BIOREDD+ Program

DELIVERABLE 13: SETUP OF MRV MECHANISM FOR FUTURE MONITORING

Subcontract number: EEP-I-00-06-00013-00-GEM-00
Name: GeoEcoMap Inc.

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1. Statement of task 11

This document summarizes the climate impact monitoring plan for the BioREDD projects in the Pacific Coast of Colombia and the step-by-step approach for future monitoring of carbon stock change and deforestation and degradation using a combination of ground and remote sensing observations. In accordance with VM0006 methodology and VCS AFOLU requirements, the BioREDD project will be using the Verified Carbon Standard methodology for the quantification of carbon stocks and net emission reductions, as well as comprehensive satellite imagery analysis, led by GeoEcoMap, Inc. GIS/Remote Sensing Specialist. An on-the-ground Plot Team comprised of community members have received extensive training on measuring forest carbon stocks and in carrying out Monitoring, Verification and Reporting (MRV) using a combination of hand-held technology for measurements and data recording. Additionally, BioREDD will be developing a community-based digital biomass collection systems for systematic and transparent monitoring of changes associated with the implementation of the REDD+ project. The remote sensing monitoring system will make use of satellite Radar and optical imagery. Monitoring will include project areas, reference areas, and areas classified as potential leakage regions. The mechanism for future monitoring of the land use change will be divided into three steps: 1. Annual monitoring of deforestation and degradation. 2. Annual monitoring forest regeneration and afforestation. 3. Annual monitoring of deforestation and degradation in areas of potential leakage.

2. Background and General Methodology

Number of BioREDD Projects

The BioREDD project selected eight areas along the Pacific coastal region of Colombia for developing REDD+ projects (Figure 1).

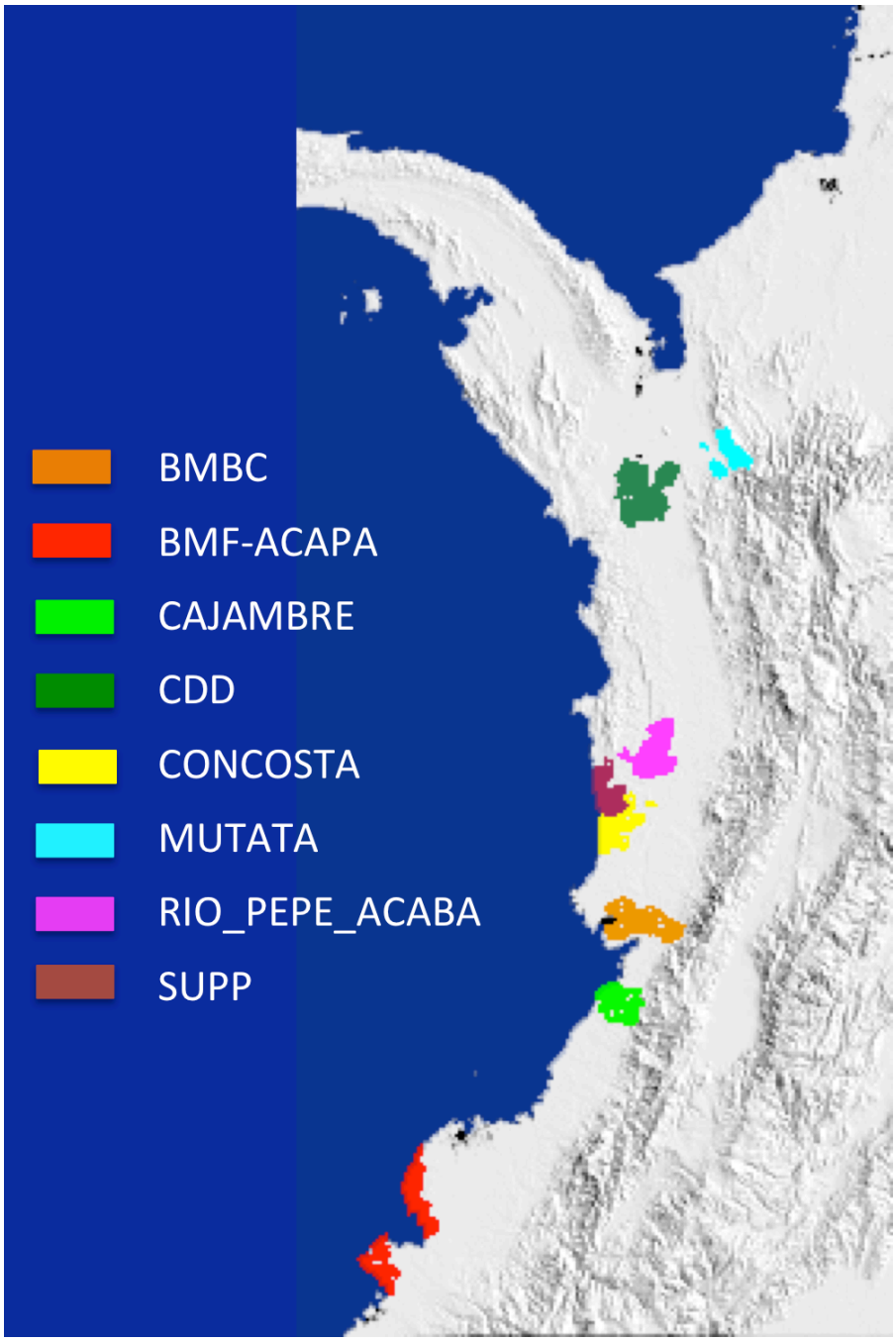

Figure 1. Location of 8 BioREDD project areas along the Pacific Coast of Colombia.

Spatial Boundaries of the Project Areas

The project areas are located along the Pacific Coast of Colombia and in most low elevation areas where human activities have created a partially deforested and degraded landscape around towns and indigenous communities. All shape files of project areas along with reference and leakage areas have been identified for the project documents and REDD+ implementation for the validation and verification for pubic investments. All GIS layers are available for validators and for groups who are interested to perform the future monitoring of the project.

For each project area, a reference region was selected to assess historical and current deforestation and forest degradation quantities and trends for the Project Area baseline according to the process set out by VCS Methodology VM0006 v2.1. Variables considered in selecting the Reference Region location were: (1) forest laws and policies, (2) land use history and dynamics (e.g. forest cover, agricultural systems), (3) ecological conditions (forest types present and climatic conditions), and (4) social conditions. The VM0006 methodology requires that the minimum size of the Reference Region excluding the Project Area and Leakage Area must be 250,000 ha or the size of the Project Area at the start of the crediting period, whichever is greater. The following conditions are required to ensure the Reference Area is representative and unbiased and these conditions are monitored throughout the project.

Minimum size: As required by the methodology, the Reference Region excluding the Project Area and Leakage Area is 250,000 ha. The Exclusive Reference regions for each project area are provided in other documents. 1) Boundaries unbiased: The boundaries of the Reference Region coincide with buffered Protected Area boundaries. 2) Accessible by agents of deforestation: The Reference Region excludes the interior core of Protected Areas (areas with distances greater than 5 km inside the Protected Area boundaries) where agents of deforestation have restricted access. Remaining areas are accessible by agents of deforestation. 3) Planned deforestation areas excluded: No known planned deforestation areas contained within the Reference Region. 4) Natural deforestation areas excluded: No historic causes of spatially constrained natural deforestation observed within the Reference Region.

Spatial Boundaries of Leakage Areas

The Leakage Area was selected to be sufficiently large to encompass all forests around the Project Areas that could be under higher pressure from deforestation displaced by Project activities during the project's lifetime. The location was selected by taking into account the "cost" local agents of deforestation would need to incur to move their activities. It is assumed that leakage will only occur when the cost to displace the deforestation activity is below a certain threshold or is less than alternative resources. To select the extent of the Leakage Area, this threshold was set conservatively by using the maximum distance travelled for forest products, 10 km, as reported in the Participatory Rural Appraisals. Leakage from drivers of deforestation that are not constrained by geography is discounted by using a factor approach
The cost distance analysis was conducted using the Spatial Analyst extension for ArcGIS software. This process requires a Cost Weight surface and the source(s) of displacement, which are the Project Areas. During the monitoring phase the changes of forest cover and their carbon content will be reported annually.

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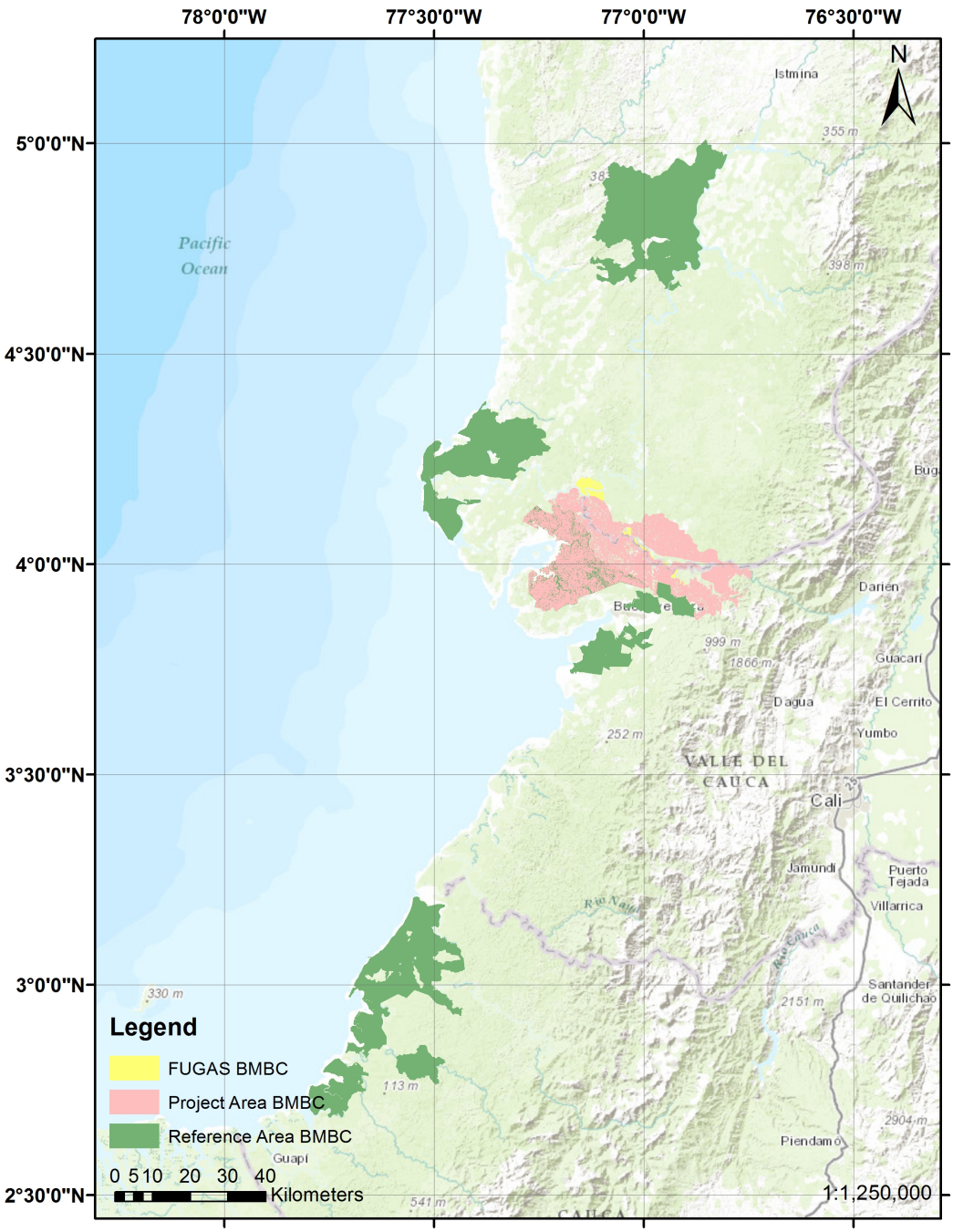

