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Forest Reference Emission Level of Madagascar

for reducing emissions from deforestation and forest degradation

Submission to the United Nations Framework Convention on Climate Change

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ACRONYMS

AB	Above-ground Biomass
BB	Below-ground Biomass
BNC-REDD+	National REDD+ Coordination Office
UNFCCC	United Nations Framework Convention on Climate Change
CH_4	Methane
CO_2	Carbon dioxide
COP	Conference Of Parties
AD	Activity Data
DGF	General Direction for Forest
DBH	Diameter at Breast Heigh
ERP-D	Emission Reduction Program document
FCPF	Forest Carbon Partnership Fund
EF	Emission Factor
FRMi	Forest Resources Management engeneering
GHG	Green House gases
GFC	Global Forest Change
IPCC	Intergovernmental Panel on Climate Change
GLS	Global Land Survey
GOFC-GOLD	Global Observation for Forest Cover and Land Dynamics
GPG-LULUCF	Good Practice Guidance for Land-Use, Land-Use Change and Forestry
GPS	Global Positioning System
IDA/GEF	International Development Association / Global Environment Facility
IEFN	National Ecological Forest Inventory
MEEF	Ministry of the Environment, Ecology and Forests
MNT	Digital Terrain Model
MOM 1	Organic Matter 1: Deadwood

MOM 2	Organic matter 2: Litter
N_2O	Nitrogen oxide
FREL	Forest Reference Emission Level
OOB	Out of Bag
PERR-FH	Humid Forest Eco-Regional REDD + Project
PHCF	Holistic Program for Forest Conservation
NTFP	Non-Timber Forest Product
REDD+	Reducing Emissions from Deforestation and Forest Degradation
R-PP	Readiness Preparation Proposal for REDD+
RSR	Root-shoot ratio
SEAS-OI	Satellite-Assisted Environmental Monitoring in the Indian Ocean
SLC	Scan Line Corrector
SOC	Organic Soil Carbon
tdm	Tones of dry matter
VCS	Voluntary Carbon Standard

1 INTRODUCTION

Reducing emissions from deforestation and forest degradation (REDD+) is a mechanism that aims to mitigate the impacts of climate change, reduce deforestation, conserve forests and support sustainable development. The main objective of REDD+ is to provide financial compensation to forested countries that reduce their Green House Gas (GHG) emissions and removals from forests.

Works for the REDD+ readiness of Madagascar were undertaken via two main initiatives:

- The Eco-Regional REDD + Humid Forests Project (PERR-FH) between 2013 and 2015. A project implemented by a Consortium constituted by the Wildlife Conservation Society (WCS), the National Office for the Environment (ONE) and ETC Terra. This project has been funded by the IDA / GEF support through the Environmental Program, Phase 3 (Additional Financing) - which has developed some key products for REDD +. Forest inventories were focused on the eastern humid forests eco-region and carried out with the intention of establishing a reference level of GHG emissions from deforestation.

- Similarly, the Madagascar REDD + Readiness Preparation Proposal (R-PP) was approved in 2014 by the Participants Committee of the Forest Carbon Partnership Facility (FCPF), which led to release funds in order to finalize Madagascar's preparation for REDD +. The National REDD+ Coordination Office (BNC-REDD +) was created within the Ministry of Environment, Ecology and Forests (MEEF) with the objective of piloting and coordinating all initiatives related to REDD+. A fraction of the readiness grant is allocated to the improvement of the national Forest Reference Emission Level (FREL) in the next few months, namely through the conduction of forest inventories in other eco-regions (dry and spiny forest).

Indeed, Madagascar has decided to submit a FREL under the United Nations Framework Convention on Climate Change (UNFCCC) on a voluntary basis and based on existing data. This FREL was established by the BNC-REDD+ with the support of FRMi, using existing data produced mainly as part of the PERR-FH. ETC Terra has also contributed to the establishment of the FREL.

As far as the planned activities of BNC-REDD + are concerned, this report also emphasizes on the action plan for the FREL improvement in the next few years, especially as a result of the on-going or planned works financed through the FCPF readiness grant.

Madagascar wishes to adopt a progressive approach for the development of its national FREL as indicated in decision 12 / CP.17, paragraph 10. As such, this FREL reflects the best information available at the time of submission. The scope of the submission and the methodologies applied will need to be modified in the future when new methodologies, data and products become available.

This communication and FREL does not prejudge or modify the Nationally Established Planned

Contribution of the Malagasy Government for the Appropriate National Mitigation Measures according to the Bali Action Plan.

All information delivered in this document is selected from reports that are freely available on the Internet and that have already been evaluated by third parties. In fact, by combining all of this information and data together with evaluation reports, this document provides transparent, inclusive, accurate and reliable methods and content.

FREL structure and content

The current document follows the following structure:

- **Chapter 2** provides information on the forest definition and how it has been taken into account not only in the development of the FREL, but also on sources and sinks (REDD + activities), especially accounted carbon pools and GHGs. This chapter also contains information on the consistency in terms of sinks, sources, pools and GHGs between FREL and GHG emissions and removals presented in the second national communication;
- **Chapter 3** provides a general description of the methodology used for FREL, based on the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories;
- **Chapter 4** provides a description of the method to estimate the activity data;
- **Chapter 5** provides a description of the method to estimate carbon stocks and emission factors;
- **Chapter 6** quantifies the FREL;
- **Chapter 7** presents uncertainties on FREL calculation
- **Chapter 8** features discussions and conclusions on the FREL calculation and presents the action plan for its improvement as future prospects. When needed, the report will present in boxes in different sections some explanations on how the methods or data will be improved later regarding this action plan.

2 EXTENT OF THE FREL

Chapter 2 presents the methodological framework and key definitions for the development of the FREL.

2.1 FOREST DEFINITION

According to the Clean Development Mechanism, the definition that is nationally embraced in Madagascar is showed in the table below. The session led by the BNC-REDD + in April 2016 in order to agree on the national definition of REDD + activities resulted in an amendment of this definition by all REDD + stakeholders as the legal one.

Table 1 : Forest definition

THRESHOLDS	VALUE
Minimum height of trees (m)	≥ 5m
Minimum canopy cover (%)	≥ 30%
Minimum area (ha)	≥ 1

The definition of the forest has been respected in the various steps of FREL development:

- Sites smaller than one hectare are excluded from the activity data: this has been done through the Minimal Mapping Unit (MMU), which is about 9 pixels of the satellite images used (1 pixel = 30 mx 30 m), corresponding to a total area of 0.81 ha (more or less 1 ha).
- Sites with less than 5 m tree height are excluded from the carbon inventory. To ensure compliance with this height parameter, the average height of each cluster was estimated for both the PERR-FH inventory and the 1996 inventory. Either for wet or dry forest clusters, the average height is scientifically much higher than 5 m. For spiny forest clusters, there are 16 clusters with height lower than 5. These clusters were excluded from the biomass calculation.

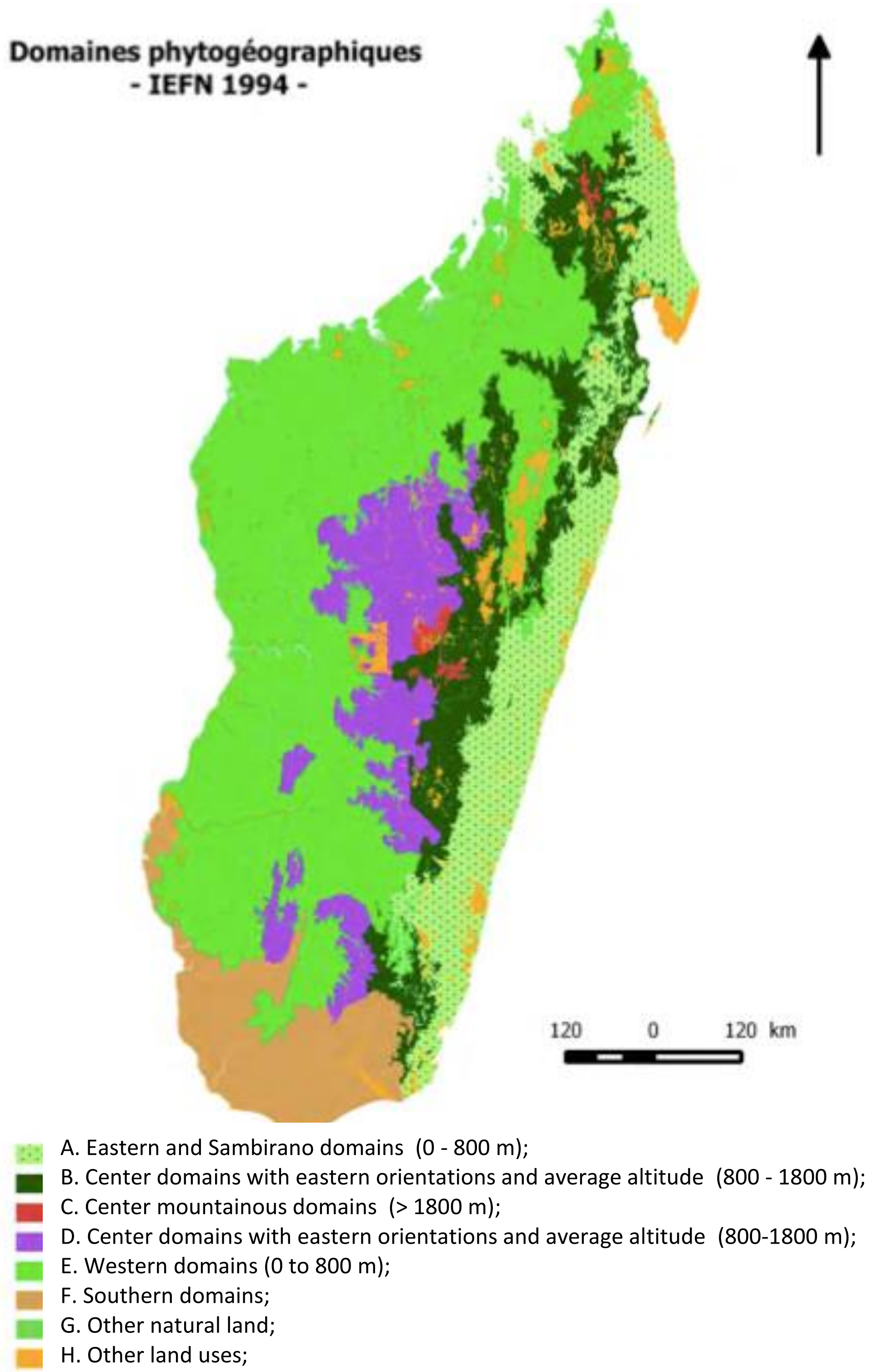
However, it was not possible to ensure that sites with a coverage rate of less than 30% were excluded from the biomass inventory. As a matter of fact, the canopy coverage was not mentioned in the existing databases because this parameter wasn't considered on the considered inventories. Biomass assessments may therefore contains some sites not respecting the definition of forest - which would be conservative (see Chapter 8).

