plan estimated demand for wood to meet needs of local communities within and adjacent to the protected area (Table 1). These demands are based on standardized estimates developed at a national level and are extrapolated according to expected population growth rates.

The CCPF Management Plan qualifies these projections as being 25-35% higher if the demand for commercial uses is included (i.e., charcoal for sale). Domestic use of forests for meeting basic fuel wood needs has generally not been considered as a driver of forest degradation (FA 2011). However, increased commercial demand for fuel wood is leading to forest degradation and should now be considered a driver (Top 2004, Top 2006). In the course of this assessment, many vehicles leaving the CCPF boundary area were encountered transporting wood or charcoal for fuel as well as active charcoal kilns (Figure 5).

Direct Driver: modified fire regimes

Fire is a natural ecosystem process in some of Cambodia's forests, particularly the deciduous forest type (Wharton 1966, Jones 1998, FA 2011). The prevalence of fire was noted in a 1962 (USAID) aerial photography survey across Cambodia. It was estimated that 60% of all deciduous forests in Cambodia had experienced at least some burning in the 12 months previous to the survey. Likewise, fire as an agent of vegetation change has a long history in Cambodia (Maxwell 2004). During our field assessment, evidence of fire in deciduous and semi-evergreen forest was observed in the form of charred wood residue, burn scars on trees, and burned non-woody vegetation. Fire regimes and forest successional dynamics are not well studied in Cambodia. However, if fire intervals have become more frequent than have occurred historically, this could result in changes to understory vegetation, reduced tree

Table 1. Estimated wood demands to meet local needs within CCPF, 2012-15. Modified from FA (2009).

Year	Population	Firewood (m3)	Charcoal (m3)	Total (m3)	Total with commercial demand (m3)
2012	33,475	14,421	6,597	21,018	26,272 – 28,374
2013	33,990	14,642	6,696	21,338	26,672 – 28,806
2014	34,514	14,868	6,804	21,672	27,090 – 29,257
2015	35,045	15,097	6,903	22,000	27,500 – 29,700

Figure 5. Wood and charcoal being transported from the Central Cardamom Protected Forest boundary area in Aoral District, Kampong Speu Province.

regeneration and increased cover of bamboo in riparian areas, with a corresponding decrease in biomass. The FCPF R-PP notes fire as a direct driver of forest degradation; however, it also describes its impact on forests as unclear (FA 2011). Research is needed to establish a knowledge base on forest fire in Cambodia, and its contribution to GHG emissions.

b. Current forest conditions

Objective, stratification and sample design

The objective of our data collection was to quickly assess forest conditions, relate these conditions to the observed current disturbances or inferred past disturbances, and use this information to refine monitoring objectives for determining a biomass change threshold. Further, this information can assist in understanding the effect of certain drivers on forest biomass for use in assessing possible forest monitoring techniques.

We intended to stratify the landscape in order to conduct sampling for approximating forest condition per forest type and disturbance level. However, no forest and land use cover map data were available. As such, time was spent with the local rangers to determine whether it would be possible to collect data from undisturbed forest. This baseline data is critical in determining the level of departure in forest carbon stocks from the natural carrying capacity of a given forest type. All of the rangers we spoke with informed us that travel distances to undisturbed forest were too far from the ranger stations. Given the onset of the rainy season and the conditions of the roads, we were not able to access these areas. In lieu of an undisturbed forest versus disturbed forest comparison, we attempted to assess varying degrees of disturbed forest and the impacts of degradation drivers on forest volume. We had significant discussion with the local rangers in how to access 'less disturbed' and 'more disturbed' forest within given forest types near each of the ranger stations.

We collected data using variable-radius plot sampling with a metric Basal Area Factor (BAF) of two for deciduous forests and a metric BAF of five for evergreen and semi-evergreen forests. Data were collected in transects, where the starting point of the transect was located 50 m from a track (i.e., unimproved road that may be accessible by some 4WD vehicles, but generally only by motor bike). The direction of the transect was in a straight line through a forest type with relatively homogenous site conditions. After the first variable-radius plot, each plot was 100 m from the previous plot. Data collected at each plot included: diameter of each 'in' tree, average overstory height, average overstory canopy cover, average understory canopy cover (in two tiered forests), GPS coordinates and notes on dominant species, disturbances (fire, logging) and proximity to riparian features.

O Som Ranger Station: evergreen forest

Near the O Som Ranger Station, at roughly 500 m elevation in the Central Cardamom plateau, we installed 4 transects. The area within a reasonable distance around the ranger station has been significantly impacted by past logging activities. Only one 'less degraded' forest condition was able to be visited. This was in the O Som Community Forest, set up with assistance from Conservation International. In general, the area is dominated by evergreen forest with a large variety of species. While the community forest had been logged of commercially valuable species in the past, large diameter remnants of Sassafras (local name 'mreahprewphnom', Latin name *Cinnamomum parthenoxylon*) dominate the overstory.

Even though 'less degraded' forest stands were under sampled, there is a marked difference in the volume and trees per hectare when compared with 'more degraded' stands (Table 2). This 'more degraded' forest condition seems to have been logged more than once, possibly several times. 59 trees were tallied on 15 plots; the average diameter was 29 cm while two-thirds of diameters fell between 17 and 38 cm.

Rolak Ranger Station: Deciduous forest and semi-evergreen forest

Using the Rolak Ranger Station as a base, we installed 6 transects of 5 plots each across gradients of disturbance in deciduous forest and semi-evergreen forest. We measured plot variables in four transects covering 'less degraded' and 'more degraded' deciduous forest, and in two transects covering semi-evergreen forest. The semi-evergreen forest was not prominent within a reasonable distance from the ranger station. Deciduous forests were dominated by trees in the Dipterocarpaecae family, including pschek (*Shorea obtusa*) and khlong (*Dipterocarpus tuberculatus*).

Table 2. Forest attributes in the evergreen forest type of the Central Cardamom Protected Forest.

Evergreen forest condition	# of samples	Avg OS Ht (m)	Avg OS CC (%)	Avg US CC (%)	BA/ha (m^2)	Trees/Ha	Volume/ha (m^3)*
Less degraded	5	29	58	62	22	388	525
More degraded	15	21	48	95	14	304	352

* Volume calculated using equations from USAID (1962), see Annex.

Avg OS Ht: Average overstory height
Avg OS CC: Average overstory canopy cover
BA/ha: Basal area per hectare

For deciduous forest, the 'less degraded' condition had consistently higher volume and density of trees per hectare (Table 3). Basal area differed little between forest conditions because there were more, smaller trees in the more degraded areas, indicating post disturbance regeneration. Activities leading to

Table 3. Forest attributes in deciduous and semi-evergreen forests along the lowlands of the eastern Central Cardamom Protected Forest.

Forest type/condition	# of samples	Avg OS Ht (m)	Avg OS CC (%)	BA/ha (m^2)	Trees/ha	Volume/ha (m^3)*
Deciduous forest						
Less degraded	10	12	49	15	259	335
More degraded	10	12	46	14	195	278
Semi-evergreen						
Less degraded	5	14	78	20	345	280
More degraded	5	16	46	14	272	321

* Volume calculated using equations from USAID (1962), see Annex.
Avg OS Ht: Average overstory height
Avg OS CC: Average overstory canopy cover
BA/ha: Basal area per hectare

a 'more degraded' condition mainly included removal of saw log sized trees greater than 30 cm dbh. Analysis results for semi-evergreen forest are inconclusive as not enough samples were collected. In general, the lowlands on the margins of the CCPF have semi-evergreen forest only along narrow riparian zones or at the base of the escarpment leading up to the Central Cardamom plateau.