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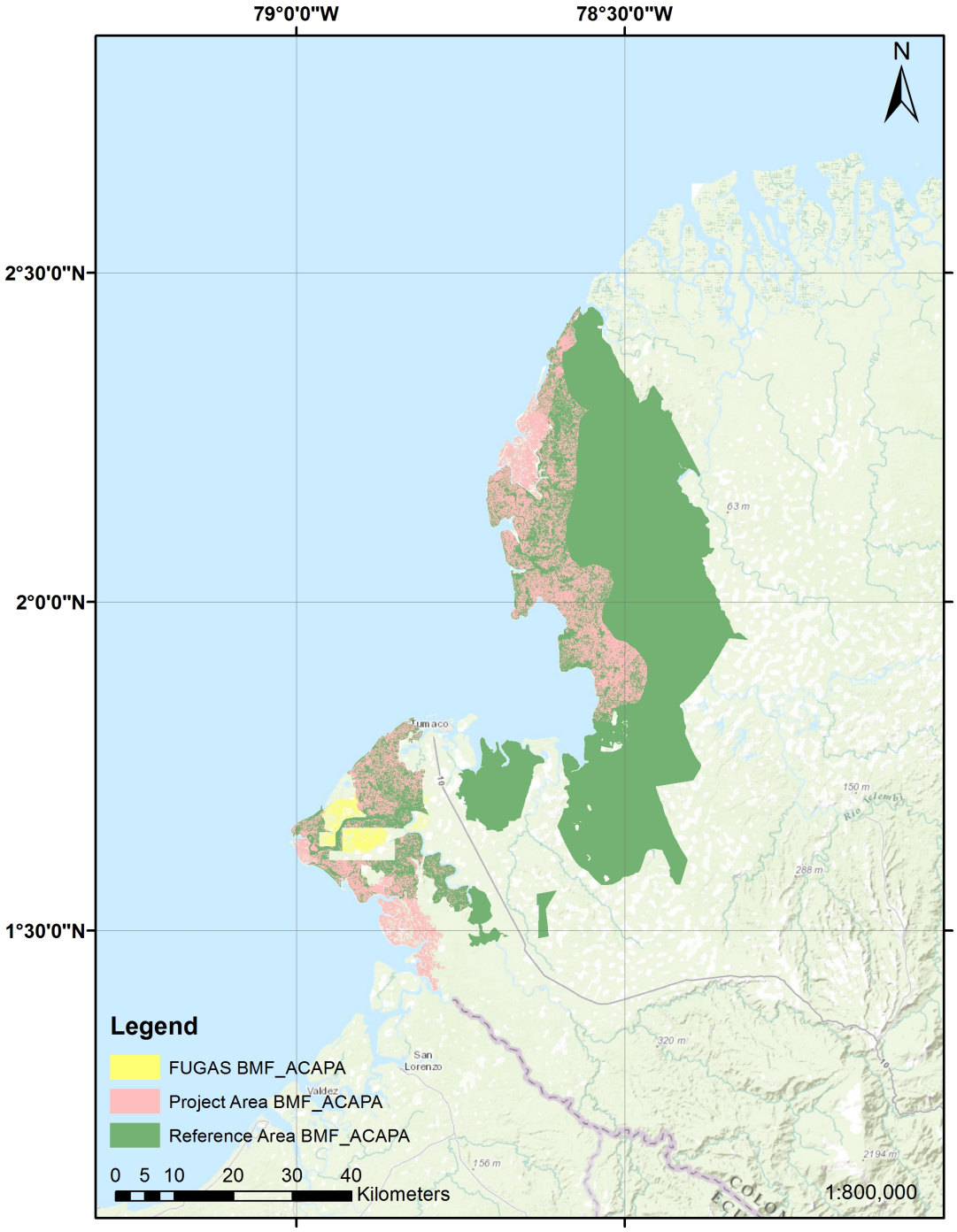

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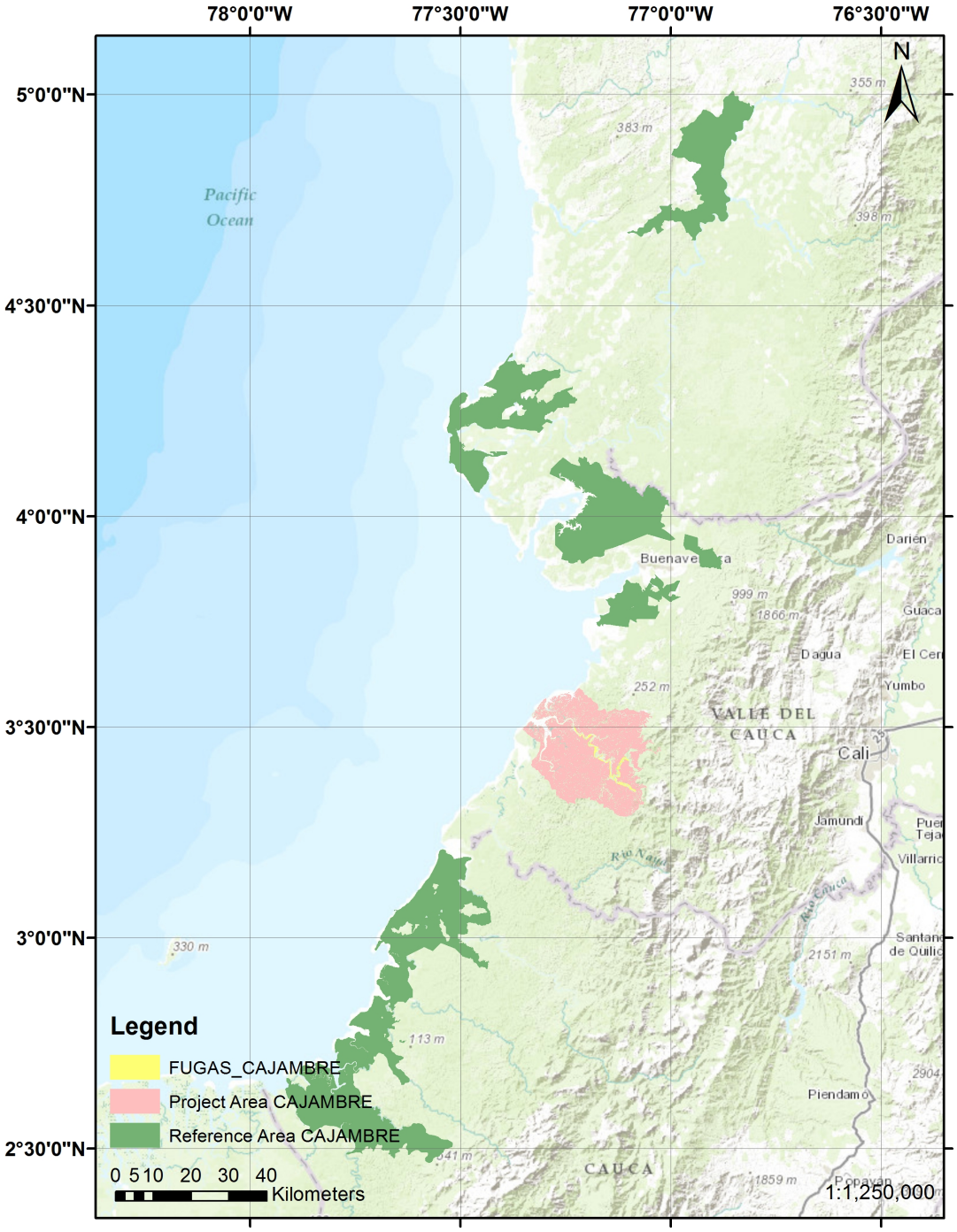

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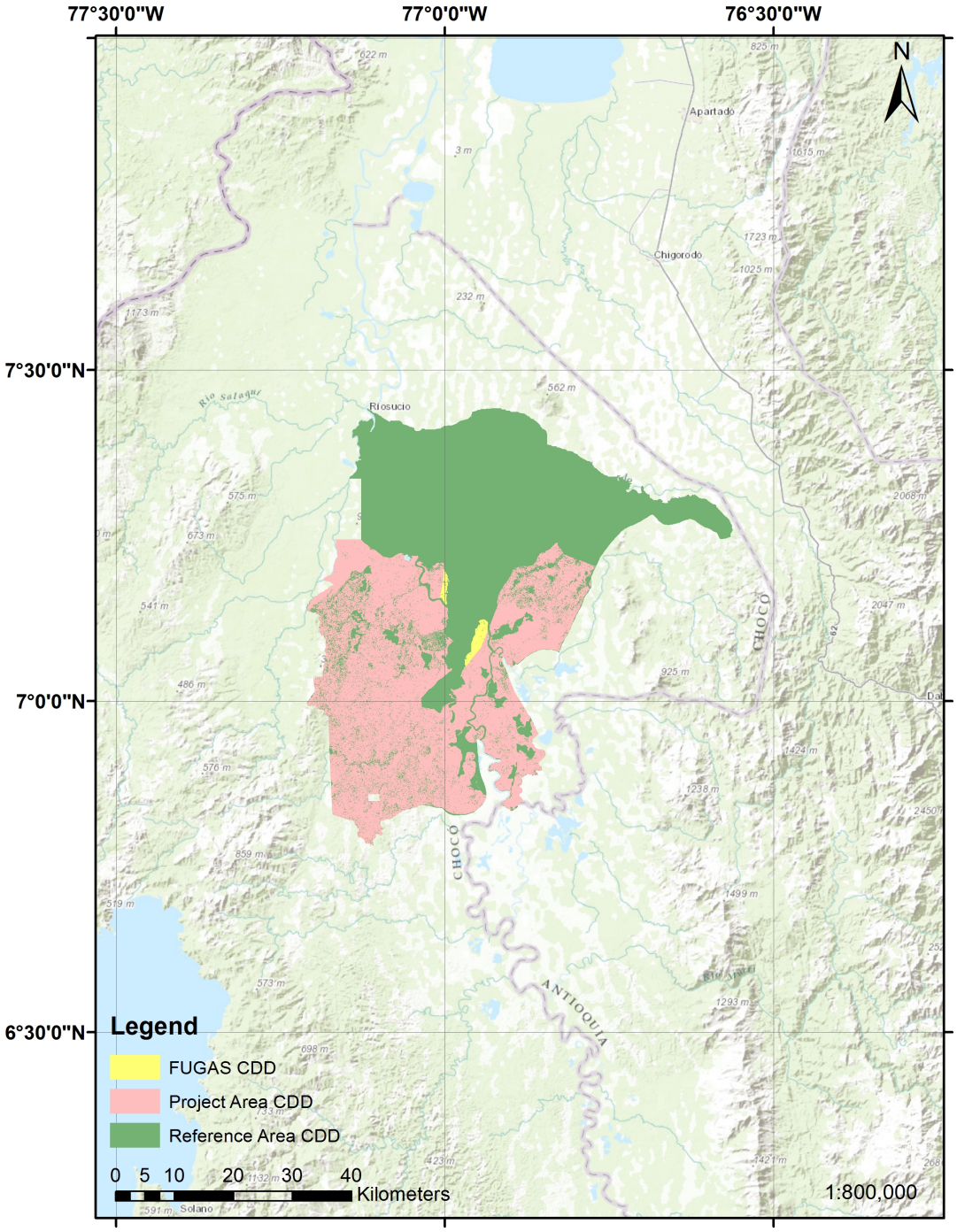

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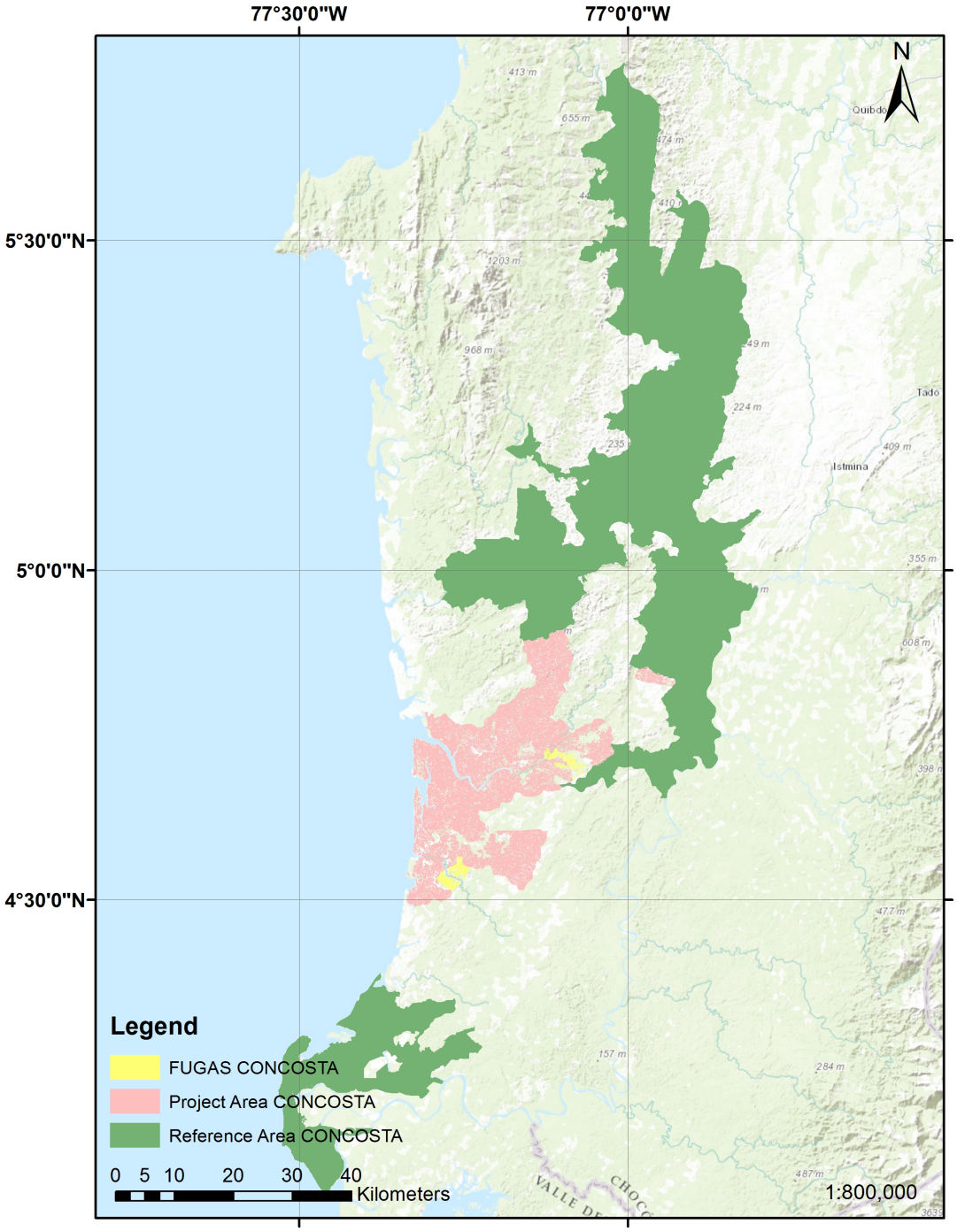