2.2 GEOGRAPHICAL SCOPE AND ECO-REGIONS DELINEATION

The scale for the FREL is national; it means that the data collected for its quantification cover the whole country. The delineation of the eco-regions was carried out on the basis of ecological criteria in line with the 2006 IPCC guidelines.

The National Forest Ecological Inventory (IEFN) of 1994 was designed to fill the gaps on information available on the state and evolution of Madagascar's forest resources, and set itself the objective of delineating the location of different forest formations, defining their main dendrological and dendrometric characteristics and ecological characteristics and their changing patterns. Thus, two maps of Madagascar vegetation were produced in 1994 and 2000 in which the phytogeographic domains are defined as following:

A. Eastern and Sambirano domains (0 - 800 m);
B. Center domains with eastern orientations and average altitude (800 - 1800 m);
C. Center mountainous domains (> 1800 m);
D. Center domains with eastern orientations and average altitude (800-1800 m);
E. Western domains (0 to 800 m);
F. Southern domains;
G. Other natural land;
H. Other land uses;



Graphic 1: Phytogeographic eco-regions of Madagascar

As part of the planning for the REDD+ readiness, Madagascar indicated in the R-PP that only four REDD+ eco-regions would be targeted at the beginning of the process: Eastern Humid Forests, Western Dry Forests, Southern Spiny Forests, and Mangroves (halophytes). These four eco-regions, based on the phytogeographic areas listed before, are defined in the following way:

1. The Eastern Humid Forest eco-region is consistent with the following areas and forests land:

    A. Eastern and Sambirano domains (0 - 800 m): all types of dense humid evergreen forests of low altitude and coastal forests;

    B. Center domains with eastern orientations and average altitude (800 - 1800 m): all kinds of humid evergreen forests;

    C. Center mountainous domains (> 1800 m) : all sorts of mountain with sclerophyll forests;

2. The Western Dry Forest eco-region contains the following areas and varieties of forests:

    D. Center domains with eastern orientations and average altitude (800-1800 m): all types of medium sclerophyll forests;

    E. Western domains (0 to 800 m): all types of dry forests (Dalbergia, Commiphora and Hidegardia series);

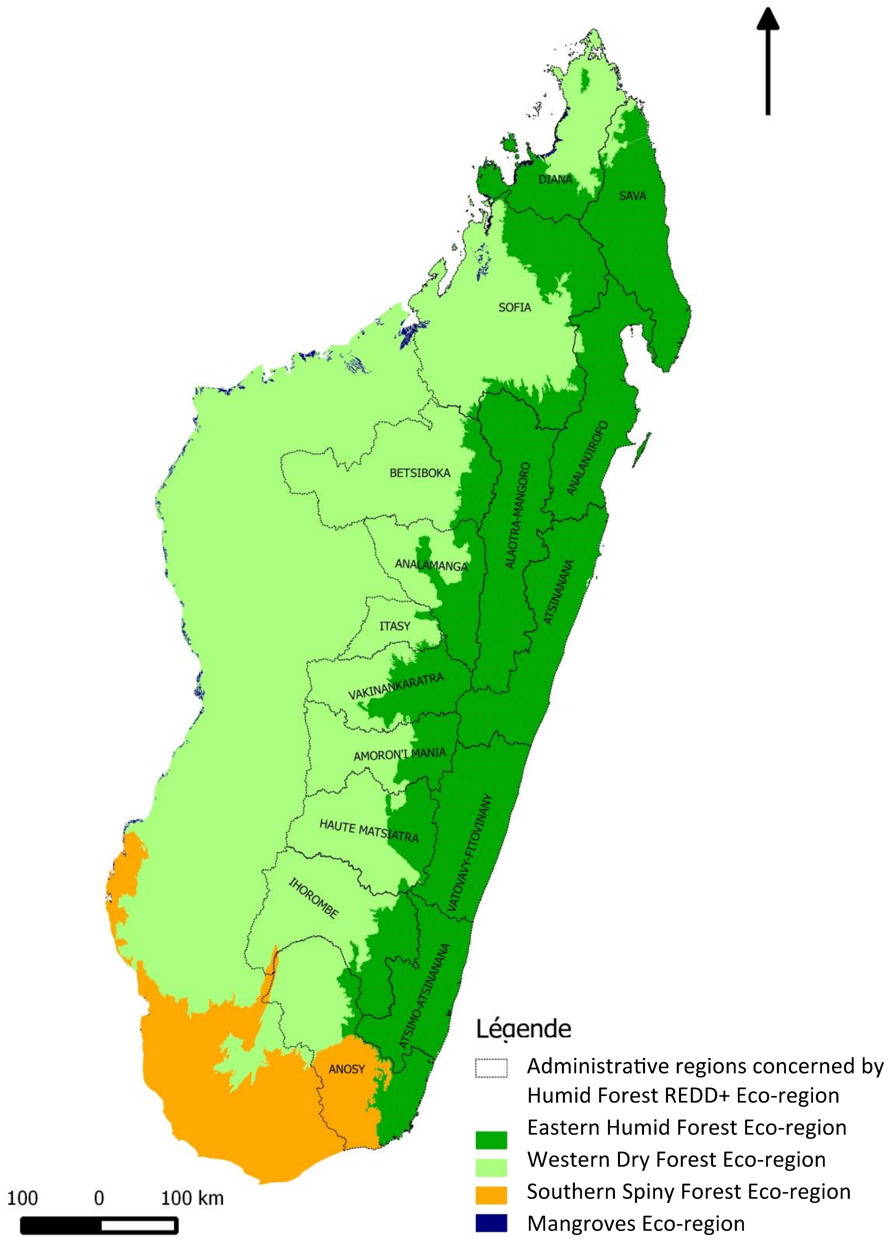
3. The Southern Spiny Forest eco-region with the following area:

    F. Southern domains: all types of dry forests and all types of xerophilous shrubs;

4. The Mangrove eco-region of which edges have been extracted from:

    G. Other natural land;

Separate biomass and emission factors were estimated for each of these four eco-regions.



Graphic 2: Land cover classes for FREL

2.3 REFERENCE PERIOD

In accordance with the Decision n°13 / COP19, 2nd paragraph, the FREL was elaborated on the basis of data from the historical reference period of 2005 – 2013. This period has been selected on the basis of available recent and comprehensive data.

Therefore, the FREL quantifies the emissions from deforestation along this period. It is important to note, however, that adequate satellite images were not available from 1 January 2005 until 31 December 2013, but rather approximately around those dates. Therefore, the reference period is not exactly nine years, but 8.31 years (periods average of all images over the entire study area, see Table 8), which corresponds to the period that was taken into account to quantify the average annual loss of forest cover.

REDD+ Activities

According to the Decision 1/COP.16, paragraph 70, defining REDD + activities, the table below shows the sources and sinks chosen for the FREL:

Table 2: Emissions and removals accounted

Activities **Sources / sinks**	**Included?**	**Justification / Explanation**
Reducing emissions from deforestation (source)	yes	The work of PERR-FH had allowed gathering useful information to establish the national FREL over the reference period for planned and unplanned deforestation.
Reducing emissions from forest degradation (source)	no	No available data. However, Madagascar wishes to develop a methodology to estimate degradation. It is therefore possible that it will be taken into account in a future submission of the FREL (see Chapter 8).
Enhancement of forest carbon stocks: plantations or reforestation leading to conversion of non-forestland to forestland (sinks)	no	No available data at this stage, since the mapping of forest plantations has not been carried out so far. Madagascar is currently launching an important reforestation program, and in this context it will be possible to include the enhancement of forest carbon stocks in a future FREL submission.
Enhancement of forest carbon stocks: natural regeneration in forestland remaining forest (sink)	no	No available data. However, as part of the FCPF grant for the REDD + readiness, Madagascar has already carried out inventories in the degraded forest areas of the Eastern humid forests and plans to carry out inventories in the Western dry forests as well as spiny forest in the south in 2017 -2018. It should allow for a future FREL submission to take account of this enhancement of carbon stocks.
Conservation of forest carbon stocks	no	Because the reduction of emissions from deforestation is overlapping with carbon stock conservation and sustainable forest management, the latter two REDD + activities are not taken into account for the FREL in Madagascar.
Sustainable management of forests	no	

Therefore, the activity data will only concern the deforestation for the different eco-regions. As indicated in the table above, the assessment of degradation is a major challenge. As part of the development of an ER Program for the FCPF Carbon Fund, BNC-REDD + is currently testing a methodology to quantify GHGs resulting from degradation. If this methodology is satisfactory, it will be tested at the national level in a later version of the FREL.