Comparison with other analyses

Based on our field assessment, we calculated rough estimates of volume, basal area, and tree density of 'less degraded' and 'more degraded' forest in the three different forest types. In general, forest structure information in Cambodia is available from only a limited number of studies, this is especially the case for deciduous and semi-evergreen forests. For evergreen forests, we compared estimates of forest structure from our study to other published estimates in order to assess the differences in volume, basal area, and stem density (Table 4). Our estimate of the difference in volume between 'less degraded' and 'more degraded' forest is consistent with differences found in the literature. Published results of basal area and stem density for evergreen forest are less frequent, and less conclusive.

Table 4. Comparison of evergreen forest structure characteristics between 'less degraded' and 'more degraded' forest conditions.

	Volume (m^3/ha)			Basal area (m^2/ha)			Density (stems/ha)		
	less degraded	more degraded	% difference	less degraded	more degraded	% difference	less degraded	more degraded	% difference
Ashwell et al. 2004	225[a]	-	-	32	-	-	384[b]	-	-
Kao 2006	186	152	18%	13	11	15%	220	242	-10%
Sasaki 2000[c]	314	195[d]	38%	-	-	-	1,105	1,017	8%
Kiyono et al. 2010	-	-	-	37	10[e]	73%	-	-	-
FAO 2010	230	165	28%	-	-	-	-	-	-
This study	525	352	33%	22	14	36%	388	304	22%
Average percent difference			29%			42%			7%

a) Range estimate volume 200-400 m^3
b) Range estimate 356-412 stems/ha
c) The high number of stems is because the data is based on forest inventory and analysis of all trees with dbh greater than 5 cm
d) Based on average of poor stocking evergreen forest (137 m3) and medium stocking evergreen forest (254 m3)
e) based on plots A, B in 2006

Our volume estimates are high when compared to the other published estimates. The differences in volume are likely attributed to the following factors of this assessment:

- small sample size with limited geographic distribution;
- use of outdated volume equations; and,
- possible differences in forest type classification.

Basal area and stem density estimates from this study fall within a reasonable range of published estimates. Stem density estimates from Ashwell et al. (2004) were based on many years of research by a wide variety of organizations.

Table 5. Comparison of volume estimates between various studies for deciduous forest and semi-evergreen forest in Cambodia.

		Volume (m^3/ha)		
Forest type	Reference	less degraded	more degraded	% difference
Deciduous forest	FAO 1998	106	-	-
	Ashwell et al. 2004	52[a]	-	-
	Top 2006	171	-	-
	FAO 2010	60	-	-
	This study	335	278	17%
Semi - evergreen forest	FAO 1998	151	-	-
	Ashwell et al. 2004	215[b]	120	44%
	Top 2006	201	-	-
	FAO 2010	145[c]	80[d]	45%
	This study	300[e]	-	-

a) Range is 20 - 100 m^3.

b) Average of dense semi-deciduous and mixed deciduous forests.

c) Based on the average between evergreen forest volume (230 m^3/ha) and deciduous forest volume (60 m^3/ha).

d) Based on the average between evergreen mosaic forest volume (100 m^3/ha) and deciduous forest volume (60 m^3/ha).

e) Our estimate is an average of 'more degraded' and 'less degraded' semi-evergreen forest conditions in this study.

Forest structure estimates of deciduous forest are even less well studied. We could only find a limited amount of information from the literature on volume within these forest types, and even less on differences between 'less degraded' and 'more degraded' conditions (Table 5). Two notable syntheses, Ashwell et al. 2004 and FAO 2010, did estimate similar differences in volume between these conditions for semi-evergreen forest. However, these estimates are composites based on expert judgment and not on analyses of forest inventory data representing these forest types/conditions. The differences in volume estimates between this study and in the published literature is likely due to the same factors noted above for evergreen forest.

Development of a biomass change threshold

One goal of our data collection was to develop a rough estimate of the difference in forest structure between 'less degraded' and 'more degraded' forest conditions within CCPF. This difference can be used as a threshold for the Y in the monitoring objective statement in Section 2. Analyses of commercial logging activities in SE Asia show that as much as 50% of forest stands are damaged by conventional timber harvesting (Sist 2002). Forest degradation drivers in CCPF are not currently dominated by large-scale logging operations, and the likely impacts of the current drivers on forest structure will be less. We estimated an average volume difference of 30% between 'less degraded' and 'more degraded' evergreen forest types. Volume is highly correlated with biomass and forest carbon stocks. We recommend refining the forest degradation monitoring objective to define the Y as 30% so that the objective is:

> **Quantitatively estimate human caused loss of at least 30% forest biomass from 'forest remaining forest' within the Central Cardamom Protected Forest beginning from at a baseline year and monitored at an interval between 2 – 4 years.**

4. Degradation Monitoring

a. Monitoring options

In this section we summarize our assessment of options for monitoring biomass/carbon change in degraded forests in CCPF, as outlined in the conceptual framework (Figure 3).Three basic monitoring approaches for monitoring forest degradation were identified: predictive modeling, remote sensing, and ground-based field measurements. The various options assessed under each approach are discussed more thoroughly in the Annex. The following is a synopsis of the three monitoring approaches:

Predictive modeling can be used stratify forested land according to the risk of degradation by predicting the probability of occurrence of a degrading activity in a particular location. This information can then be used to interpret canopy cover changes detected through imagery classification. If the biomass loss associated with a particular activity can be quantified (such as through ground-based field measurements), then modeling can serve as the basis for a ‘gain-loss’ approach to carbon accounting as defined by the IPCC. Modeling may also be able to predict changes in biomass from degradation activities such as fire or fuel wood gathering that may not immediately result in detectable changes in overstory canopy cover, and it may serve as a surrogate for remote sensing data if there are gaps in imagery coverage for the area or if a remote sensing system has not been implemented.

Developing robust models requires a sufficient amount of relevant field data for both model training and accuracy assessment. Some models can integrate several different types of data, including both continuous and categorical variables, and the algorithms are often nonparametric, i.e. they do not require data to have a normal distribution or even be monotonic. Once models are operational, runs can be repeated whenever new data becomes available, allowing degradation risk to be assessed at frequent time intervals. Any potential bias in the collection of field data needs to be recognized and assessed when it is used to train or test a predictive model.

Remote sensing is used to detect changes in forest canopy cover over time, which can then be related to biomass changes by incorporating ground-based field measurements. Satellite imagery must be of sufficient resolution to detect changes in canopy in forests caused by degradation activities, i.e. canopy cover changes that are of insufficient scale to cause the land cover classification to change from forested to deforested. Imagery platform sensors are of two general types: those using active sensors such as LiDAR or radar, and those with passive sensors such as LandSat or RapidEye.

High resolution imagery provides the finest detail for detecting canopy changes; however, it is usually expensive to acquire and process, and the spatial and/or temporal coverage of a large landscape may be insufficient. Low and medium resolution imagery is less expensive, or even free, but detecting small changes in forest canopy cover can be problematic. Some degradation activities such as fuel wood gathering or fire may not result in overstory canopy disturbance, and therefore may not be detectable by remote sensing. Classification may rely on complex analysis and requires supplemental field inventory data and/or high resolution imagery for validation. High resolution imagery may also be used for detecting indirect evidence of degradation activities, such as logging tracks and landings that could serve as infrastructure data for degradation risk modeling.

Ground-based field measurement of vegetation and site data is normally from a system of permanent or temporary sample plots. Interpretation of sample plot data relies on statistical analyses to assess biomass stocks and changes on the sample landscape. Forest inventories use established, repeatable methods and if used exclusively for carbon accounting they can be considered a ‘stock difference’ approach in IPCC terms.Forest inventory data may also be used in the ‘gain-loss’ accounting by providing supporting data for spatial modeling and/or remote sensing monitoring approaches.