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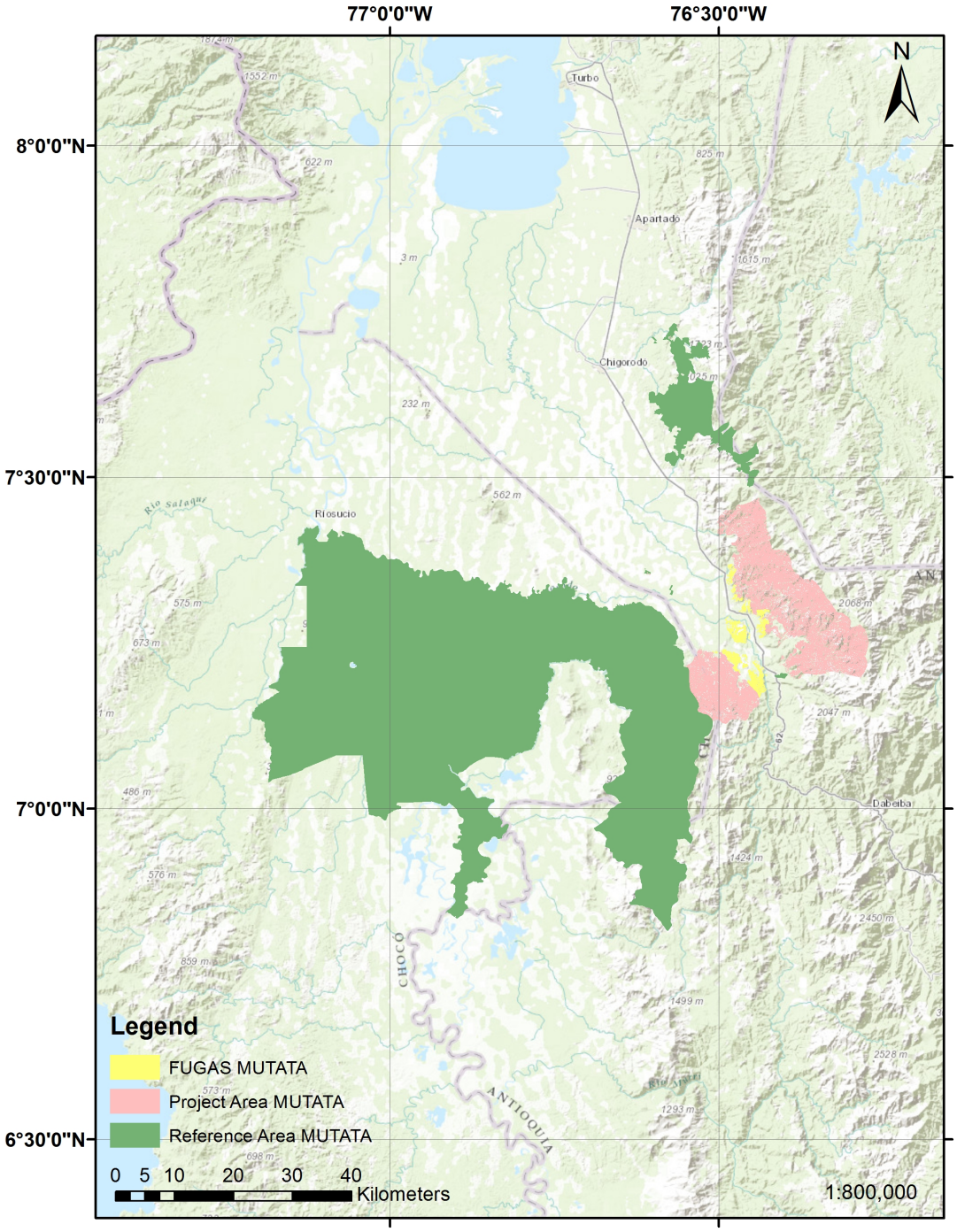

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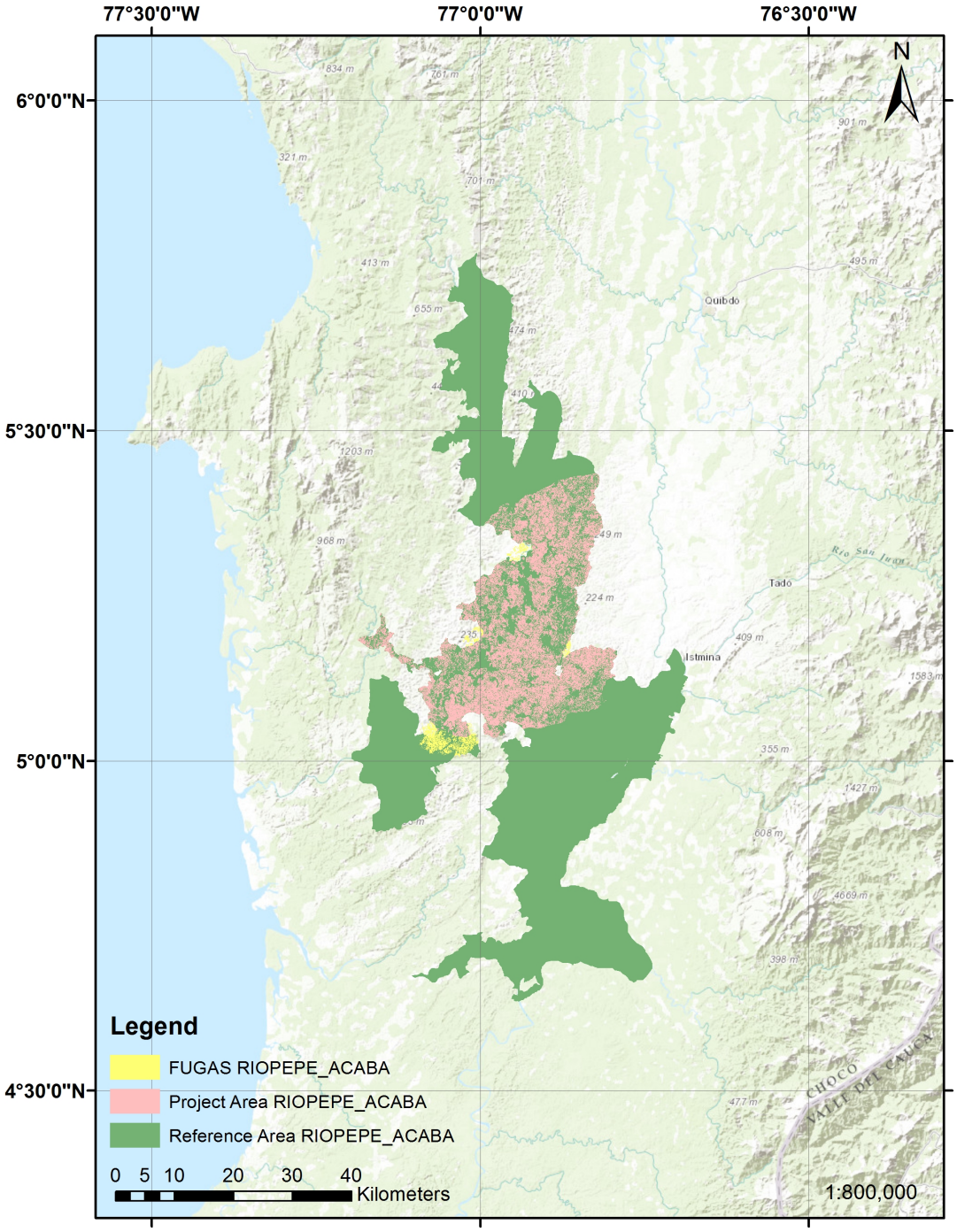

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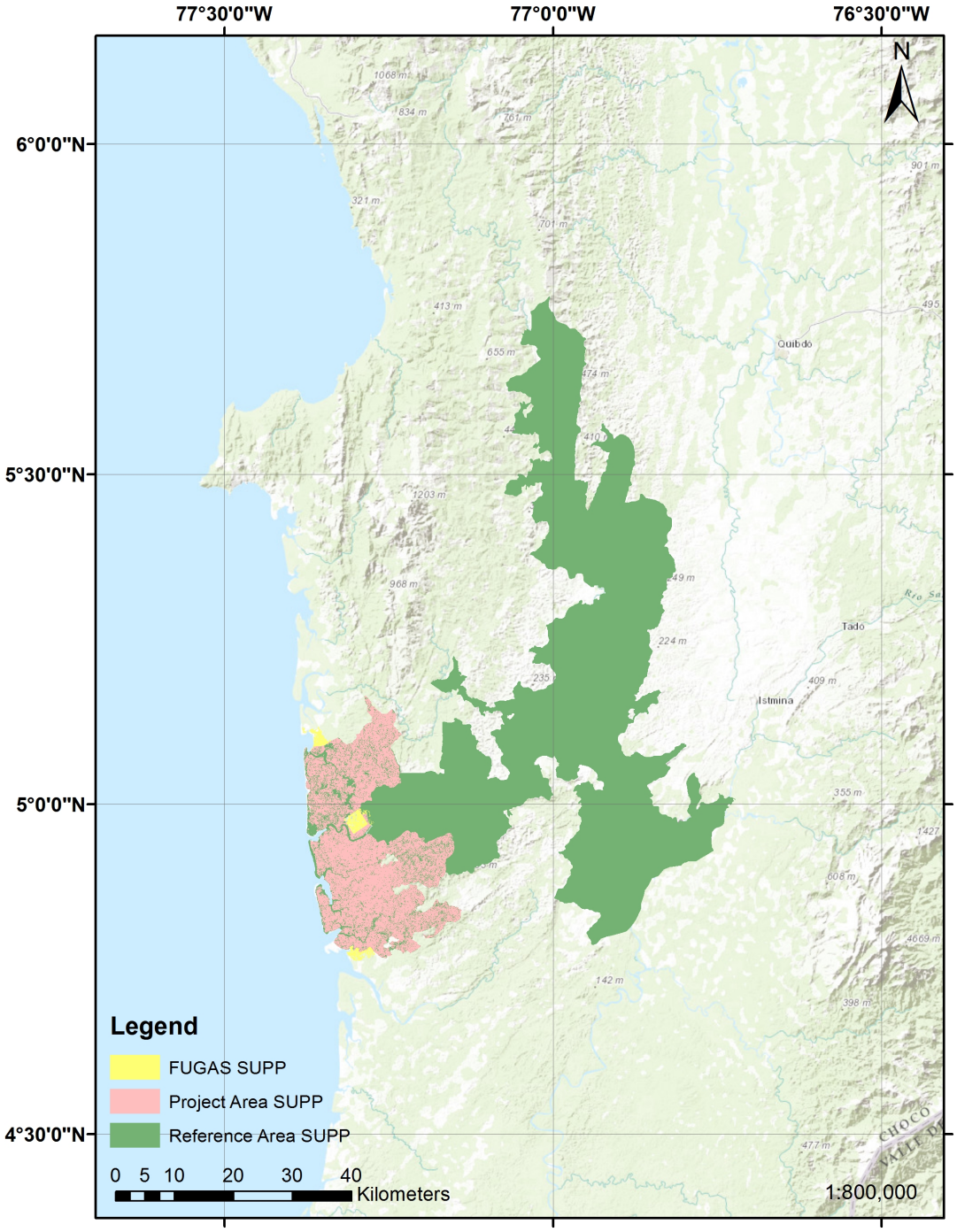


Temporal Boundaries of the Project
The temporal boundaries of the project are as follows:
Historical reference period: 1990 - 2012

Project crediting period: 30 years (2013 – 2043)

Verification frequency: annual to periodic

Frequency of baseline update: 10 years

3. Climate Impact Monitoring

Climate benefits will be determined and monitored in accordance with VM0006 v2.1 using remote sensing and permanent forest plots. Details on these procedures are included in the Remote Sensing and Forest Measurement SOPs.