Here below are the interim definitions of REDD + activities that have been decided in Moramanga and that will be tested in the Emission Reduction Program (ER-P) over Eastern Humid Forest.

Deforestation: A direct human induced conversion of forestland to non-forestland, of a continuous area of at least 0.36 ha, whether temporal or permanent.
For example, conversion of primary forest into "Tavy-land" would be deforestation even though this conversion is temporary. The conversion of a secondary forest to a non-forest would also be deforestation.

Degradation: Reduction of forest carbon stocks due to anthropogenic disturbances resulting from canopy loss, not qualified as deforestation.
For example: forest degradation represents the gross loss of forest carbon in mature forest.

Enhancement of carbon stocks: Increased forest carbon stocks, either through a transition from non-forestland to forestland, or through the growth and / or restoration of existing forests.

2.4 CARBONE POOLS

This chapter presents and justifies the choice of the different carbon pools for FREL calculation.

Table 3: Selected carbon pools

Carbon Pool	**Selected**	**Justification / Explanation**
Above-ground Biomass (AB)	Yes	Emissions from above ground biomass constitute the majority of emissions and it is therefore essential to take into account this pool.
Below-ground Biomass (BB)	Yes	Considering a BB/AB ratio in the range of 20% to 56%, this pool is significant at the national level and will therefore be taken into account.
Deadwood (MOM 1) and litter (MOM 2)	No	No current available and reliable data.

Organic Soil Carbon (SOC)	No	Madagascar has accurate and reliable data for the humid forest eco-region but not for any other eco-regions. Despite the high-quality SOC data in the eastern humid forests, it was not possible to develop a reliable model that predicts SOC emissions (SOC evolution during the transition from forest to non-forest). This may be due to the multiple cycles of deforestation / fallow / regeneration that can generate highly variable SOC values over sites with equivalent AB.
Harvested Wood Product	No	No current available and reliable data.

2.5 GREENHOUSES GASES

Table 4 : GHGs selected in the accounting area

GHG	SELECTED ?	JUSTIFICATION / EXPLANATION
CO_2	yes	CO2 represents the most important part of emissions from deforestation in Madagascar, mainly due to slash and burn agriculture.
CH_4	No	Without reliable data, CH4 will not be taken into account. Considering the importance of fire in Madagascar, this approach is conservative (see Chapter 8)
N_2O	No	Without reliable data, CH4 will not be taken into account. Considering the importance of fire in Madagascar, this approach is conservative (see Chapter 8)

3 GENERAL METHODOLOGICAL APPROACH

It is recommended that FREL development needs to be done following IPCC guidelines, indeed:

- The UNFCCC Decision 4/CP15 encourages developing countries to use the guidelines and the latest IPCC directives, as adopted or encouraged by the Conference of Parties (COP), in the calculation forest related GHG emissions (sources) and absorptions (sinks) of GHG.
- The FCPF Methodological Framework asks through its criteria 5 that "The ER Program uses the most recent Intergovernmental Panel on Climate Change (IPCC) guidance and guidelines, as adopted or encouraged by the Conference of the Parties as a basis for estimating forest-related greenhouse gas emissions by sources and removals by sinks".

In compliance with these recommendations, the FREL has been developed according to the rules and methodologies requested by the 2006 IPCC Guidelines. According to these IPCC definitions, the methodology is based on the gain-loss approach and thus the net balance estimation (the sum of gains and losses) in carbon pools (IPCC, 2006 Guidelines for National Greenhouse Gas Inventories, Volume 4, section 2.2). The following table presents an overall view :

Table 5: IPCC Equations used for FREL development

REDD+ ACTIVITIES (SOURCES AND SINKS)	EQUATIONS APPLIED	REFERENCE
All activities	Equation 2.2 Equation 2.3	Vol. 4, chapter 2, section 2.2.1, page 2.7
Deforestation	Equation 2.16	Vol. 4, chapter 2, section 2.3.1.2, page 2.20

The annual changes in carbon stocks over the reference period in the Accounting Area ($\Delta \boldsymbol{C_{LU}}$) are equal to the sum of annual change in carbon stocks for each of the $\boldsymbol{i}$ REDD+ activities ($\Delta \boldsymbol{C_{LU_i}}$).

Following the IPCC notation, the sum of annual change in carbon stocks for each of the $\boldsymbol{i}$ REDD+ activities ($\Delta \boldsymbol{C_{LU_i}}$) would be equal to the annual change in carbon stocks in the aboveground biomass carbon pool ($\Delta \boldsymbol{C_{AB}}$) and the annual change in carbon stocks in belowground biomass carbon pool ($\Delta \boldsymbol{C_{BB}}$) accounted.

$$\Delta \boldsymbol{C_{LU_i}} = \Delta \boldsymbol{C_{AB}} + \Delta \boldsymbol{C_{BB}} = \Delta \boldsymbol{C_{B}} \qquad \textbf{\textit{Equation 1}}$$

Avec

ΔC_{LU_i}	Carbon stock changes, for the REDD+ activities i, during the reference period, in tones C yr-1
ΔC_{AB}	Above-ground biomass carbon stock changes during the reference period, in tones C yr-1
ΔC_{BB}	Below-ground biomass carbon stock changes during the reference period, in tones C yr-1
ΔC_{B}	Total biomass carbon stock changes during the reference period, in tones C yr-1

Following the 2006 IPCC Guidelines the annual change in carbon stocks in biomass on forestland converted to other land-use category (ΔC_B) would be estimated through the following equation:

$$\Delta C_B = \Delta C_G + \Delta C_{CONVERSION} - \Delta C_L$$ ***Equation 2***

Avec

ΔC_{B}	Annual change in carbon stocks in biomass on land converted to other land- use category, in tones C yr-1
ΔC_{G}	Annual increase in carbon stocks in biomass due to growth on land converted to another land-use category, in tones C yr-1
$\Delta C_{CONVERSION}$	Initial change in carbon stocks in biomass on land converted to other land-use category, in tones C yr-1
ΔC_{L}	Annual decrease in biomass carbon stocks due to losses from harvesting, fuel wood gathering and disturbances on land converted to other land-use category, in tones C yr-1

Following the recommendations set in chapter 2.2.1 of the GFOI Methods Guidance Document for applying IPCC Guidelines and guidance in the context of REDD+, the above equation will be simplified and it will be assumed that:

a) the annual change in carbon stocks in biomass (ΔC_B) is equal to the initial change in carbon stocks ($\Delta C_{CONVERSION}$);

b) it is assumed that the biomass stocks immediately after conversion is the biomass stocks of the resulting land-use.

Therefore, and because we only consider deforestation, the annual change in carbon stocks would be estimated as follows:

$$\Delta C_{CONVERSION} = \sum_{j} EF_j \times \Delta A_j$$ ***Equation 3***

Avec

$\Delta C_{CONVERSION}$	Initial change in carbon stocks in biomass on land converted to non forest category, in tones C yr-1
EF_j	Emission factor for transition j (here deforestation), tones CO2 ha-1
ΔA_j	Area of forest converted to non forest in a certain year, ha yr-1

The emission factor is defined as following:

$$EF_j = \left(B_{Before,j} - B_{After,j}\right) x\ CF\ X\ \frac{44}{12}$$ ***Equation 4***

Avec

EF_j	Emission factor for transition j (here deforestation), tones CO2 ha-1
$B_{Before\ ,j}$	Biomass stocks on land use transition j before the conversion, tones d.m. ha-1.
$B_{After\ ,j}$	Biomass stocks on land use transition j immediately after the conversion, tones d.m. ha-1.
CF	Carbon fraction of dry matter, tone C (tone d.m.)-1
44/12	Carbon extension factor for CO2

In accordance with the methodological approach presented above, chapter 4 gives activity data (ΔA_j) according to historical deforestation analysis. Then, Chapter 5 presents data on emission factors for aboveground and belowground biomass.

4 ACTIVITY DATA

Activity data were generated as part of the Humid Forest Eco-Regional REDD+ Project (PERR-FH), funded by the Environmental Program. A consortium composed of Wildlife Conservation Society, the National Environmental Office, Madagascar National Parks and ETC Terra lead this work.

This chapter explains how activity data were generated using the methodology presented in the sub-component 2.4 of PERR-FH “Historical analysis of deforestation in the humid forest eco-region of Eastern Madagascar: 2005 – 2010 – 2013”. It describes specifically the acquisition process, pre-processing, processing and post-processing and the main results obtained.