A systematic inventory of permanent plots usually provides the most reliable and precise data if the sample grid is of sufficient density; however, no such inventory is currently in place in CCPF. Alternatively, temporary forest inventory plots may be located using a stratified random or cluster design to ensure efficiency and representativeness in all identified degradation strata. Higher numbers of samples may be required in strata with high variability, which will likely include areas subject to varying types and intensities of degradation activities.

Participatory forest monitoring may also contribute valuable inventory and activity data for modeling, depending on the skill levels of the participants and the protocols used. If field inventory data is not sufficient to obtain reliable estimates during a monitoring cycle, then high resolution imagery or aerial photo plots may be employed to obtain canopy cover estimates, and standard carbon stock estimates for the region and particular forest type may be used in place of locally derived data.

b. Monitoring recommendations

To provide reliable information on carbon stocks in degraded forest in the context of the Central Cardamom Protected Forest, we recommend an integrated monitoring approach to quantitatively estimate human-caused loss of at least 30% above-ground biomass (with a 95% confidence interval) from 'forest remaining forest' within CCPF, within strata defined by degradation risk and forest type. To capture the impacts of degradation effectively using expected monitoring capacity, we recommend a monitoring cycle of between two and four years. We recommend using 'gain-loss' accounting in IPCC terms, beginning at a Tier 2 level and moving to Tier 3 as better data and information become available. The sections below outline the conceptual opportunities we believe will have a high likelihood of success.

Each of the three basic monitoring approaches (modeling, remote sensing, and field inventory) has a unique set of strengths and weaknesses for detecting forest carbon loss due to degradation. Relying on only one or even two of the approaches will likely present technical or capacity challenges that will be difficult to overcome. Therefore, we recommend an integrated system in which each approach supports the others to mitigate technical and capacity challenges and reduce uncertainty. The links between the three monitoring approaches is the focus of this monitoring design. Figure 6 clarifies the workflows among the monitoring approaches that will occur within the general conceptual framework (Figure 3).It is recommended that this monitoring system be implemented initially through a demonstration phase to confirm the appropriate data sources and analysis methods to be used, as well as calibrate the monitoring to obtain reliable and useful results.

Modeling

Models are central to the CCPF monitoring recommendation, because they provide the framework within which the other approaches are applied. Two modeling approaches are recommended:

Degradation risk modeling – stratifies the landscape by degradation activity risk for use in interpretating the source of canopy disturbance identified by remote sensing analysis of satellite imagery. The model

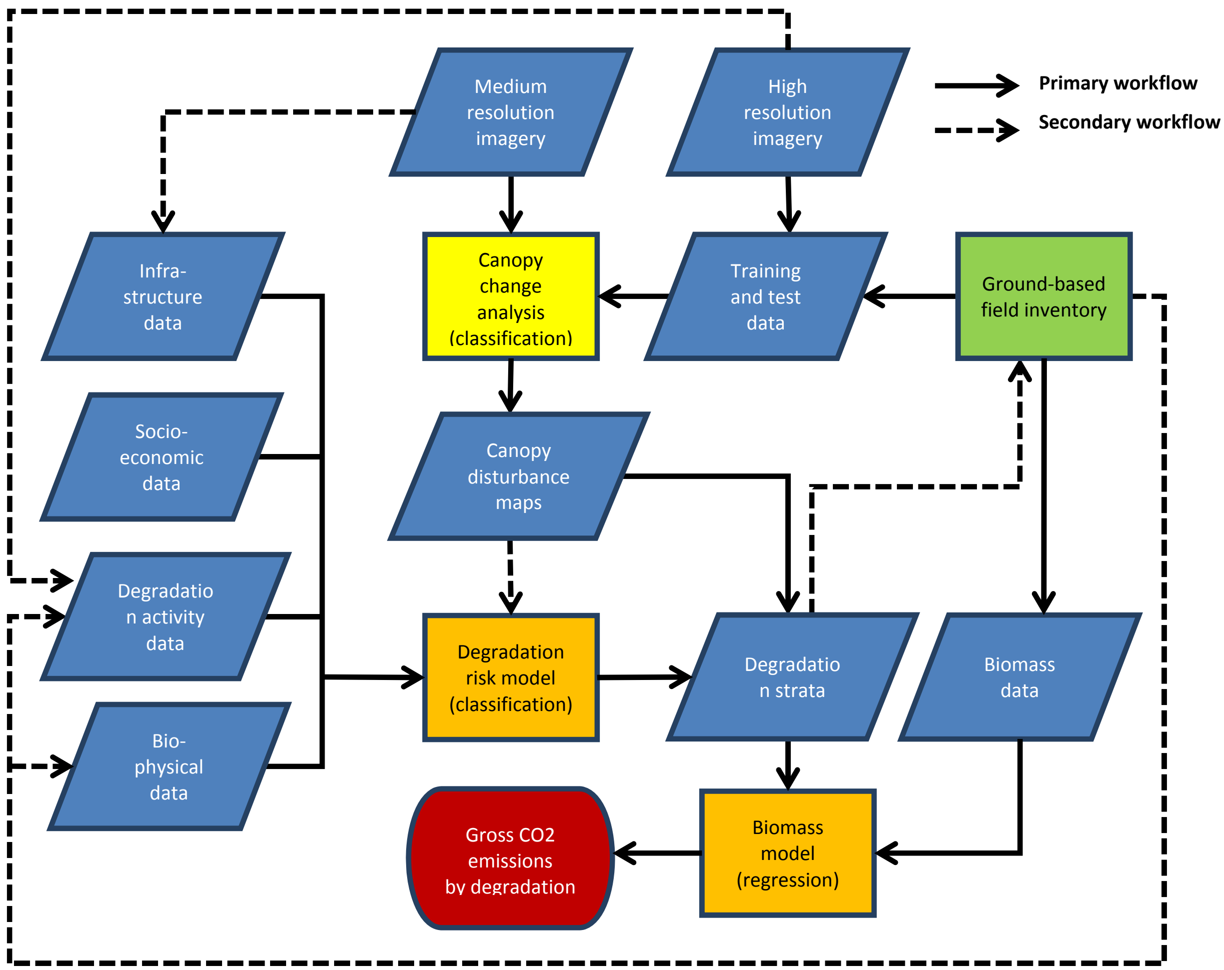

Figure 6. Conceptual design of the integrated monitoring system workflows to assess biomass/carbon stock change resulting from forest degradation.

provides a basis for classifying canopy disturbance by degradation driver. The assessment of the main degradation drivers is used to select appropriate predictor variables, including relevant biological, physiological, and socio-economic factors that are associated with degradation activities. Known locations of degradation activities analyzed in a decision-tree or machine-learning classification algorithm such as Random Forests (Brieman 2001) or Maxent (Phillips et al. 2006) to predict the target variable (degradation activity class) based on spatial relationships of the known locations with predictor variables. The model is evaluated by generating an error estimate, such as cross-validation or out-of-bag error. We recommend an overall misclassification error rate of less than 20 percent.

Degradation risk modeling should be based on four general categories of data:

1) Degradation activity (logging, fuel wood collection, anthropogenic fire)
2) Biophysical data (elevation, slope, forest type, tree volume, tree age)
3) Infrastructure (villages, roads, logging trails)

4) Socio-economic conditions (population density, income/poverty data, land tenure).

A model-based stratification of degradation activity risk can be used to ensure efficient and representative sampling of ground-based field data.