3.1 Data and Parameters Available at Validation

The following data and parameters are defined for standalone projects. For projects that are nested within a jurisdictional REDD+ program, at the time of validation the project will identify any data or parameters in the project document, if any, that will be adopted from the jurisdictional REDD+ program.The parameters listed here are required for validation. Some of these values have not been filled in due to missing information.

Data/parameter [EA1]:	CF
Data unit:	[Mg C (Mg DM)$^{-1}$]
Description:	Carbon fraction of dry matter in wood
Sources of data:	Default value of 0.5 (IPCC GPG-LULUCF 2003)
Value applied:	0.5
Justification of choice of data or description of measurement methods and procedures applied:	According to the IPCC, the default value of 0.5 Mg C (Mg DM)^-1 is applicable for all three tiers when remaining forest land, forest land or biomass carbon is a key or non-key category.
Any comment:	

Data/parameter [EA2]:	E
Data unit:	[-]
Description:	Average combustion efficiency of the aboveground tree biomass
Sources of data (*):	Project-specific measurements Regionally valid estimates Estimates from Table 3.A.14 of IPCC GPG LULUCF If no appropriate combustion efficiency can be used, use the IPCC default of 0.5
Value applied:	0.3
Justification of choice of data or description of measurement methods and procedures applied:	IPCC 2006 gives this value for tropical moist primary forest types.
Any comment:	The value of 0.40 is provided as an average combustion efficient for aboveground tree biomass in tropical moist secondary forests.

Data/parameter [EA3]:	P
Data unit:	[-]
Description:	Average proportion of mass burned from the aboveground tree biomass.
Sources of data:	GPG-LULUCF Table 3A.1.13
Value applied:	83.9
Justification of choice of data or description of measurement methods and procedures applied:	83.9 is the mean provided by the IPCC for the average proportion of mass burned from the aboveground tree biomass in primary tropical forests which is the forest type the project for the most part, aligns with.
Any comment:	For secondary tropical forests, 8.1 is provided as an average

	value for young secondary tropical forests, 41.1 for intermediate secondary tropical forests, and 46.4 for advanced secondary tropical forests. These are provided here because some of growth within the project area is secondary but as a majority, it is still primary forest.

Data/parameter [EA4]:	sc_1
Data unit:	[-]
Description:	First shape factor for the forest scarcity equation; steepness of the decrease in deforestation rate (greater is steeper).
Sources of data:	Statistical fitting procedure. Using remotely sensed forest cover data in heavily deforested areas close to the project area such as neighboring provinces, states or countries
Value applied:	
Justification of choice of data or description of measurement methods and procedures applied:	Use procedure from VM0006 v2.1
Any comment:	

Data/parameter [EA5]:	sc_2
Data unit:	[-]
Description:	Second shape factor for the forest scarcity equation; relative deforested area at which the deforestation rate will be 50% of the initial deforestation rate.
Sources of data:	Statistical fitting procedure. Using remotely sensed forest cover data in heavily deforested areas close to the project area such as neighboring provinces, states or countries
Value applied:	
Justification of choice of data or description of measurement methods and procedures applied:	Use procedure from VM0006 v2.1
Any comment:	

Data/parameter [EA6]:	$wwf(ty)$
Data unit:	[-]
Description:	Fraction of carbon in harvested wood products that are emitted

	immediately because of mill inefficiency for wood class ty. This can be estimated by multiplying the applicable fraction to the total amount of carbon in different harvested wood product category.
Sources of data:	The default applicable fraction is 24% and 19% respectively for developing and developed countries (Winjum et al. 1998).
Value applied:	24%
Justification of choice of data or description of measurement methods and procedures applied:	Winjum et al. 1998 states that the default fraction is 24% for developing countries.
Any comment:	Any new updates from locally generated results can be used instead of the default values.

Data/parameter [EA7]:	$slp(ty)$
Data unit:	[-]
Description:	Proportion of short lived products
Sources of data:	Default values are 0.2, 0.1, 0.4 and 0.3 respectively for wood class ty, i.e., sawnwood, wood-based panel, paper and paper boards and other industrial round woods as described in Winjum et al. (1998).
Value applied:	0.2
Justification of choice of data or description of measurement methods and procedures applied:	Winjum et al. provides the above values for sawnwood, wood-based panel, paper/paper boards and industrial roundwood
Any comment:	Any new updates from locally generated results can be used instead of the default values. The methodology assumes that all other classes of wood products are emitted within 5 years.

Data/parameter [EA8]:	$fo(ty)$
Data unit:	[-]
Description:	Fraction of carbon that will be emitted to the atmosphere between 5 and 100 years of harvest for wood class ty.
Sources of data:	See (Winjum et al. 1998).
Value applied:	0.84
Justification of choice of data	Winjum et al. provides these values for the fraction of carbon

or description of measurement methods and procedures applied:	that will be emitted into the atmosphere between 5 and 100 years after harvest for tropical wood classes.
Any comment:	Any new updates from locally generated results can be used instead of the default values.

Data/parameter [EA9]:	$\rho_{wood,j}$
Data unit:	[Mg DM m^{-3}]
Description:	Average basic wood density of species or species group j
Sources of data:	GPG-LULUCF Table 3A.1.9. or published data/literature.
Value applied:	Average wood density values for BioREDD region and each project area are provided in Appendix on Carbon pools and stocks. BioREDD project measured wood density for dominant species in Pacific coastal regions of Colombia
Justification of choice of data or description of measurement methods and procedures applied:	We compared the local data with IPCC table 3A. 1.9-2 that provides average basic wood densities for multiple species in tropical America and found local measurements more relevant to the project because of differences in soil, climate, and biogeography.
Any comment:	

3.2 Data and Parameters Monitored

The following data and parameters will be monitored by the BioREDD monitoring teams prior each verification event. These parameters have been selected to correspond to the requirements of VM0006 and the outputs and outcomes of the theory of change model. The following section sumamrizes the methodology for monitoring along with data sources for each parameter categories. In this report, we focus on three parameter categories:

1. Sizes, Areas, and Transitions
2. Land cover and Land Use and Transitions
3. Carbon Changes (loss and regeneration)

Details on data and parameters monitored are provided below. We provide the general methodology with specific measurement and monitoring approach. We also leave some flexibility in measurement and monitoring approach, essential for any longterm monitoring, reporting and verification (MRV) plan.

Data/parameter [MN1]:	$size_{projectArea}$, $size_{leakageArea}$. $size_{referenceregion}$, $size_{referenceForest}$
Data unit:	[ha]
Description:	Size of project area, leakage area, reference region, and forest area in the reference region
Sources of data:	Project design
Description of measurement methods and procedures to be applied:	Coverage and demarcations will be monitored and created through the use of satellite imagery and on-the-ground monitoring teams making observations and taking measurements in terms of forest cover, class cover, total area and tree classifications.
Frequency of monitoring/recording:	$size_{projectArea}$ and $size_{leakageArea}$ may be adjusted during crediting period per the rules for grouped projects and updated at verification, but only for the additional instances that were added after the project start date.
Value applied:	
Monitoring equipment:	GIS software, Landsat and radar imagery, 30 meter tape, GPS, compass, clinometer, notebooks, water, writing utensils
QA/QC procedures to be applied:	
Calculation method:	
Any comment:	

Data/parameter [MN2]:	$\Delta area_{projectAreaEAH,projectScenario}(t,i)$
Data unit:	[ha yr^{-1}]
Description:	Hectares undergoing transition i within the project area, excluding ANR and harvest areas, under the project scenario during year t. [ha yr^{-1}].
Sources of data:	Remote sensing analysis
Description of measurement methods and procedures to be applied:	Procedures are provided in the climate monitoring plan of BioREDD project provided by GeoEcoMap, Inc.
Frequency of monitoring/recording:	At least once before verification
Value applied:	
Monitoring equipment:	GIS software, Landsat and radar imagery, 30 meter tape, GPS, compass, clinometer, notebooks, water, writing utensils
QA/QC procedures to be	Data is to be entered into internal archive. Archive is accessed by qualified, authorized technical experts. All documents for

applied:	monitoring, validation, verification and certification are reviewed and signed off by several team members. Data will be reported to project proponents and stakeholders. Discrepancies or disagreements will be justified by explanation or by visitation of the activities in question. All available satellite data for monitoring, validation, verification and certification will be archived and made available to auditors.
Calculation method:	
Any comment:	

Data/parameter [MN3]:	$\Delta area_{projectAreaEAH,baselineScenario}(t,i)$
Data unit:	[ha yr^{-1}]
Description:	Hectares undergoing transition i within the project area, excluding the ANR area, and harvest areas, under the baseline scenario for year t.
Sources of data:	Land-use change modeling
Description of measurement methods and procedures to be applied:	Procedures should be described in the BioREDD project Monitoring plan developed by GeoEcoMap, Inc.
Frequency of monitoring/recording:	At least once before every baseline. For added instances, may be recalculated at verification.
Value applied:	
Monitoring equipment:	GIS software, Landsat and radar imagery, 30 meter tape, GPS, compass, clinometer, notebooks, water, writing utensils
QA/QC procedures to be applied:	Data is to be entered into internal archive. Archive is accessed by qualified, authorized technical experts. All documents for monitoring, validation, verification and certification are reviewed and signed off by several team members. Data will be reported to project proponents and stakeholders. Discrepancies or disagreements will be justified by explanation or by visitation of the activities in question. All available satellite data for monitoring, validation, verification and certification will be archived and made available to auditors.
Calculation method:	
Any comment:	

Data/parameter [MN4]:	$\Delta area_{projectAreaWithANR,baselineScenario}(t,i)$
Data unit:	[ha yr^{-1}]
Description:	Hectares undergoing transition i within the leakage area under

	the project scenario for year t.
Sources of data:	
Description of measurement methods and procedures to be applied:	Procedures should be described in the BioREDD project Monitoring plan developed by GeoEcoMap, Inc.
Frequency of monitoring/recording:	Annual to ≤ 5 years
Value applied:	
Monitoring equipment:	GIS software, Landsat and radar imagery, 30 meter tape, GPS, compass, clinometer, notebooks, water, writing utensils
QA/QC procedures to be applied:	
Calculation method:	
Any comment:	Only applicable if project proponent decides to include ANR activities.