4.1 SPECIFIC METHODOLOGY

Methodologies to realize this study on forest cover evolution are based on REDD+ guidelines set and validated for the eco-region during a workshop organized in Antananarivo in December 2013 and that aimed at defining the more appropriate methodologies in line with the FCPF and VCS guidelines. The content of this approach, the type of data used and the treatment process are summarized in Table 6 below.

This method is also inspired from a previous study realized by Grinand et al (2013) in the context of the Holistic Program of Forests Conservation (PHCF), one the REDD+ project initiated in Madagascar in 2008.

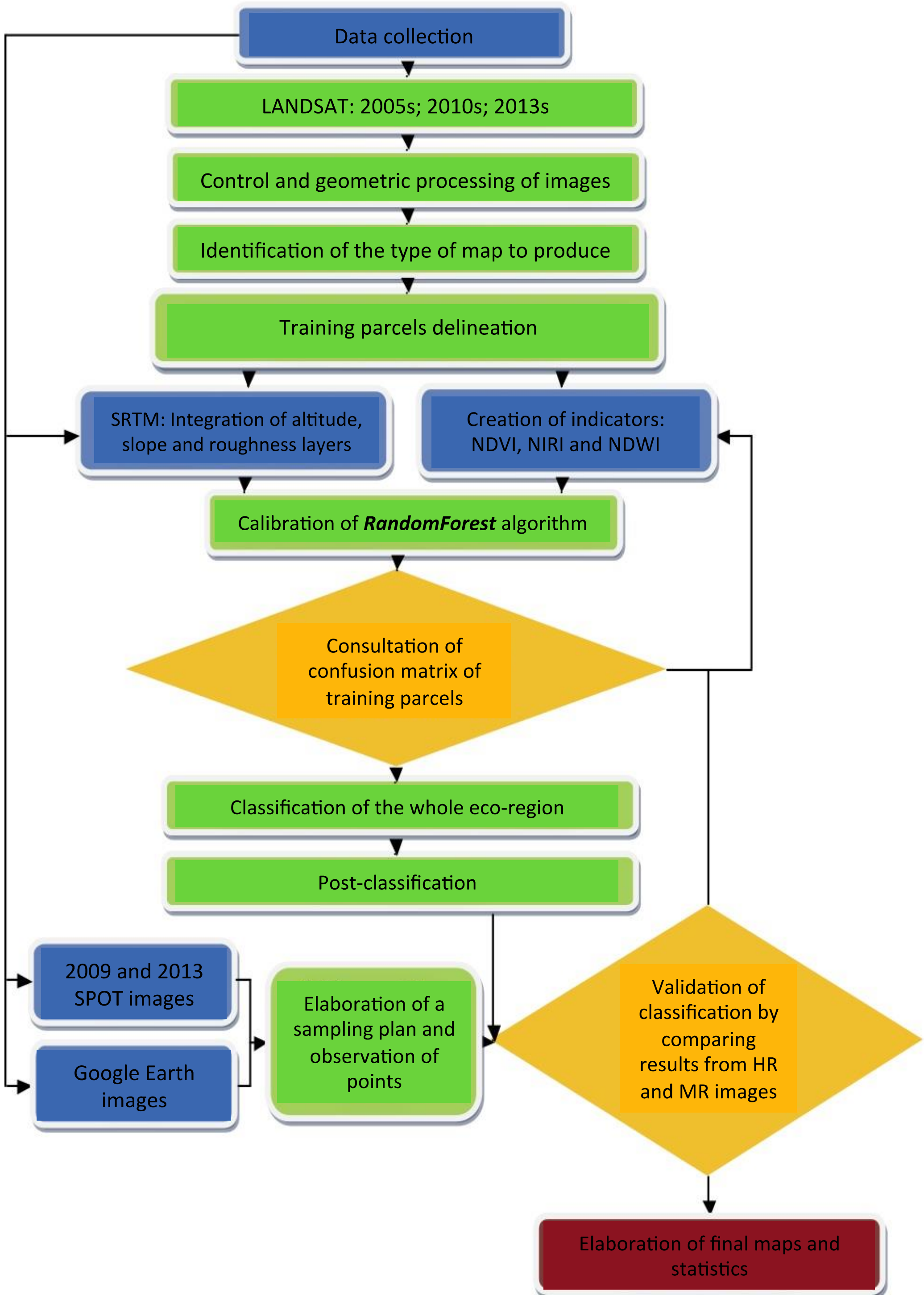
Table 6 : Methodological framework for historical analysis of deforestation

Step 1: Data characterization	
Satellite images type	High-resolution images (30m or better) All images for the eco-region were coming from the same provider LANDSAT images were preferably used because of their public and free availability.
Period and date for observation	Images from years 2005, 2010 et 2013/14. Images from the same years have been used in priority, in order to ensure homogeneity.
Step 2: Treatment and analysis	
Pre-processing	- When the images weren’t preprocessed, an atmospheric and geometrical correction were applied - When the cloud cover exceeded 10% within an area of the eco-region, a combination of different scene at different dates were applied in order to decrease this cloud cover

Classification	A supervised classification method was used (involving a delineation of training areas) and the 6 IPCC land use categories were used. High resolution Google Earth images were used to delineate training areas. The Software R was used with RandomForest algorithm
Analysis	The analysis was realized on an automatic way using R/RandomForest. It was conducted one area after the other in order to facilitate the work of operators and the use of computers.
Post processing	3 levels of post-treatment of data were done: • 3x3 pixels smoothing, over a majority filter • Filter for the forest under 1ha • Filter for deforested area under 0,36 ha (over 2x2 pixels)
STEP 3: PRECISION ESTIMATION	
Precision estimation of maps	Use of one third of the training data to evaluate the precision. Moreover, and external evaluation of the precision was done using very high-resolution images. The overall accuracy objective for forest/non forest classification was of minimum 75%

Processing chain of data

The processing chain is summarized in the Graphic 3 below.



Graphic 3: Steps in data treatment for historical analysis of deforestation.

Type of satellite imagery

LANDSAT images were used in order to ensure homogeneity in the type of images used but also availability of data over important geographic area and period. Also, this type of images are recommended for the mapping of deforestation because they ensure a resolution corresponding to the maximum limit of 30m required for REDD+ methodologies (GOFC-GOLD 2013).

These images are available for free on the data sharing web server of USGS, Clovis and Earth Explorer. Characteristic of these images are summarized in the Table 7 here below.

Table 7 : Characteristic of the differents spectral bands of LANDSAT

LANDSAT 5/7			LANDSAT 8		
Spectral Band	**Wavelength**	**Resolution**	**Spectral Band**	**Wavelength**	**Resolution**
Band 1 - Blue (B)	0,45 - 0,52	30 m	Band 2 – Blue (B)	0,450 - 0,515	30 m
Band 2 – Green (G)	0,52 - 0,60	30 m	Band 3 – Green (G)	0,525 - 0,600	30 m
Band 3 - Red (R)	0,63 - 0,69	30 m	Band 4 – Red (R)	0,630 - 0,680	30 m
Band 4 - Near-Infrared (NIR)	0,76 - 0,90	30 m	Band 5 - Near-Infrared (NIR)	0,845 - 0,885	30 m
Band 5 - Near-Infrared 1 (NIR1)	1,55 - 1,75	30 m	Band 6 - Near-Infrared 1 (NIR1)	1,560 - 1,660	30 m
Band 7 - Mid-Infrared (MID)	2,08 - 2,35	30 m	Band 7 - Mid-Infrared (MID)	2,100 - 2,300	30 m

Dates and period of reference

As presented in the Chapter 2.3, the historical reference period covers 2005-2013. Within this period, years 2005, 2010 and 2013 have been taken as reference years (“pivot year”).

It is important to mention that cloud cover within the study area limits the choices in terms of selecting a specific date for all images. Thus, dates were chosen within a year of difference compared to the reference date.

Table 8 below presents the dates of images that were used, I1 being the time interval (in decimal number or years) for the period 2005-2010, and I2 the time interval for the period 2010-2013.