Biomass gain/loss modeling – extrapolates biomass values to each forest/degradation class using forest inventory data, allowing carbon stocks to be estimated across the suite of strata mapped on the landscape. Field data collection is likely to be limited due to capacity constraints, which in turn could prevent development of a statistically valid estimate of biomass change across a stratum.

Modeling provides a potential way to obtain a robust estimate of biomass within a stratum using predictor variables, even with a relatively small sample size compared to the number of predictor variables (Blackard et al. 2008, Pearson et al. 2007). Decision-tree regression analysis (e.g. Random Forests) is recommended to predict the target variable (biomass value) at a given location in a spatial grid within a stratum based on relationships between biomass measurements from available forest inventory data and a set of predictor variables similar to those used in the degradation risk model.

Remote sensing

The main purpose of obtaining remotely sensed imagery in the context of this monitoring system is to quantify the amount and location of canopy disturbance in the study area. This will form the basis for quantifying biomass loss from disturbance due to degradation activity. Although several methods exist for detecting canopy disturbance, relating this disturbance to specific degradation activities usually requires additional inputs from ground-based field data or a predictive degradation model. Therefore, the desired end product should contain an accurate delineation of canopy disturbance stratified by degradation class. This stratified degradation-disturbance map is then used to located field sample plots in disturbance areas.

Due to the temporal nature of the main degradation drivers, the time frame for analysis will require acquisition of imagery at 2 to 4 year intervals. Considering the technical and financial requirements and the existing capacity for implementing imagery classification in CCPF, the most appropriate remote sensing product for analysis would likely be medium resolution imagery. The monitoring objective would be to detect a change in canopy cover of at least 10% with a 95% confidence interval. Accuracy would be assessed using a combination of ground-based plots and high-resolution imagery sample plots. The recommended minimum mapping unit for analysis is 0.5 hectare.

Of the various methods currently available for imagery classification, CLASLite (Asner et al. 2009) would likely be the most technically feasible to employ due to its ability to quantify canopy disturbance using a variety of lower cost imagery products (SPOT, Aster, Landsat, etc.). This allows flexibility in determining which imagery product is the most cost-effective, has the best coverage for a given time interval, and has sufficient resolution to detect the desired change threshold. CLASlite employs algorithms to correct for haze or cloud cover, both of which are prevalent in imagery taken in tropical regions. CLASlite also has low technical capacity requirements, because most of the system is automated.

There are several potential difficulties to address in implementing CLASlite. Although the system has been tested in Borneo, it has not yet been applied in mainland Southeast Asia; therefore, a pilot project may be necessary to calibrate the system to CCPF forests. Alternatively, existing calibration libraries for tropical forests in other regions could be used until more localized information from ground-based field plots becomes available. Licensing permission for use of the software would also need to be obtained from the developers. To detect canopy cover changes between removal and regrowth, imagery acquisition is required at frequent time intervals (perhaps two years or less), and interpretation of imagery in seasonally dry deciduous forests may be problematic due to seasonal leaf fall.

If CLASlite is not implementable in CCPF, the recommended alternative is Normalized Differential Fraction Index (NDFI) using medium-resolution imagery. NDFI measures the forest degradation signal caused by selective logging (Souza et al. 2005). It is calculated from fractional images obtained from spectral unmixing analysis, which separate signals from spectral bands into photosynthetic vegetation, non-photosynthetic vegetation, and bare soil. These fractional images are then analyzed with respect to their proximity to logging roads and log landings. High NDFI values indicate the presence of intact forest, and lower NDFI values indicate degraded forest. The analysis requires extensive field data for calibration and trained GIS/Remote Sensing professionals to implement, both of which can be costly. Haze and cloud cover corrections would likely need to be applied to imagery, and relatively cloud-free imagery will most likely be difficult to obtain in the study area due to the extensive cloud cover that occurs during much of the year.

Field inventory

Field inventory plots serve several potential roles:

1. Providing canopy cover data for training and accuracy assessment of imagery classification,
2. Providing biophysical information (forest type, site environmental characteristics, degradation activity) for training and accuracy assessment of degradation models,
3. Relating carbon stocks tithe strata defined by the degradation models, and
4. Developing biomass estimates for emission factors related to the specific activities driving forest degradation.

We recommend two types of ground-based field data be collected: forest inventory plot data, and degradation activity data. Inventory data will be used in developing estimates of carbon stock change in forest areas subject to canopy disturbance due to degradation activities during a monitoring period. Activity data will be used to model degradation risk for stratification of the study area for sampling and analysis. Data should be compiled at the beginning of each monitoring period. Data collected during a monitoring period would be incorporated into the following monitoring period for use in degradation risk modeling, remote sensing accuracy assessment, and carbon stock change estimation.

Biomass inventory

We recommend that biomass data be collected from either permanent or temporary forest inventory plots randomly located in disturbed areas identified within degradation strata. Data collection should follow established procedures for measuring terrestrial carbon (Walker et al. 2012). Field data should include forest measurements (e.g. species, diameter, height, stand age, canopy cover) site characteristics (e.g. slope, aspect, soil conditions) and evidence of disturbance (e.g. logging damage, fuel wood gathering, fire scars).

Degradation activity

We recommend that degradation activity data be collected as they are encountered during CCPF ranger patrols. This should include spatial location of known or suspected logging and fuel wood gathering activity, logging tracks and landing decks, and anthropogenic fire occurrence. Additional data to be collected at the activity locations should include relevant biophysical, infrastructure, and socio-economic data.

Activity data could also be collected through participatory forest monitoring (PFM) in cooperation with village community forest councils. This data source will likely be considered as supplemental to data collected from ranger patrols. PFM may also provide additional data on socio-economic variables (income levels, farming practices) that may influence degradation activities.

5. Next Steps

The following are recommendations for implementing of the monitoring approaches included in the CCPF forest degradation monitoring system:

Modeling

Modeling generally incurs low equipment costs since most algorithms can be applied using standard desktop computing environments; however, the expertise of a technical specialist is vital to developing a successful modeling protocol. Therefore, organizations with experience in spatial modeling may need to be employed for initial model development, as well as training local staff in its use. Personnel from international government resource agencies, universities, or non-profit organizations may provide technical assistance during the initial implementation of degradation modeling.

Remote sensing

Implementation will require identification of resources and personnel who will be dedicated to developing disturbance maps from imagery. Responsibility for remote sensing should be conveyed to an organization with experience working on forest degradation issues in the study area and who have existing in-house equipment and expertise to perform imagery analysis. In the context of CCPF, this would most likely be a consortium that includes the FA, CI, and/or a private contractor.

This assessment did not interview any FA staff involved in remote sensing at the provincial level. However, secondary information from informants suggests that there may be some capacity at this level to conduct remote sensing analyses that could be consistent with the needs for degradation monitoring. This would likely target visual interpretation of medium resolution satellite imagery in Step 1. Attention would need to be given to Quality Control/Quality Assurance and Standard Operating Procedures to minimize errors between interpreters.

Ground-based field measurements

We recommend the bulk of biomass data collection be conducted using CCPF district personnel, who can be tasked to efficiently collect relevant data for carbon stock change modeling and remote sensing training and evaluation. This will require training forest rangers in collecting accurate field data using standard protocols for terrestrial carbon measurement. Additional personnel may need to be provided to the districts to avoid impacts on the ranger's existing law enforcement duties. Alternatively, a dedicated inventory crew could be tasked to collect inventory data across CCPF. Additional data may be collected in limited areas using PFM in cooperation with village and community forest councils. International government agencies with experience in establishing and maintaining forest inventory systems and databases would be good resources for developing forest inventory protocols and training local personnel in implementation.

Data formats

The data specifications for the recommended monitoring framework are clarified in Table 6. These data types and sources are feasibly acquired. For example, degradation risk models can initially be developed from existing data collection activities conducted by CCPF rangers as part of their normal duties. There will be a need to strengthen data management and quality assurance procedures.