Data/parameter [MN5]:	$\Delta area_{leakageArea,projectScenario}(t,i)$
Data unit:	[ha yr^{-1}]
Description:	Hectares undergoing transition i within the leakage area under the project scenario for year t
Sources of data:	Remote sensing analysis
Description of measurement methods and procedures to be applied:	Procedures should be described in the Monitoring Report
Frequency of monitoring/recording:	At least once before verification
Value applied:	
Monitoring equipment:	GIS software, Landsat imagery, 30 meter tape, GPS, compass, clinometer, notebooks, water, writing utensils
QA/QC procedures to be applied:	Data is to be entered into internal archive. Archive is accessed by qualified, authorized technical experts. All documents for monitoring, validation, verification and certification are reviewed and signed off by several team members. Data will be reported to project proponents and stakeholders. Discrepancies or disagreements will be justified by explanation or by visitation of the activities in question. All available satellite data for monitoring, validation, verification and certification will be archived and made available to auditors.
Calculation method:	

Any comment:	

Data/parameter [MN6]:	$\Delta area_{leakageArea,baselineScenario}(t,i)$
Data unit:	[ha yr^{-1}]
Description:	Hectares undergoing transition i within the leakage area under the baseline scenario during year t
Sources of data:	Land-use change modeling
Description of measurement methods and procedures to be applied:	Procedures should be described in the Monitoring Report
Frequency of monitoring/recording:	Once every baseline update. May also be updated at the time of instance inclusion that requires new leakage area.
Value applied:	
Monitoring equipment:	GIS software, Landsat imagery, 30 meter tape, GPS, compass, clinometer, notebooks, water, writing utensils
QA/QC procedures to be applied:	Data is to be entered into internal archive. Archive is accessed by qualified, authorized technical experts. All documents for monitoring, validation, verification and certification are reviewed and signed off by several team members. Data will be reported to project proponents and stakeholders. Discrepancies or disagreements will be justified by explanation or by visitation of the activities in question. All available satellite data for monitoring, validation, verification and certification will be archived and made available to auditors.
Calculation method:	
Any comment:	

Data/parameter [MN7]:	$\Delta area_{historical}(CS_1 \rightarrow CS_2, t_1 \rightarrow t_2)$
Data unit:	[ha yr^{-1}]
Description:	Area of transition from LULC class or forest stratum 1 to 2 from time 1 to 2 during the historical reference period
Sources of data:	Remote sensing analysis
Description of measurement methods and procedures to be applied:	Procedures should be described in the Monitoring Report
Frequency of monitoring/recording:	At least once before every baseline update
Value applied:	
Monitoring equipment:	GIS software, Landsat imagery, 30 meter tape, GPS, compass,

	clinometer, notebooks, water, writing utensils
QA/QC procedures to be applied:	Data is to be entered into internal archive. Archive is accessed by qualified, authorized technical experts. All documents for monitoring, validation, verification and certification are reviewed and signed off by several team members. Data will be reported to project proponents and stakeholders. Discrepancies or disagreements will be justified by explanation or by visitation of the activities in question. All available satellite data for monitoring, validation, verification and certification will be archived and made available to auditors.
Calculation method:	
Any comment:	

Data/parameter [MN8]:	$RFRGrate(CS_1 \rightarrow CS_2)$
Data unit:	[yr^{-1}]
Description:	Relative annual forest cover increase and regeneration factor for the transition from class or stratum 1 to 2.
Sources of data:	Remote sensing analysis
Description of measurement methods and procedures to be applied:	Procedures should be described in the Monitoring Report
Frequency of monitoring/recording:	At least once before every baseline update
Value applied:	
Monitoring equipment:	GIS software, Landsat imagery, 30 meter tape, GPS, compass, clinometer, notebooks, water, writing utensils
QA/QC procedures to be applied:	Data is to be entered into internal archive. Archive is accessed by qualified, authorized technical experts. All documents for monitoring, validation, verification and certification are reviewed and signed off by several team members. Data will be reported to project proponents and stakeholders. Discrepancies or disagreements will be justified by explanation or by visitation of the activities in question. All available satellite data for monitoring, validation, verification and certification will be archived and made available to auditors.
Calculation method:	
Any comment:	It can be used for producing baseline transition matrix for new instances to be added into the project area.

Data/parameter [MN9]:	$area_{historical}(CS_1, t_1)$

Data unit:	[ha]
Description:	Total area of LULC class or forest stratum 1 at time 1
Sources of data:	Remote sensing analysis
Description of measurement methods and procedures to be applied:	Procedures should be described in the Monitoring Report
Frequency of monitoring/recording:	At least once before every baseline update
Value applied:	
Monitoring equipment:	GIS software, Landsat and radar imagery, 30 meter tape, GPS, compass, clinometer, notebooks, water, writing utensils
QA/QC procedures to be applied:	Data is to be entered into internal archive. Archive is accessed by qualified, authorized technical experts. All documents for monitoring, validation, verification and certification are reviewed and signed off by several team members. Data will be reported to project proponents and stakeholders. Discrepancies or disagreements will be justified by explanation or by visitation of the activities in question. All available satellite data for monitoring, validation, verification and certification will be archived and made available to auditors.
Calculation method:	
Any comment:	

Data/parameter [MN10]:	$area_{biomssLos}(i)$
Data unit:	[ha yr^{-1}]
Description:	Total annual area of LULC class that was cleared for creating firebreaks
Sources of data:	
Description of measurement methods and procedures to be applied:	
Frequency of monitoring/recording:	Annual to ≤ 5 years
Value applied:	NA
Monitoring equipment:	GIS software, Landsat and radar imagery, 30 meter tape, GPS, compass, clinometer, notebooks, water, writing utensils
QA/QC procedures to be applied:	
Calculation method:	

Any comment:	Analysis of fire breaks needs to be completed.

Data/parameter [MN11]:	$area_{fireBiomassLoss}(i)$
Data unit:	[ha yr^{-1}]
Description:	Annual area of forest stratum that was cleared by using prescribed burning
Sources of data:	
Description of measurement methods and procedures to be applied::	
Frequency of monitoring/recording:	Annual to ≤ 5 years
Value applied:	NA
Monitoring equipment:	GIS software, Landsat and radar imagery, 30 meter tape, GPS, compass, clinometer, notebooks, water, writing utensils
QA/QC procedures to be applied:	
Calculation method:	
Any comment:	Analysis of prescribed burns needs to be completed.

Data/parameter [MN12]:	$area_{fireBiomassLoss,ANR}(t,i)$
Data unit:	[ha]
Description:	Area of biomass removed by prescribed burning within ANR stratum i during year t
Sources of data:	
Description of measurement methods and procedures to be applied:	
Frequency of monitoring/recording:	Annual to ≤ 5 years
Value applied:	NA
Monitoring equipment:	GIS software, Landsat and radar imagery, 30 meter tape, GPS, compass, clinometer, notebooks, water, writing utensils
QA/QC procedures to be applied:	
Calculation method:	
Any comment:	Analysis of prescribed burns needs to be completed.

Data/parameter [MN13]:	$area_{projectAreaWithANR,projectScenario}(t,i)$
Data unit:	[ha]
Description:	Amount of land on which ANR activities are planned under the project scenario for year t and in stratum i
Sources of data:	
Description of measurement methods and procedures to be applied:	
Frequency of monitoring/recording:	Annual to ≤ 5 years
Value applied:	NA
Monitoring equipment:	GIS software, Landsat and radar imagery, 30 meter tape, GPS, compass, clinometer, notebooks, water, writing utensils
QA/QC procedures to be applied:	
Calculation method:	Only applicable if ANR activities are included in the project.
Any comment:	

Data/parameter [MN14]:	$area_{harvest}(t,i)$
Data unit:	[ha]
Description:	Area of forest in harvest stratum i that is harvested at time t.
Sources of data:	
Description of measurement methods and procedures to be applied:	
Frequency of monitoring/recording:	Annual to ≤ 5 years
Value applied:	NA
Monitoring equipment:	GIS software, Landsat and radar imagery, 30 meter tape, GPS, compass, clinometer, notebooks, water, writing utensils
QA/QC procedures to be applied:	
Calculation method:	
Any comment:	No harvesting activity in project area.

Data/parameter [MN15]:	$area_{projectAreaWithHarvest,projectScenario}(t,i)$
Data unit:	[ha yr^{-1}]

Description:	Size of strata i within the project area with harvest activities during year t under the project scenario.
Sources of data:	
Description of measurement methods and procedures to be applied:	
Frequency of monitoring/recording:	Annual to ≤ 5 years
Value applied:	NA
Monitoring equipment:	GIS software, Landsat and radar imagery, 30 meter tape, GPS, compass, clinometer, notebooks, water, writing utensils
QA/QC procedures to be applied:	
Calculation method:	
Any comment:	No harvesting activity in project area.

Data/parameter [MN16]:	$\Delta area_{projectAreaWithHarvest,baselineScenario}(t,i)$
Data unit:	[ha yr^{-1}]
Description:	Hectares undergoing transition i within the harvest areas under the baseline scenario during year t.
Sources of data:	
Description of measurement methods and procedures to be applied:	
Frequency of monitoring/recording:	Annual to ≤ 5 years
Value applied:	NA
Monitoring equipment:	GIS software, Landsat and radar imagery, 30 meter tape, GPS, compass, clinometer, notebooks, water, writing utensils
QA/QC procedures to be applied:	
Calculation method:	
Any comment:	No harvesting activity within project area.

Data/parameter [MN17]:	$BetaReg_{DF}(t)$and $BetaReg_{DG}(t)$
Data unit:	[ha yr^{-1}]
Description:	Beta regression model describing the relationship between time and deforestation/degradation rate in the reference region during

	the historical reference period.
Sources of data:	
Description of measurement methods and procedures to be applied:	
Frequency of monitoring/recording:	Annual to ≤ 5 years
Value applied:	NA
Monitoring equipment:	GIS software, Landsat and radar imagery, 30 meter tape, GPS, compass, clinometer, notebooks, water, writing utensils
QA/QC procedures to be applied:	
Calculation method:	
Any comment:	Model used to predict deforestation must be clarified, and analysis must be completed.

3.3 Description Monitoring Plans

This monitoring plan has been developed in close conjunction with module VM0006 of the REDD Methodological Module, "Carbon Accounting for Mosaic and Landscape-scale REDD Projects." This section focuses on establishing procedures for monitoring deforestation, illegal degradation, natural disturbance, and project emissions ex-post in the project area and leakage belt. Further, procedures for updating the forest carbon stocks and revising the baseline are also provided below. A separate section on quality assurance/quality control and data archiving procedures covers all monitoring tasks. Organizations responsible for monitoring are also listed below. These organizations are responsible for implementing all aspects of a particular monitoring task, as described in the monitoring sub-sections below.

The monitoring methodology outlines methods to monitor both carbon stock changes in the living biomass and emissions of project activities and any changes in the GHG emissions that result from the implementation of the project activity. The methodology outlines methods and procedures that complement the provisions of the baseline methodology. As per this methodology, the baseline scenario is identified and quantified *ex ante* at the beginning of the project activity and shall be re-assessed/revised every 10 years in accordance with VCS guidelines by taking into account the latest scientific and technical understanding. The VM0006 methodology recommends the use of remotely sensed data to monitor the project carbon stocks as well as disturbances within the project boundary. The methodology specifies annual monitoring and supports the recording of disturbances, if any. It recommends the adoption of standard operating procedures for monitoring, data collection and archival in order to maintain the integrity of the data collected in the monitoring process.

This methodology requires the following monitoring components for calculating actual Net Greenhouse Gas Emission Reductions (NERs):

1. Monitoring of drivers of deforestation, project activities and emission sources related to REDD project activities inside and outside of the project area.
2. Monitoring LULC class and forest strata transitions in the project area, leakage

area, and reference region using remote-sensing technologies, and validated with ground-truthing data.

3. Monitoring carbon stock densities in LULC classes and forest strata.
4. Monitoring carbon stock increases in the area on which Assisted Natural Regeneration Activities ANR are performed.
5. Monitoring of carbon stock in long-lived wood products.
6. Monitoring of natural disturbances.
7. Monitoring of harvesting activities.

A monitoring report is produced which contains all of the information above, and which outlines the calculations for actual NERs generated. At each monitoring event, the project proponent must clearly confirm the existence of GHG projects in the project area and a formal statement to that effect must be included in the monitoring report.

In addition to monitoring human induced changes, the natural disturbances and causes of changes of carbon need to be monitored and recorded. Given that any natural disturbance is fully accounted as part of the on-going monitoring during the crediting period, any loss of biomass during the credited period must also be accounted for and reported in the monitoring report regardless of the cause of the loss. However, where an event that qualifies as a loss event occurs and VCUs have previously been issued, project proponent must follow the applicable VCS rules.

Monitoring methodology

1. The project implementation is monitored, including the project boundary, the area prevented from land use change and any activities that reduce carbon stocks or result in emissions in the project area over the crediting period. All project boundaries in the BioREDD program are functionally discrete units with distinct reference regions and buffer zones for leakage and do not require any additional regions for monitoring for emissions.

2. Stratification of the project area is monitored periodically because two different strata may become similar enough in terms of carbon to justify their merging. The *ex-post* stratification considers monitoring of the project strata to verify the applicability of the *ex-ante* stratification, and variables that influence the strata. The *ex post* stratification procedures facilitate cost-effective, consistent and accurate monitoring of carbon stock changes of the project during the crediting period. In the BioREDD regions, we developed stratification based on available data sets and calculated the carbon stocks accordingly. However, our baseline methodology was based on random sampling of a large area of the region that allowed carbon assessments based on stratification and LULC classes. In addition, we developed a wall-to-wall map of the carbon stocks and pools of the BioREDD region encompassing project, reference, and leakage areas, allowing to develop monitoring procedures at different levels and potential changes for *ex post* stratification if the cost and efficiency becomes important components of future monitoring.