Table 8 : Landsat images dates used for historical analysis of deforestation

Scene	Images 2005	Images 2010	Images 2013	I1	I2	Total period
157 - 071	25.03.2005	04.11.2011	07.02.2014	6,62	2,26	8,88
158 - 069	02.06.2004	09.08.2008	28.12.2013	4,19	5,39	9,58
158 - 070	27.08.2006	05.10.2010	19.06.2013	4,11	2,71	6,82
158 - 071	27.01.2005	20.05.2011	18.03.2014	6,31	2,83	9,14
158 - 072	10.06.2007	18.01.2011	18.03.2014	3,61	3,16	6,77
158 - 073	11.06.2007	08.07.2011	18.05.2013	4,08	1,86	5,94
158 - 074	24.06.2006	08.07.2011	18.05.2013	5,04	1,86	6,9
158 - 075	26.04.2005	15.11.2009	05.07.2013	4,56	3,64	8,2
158 - 076	03.08.2005	30.11.2009	13.08.2013	4,33	3,7	8,03
158 - 077	12.04.2006	20.04.2009	26.06.2013	3,02	4,19	7,21
159 - 068	24.04.2005	19.04.2009	22.04.2013	3,99	4,01	8
159 - 069	18.08.2006	10.06.2010	26.06.2013	3,81	3,05	6,86
159 - 070	24.04.2005	26.03.2009	22.04.2013	3,92	4,08	8
159 - 071	06.02.2006	05.05.2009	13.08.2013	3,24	4,28	7,52
159 - 072	20.03.2004	30.04.2010	13.08.2013	6,12	3,29	9,41
159 - 073	28.04.2006	01.05.2010	25.05.2013	4,01	3,07	7,08
159 - 074	25.04.2005	07.06.2009	25.05.2013	4,12	3,97	8,09
159 - 075	11.09.2006	30.03.2010	23.04.2013	3,55	3,07	6,62
159 - 076	10.01.2005	05.11.2009	16.09.2014	4,82	4,87	9,69
159 - 077	11.04.2006	19.04.2009	22.04.2013	3,02	4,01	7,03
159 - 078	07.11.2004	24.03.2011	22.04.2013	6,38	2,08	8,46
160 - 070	28.05.2006	28.11.2009	29.04.2013	3,51	3,42	6,93
160 - 071	23.04.2005	20.05.2009	07.09.2014	4,08	5,3	9,38
160 - 072	13.08.2005	05.06.2009	06.08.2014	3,81	5,17	8,98
160 - 073	22.03.2005	29.04.2010	05.07.2014	5,11	4,19	9,3
160 - 074	22.03.2005	12.11.2009	10.11.2014	4,65	5	9,65

160 - 075	17.01.2005	12.11.2009	10.11.2014	4,82	5	9,82
160 - 076	09.05.2005	15.03.2011	29.04.2013	5,85	2,13	7,98
160 - 077	23.04.2005	15.03.2011	02.05.2014	5,9	3,13	9,03
161 - 071	29.03.2005	25.04.2009	29.08.2014	4,08	5,35	9,43
161 - 072	16.05.2005	25.04.2009	25.05.2014	3,95	5,08	9,03
161 - 073	16.05.2005	17.04.2009	28.07.2014	3,92	5,28	9,2
161 - 074	29.03.2005	25.04.2009	30.09.2014	4,08	5,44	9,52
161 - 075	29.03.2005	20.04.2010	12.07.2014	5,06	4,23	9,29
161 - 076	16.05.2005	25.04.2009	25.05.2014	3,95	5,08	9,03
Average						8,31

Pre-processing

Apart of the different characteristic of spectral information, the choice of the images was also based on the following criteria:

- Percentage of cloud cover;
- Geometric characteristic of the image;
- Presence or not of default effect of Landsat 7 sensor (SLC – off)

The pre-processing phase aims at obtaining usable data for temporal analysis, which means with a low or inexistent cloud cover, a geometric lag inferior to 1 pixel and no or few stripping effect. This work was realized thanks to ENVI, ERDAS Imagine and QGIS software, and it consists in respecting spatial conformity of data, especially regarding the future mosaic of images and layer stacking. Thus, all images uploaded were verified and received a geometric correction.

As mentioned before, image availability without cloud cover within the Eastern study area of Madagascar is very limited. Globally images selected for the analysis have less than 20% of cloud coverage except for some area: Makira-Masoala, Antongil bay and COMATSA area. Thus, a supervised classification was realized on multi-date composites over the full ecoregion in order to reduce uncertainties. Indeed, according to GOFC-GOLD (CP18, 2012), multi-date analysis or direct change detection reduces errors compared to post-classification methods.

In order to guarantee geometric characteristic of images, Global Land Survey (GLS) and Level-1T (L1T) products were used. According to Gutman et al (2008), these data have satisfying radiometric and geometric qualities for land-cover change analysis, especially for historical analysis of deforestation. However their use is highly limited due to the presence of cloud cover in the North region (COMATSA) and North-East (Makira-Masoala). In these regions GLS and L1T data can be complemented using other images with geometric levels that needs meticulous verifications. Images that present important geometric issues (distorsion) have been removed from the analysis. However, those who presented only simple geometric issues have been corrected et used in the study (COMATSA: 158-069 [2005 et 2010], COFAV: 158-073 [2005]).

Due to SLC-off issue in the Landsat-7 sensor since 2003, spectral bands of hundreds of meters or kilometers but without information appear on these images. The presence of such bands on 2005 and 2010 images has also limited the choice because the only possibility was to create a mosaic with two scenes over the same date to correct the problem.

Globally, such data weren’t used for the analysis when other images with better quality existed, but some of these images had lower cloud coverage and good geometric properties that gave them some advantages.

4.2 LAND CLASSIFICATION AND CHANGE CLASSES

Cartographic approach for deforestation is exhaustive over the total area to study, namely that data processing is homogenous over the whole study area in order to avoid methodological bias due to operators.

Practically, this activity has 3 main steps:

- Definition of Land-use classification system;
- Delineation of training areas;
- Classification using a machine learning classifier.

Definition of Land-use classification system

The definition of the different land-use classes was discussed between the members of the consortium that worked on this study. Taking into account IPCC recommendations (IPCC, 2006) and the diversity of land-uses known over the eco-region, plus those that can be identified with Landsat imagery, vegetation and land-use class had been identified as following:

Table 9 : Land-use classes definition

NAME	ACRONYM	DEFINITION
Forestland	F	Forested area bigger or equal to 1 ha with a tree cover higher or equal to 30%, and with a tree height equal or above 5m, located in the eco-regions of humid, spiny and dry forest as well as mangroves.
Grasslands and croplands	P	Grasslands or croplands with a tree cover inferior to 30%, and/or height inferior to 5m and/or an area inferior to 1 ha.
Wetlands	H	Wetlands with a tree cover inferior to 30%, and/or height inferior to 5m and/or an area inferior to 1 ha.
Clouds / shadows	O	Area covered with clouds of shadows.

Because historical analysis of deforestation prioritized land cover change for forestry lands, the classification adopted is shown in Table 10.

Table 10 : Classification of land-use classes for multi-date analysis

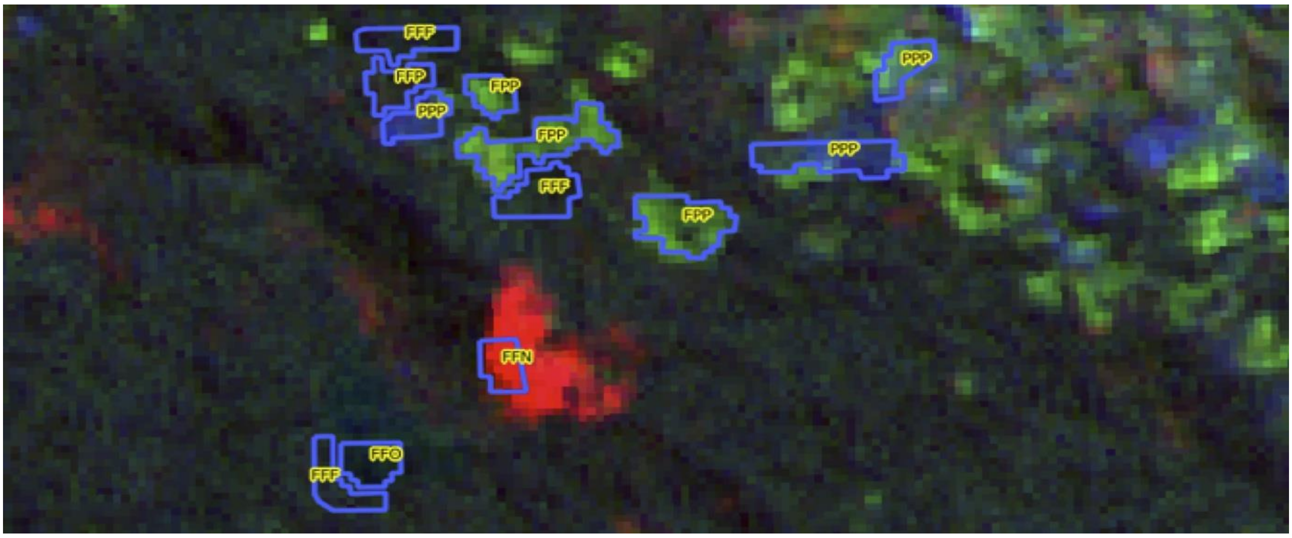
Code	Land cover in 2005	Land cover in 2010	Land cover in 2013	Land cover change	Acronym
111	Humid forest	Humid forest	Humid forest	Intact humid forestland	FFF
113	Humid forest	Humid forest	Non-Forest	Humid forestland converted in grasslands or croplands between 2010 and 2013	FFN
133	Humid forest	Non-Forest	Non-Forest	Humid forestland converted in grasslands or croplands between 2005 and 2010	FNN
183	Humid forest	Clouds/shadow	Non-Forest	Humid forestland converted in grasslands or croplands between 2005 and 2013	FON
222	Dry forest	Dry forest	Dry forest	Intact dry forestland	SSS
223	Dry forest	Dry forest	Non-Forest	Dry forestland converted in grasslands or croplands between 2010 and 2013	SSN
228	Dry forest	Dry forest	Clouds/ shadow	Intact dry forestland	SSO
233	Dry forest	Non-Forest	Non-Forest	Dry forestland converted in grasslands or croplands between 2005 and 2010	SNN
288	Dry forest	Clouds / shadow	Clouds / shadow	Intact dry forestland	SOO
333	Non-Forest	Non-Forest	Non-Forest	Non-forest	NNN
444	Wetland	Wetland	Wetland	Unchanged wetlands	HHH
533	Spiny forest	Non-Forest	Non-Forest	Spiny forestland converted in grasslands or croplands between 2005 and 2013	ENN