Table 6. Data inputs for a monitoring program to assess change in biomass due to forest degradation activities within the Central Cardamom Protected Forest. Specific information on aquiring appropriate data would be developed during the project demonstration phase.

Input data	Format	Scale; accuracy	Time
Modeling data	Vector and point, established by activity, biophysical, infrastructure, and socio-economic data collected by GPS	Begin with $\geq$ 1 Ranger Station, 100% of all existing infrastructure data; goal to cover all CCPF	100% at the reference year, add data when available
Ground-based inventory data	Tabular, tons biomass/ha per forest type per buffer	Disturbed forest stratified by degradation; +/- 20% @ 90% CI	At baseline year, then 1 time every 2-4 years
Medium resolution satellite imagery	Raster, forest cover type& condition, infrastructure	Entire CCPF; $\geq$ 80% when compared to forest inventory data	At baseline year, then 1 time every 4 years
High resolution satellite imagery	Raster, forest canopy cover, forest type	10% sample of all buffer zone area; $\geq$ 80% when compared to forest inventory data	At baseline year, then 1 time every 2-4 years

Implementation schedule

Monitoring of forest degradation according to the set objectives will need to be developed in an iterative fashion over time yet with full consultation of relevant stakeholders. The recommendations here are meant to be used as a starting point from which refined protocols and methods could be developed according to circumstances and conditions. A suggested initial implementation schedule for the initial monitoring period is presented in Table 7. Subsequent monitoring periods would follow a similar schedule beginning at the conclusion of the previous period.

Conservation International is likely to be in the best position to guide the development and implementation of a recurring transparent monitoring program due its strong partnership with the RGC Forestry Administration.

Lessons learned through demonstrating this approach can be used to inform development of monitoring activities other areas as well as contribute to the process of model refinement. Involving people living and working in the CCPF area in data collection activities will help increase their awareness of forest degradation issues, as well as allow for greater knowledge of specific degradation drivers to be included in model development.

Table 7. Implementation schedule for degradation monitoring system for the Central Cardamom Protected Forest.

Year	Monitoring	Remote sensing	Forest Inventory
Year 1:	• Assemble available activity, biophysical, infrastructure, and socio-economic datasets. • Develop degradation risk model.	• Aquire medium and high resolution satellite imagery. • Develop canopy disturbance baseline map.	• Develop resources and training for CCPF district staff and PFM partners.
Year 2:			• Implement sample design for forest inventory plots. • Collect activity data.
Year 3:			• Collect forest inventory and activity data.
Year 4:	• Develop biomass change model. • Develop degradation risk model for next monitoring cycle. • Update datasets for next monitoring cycle.	• Acquire medium and high resolution satellite imagery. • Develop canopy disturbance change map.	• Compile forest inventory and activity data. • Implement sample design for forest inventory plots. • Collect activity data.

This assessment should be considered a living document that has the potential to guide strategies for monitoring forest degradation at the sub-national level in Cambodia and other parts of the Mekong region. This report has not assessed these methodologies in the context of a monitoring framework that is intended to nest into a national monitoring program. However, the lessons learned through the development of this process will be able to greatly contribute to future national monitoring program design.

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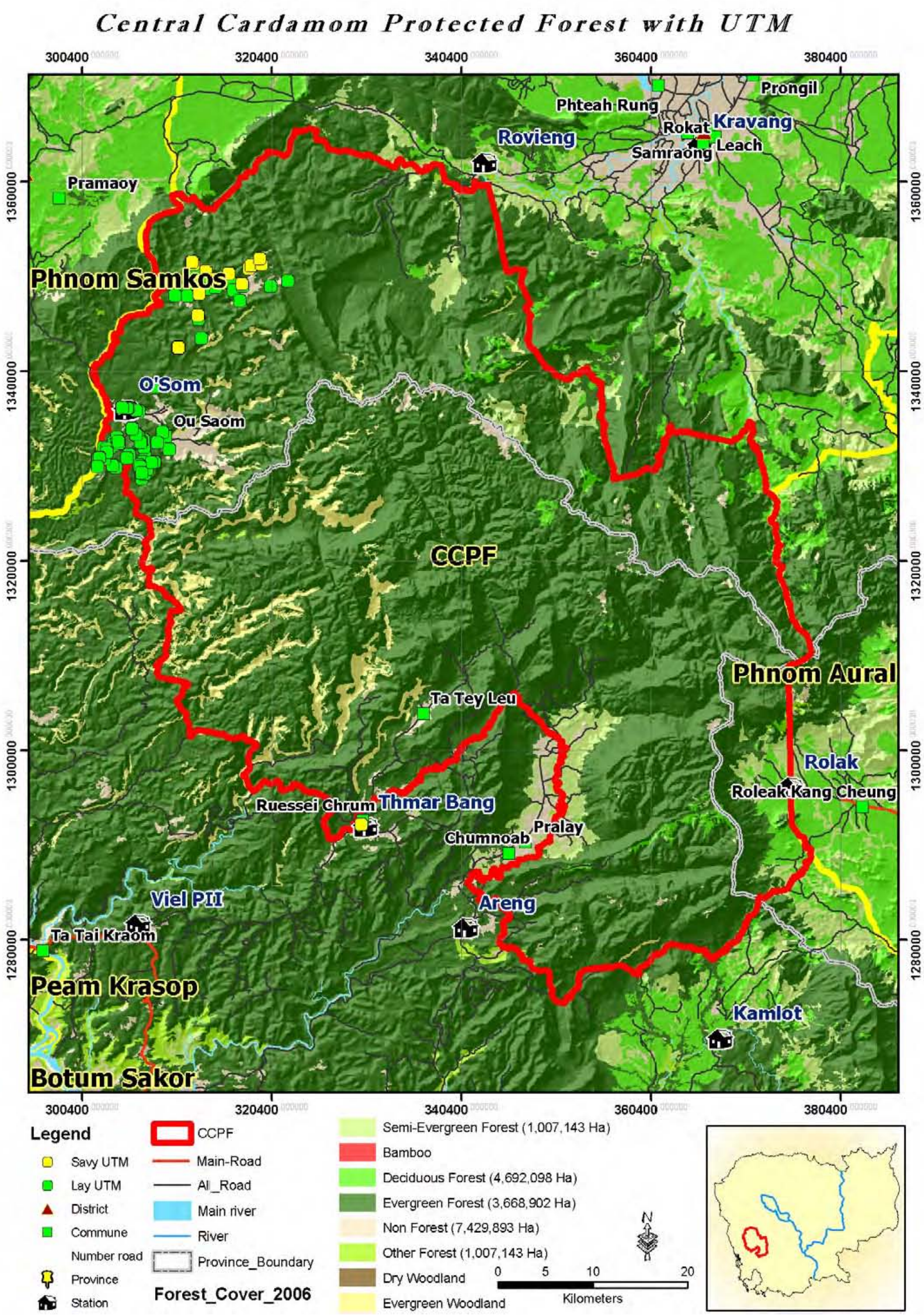
7. Annex

a. Formula for standing timber volume

Source: USAID. 1962. Forest Inventory Manual (Techniques and Procedure for Cambodia).