3. Baseline net GHG emissions are not monitored in this methodology. The methodology prescribes validity of the baseline identified *ex ante* at the start of the project activity for the crediting period, thereby avoiding the need for monitoring of the baseline over the crediting period, and achieves savings in the costs associated with baseline monitoring.

The calculation of *ex-post* actual net GHG emissions avoided is based on data obtained from sample plots, regional literature values and methods developed in IPCC GPG-LULUCF to estimate carbon stock changes in the carbon pools and peat emissions.

Leakage due to activity displacement is monitored and accounted in order to calculate the net GHG emissions avoided.

The QA/QC guidelines proposed as part of the monitoring plan verify the accuracy and consistency of field measurements and ensure the integrity of data collection, management of project databases and the database archival during the crediting period.

When a project is undergoing validation and verification, non-permanence risk analysis shall be conducted by both the project developer and the verifier at the time of verification in accordance with the VCS Tool for AFOLU Non-Permanence Risk Analysis and Buffer Determination.

3.4 Monitoring Deforestation and Disturbance

Parameter	***Data Source***	***Methodology***
$\Delta Area_{project}$, $\Delta Area_{leakage}$. $\Delta Area_{reference}$ Justification Size of project, leakage, and reference area may be adjusted during crediting period. VM0006 methodology requires monitoring the size and quantifying the changes of the areas or forest cover in project, leakage, and reference areas.	1. Landsat 8 satellite at 30 m resolution and 15 m resolution panchromatic data. Multiple date imagery must be acquired to have relatively cloud free data over the project areas on the annual basis 2. ALOS-2 PALSAR, dual-pol data at ~ 20m resolution. 3. Other potential data sets include Terra-XSAR at 6 m resolution, and high resolution commercial optical imagery at 1-5 m resolution.	1. Landsat data will be used to monitor changes of the areas using classification/segmentation[1] approaches along with quantifying transitions, GIS analysis of of boundaries[2], and sampling techniques in case of extensive cloud cover[3]. 2. ALOS PALSAR Radar imagery are cloud free and can be used to replace or cloudy Landsat pixels or used indepently to monitor changes of area and size of the project, leakage, and reference areas. Change detection[4] and segmentation approaches are the most common and reliable methods for quantifying any changes in size and areas. 3. Other Radar and optical data sets can be used to compensate for the cloud cover in Landsat data and improve the detection of changes using higher resolution imagery.

Parameter	***Data Source***	***Methodology***
$\Delta Area_{project}$, $\Delta Area_{leakage}$. $\Delta Area_{reference}$ Justification Size of project, leakage, and reference area may be adjusted during crediting period. VM0006 methodology requires monitoring the size and quantifying the changes of the areas or forest cover in project, leakage, and reference areas.	1. Landsat 8 satellite at 30 m resolution and 15 m resolution panchromatic data. Multiple date imagery must be acquired to have relatively cloud free data over the project areas on the annual basis 2. ALOS-2 PALSAR, dual-pol data at ~ 20m resolution. 3. Other potential data sets include Terra-XSAR at 6 m resolution, and high resolution commercial optical imagery at 1-5 m resolution.	1. Landsat data will be used to monitor changes of the areas using classification/segmentation[1] approaches along with quantifying transitions, GIS analysis of of boundaries[2], and sampling techniques in case of extensive cloud cover[3]. 2. ALOS PALSAR Radar imagery are cloud free and can be used to replace or cloudy Landsat pixels or used indepently to monitor changes of area and size of the project, leakage, and reference areas. Change detection[4] and segmentation approaches are the most common and reliable methods for quantifying any changes in size and areas. 3. Other Radar and optical data sets can be used to compensate for the cloud cover in Landsat data and improve the detection of changes using higher resolution imagery.

3.5 Monitoring LULC and Degradation

Parameter	***Data Source***	***Methodology***
LULC Cover change $\Delta area_{his\square orical}(CS_1 \rightarrow CS_2, t_1 \rightarrow t_2)$ Forest Degradation Jusification Methodology requires the monitoring any changes of the forest cover or LULC class between time 1 and time 2 and all the transitions between one class to other classes. All changes must be updated at least once before every baseline updates.	1. Historical classification of the LULC over the project, reference, and leakage area established for the period before the start date of the project (2012 for BioREDD projects). 1. Landsat 8 satellite at 30 m resolution and 15 m resolution panchromatic data. Multiple date imagery must be acquired to have relatively cloud free data over the project areas on the annual basis. 2. ALOS-2 PALSAR, dual-pol data at ~ 20m resolution. 3. Other potential data sets include Terra-XSAR at 6 m resolution, and high resolution commercial optical imagery at 1-5 m resolution. Any Future satellites with potential monitoring capacity.	1. Landsat data will be used to monitor changes of LULC through classification or change detection approaches for LULC on the annual basis. In the case of the extensive cloud cover sampling approaches[3] can be used to quantify the transitions. Minimum number of classes used for classification and transition analysis are provided by the VM0006 methodology and includes, forest, degraded forests, grasslands, croplands, wetlands, settlements, and other nonforest lands. 2. Radar imagery are cloud free and can be used to replace or cloudy Landsat pixels or used indepently to monitor changes of changes of forest cover areas and transition of forests to other land cover units. The strength of the Radar imagery is to monitor the forest cover and quantify transitions from intact to degraded forests on the annual basis. A simple methodology for detecting degradation will use polarization ratios for time 1 and time 2. The changes derived from Radar imagery can be compared to historical LULC maps to identify the type of transitions. 3. Other Radar and optical data sets can be used to compensate for the cloud cover in Landsat data and improve the detection of changes using higher resolution imagery.

Emissions due to illegal logging will be tracked by conducting surveys surrounding the project, leakage and reference areas annually or every two years. Locations surveyed will include: Families residing inside adjacent to the project area; and nearby ranches and rural properties, along the project and leakage areas, particularly around trails and secondary roads approaching the project area.

Sensing approaches will be used to identify and estimate the area and intensity of logging in the project and leakage areas. In general remote sensing approaches may not be able to detect selective and illegal logging where a small number of trees are extracted by local communities. Ground surveys will produce information on wood consumers (i.e., fuel wood and wood for construction and charcoal production) in the surroundings areas, as well as general indications on the areas where wood is sourced from and maximum depth of penetration of harvest activities from access points.

In the event that any potential of illegal logging occurring in the project area is detected from the surveys or remote sensing data (i.e. ≥ 10% of those interviewed/surveyed believe that degradation may be occurring within the project boundary), temporary sample plots will be allocated and measured in the area of the project indicated by the surveys as a potential source area for illegally-harvested wood. The potential degradation area within the project area will be delineated based on survey results, incorporating general area information and maximum depth of penetration and potential biomass plots.

3.6 Monitoring Project Emissions

Parameter	***Data Source***	***Methodology***
$RFRG_{rate}(CS1 - CS2)$ Justification Relative annual forest cover increase or regeneration is an important factor for developing REDD credits in VM0006 methodology. The forest increase can be quantified for project, reference, or leakage areas and similarly for each stratum identified in the baseline LULC analysis.	1. Historical classification of the LULC over the project, reference, and leakage area established for the period before the start date of the project (2012 for BioREDD projects). 1. Landsat 8 satellite at 30 m resolution and 15 m resolution panchromatic data. Multiple date imagery must be acquired to have relatively cloud free data over the project areas on the annual basis 2. ALOS-2 PALSAR, dual-pol data at ~ 20m resolution. 3. High resolution commercial optical imagery at 1-5 m resolution such as rapid-eye, or airborne surveys with optical sensors (photography) or Lidar techniques. 4. Field surveys for estimating changes of forest cover or regrowth of forests through inventory or simple survey techniques.	1. Multiple imagery is required to establish rates of forest growth or regeneration in project areas. The methodology requires three steps Step.1. Area of change of forest cover will be quantified using the methodology for LULC change as discussed above. The positive change and transition from non-forest classes such as grasslands and croplands to forests will be recorded and quantified as rate of change in terms of area/year. Step 2. Increasing cover or density of degraded or secondary forests must be idenitified by developing metrics from Landsat TM such as EVI or NDVI or shade fraction or from Radar metrics such as RFDI[5] or ratio of cross-polarization. The methodology of using Landsat and Radar imagery is limited in applicabaility to forests under early sucessional stages. Step 3. Late successional or regeneration of selectively logged forests may be detected using high resolution (1-5m) commerical satellite data or repeated airborne remote sensing data using aerial photography or Lidar techniques. An alternative approach will include direct detection of changes of forest regeneration using ground surveys. Step 4. To accurately quantify the magnitude of the rate of change in terms of percent cover or biomass, ground surveys or repeated Lidar measurements may be required. A methodology of change detection from fusion of ground and remote sensing techniques[6] is considered the best approach to quantify the rate of change in forest biomass.

Parameter	*Data Source*	*Methodology*
$Are\square_{Biomass\ Loss}$ Justification VM0006 methodology requires idenitfiication and quantification of areas of biomass loss due to several activities such as selective logging, fire breaks, prescribed fire, any harvesting of timber and non-timber products or other activities resulting in biomass loss either from changes of forest cover or changes of biomass.	1. Historical classification of the LULC over the project, reference, and leakage area established for the period before the start date of the project (2012 for BioREDD projects). 1. Landsat 8 satellite at 30 m resolution and 15 m resolution panchromatic data. Multiple date imagery must be acquired to have relatively cloud free data over the project areas on the annual basis 2. ALOS-2 PALSAR, dual-pol data at ~ 20m resolution. 3. High resolution commercial optical imagery at 1-5 m resolution such as rapid-eye, or airborne surveys with optical sensors (photography) or Lidar techniques. 4. Field surveys for estimating changes of forest cover or regrowth of forests through inventory or simple survey techniques.	1.Biomass loss from changes of LULC or forest area has been discussed earlier. Here, we focus on the area of biomass loss without changes in area of forest type from historical LULC map. 2. Time series of Landsat data using NIR band or any vegetation indicies such as NDVI and EVI may provide estimates of gain or loss of biomass without changes of forest area. However, the optical techniques must be validated by ground surveys. 3. Change detection using time series of data from Radar imagery provide a reliable approach to estimate forest biomass loss. Radar metrics such as cross-polarized measurements from dual-pol ALOS2 PALSAR data can be used to directly detect forest biomass loss. The magnitude of the loss depend on the forest type and the original of the biomass. Significant loss of biomass such as 25-50% can be detected readily from Radar data. However, smaller increments of loss from low impact seleective logging must be detected by a combination of Radar and optical imagery and field surveys. 4. Loss of biomass from selective logging and small scale extractions can be verified using ground surveys of plots randomly established in the project, refernce, and leakage regions.

Using the above methodology and data for estimating forest area and biomass loss in project, leakage, or reference area, the emissions are calculated as the sum of emission from fossil fuel combustion and non-CO_2 emissions due to biomass burning or loss. As stipulated in the methodology, fossil fuel combustion in all situations is an optional emission source. Further, no nitrogen is applied on alternative land uses in the with-project case and hence project emissions therefore equal EBiomassBurn and are calculated using the VM0006 methodology. Non-CO_2 emissions from biomass burning in the project case include emissions from burning associated with deforestation and burning associated with natural disturbance, i.e. forest fire.

3.7 Monitoring Leakage:

Leakage by local agents of deforestation is quantified in the leakage belt. The area deforested in the leakage belt is estimated in the same manner as the area deforested in the project are using the procedures outlined above in the monitoring deforestation section. Activity shifting leakage within the leakage belt is then calculated as the with project emissions in the leakage belt.

3.8 Monitoring Forest Carbon Stocks

Monitoring carbon stocks will be performed frequently during the project implementation to revise the carbon stocks and monitor any changes associated with regeneration and loss. During the project development, carbon in forests in project areas and reference and leakage were estimated using airborne Lidar remote sensing along with field inventory plots in various regions of the BioREDD project areas where we have access for field surveys and data collection.

This section provides a basic description of biomass plot measurements, which are further described in the reports provided by CONIF and Alvaro Duque, for the Forest Carbon Monitoring System and calibration and validation of the Lidar data. For the BioREDD project areas, we established both permanent and temporary sampling plots to be used to estimate carbon stocks across the landscape and for implementation of future monitoring for detecting changes. The size and shape of the sample plots for tree biomass measurement is a trade-off between accuracy, precision, time, and cost for measurement, and finally the compatibility with the remote sensing data. The most appropriate size and shape may also be dependent on the vegetation type found in the sampling area. In addition, the plots must be large enough to reduce errors associated with geolocation and edge effects when used to calibrate the RS data. The minimum size of plots selected for this project is 0.25 ha (Asner and Mascaro, 2013; Meyer and Saatchi et al. 2013).