Code	Land cover in 2005	Land cover in 2010	Land cover in 2013	Land cover change	Acronym
553	Spiny forest	Spiny forest	Non-Forest	Spiny forestland converted in grasslands or croplands between 2010 and 2013	EEN
555	Spiny forest	Spiny forest	Spiny forest	Intact spiny forestland	EEE
666	Other lands	Other lands	Other lands	Other lands	AAA
733	Mangroves	Non-Forest	Non-Forest	Deforested mangroves between 2005 and 2010	MNN
773	Mangroves	Mangroves	Non-Forest	Deforested mangroves between 2010 and 2013	MNN
777	Mangroves	Mangroves	Mangroves	Unchanged mangroves	MMM
778	Mangroves	Mangroves	Clouds / shadow	Unchanged mangroves	MMO
788	Mangroves	Clouds / shadow	Clouds / shadow	Unchanged mangroves	MOO
888	Clouds / shadow	Clouds / shadow	Clouds / shadow	Clouds / shadow	OOO

Delineation of Training areas

In a supervised classification approach, this step is necessary in order to calibrate the classification algorithm. Quality of the result depends largely of the quality on the delineation of these trainings areas. In this study, the delineation had been realized through visual interpretation of the images to classify and through other sources of information. In order to better locate changes between classes, a colored multi-date composition of the spectral band of images had been produced.

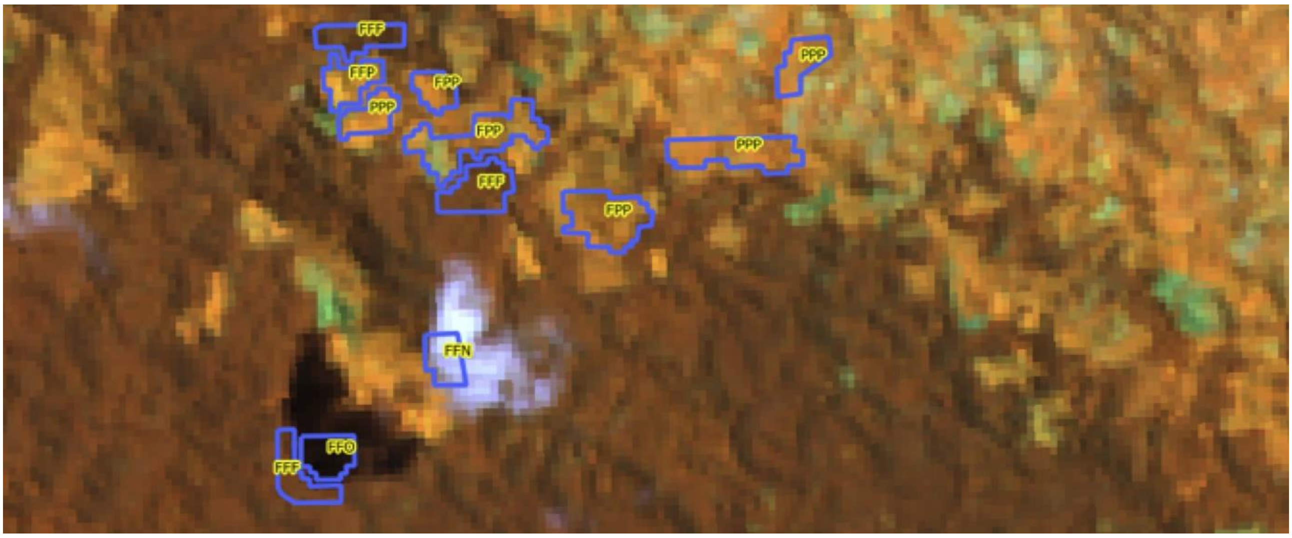
Classes had been located into clusters : combination of several training parcels into the same landscape, ensuring that a minimum of 3 different land-use classes (FFF, FFP and FPP) were delineated into each cluster. Then, the delineation of the training areas were refined and checked by overlying very high resolution satellite images available in Google Earth. Finally, a geolocated database was produced compiling all polygons and results of visual interpretation for the three dates studied. Graphic 4 and Graphic 6 here below represents some aspects of this process.



(R: Band 3-2013; G: Band 3-2010; B:Band3-2005) : In green deforestation between 2005 and 2010, in red are clouds in 2013 or deforestation between 2010 and 2013.

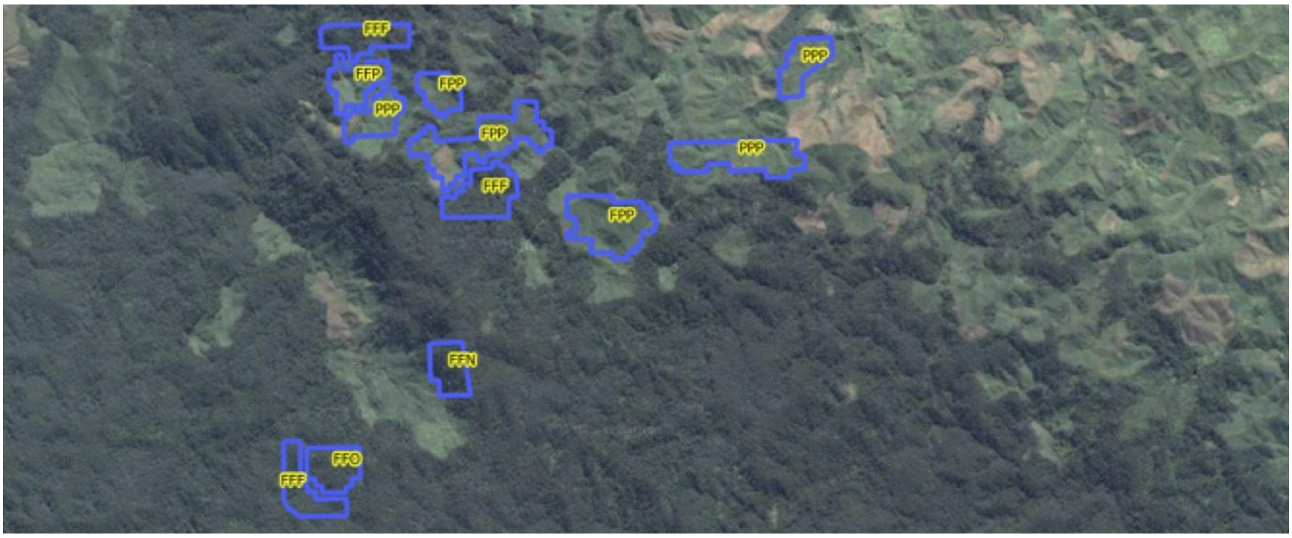
Graphic 4: Highlighting of land-use changes using a colored multi-date composition

(R : Band4 ; G : Band 5 ; B : Band 3) : In black shadow of the cloud and in white the cloud, forest are in



dark orange, and deforestation in light orange.

Graphic 5: Delineation of classes in 2013

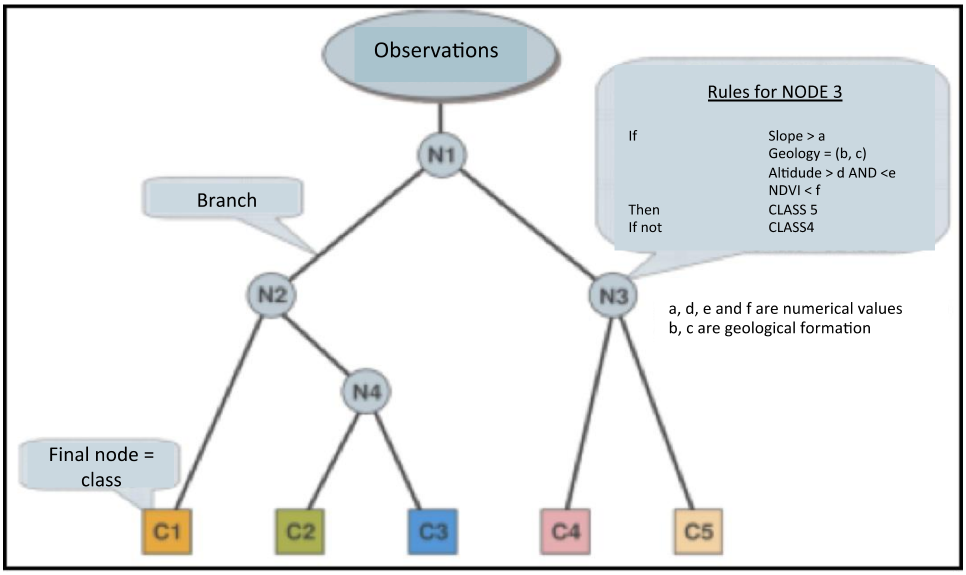


Graphic 6 : Verification and refining on Google Earth

Classification using a machine learning algorithm

The *RandomForest* algorithm developed by Breiman et al (2001) was selected for the classification. This is a supervised learning algorithm that combines a bagging technique and a decision tree algorithm as described in

Graphic 7. It was uploaded into the software R with Liaw and Wiener (2002), directly into the *RandomForest* package



Graphic 7: Tree decision classification

First, RandomForest algorithm was calibrated to predict the different land use classes. Calibration of the model was done with 70% of the training data, the remaining 30% being used for validation. It's considered as an internal validation because not all training areas are used and the map isn't produced at this stage. Furthermore, the algorithm calculates another performance indicator of the model, an estimation of its generalization error on the 30% remaining data for the development of the classification model: the "Out-of-bag" error (OOB).