Forest type	Pole D = 10 – 29 cm	Construction Timber D ≥ 30 cm
Evergreen or semi-evergreen	$V = 0.02197 + 1.67851\ (D^2H)$	$V = 0.28053 + 1.89533\ (D^2H)$
Deciduous	$V = 0.02756 + 1.49511\ (D^2H)$	$V = 0.00156 + 1.44890\ (D^2) + 1.40889\ (D^2H)$

b. Map of Central Cardamom Protected Forest



c. Assessment of forest degradation monitoring options

Remote sensing

Dozens of options exist for use of remotely sensed data to capture information on change within forests. Costs, data availability, institutional and human resource capacity are all key considerations in monitoring systems design. Temporal aspects of monitoring with remotely sensed data are a key component, allowing for inter-annual change assessment (Lambin 1999). Herold et al. (2011) made a broad assessment at national level scale of opportunities to assess areas of historical degradation (Table 8).

An assessment of pilot activities across Asia was conducted by experts from Japan in order to rank the potential usefulness of remotely sensed data for monitoring variables related to forest degradation process (Table 9). This study used a qualitative ranking to determine relevance of methodologies by degradation driver. According to the knowledge gained through these pilot studies in Asia, very few remote sensing options are feasible with current levels of knowledge and research. Assessing six approaches for three different drivers, only four out of 18 of the approaches were considered 'possible'. Further, methodologies that do exist are hampered by cloud cover and steep terrain. The former is a large constraint in Cambodia where cloud cover is prevalent throughout the year (Martin Herold pers comm.).

Table 8. Options for estimating activity data for historical degradation on the national level beyond the use of default globaldata. Adapted from Herold et al. (2011).

Activity and driver of forest degradation	**Suitable and available data sources for activity data (national level)**
Extraction of forest products for subsistence and local markets, such as fuelwood and charcoal	• Limited historical data • Information from local scale studies or national proxies (i.e., population growth and wood demand), if available • Only long-term cumulative changes may be observed from historical satellite data
Industrial/commercial extraction of forest products such as selective logging	• Historical satellite data analyzed with concession areas • Direct approach should be explored for recent years (since ~2000, depending on national coverage) • Indirect approach should be explored for historical period (back to 1990)
Other disturbances, such as (uncontrolled) wildfire	• Historical satellite-based fire data records (since 2000) to be analysed with Landsat-type data

Table 9. Options for use of remotely sensed data to characterize variables of interest that relate to forest degradation processes in Cambodia (adapted from Kiyono et al. 2011).

		Considerations			**Ranking by driver**	
Variable of interest	**Data source**	**Costs**	**Large area acquisition**	**Technical difficulties**	**Logging**	**Fuelwood collection**
Forest cover classification						
Area	Optical RS data, med to high resolution	Medium	Easy	Not applicable when clouded	Partially possible	Partially possible
Area	Radar, longer than L-band	Medium	Easy	Not applicable to areas with steep slopes	Unknown	Unknown
Forest structure classification						
Crown diameter	High resolution aerial photography	High	Medium	Not applicable when clouded; Crown recognition difficult in some forests	Partially possible	Impossible
Overstory height	Radar, multi-polarization SAR	Low	Medium	Methods not tested; Applicable to small parts of the globe	Unknown	Impossible
Overstory height	LiDAR, airborn	High	Difficult	Nothing in particular	Possible	Impossible
Overstory height	High resolution aerial photography, stereo mapping	Medium	Easy	Not applicable when clouded; Methods not tested	Unknown	Impossible

The US Forest Service (USFS) Remote Sensing Applications Center reviewed selected remote sensing methodologies to provide a snapshot in time of current applications used to establish a baseline and monitor change in forest attributes for REDD+ (Brewer et al. 2011). A ranking (low, medium, high) was done of 11 methodologies to assess operational readiness. Four of these were considered to be in high stage of operational readiness and all four have the potential for degradation monitoring. Three of these four are in development by Asner's Carnegie Airborne Observatory with a wide array of partners. None of these approaches have been rigorously tested in the Asia-Pacific region. Three of the four rely on highly expensive LiDAR data and aerial collection methods. CLASLite, the fourth approach, has the ability to mitigate cloud cover to some extent,but the persistent annual cloud cover in the study area may still pose a challenge. CLASLite used in combination with LiDAR has been employed through the Asner Observatory in the Peruvian Amazon with initial success (Asner et al. 2009),however implementation would likely be cost-prohibitive in developing countries.In the USFS assessment, only one approach for degradation monitoring was assessed which could be considered cost-effective – Normalized Difference Fraction Index using free LandSat archived data. The authors considered the operational readiness of this approach to be low due to the extensive field work required for calibration, along with the technical expertise required.

Sampling with satellite imagery to estimate land cover has been proven as a useful approach at global scales (Ridder 2007). Scaling down this strategy to estimate land cover and land cover changes at sub-national scales with multiple-date high resolution imagery could prove to be a useful concept for assessing forest degradation. Visual interpretation methods would be best applied in this type of estimation. Kiyono et al. (2011) mentions this as a 'partially possible' technique based on ease of acquisition and medium level costs. Multiple date sampling of images covering the same area could prove most challenging in the context of persistent cloud cover.

Use of high resolution remote sensing data products will provide key inputs into detection of changes in canopy cover that indicate human activity. A sampling approach could be employed so that acquisition of high resolution imagery occurs only within the areas of interest, i.e., within the buffer zones around infrastructure as suggested in the stratification above. Wall-to-wall high resolution data would not be needed if enough samples are collected to provide statistically valid estimates. Use of high resolution data would not need sophisticated processing techniques as visual interpretation would likely suffice. However, analysis of remote sensing indices has been used to assess statistical changes in forest canopy spectral reflectance due to degradation according to buffer distances around infrastructure (Sandra Brown pers. comm.). This is a promising approach and indices could be assessed within the modeling framework as well as to assess spectral changes in biomass in degradation strata.

Medium resolution data covering the entire CCPF could be used for: a) input into a modeling framework to assess its usefulness in detecting changes in biomass patterns, b) be employed as an 'early warning' system to identify significant human caused activities (road/track extension, significant timber removal, extent of severe fire).Automated classification techniques to identify significant canopy disturbance within 'forest remaining forest' would be best employed for large area mapping. Field visits for ground truth data would be needed after the first mapping exercise in order to validate results. Ground truth points should also have high resolution imagery to aid field crews in canopy cover and forest type interpretation. However, subsequent mapping exercises in undisturbed areas outside the degradation strata could rely on high resolution imagery alone for ground truthing purposes, eliminating the need for repetitive data collection.

Ground based field measurements

Options for collecting and analyzing forest inventory data are no less than the options for remote sensing. In considering design of monitoring options in a developing country context, capacity and funding are critical components to assess prior to sample design and data collection protocols. Danielsen et al. (2009) approached design of potential options from the perspective of who is to accomplish data collection and interpretation (Table 10). Externally driven, in this context, is assumed to place responsibility with international and/or national experts while local monitoring is assumed to be at the sub-national level.

Danielsen et al. (2009) determined that the costs of professional, external expertise of forest inventory monitoring is high, yet so is the accuracy and precision (Table 11). At the other end of the spectrum, accuracy and capacity to inform national monitoring systems are determined to be low if local level monitoring is implemented without assistance from other actors. In any nested approach to monitoring

Table 10. Categories of actors involved in forest monitoring (adapted from Danielsen et al. 2009).

Monitoring category	Category definition	Primary data gatherers	Primary data users
1	Externally driven, professionally executed	Professional researchers	Professional researchers
2	Externally driven with local data collectors	Professional researchers and local people	Professional researchers
3	Collaborative monitoring with external data interpretation	Local people with professional researcher advice	Local people and professional researchers
4	Collaborative monitoring with local data interpretation	Local people with professional researcher advice	Local people
5	Autonomous local monitoring	Local people	Local people

Table 11. Design considerations for field based forest monitoring by category of participants (adapted from Danielsen et al. 2009).