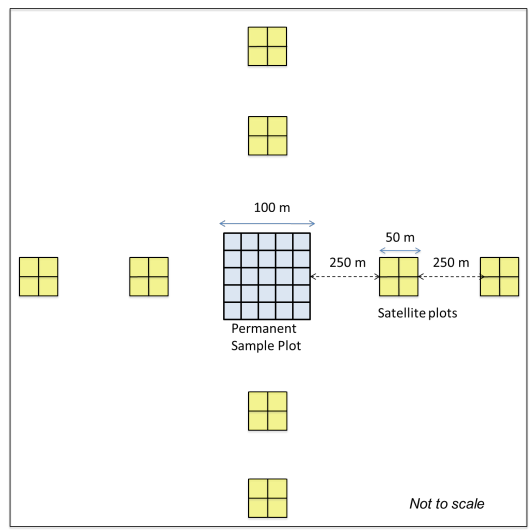


Fig. 6.1 Shape and size of permanent and satellite plots within the lidar transect.

The 0.25 ha size plot is a compromise between small plot sizes that are efficient in the field inventory approaches (e.g. < 0.1 ha) but provide models with large uncertainty between RS and ground estimates of AGB, and large plots (e.g. 1.0 ha) that are costly and difficult to establish in the field but provide models with the low unceratinty (~ 10% relative error and no bias) (Meyer et al., 2013; Asner and Mascaro, 2014).

In the BioREDD project, the plots are only used for calibration and validation of lidar to AGB model. The minimum number of plots required for developing and validating the remote sensing to AGB predictive model was estimated to be 45, with 30 plots for calibration and 15 plots for validation. This requirements were based on a similar methodology as in CDM A/R tools for Calculation of the number of sample plots for measurements within A/R CDM project activities, and based on minimum number for developing

remote sensing and AGB predictive model (Asner and Mascaro, 2014). In general one predictive model is enough to estimate forest biomass from lidar in BioREDD regions if the ground allometric model used in estimating AGB at the plot level is also one. If the number of ground allometry changes in the project area because of the presence of various forest types, as in Chave et al., 2005 for wet, moist, and dry forests, then the number of remote sensing predictive models will also change.

In the BioREDD project we increased the number of calibration and validation plots in order to make sure that the numbers are enough for developing more than one lidar to AGB predictive model if necessary. A total 15 cluster plots were used in 15 lidar transects covering different strata in the BioREDD regions. Each cluster plot met the following requirements:

1. Each cluster plot had one permanent plot of 1-ha in size (100 m x 100 m) and 8 satellite or auxiliary plots at 0.25 ha in size (50 m x 50 m).
2. The center location of permanent plot was selected randomly in the lidar transect in the forest area to allow sampling all forest conditions as in fragmented, degraded or secondary forests. The satellite plots were located at 250 m and 500 m away from the center permanent plots in four cardinal directions (Fig. 6.1).
3. The measurements in the permanent plots followed the RAINFOR protocols (REF?) All trees with DBH ≥ 10 cm in diameter were measured in each plot, with trees being tagged and recorded, x,y coordinates were recorded for permanent plots but not the satellite plots, and trees were identified in all plots by species for wood density values.
4. A minimum number of 50 trees in different DBH classes were selected for height measurements and development of DBH-H allometry for the plots or forest type. The number of trees with height measurement represented between 7 and 16% of the total number of trees registered in each site. All trees in San Pablo already had height measurements.
5. A tree-diameter height (H-D) relationship or predictive model was developed for each cluster plot and also combined for the region. Fig.6.2 shows the allometry used to convert tree diameter to height for all the trees in the plots. We used a Weibull model to estimate the height of trees that were not measured directly:

For AGB estimations of sample plots, we used the allometric model developed for the study region by the BioREDD team. First we used the Chave et al. 2005 model for moist forests to estimate the biomass for each plots. However, the BioREDD project provided funding to develop local allometric equations for the trees of the Pacific coastal forests. The models developed for the region included three types of forests in the regions: Terra firme (Colinas), Inundated forests (Guandal), and mangrove forests (Manglar). Trees were harvested in the region and combined by harvested trees from past research activities to develop the models. The models included uncertainty analysis and comparison with Chave et al. (2005) and (2014) allometric equations and differences were reported (see BioREDD project report BR-SUBK-FP-022). The equations are summarized below:

Colinas $\ln(AGB) = -2.130+2.015\times\ln(D)+0.724\times\ln(H)+1.002\times\ln(WD)$

Guandal $\ln(AGB) = -2.328+1.833\times\ln(D)+0.724\times\ln(H)+0.151\times\ln(WD)$

Manglar $\ln(AGB) = -2.818+2.185\times\ln(D)+0.724\times\ln(H)+0.650\times\ln(WD)$

For estimation of the biomass of palm trees in all types of forests, we used the allometric equation developed by Saldarriaga (2014).

$$\ln(AGB) = -0.173+0.700\times\ln(D^2\times H\times WD)$$

For biomass values estimated in individual permanent and satellite plots see table 6.3. For each plot, we also have an indentifier and discription by the field group that summarizes the type an condition of the forests such as degraded, secondary forests, Guandal, Colinas, Manglar, etc. Most plots fall in mixed forests, therefore the biomass values estimated from allometric models are applied on the tree level to provide estimates of the biomass at the plot level.

Revision of the Baseline
The baseline as outlined in the VCS Project Description is valid for 10 years. The baseline will be revised every 10 years from the project start date. Data collection procedures in regards to revision of the baseline will include participatory rural appraisals, interviews and collaboration with the BioREDD regional communities, the GIS experts in BioREDD project, and municipal officials. In the case, where the BioREDD project no longer produces the annual dataset on the extent and spatial location of all deforestation within the region deforestation maps will be prepared by classifying remotely sensed imagery. Other datasets used to substantiate aspects of the baseline with be from official government sources, peer reviewed publications, or other reputable sources.

Quality Assurance/Quality Control and Data Archiving Procedures
To ensure consistency and quality results, spatial analysts carrying out the imagery processing, interpretation, and change detection procedures will strictly adhere to best practices and good practice guidelines, when using the alternative method for quantifying deforestation. All data sources and analytical procedures will be documented and archived (detailed under data archiving below). Monitoring deforestation, natural disturbance, and leakage accuracy of the classification will be assessed by comparing the classification with ground-truth points or samples of high-resolution imagery. Any data collected from ground-truth points will be recorded (including GPS coordinates, identified land-use class, and supporting photographic evidence) and archived. Any sample points of high-resolution imagery used to assess classification accuracy will also be archived. Samples used to assess classification accuracy should be well-distributed throughout the project area (as far as is possible considering availability of high resolution imagery and/or logistics of acquiring ground-truth data), with a minimum sampling intensity of 30 points each for the forest and non-forest classes. Note that the classification will only be used in the forest cover change detection step if the overall classification accuracy, calculated as the total number of correct samples / the total number of samples, is equal to or exceeds 90%.

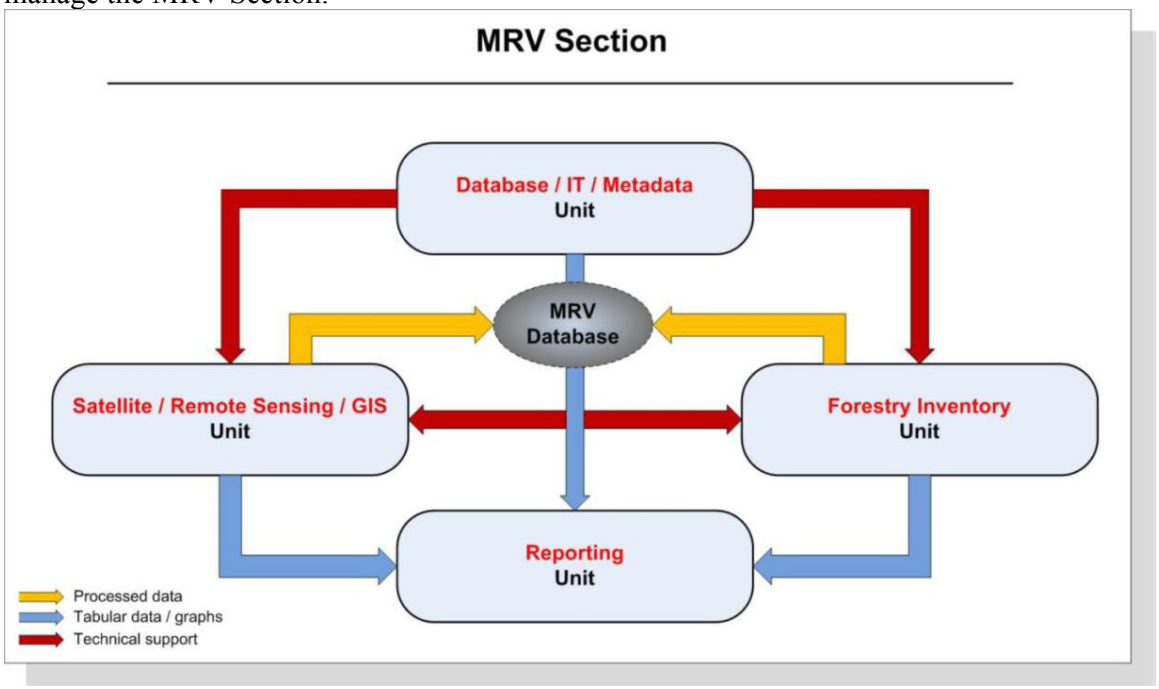
4. Organizational Structure

The MRV system–management architecture
The MRV Section: To manage the different functions of the MRV system, a centralized management office is proposed. This office can be located in either one of the government

offices such as IDEAM, local NGOs working with the REDD project, or any other government or private institutions. Its main objective is to organize and manage the MRV experts at the national and local level, in order to maintain the MRV system and promote data dissemination. The same MRV Section to be established for the national MRV will be responsible for executing MRV at the project level and building capacity of the relevant stakeholders to perform the tasks. In the BioREDD program, there are several projects within the same geographical regions. One or all of the projects can have one single management structure and unit. The MRV Section is subdivided in to four independent but strictly connected units:

1. Database/IT/Metadata Unit (DBM)
2. Satellite/Remote Sensing/GIS Unit (RS)
3. Forest Inventory Unit (FIN)
4. Reporting Unit (REP).

Each Unit has its own experts and IT software applications. An MRV Coordinator will manage the MRV Section.



The Satellite / Remote Sensing / GIS Unit (RS)

The main objective of the RS Unit will be image processing and analysis to produce Land Use/Land Cover classification layers and perform GIS editing and analysis to ensure data integrity in the monitoring and reporting (MRV in general) database. Multi-temporal satellite images, DEM and eventually other ancillary data will be used to identify change detection in forestry classes. Once LULC layers have been produced and validated, they will be uploaded into the monitoring database. Graphs and tabular data should be provided to the Reporting Unit upon periodical requests. This Unit, which should include two experts, could also take advantage of technical support from the REP and FIN Unit for specific tasks.

The Forest Inventory Unit (FIN)

The main objective of the FIN Unit will be forestry inventory production (also integrated by the national and subnational institution such as CONIF and IDEAM) to estimate GHG emission using very specific algorithms and models applied to local data collected by FIN field team. Once GHG estimates have been produced and validated, they will be loaded into

the MRV database. The Unit could also take advantage of technical support from the RS and other unites for specific tasks. Graphs and tabular/aggregated data should be provided to the Reporting Unit upon periodical requests. The human resources needed to manage this unit include one forestry expert.

The Reporting Unit (REP)

This Unit provides periodic standard MRV reports (consistent with the reporting requirements outlined in the UNFCCC guidelines and VCS methodology) for dissemination of aggregated data and information, collecting the necessary info by the other three units. Reporting is a key element of MRV because it provides the means by which, in a future REDD+ mechanism, the performance of the project will be assessed compared to its commitments or reference scenario, and therefore will represent the basis for assigning incentives. The human resources needed to manage this unit is one REDD MRV expert.

Summary of Remote Sensing Techniques

Change Detection Analysis encompasses a broad range of methods used to identify, describe, and quantify differences between images of the same scene at different times or under different conditions. One can use many of ENVI's toolsor any other softwares for image processing (such as Band Math or Principal Components Analysis) independently, or in combination, as part of a change detection analysis. In addition, the routines found under the Toolbox menu Change Detection offer a straightforward approach to measuring changes between a pair of images that represent an initial state and final state. Use Change Detection Statistics for classification images; use Change Detection Difference Map for gray scale (single-band) images.