RandForest Package allows obtaining information on the significance of variables used. What are the variables that are highly necessary to explain the classification? What are the variables that we can remove? These are the questions that can be answered. With this aim, a significance indicator for specific forest variables was developed by Breiman (2001) and it uses random permutation of variables. The more these random permutations of variables generate a high increase in the error, the more significant is the variable. On the contrary, if these permutations don't have an important impact on the error, then the variable is considered as negligible.

Spatial information layers

In order to improve the degree of discrimination of the studied classes, several layers of indicators derived from primary bands were calculated, especially:

- NDVI: Normalized Difference Vegetation Index;

$$NDVI = \frac{NIR1 - R}{NIR1 + R}$$ (Equation 5)

- NIRI: Near Infrared Reflectance Index;

$$NIRI = \frac{NIR2 - NIR1}{NIR2 + NIR1}$$ (Equation 6)

- NDWI: Normalized Difference Water Index.

$$NDWI = \frac{NIR1 - V}{NIR1 + V}$$ (Equation 7)

Besides these indicators, morphometric indicators (exo-canals) were introduced (altitude, slope, roughness) and derived from a Numerical Field Model (MNT) in order to mitigate topography effect and reflectance of primary canals.

4.3 POST-PROCESSING

After the classification process some problems were still remaining: clouds / shadows classes, low rate of isolated pixels linked to very small forest or parcels, and classification errors. Thus, post-processing is needed to clean the classified image so that it fits with MMU requirements and reduces errors.

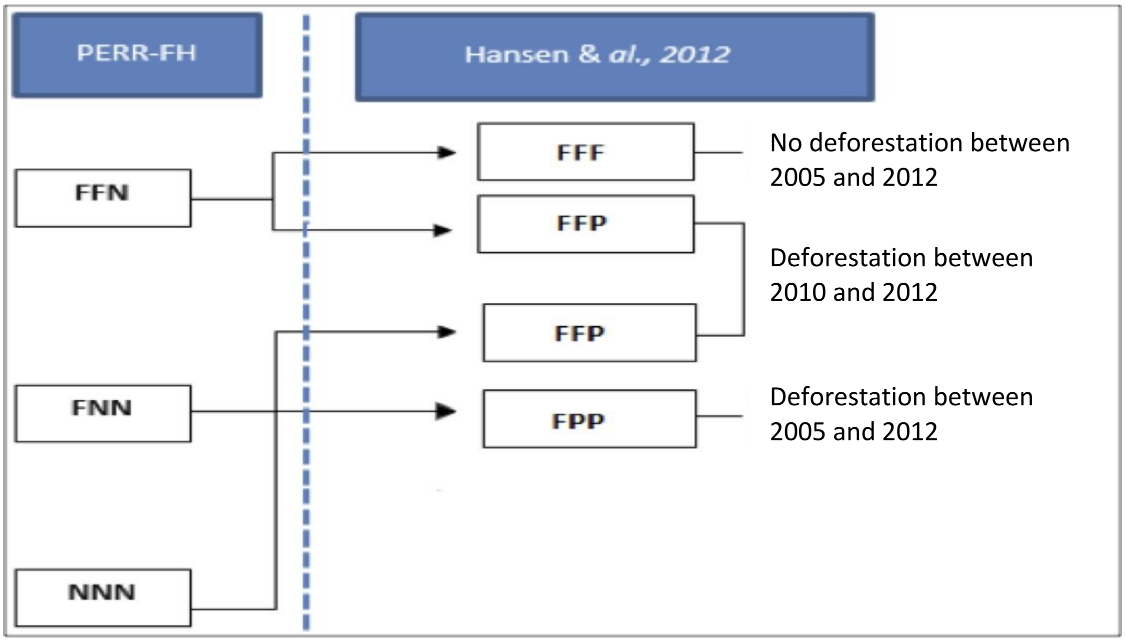
Filtering

This step begins by cleaning the noise on the classified image with a convolutional filter using a moving window of 3 x 3 pixels. Then, the next step consists in applying consecutively two functions allowing deleting forest and deforestation patches according to the following conditions:

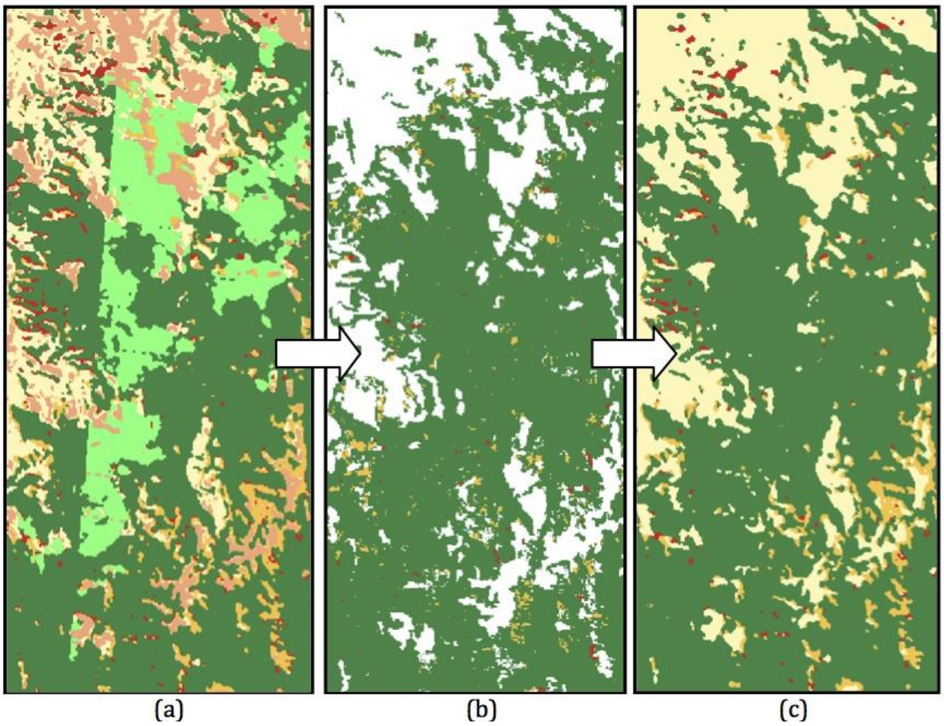
- 0,81 ha for forest (around 3x3 LANDSAT pixels)
- 0,36 ha for deforestation (around 2x2 LANDSAT pixels)

Suppression of clouds/shadows

In order to have a complete cartography of the eco-region, shadows and clouds were replaced with the Global Forest Change product (Hansen et al., 2012) that provide on a free basis an important quantity of data for the period 2000-2012 (percentage of forest cover, deforested pixels per year, raw images). Data had been processed in a way to produce forest cover change map in 2005 and 2012. Thus, it had been possible to classify an important part of shadows and clouds pixels. Graphic 8 and **Graphic 9** here below illustrate the adopted approach.



Graphic 8 : Elimination process of clouds



Graphic 9: Post-classification example

(a) Classification with humid forest class under clouds and shadows (un light green, noise already treated); (b) Hybrid deforestation map for 2005 – 2012 obtained from Global Forest Change map; (c) Historical map of deforestation between 2005 and 2013 (deforestation patches ≥ 0,36 ha and forest patches ≥ 1 ha). In green are represented intact forests, in orange deforestation between 2005 and 2010, and in red deforestation between 2010 and 2013.

4.4 EXTERNAL VALIDATION OF RESULTS

See chapter 7.2.1.

4.5 LAND-USE CHANGE FROM 2005 TO 2013

The table below presents the results of the analysis of deforestation between 2005 and 2013 and over the four eco-regions and at national level.

Table 11 : Forest area loss per eco-region

	FOREST LOSS [IN HA]					
ECO-REGION	**2005-2010**	**2010-2013**	**2005-2013**	**TOTAL LOSS DURING THE REFERENCE PERIOD**	**ANNUAL LOSS**	**DEFORESTATION RATE [1] (%)**
Humid forest	82 108	91 692	14	173 814	20 916	0,47
Dry forest	203 389	264 271	-	467 660	56 277	1,89
Spiny forest	120 621	86 507	-	207 128	24 925	1,58
Mangrove	2 288	1 313	-	3 601	433	0,25
Total	**408 406**	**443 783**	**14**	**852 203**	**852 203**	**1,11**

Activity data

This section presents the results of the analysis of activity data per eco-region. There is no official template to report activity data of a FREL for the UNFCCC submission. Thus we have chosen to use the template that FCPF provides for Emission Reduction Program (ER-PD).

Description of the parameter	**Annual loss in humid forest**
Sources and sinks	The parameter is GHG estimation due to deforestation
Unit	Ha / year
Value	20 916
Origin of the data or description of the methodology used	Landsat 5, 7 and 8 images for humid forest ecosystem have been overlapped to determine land-use change from forest to non-forest between 2005 and 2010 first and then between 2010 and 2013. The methodology for calculation is presented in chapter 4.
Spatial scale	The parameter is applicable for the whole humid forest eco-region, 20 585 864 ha.
Analysis of uncertainties	Uncertainty is essentially due to errors in the classification of Landsat images

[1] Calculated using Puyravaud (2002) formula and the period of time of 8,31 years for the 2 period.