Monitoring category	Cost to local stake - holders	Cost to others	Require-ment for local expertise	Requirement for external expertise	Accuracy and precision	Capacity to inform national monitoring schemes
Externally driven, professionally executed	*	***	*	***	***	***
Externally driven with local data collectors	**	**	**	***	***	***
Collaborative monitoring with external data interpretation	**	**	**	***	***	***
Collaborative monitoring with local data interpretation	***	* and ***[1]	***	** and ***[2]	**	**
Autonomous local monitoring	***	*	***	*	*	*

* = low; ** = moderate; *** = high

1. Recurrent costs to non-locals is low, set-up and training costs to non-locals is high.
2. Recurrent requirement for non-local expertise is intermediate; requirement for non-local expertise is high during set-up and training phases.

and the broader MRV context, this is a serious consideration. The USFS-International Programs assisted in the design and initial training for Participatory Forest Monitoring in Ghana in 2009-10. Main findings demonstrate that successful approaches must include continued mentoring for local actors in collaborative approaches (Stanturf et al. 2011). Step-wise approaches that build upon training and mentoring that is coordinated with higher level institutions and processes was considered as potentially successful.

Sampling design, data collection design, protocol development are criticalsteps in determining how information is collected and assessed. One common ground based field measurement framework is the implementation of Permanent Sample Plots (PSP), sometimes through a National Forest Inventory. Kiyono et al. (2011) notes that PSP's can be used to monitor changes in biomass due to degradation drivers, although the costs are predicted to be high. Temporary sample plots may be employed in forest strata based on risk of the occurrence of drivers and has been tested other tropical forest countries (Sandra Brown, pers. comm).

Inventory methods can employ a wide range of data collection procedures covering many variables. An analysis to assess accuracy and efficiency of forest density estimation was carried out in the south-central United States using six different methods (Sparks et al. 2002). Findings indicate that fixed-radius plots and the point-center quarter method were most accurate. However, when combining accuracy and efficiency, the variable-radius point sampling method was recommended for sampling stands with larger stems.

Other methods were also compared in high elevation forests of Tanzania to assess accuracy and efficiency in estimating levels of disturbance (Holck 2008). Results of data analysis by local participantswere compared to results from professionally trained scientists for two of the four methods in the analysis. It was determined that proper training can improve reliability of results, and that simplified methods also play a large part in accurate estimations. The four methods were assessed contextually to provide an overview of the pros and cons of each method (Table 12). Findings indicate costs can be kept low, butat the sacrifice of accuracy. The author noted that the Bitterlich angle gauge method was most suitable in this local context in Tanzania.

In the context of CCPF, this assessment showed that variable-radius plot sampling is easily employed in deciduous forests. Secondary evergreen and semi-evergreen forests pose a greater challenge. Re-growth tends to be thick with vines, bamboo, and a high stem density limiting visibility through angle gauge devices. It may be possible to use either fixed or variable-radius plots depending on forest type. The time efficiency of variable-radius plots in deciduous forest is a consideration if increasing sample size is an objective. Cambodia does not currently have a National Forest Inventory system of permanent sample plots (PSP's), though an NFI may be under development (FA 2011). Some PSP's do exist though these are scattered and do not seem to be well-coordinated (FA 2011). The largest source of plot data seems to have been generated for the Sustainable Forest Management Plan process, on the order of 6,000 plots. PSP's within CCPF may be an option depending on external funding levels, though the external funding would need to be committed through at least one full measurement cycle. Temporary sample plots may be more feasible, but would require proper forest type maps for good stratification. There are no current, publicly available, forest cover maps for CCPF. Any historical CCPF project maps would likely reside with the data developers. The 2010 national level forest cover map produced by the FA is not publicly available.

Table 12. An assessment of four forest inventory sampling methods to compare precision and cost-effectiveness.

	20 trees method	**Bitterlich angle gauge**	**Disturbance checklist**	**Permanent plots**
Costs (USD/ha/yr)	0.08 - 0.12	0.04	0.08 - 0.12	1.88
Pros	Easy Cost effective Equipment locally available	Easy Cost effective Equipment locally available Provides useful data on a short term scale	Easy Cost effective Equipment locally available Provides useful data on a short term scale	Provides scientifically precisedata Detects long term changes Can also be used for biodiversity studies
Cons	Less precise More time consuming Needs many samples Not shown as capable of describing disturbance	Less precise Requires training Results can by the individual recording the measurements	Less precise Requires training Requires a team of least 3 people Need to develop biomass relationships **	Number of plots needed is high Expert needed for identification Relatively expensive Very time consuming Not suitable for short term disturbance monitoring

** Added by J. Halperin.

Modeling and integration of ground based field measurements with other data

Models which apply to forests and forest dynamics in Cambodia are scant (FA 2011). There have been two notable attempts to develop models of forest degradation spatial extent, using buffers on existing infrastructure and villages/towns. For the Independent Forest Sector Review, Ashwell et al. (2004) developed a basic buffer model of potential forest degradation at the national level. A study commissioned by the Wildlife Alliance created a spatial model of forest disturbance specific to the nearby Southern Cardamoms Ecosystem (Grogan et al. 2009). The latter study also used the basic buffer model but with refinements. Buffer zones for both efforts were determined based on expert opinion. Definitions of both are included for comparative purposes (Table 13).

According to a recent buffer model of potential forest degradation extent in the nearby Southern Cardamoms ecosystem, 38% of the total forest area lies within the 'Disturbed forest' class and 54% of the total forest area is either 'Disturbed forest' or 'Less Disturbed forest' (Grogan et al. 2009). This ratio is consistent with a nation-wide buffer zone analysis of protected areas performed by Ashwell et al. (2004). They found that approximately 50% of all protected areas lie within degraded buffer zones. The

Table 13. Buffer zones to assess extent of possible forest disturbance in Cambodia.

Author	Zone class	Zone definition	Buffer definition
Ashwell et al. 2004	Level 1: Low degradation	Untouched by a buffer	Forest outside a buffer area
	Level 2: Some degradation	Within a road or track buffer	1.5 km
	Level 3: Moderate degradation	Within a village buffer	5 km
	Level 4: Heavy degradation	Within both road and village buffer	Intersection of road/track & village
Grogan et al. 2009	Intact forest	Untouched by a buffer	Forest outside a buffer area
	Les s disturbed forest	60 – 80% of biomass in intact forest of a given forest type	Main road: 1 – 1.5km Track: 500 – 1000 m Village: 2.5 – 5 km
	Disturbed forest	< 60% of biomass in intact forest of a given forest type	Main road: < 1km Track: < 500 m Village < 2.5 km

two models had similar results despite the fact that different baseline forest cover maps were used. Neither of these models attempted to quantify biomass or carbon loss resulting from forest degradation. Rather, the models attempted to develop rough estimates of biomass stocks within forest condition classes.

Conservation International's program of assisting FA rangers in CCPF is comprehensive. CI works to help the rangers record data regarding incidents of illegal logging within CCPF, including GPS coordinates. This information could be correlated with the buffer zone analyses above in order to confirm the zone areas or identify a need to re-assess past thinking. Other established techniques, such as classification and regression trees (e.g. CART, Random Forests) or geospatial predictive modeling (e.g. Maxent) could potentially make use of locally derived data on degradation activities in combination with biomass estimates from plots to develop a more robust and quantitative risk stratification model.

Efficiently developing a predictive model involves the development of an ecological conceptual model as an initial 'working hypothesis' that will inform the types of data that will be required for both predictor and dependent variables. Some modeling techniques can predict a continuous variable (e.g. ,m^3/ha or tons C/ha) which could potentially be used to estimate changes in forest biomass over time according to spatial relationships with degradation activities, assuming appropriate data are available. For example, Classification and Regression Trees (CART) is a statistical technique that analyzes multiple independent variables to predict a dependent variable. The results can then be used to assign values to mapping units with similar conditions across a landscape. CART approaches have been used to successfully estimate biomass at national scales (Blackard et al 2008) and at sub-national scales (Main-Knorn et al. 2011).