Digital change detection approaches may be broadly characterized by (1) the data transformation procedure (if any) and (2) analysis techniques used to delineate areas of significant alterations. There are two basic approaches for change detection; (1) comparative analysis of independently produced classifications for different dates and (2) simultaneous analysis of multitemporal data.

When performing a change detection analysis on non-thematic images (gray scale data), it is important to consider all of the factors that can cause scenes of the same area to look different. The following are a few notable factors:

- *Differences in the instrument or sensor:* Consider the similarity of the sensors that collected the images. Even bands collected in the same part of the spectrum (for example, two red bands) may have different band center wavelengths, or different spectral response functions, which can lead to different pixel values for the same material.
- *Differences in the collection date and time:* Seasonal changes can impart big differences in scenes containing vegetation (due to plant senescence and canopy architecture development). Differences in the season and time of day will also affect the solar azimuth and elevation.
- *Differences in Atmospheric Conditions:* The dominant weather conditions can affect atmospheric transmission and scattering. Consistent differences in gross atmospheric conditions are often associated with seasonal changes. For example, differences in the predominant wind direction can be important (winds blowing in over the ocean contain different aerosols with different scattering properties from those blowing in over an urban area). Another common, yet consistent, atmospheric difference is the water content of the atmosphere. Summer atmospheres tend to be wetter than winter atmospheres. Atmospherically corrected images can reduce such influences.
- *Differences in Image Calibrations:* For the most accurate change detection results, it is important to work with images that are calibrated into the same units. If a calibration into physical units (such as radiance) is not possible, a relative calibration may be better than none at all (especially if the instruments that collected the images have different dynamic ranges).

- *Differences in Image Resolution:* Differing pixel sizes can lead to false change detections. It is important that the original images (prior to resampling or re-projection) have the same pixel resolution. For scenes with large swaths (such as AVHRR, SeaWiFS, or MODIS) the actual pixel sizes differ across the scene. In such cases, differences in the sensor viewing geometry can also be important.
- *Coregistration Accuracy:* Accurately coregistered images are critical for change detection analyses. While the Compute Difference Map routine will automatically coregister the input images using the available map information, if the differences in the image geometry are substantial, it is well worth the effort to ensure that the coregistration is as accurate as possible before performing a change detection. VM0006 methodology requires image registeration accuracy of less than 1 pixel (<30 m).

Among techniques used for monitoring changes, we outline the following as the most common methodologies:

The Change Detection Difference Map: Image differencing approach does not compensate for any of these (or other) conditions. Its results are strictly dependent on pixel-for-pixel comparisons. The input images must be georeferenced or coregistered. If the images are not coregistered, then the available map information will be used to automatically coregister the area of project or reference areas that are common to both images. To be efficient in change detection approach, it is recommended to only select an area of interest to perform the change detection or difference map. Using the entire image such as Landsat scenes may increase the processing time and to some extent the errors associated with registration and radiometric calibration. The methodology can be summarized in following steps:

1. Select a single band image representing the initial state of LULC and perform optional spatial subsetting for areas delineated for baseline classification over project, leakage, and reference areas.
2. Select a single band image representing the final state of the monitoring period and perform optional spatial subsetting over the project, reference, and leakage area and compute difference map for further analysis.
3. Enter the number of classes to use. Each class is defined by a difference threshold that represents a varying amount of change between the two images. The minimum number of classes is two. The default classification thresholds are evenly spaced between (-1) and (+1) for simple differences, and (-100%) and (+100%) for percent differences. The default class definitions attempt to produce symmetric classes, with an equal number of positive and negative change classes surrounding a no change category. The order in which the classes are defined is as follows.
4. For n classes, where n is odd, the first (n/2) classes represent positive changes, starting with the largest positive changes and ending with the smallest.
5. The middle class, (n/2) + 1, represents no change.
6. The last (n/2) classes represent negative changes, starting with the smallest negative changes end ending with the largest.
7. For an even number of classes the definitions remain the same except that the number of negative classes is reduced by one. In short, the default class definitions range from positive to negative, with the magnitude of the change increasing with distance from the middle no change class.
8. While it is better to customize the criteria to use to define the change thresholds, It is also recommended that the classes retain their default symmetrical property, with an equal number of positive and negative classes surrounding a no change class in the middle. Retaining the default position (order) and type (negative or positive) of classes will make the results easier to interpret using the classification color assignments.
9. It is recommended to iterate on thresholds to find the optimum values for separating changes. The best approach is to use one threshold for one class and separate the class from the rest of classes and repeat the process. It is also recommended to use different bands for different classes to reduce any confusion and errors associated with separation of different classes.
10. For multiple year monitoring, it is recommended to automatically set the classification change thresholds to match those used in a previous monitoring time or analysis. This requires multiple images are from the same satellite with same image characteristics such as band, resolution, and geometry of observations.

Image Regressing: In the regression method of change detection, pixels from time t_1, are assumed to be a linear function of the time t_2 pixels. So one can regress the band values of the pixels of image 1 against band values of pixels of image 2 using a least-squares regression. If the predicted value obtained from the regression line used as one layer, the difference image can be developed similar as in image differencing method discussed earlier. A thresholding technique, as described earlier, is applied to detect areas of change (Singh, 2010). The regression technique accounts for differences in the mean and variance between pixel values for different dates so that adverse effects from differences in atmospheric conditions or sun angles or any processing effects are reduced (Jenson 1983). In most cases, the image regressing approach has performed marginally better than the univariate image differencing technique discussed earlier, particularly in detecting urban land cover changes and tropical forest cover changes.

Image Ratioing: Ratioing is considered to be a relatively rapid means of identifying areas of change particularly in optical imagery such as Landsat. In ratioing two registered images from different dates with one or more bands in an image are ratioed, band by band. The data are compared on a pixel by pixel basis. If the intensity of reflected energy is nearly the same in each image then the ratio=1 and this indicates no change. In areas of change the ratio value would be significantly greater than 1 or less than 1 depending upon the nature of the changes between the two dates. The critical element of the methodology is selecting appropriate threshold values in the lower and upper tails of the distribution representing change pixel values. The usual practice has been in selecting arbitrary threshold values and testing them empirically to determine if the change detection was performed accurately. In most cases, the threshold can be determined if areas of changes are identified both on the imagery and the ground. Ratioing has several problems and sources of errors. Among them the noisy nature of ratio causing ambiguity in detecting changes, and the non-normal distribution of the ratio are the most critical ones.

Vegetation index differencing: Different vegetation indices relating to the vegetation cover or the greenness of vegetation can be used to detect changes. One of the most used vegetation index in optical imagery such as in Landsat data is NDVI = (NIR-RED)/(NIR+RED) as the normalized difference vegetation index developed from near infrared (NIR) and red (RED) Landsat bands. Vegetation indices are used to enhance the spectral differences related to vegetation characteristics and can improve change detection approaches. In most case, vegetation index is used similar to a band and can be incorporated in band ratioing or differencing approaches. There has been strong evidences normalized difference ratios of bands or vegetation indices can also enhance the performance of the methodology as in the following case (Nangendo et al. 2005; Mitchard et al., 2009):

$$change = \frac{NDVI_2 - NDVI_1}{NDVI_2 + NDVI_1}$$

Where 1 and 2 represents the NDVI images for time 1 and 2 respectively. This produces change images, with every pixel having a value from -1 to +1, where zero indicates no change, positive values positive change (i.e., an increase in woody cover), and negative values negative change (i.e., a decrease in woody cover).

Post Classification Comparison: This is the most obvious method of change detection which requires the comparison of independently produced classified images. By properly coding the classification results for times t_1, and t_2,, the analyst can produce change maps which show a complete matrix of changes. In addition, selective grouping of classification results allows the analyst to observe any subset of changes which may be of interest. Post classification comparison holds promise because data from two dates are separately classified, thereby minimizing the problem of normalizing for atmospheric and sensor differences between two dates. The method also bypasses the problem of getting

accurate registration of multidate images.
This methodology, however, may have uncertainty larger that individual classification accuracies because the error of comparison is approximately the error of classification of time and 1 multiplied by time 2. Computationally, it requires classification of the whole scenes twice
found that the post-classification comparison technique reliably identified areas of change but they did not use any coincident ground information for comparison purposes. In VM0006 methodology, comparing the baseline image with a new classified image performed annually for the project, leakage, and reference area can readily provide estimated of forest cover change.

1. *Radar change detection approach*

Radar polarimetry from airborne and spaceborne sensors are renown for their application of land cover classifictation and extraction of information such as structure and biomass about the vegetated landscapes. Radar based classification techniques are broadly divided into two categories, i.e., parametric (e.g., supervised, unsupervised, and semi-supervised) and nonparametric classification methods. Each of these classification techniques has its own advantages and disadvantages. Polarization in radar imagery can be used similar to bands in optical data by providing features that can accurately separate land cover or land use types. Thus, polarimetric parameters as in polarization ratios that can physically interpret the scattering behavior of different targets may prove useful in land cover classification of those sites, where sufficient a priori information is not available. Different polarimetric indexes have been used by researchers for various applications such as backscattering coefficients of different polarizations (linear: HH ,HV, VV), and their ratios have been widely used for crop classification/ vegetation identification, bare soil/vegetation discrimination , and wetland/water discrimination from other classes; normalized difference polarization index (NDPI) has been used for hazard monitoring, ratio vegetation index (RVI) for canopy characterization, weighted polarization sum (WPS) for urban mapping, and cross-polarization ratio for separation of bare or sparsely vegetated fields and forested areas.

Radar RFDI metric

We have developed a simple metric from the polarimetric backscatter measurements collected by long wavelength SAR sensors to detect deforestation and degradation, that has a consistence performance over all types of complex landscapes and environmental conditions (Saatchi et al. 2014). We have assesed the performance of the metric and developed applications compatible with what is currently established and recommended under the negotiated methodologies of land use, land-use change and forestry (LULUCF) under the UNFCCC, and "The Good Practices Guidance" of IPCC [*IPCC*, 2006].
To develop this metric we focused on dual-polarization SAR data provided at HH (Horizontal transmit and Horizontal receive) and HV (Horizontal transmit and Vertical receive) radar backscatter intensities. These polarizations are the most common mode of operation of most radar sensors such as ALOS PALSAR in space. We define the Radar Forest Degradation Index (RFDI) as the normalized ratio of the two radar polarization channels, given by:

$$RFDI = \frac{HH - HV}{HH + HV}$$

where the backscatter intensities are in linear units (m^2/m^2). The value of RFDI varies between 0 and 1, as even in most topographically complex terrains HH is always larger than HV backscatter. For ALOS PALSAR FBD mode data, the geometry and incidence angle do not vary over SAR pixels, allowing temporal analysis of RFDI without concerns for changes in geometry and incidence angle or any other image characteristics.

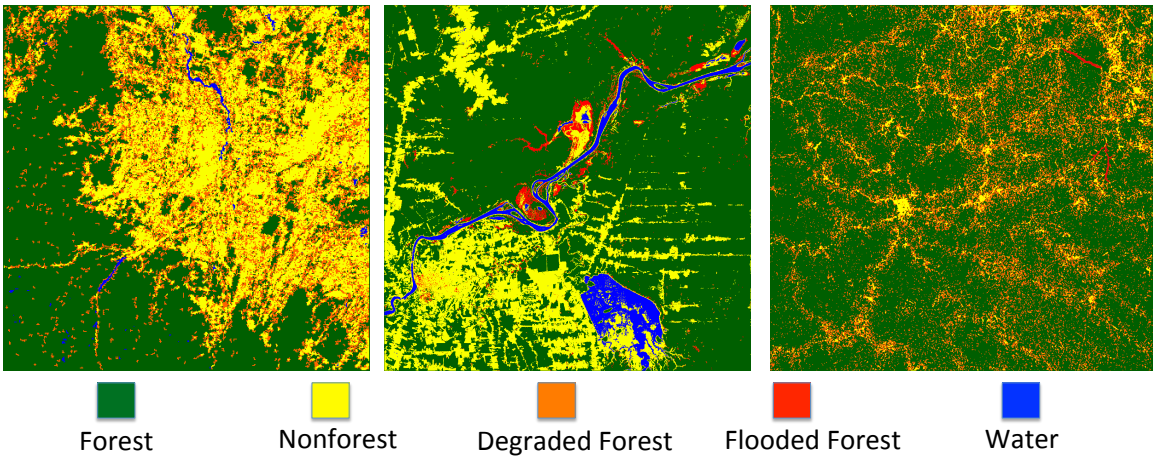


Fig. 1. Application of RFDI for monitoring deforestation and degradation in tropical forests. The maps provide three examples in Costal Rica (left), Rondonia, Brazil (center), and Cameroon (right).