Classification and regression decision trees attempt to predict the values of a dependent target variable from one or more continuous and/or categorical independent variables. For example, we may want to predict a continuous dependent variable (e.g. the biomass volume of a degraded forest) from various other continuous predictors (e.g., distance from roads, population density, poverty rate, etc.) as well as categorical predictors (e.g., forest type, disturbance type, land ownership, etc.). Classification trees attempt to predict categorical dependent variable (e.g. forest disturbance risk class) from one or more continuous and/or categorical predictor variables, such as the ones listed above. The main weakness of a decision-tree approach is that it is not able to generate confidence intervals. At this time, this is not seen as a major drawback because the accuracy and precision can be addressed through assessment of model uncertainty through error estimates using a test dataset.

Random Forests is a robustvariant of decision-tree modeling that provides well-supported predictions (Brieman 2001). Random Forestmodels consist of many independent regression trees, where for each regression tree, a bootstrap sample of the training data is chosen. At the root node, a small random sample of explanatory variables is selected and the best split made using that limited set of variables. At each subsequent node, another small random sample of the explanatory variables is chosen, and the best split made. The regression tree continues to grow until it reaches the largest possible size, and is left un-pruned. The whole process is often repeated based on new bootstrap samples. The final prediction is a weighted plurality vote or the average from predicting all regression trees. RF has the ability to deal with non-linearity between predictors as well as with missing values, which are handled effectively and with minimal loss of information.

Maximum entropy (Maxent) is a general purpose machine-learning algorithm that was developed to model species' geographic distributions based on the relationship between species occurrences and environmental variables (Phillips et al. 2006). Maxent produces a continuous probability distribution of species presence within the study area, represented by a spatial grid of cells. Each cell in the grid is given a value between 0 and 1, with 0 indicating no probability of occurrence and 1 indicating absolute certainty of occurrence. Unlike some similar modeling algorithms, Maxent requires only presence data (known locations where a species occurs) and does not require reliable, unbiased absence data (known locations where a species does not occur), which are seldom available and difficult to obtain. Maxent also allows the analysis of both continuous and categorical environmental data. Although analysis based on only a few presence locations for a species relative to the study area size may negatively influence model fitness and accuracy. However, Maxent generally works well with smaller data sets; some studies have indicated that Maxent is capable of producing useful modeling results with as few as 5 presence locations (Hernandez et al 2006).

There are number of other statistical and geospatial methods for analyzing both regression and classification type problems. However, decision-tree and machine-learning techniques have some potential advantages over other methods, including simplicity of results that can more easily be interpreted due to its logical 'if-then' conditions (tree nodes, or branches), and no implicit assumption that the underlying relationships between the predictor variables and the dependent variable are linearor that they are even monotonic in nature. These methods can often reveal simple relationships between just a few variables even when there is often little a priori knowledge nor any coherent set of theories or predictions regarding which variables are related and how (Brieman 2001, Phillips et al. 2006).

Comparison of monitoring method feasibility

The need to assess multiple criteria across monitoring metrics is a challenging task. Multiple participants, levels of capacity, approaches, systems, data, research, feasibility all play a role in the potential success of any monitoring system. In order to facilitate this assessment, a simple ranking system was developed for quantifying potential success based on information presented in this report (Table 14). There are six criteria, each scored between 0 – 3. The highest possible score would be 18.

Table 14. Ranking of approaches that are relevant to conditions in the Central Cardamoms Protected Forest. Definitions for criteria are listed below.

APPROACH	METRIC	TECHNICAL DIFFICULTY	EXISTING CAPACITY	SUSTAINABILITY	EXISTING RESEARCH	POSSIBLE TO USE FOR HISTORICAL	USE IN MRV SYSTEM	TOTAL
Forest inventory: PSPand/or TSP Category 2*	t C/ha	2	1	0	1	0	2	6
Forest inventory: PSP and/or TSP Category 3*	t C/ha	2	1	2	1	0	2	8
Modeling	t C/ha in buffer zones	2	2	2	1	1	3	11
Remote sensing: med resolution	ha (provincial level)	2	0	2	2	2	1	9
Remote sensing: med resolution	ha (FMU level)	3	1	1	2	2	1	10
Remote sensing: high resolution	ha (FMU level)	3	1	1	3	1	1	10
Remote sensing: CLASLite + LiDAR	ha + t C/ha	1	0	0	0	0	1	2

Technical difficulty: 0 – impossible, 1 – high, 2 – medium, 3 – low
Existing capacity (human resources and institutional capacity at sub-national levels): 0 – none, 1 – low, 2 – medium, 3 – high
Sustainability (ownership by stakeholders, financing commitments): 0 – not sustainable, 1 – low, 2 – medium, 3 - high
Existing research: 0 - no data or previous research in the Mekong; 1 - one to two initiatives to pilot a similar approach in Cambodia and/or another Mekong country; 2 - more than three initiatives in the Mekong region AND at least one similar initative in the province/country; 3 - two or more similar initiatives in the province/country
Possible to use for historical (possibility to use for generation of historical reference emission levels): 0 - not possible to develop; 1 - at least one historical reference point OR at least two historical reference points where uncertainty is unknown; 2 - at least 2 historical reference points where uncertainty has been assessed
Use in MRV system (potential to be incorporated into MRV systems for assessing change in biomass): 0 – not possible, 1 – low, 2 – medium, 3 – high
* **Category 2 - External**: data collection led by outsiders, analysis, and use of findings done without involving stakeholders (other than delivery of a report)
*** Category 3 - Collaborative PFM**: a step-wise approach to data collection, analysis, and use of findings that involves capacity building and awareness raising of local stakeholders

A predictive modeling approach, using degradation risk stratification and ‘gain-loss’ accounting, scores the highest amongst all options considered. This is because there is a functioning process where forest rangers collect frequent data on degradation drivers while on patrol. Developing such a model so that it can reliably and accurately predict changes in biomass that is dependent on this information could be challenging. However, because ranger patrols are embedded into current institutional structures, this data-collection approach could have potential for expanding their usefulness beyond law enforcement.

Among all the approaches, remote sensing technical difficulty could be considered to be the lowest. This is especially the case if visual interpretation approaches are considered using high resolution imagery. However, thorough consideration by leading experts in the Asia region indicates that forest degradation monitoring using medium and high resolution imagery is only ‘partially possible’ (Kiyono et al. 2011). Care must be taken to account for challenges of persistent cloud cover, geo-location of multiple-date imagery, and terrain correction. The need to include thorough and transparent accuracy assessments in any remote sensing program must also be considered.

Kiyono et al. (2011) indicated that LiDAR is a possible tool for monitoring forest structure changes due to degradation drivers. However, he indicated that large area LiDAR acquisition is very difficult. One way to scale up the use of LiDAR is the Asner approach that combines LiDAR and CLASLite. However, given current national and sub-national capacities, this approach scored the lowest among all options. This approach has not been demonstrated in Mekong or in the Asia region, and its start-up cost is very high when compared to other approaches.

Ground-based forest inventory approaches applied alone can be used to develop area based estimates of volume or biomass, commonly called a ‘stock-difference’ or direct approach. Inventory that combines a Category 3 step-wise approach scores higher than a Category 2 externally led approach. External-only and local-only approaches are not possible as there must be some integration between external forest inventory experts and the FA. Current capacity within FA is low, considering any approach.