Estimation of the precision, accuracy and confidence level estimation	See section 7

Description of the parameter	**Annual loss in dry forest**
Sources and sinks	The parameter is GHG estimation due to deforestation
Unit	Ha / years
Value	56 277
Origin of the data or description of the methodology used	Landsat 5, 7 and 8 images for dry forest ecosystem have been overlapped to determine land-use change from forest to non-forest between 2005 and 2010 first and then between 2010 and 2013. The methodology for calculation is presented in chapter 4.
Spatial scale	The parameter is applicable for the whole humid forest eco-region, of 32 850 415 ha.
Analysis of uncertainties	Uncertainty is essentially due to errors in the classification of Landsat images.
Estimation of the precision, accuracy and confidence level estimation	See section 7

Description of the parameter	**Annual loss in spiny forest**
Sources and sinks	The parameter is GHG estimation due to deforestation
Unit	Ha / years
Value	24 925
Origin of the data or description of the methodology used	Landsat 5, 7 and 8 images for spiny forest ecosystem have been overlapped to determine land-use change from forest to non-forest between 2005 and 2010 first and then between 2010 and 2013. The methodology for calculation is presented in chapter 4.
Spatial scale	The parameter is applicable for the whole humid forest eco-region, of 5 479 843ha.
Analysis of uncertainties	Uncertainty is essentially due to errors in the classification of Landsat images.

Estimation of the precision, accuracy and confidence level estimation	See section 7

Description of the parameter	**Annual loss in mangrove**
Sources and sinks	The parameter is GHG estimation due to deforestation
Unit	Ha / years
Value	445
Origin of the data or description of the methodology used	Landsat 5, 7 and 8 images for spiny forest ecosystem have been overlapped to determine land-use change from forest to non-forest between 2005 and 2010 first and then between 2010 and 2013. The methodology for calculation is presented in chapter 4.
Spatial scale	The parameter is applicable for the whole humid forest eco-region, of 293 315 ha.
Analysis of uncertainties	Uncertainty is essentially due to errors in the classification of Landsat images.
Estimation of the precision, accuracy and confidence level estimation	See section 7

5 CARBON STOCK AND EMISSION FACTORS

Forest biomass estimates by ecoregion were developed based on the following sources:

1. For the dense humid forest ecoregion, 567 clustered ground inventory plots from the PERR-FH project were analyzed.
2. For the dry forest ecoregion, 187 ground inventory clusters (3 plots each) from the 1996 national forest inventory were analyzed
3. For the thorny forest ecoregion, 122 ground inventory clusters (3 plots each) from the 1996 national forest inventory were analyzed
4. For the mangrove forest ecoregion, biomass estimates are based on a peer-reviewed paper by Jones et al (2014)

Biomass in non-forest was estimated based on a peer-reviewed paper by Andriamananjara et al (2016).

Below ground biomass estimates were then calculated based on root-shoot ratios published in a peer-reviewed paper by Mokany et al. (2006). Finally, emission factors were calculated by subtracting non-forest biomass from forest biomass by ecoregion (see Table 12) and then converting biomass loss to CO2 emissions.

Table 12: Calculation of emission factors

ORIGINAL LAND COVER	POST-DEFORESTATION LAND-COVER	EMISSION FACTOR
Humid forest	Non-forest	Humid forest deforestation (D_{FH})
Dry forest	Non-forest	Dry forest deforestation (D_{FS})
Spiny forest	Non-forest	Spiny forest deforestation (D_{FE})
Mangrove	Non-forest	Mangroves deforestation (D_{M})

5.1 FOREST INVENTORY DATA

5.1.1 Ecological National Forest inventory of 1996 (IEFN)

Until today the IEFN is the only and first ecological forest inventory that covers all inland ecosystems in Madagascar. It had as main objective to fill the gaps in terms of information on current state and the evolution of forestry resources in Madagascar, which is crucial information for a sustainable and strategic management of natural forest resources at national and regional level. Therefore this inventory aimed at identifying location and geographical distribution of the different forestry formations.

The method used for this IEFN had two phases:

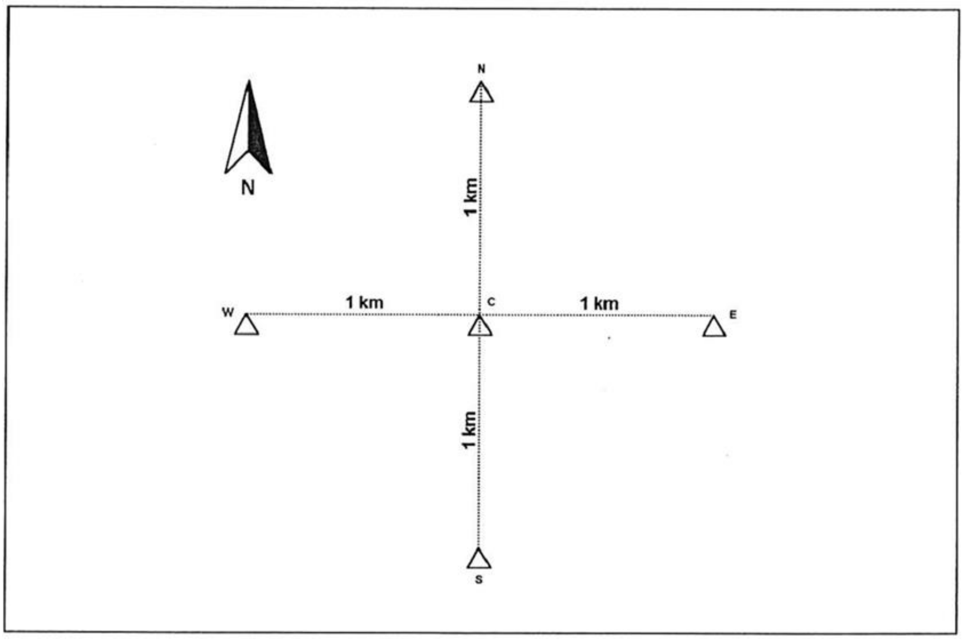
- The first one, dedicated to the treatment and analysis of LANDSAT 5 satellite imagery in order to realize cartography of forestry formations,
- The second one, dedicated to data collection through sampling of main dendrological, dendrometric, floristic and faunal parameters of the main forest formations leading to the elaboration of a database used for examination and analysis of collected data.

The inventory contained 196 “camps” each one with 5 clusters. One of these five clusters was directly located in the middle of the camp, while the others were located at 1 km distance from the central cluster in the North, South, East and West direction see Graphic 10.

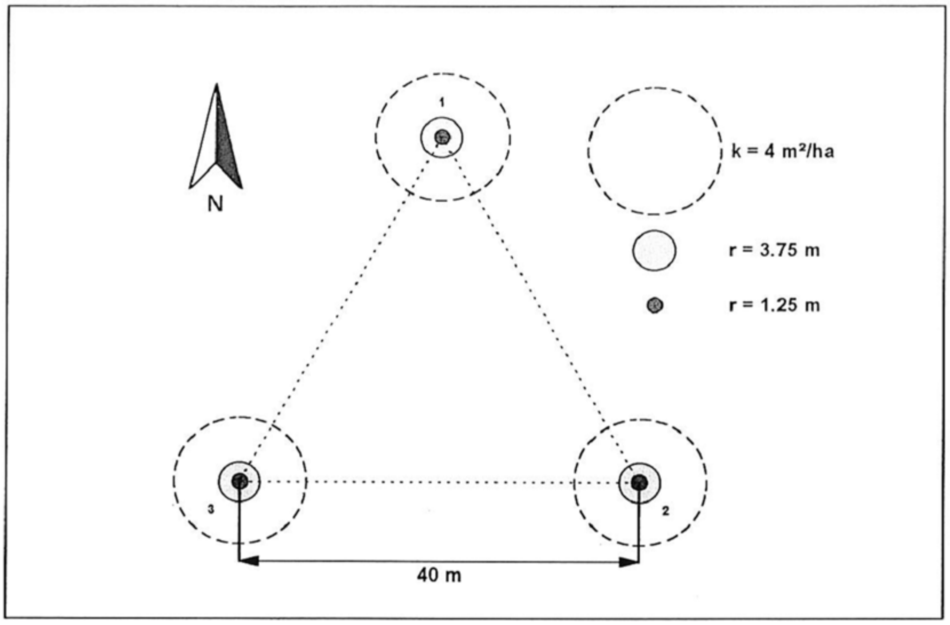
These samplings arrangements in clusters are divided in two types:

- Clusters with 6 plots, in dense humid forest: samplings at the top and halfway of an edge of an equilateral triangle of 80m per side;
- Clusters with 3 plots, in dense dry forests and in the spiny forests: samplings at the top of a triangle of 40m side;

Graphic 10 : « Camps » arrangements in the IEFN (Source: IEFN 1994)



Graphic 11 : Clusters arrangements in IEFN for dry and spiny forest (Source: IEFN 1994)



This inventory allowed recording 773 samples, representing 678 species included in 378 genus and 116 families. Thus, a vegetation map of Madagascar (scale 1/200 000) was produced for 1996 (FTM, ONE, Direction des Eaux et Forêts).

Phytogeographical areas are presented and delineated in section 2.

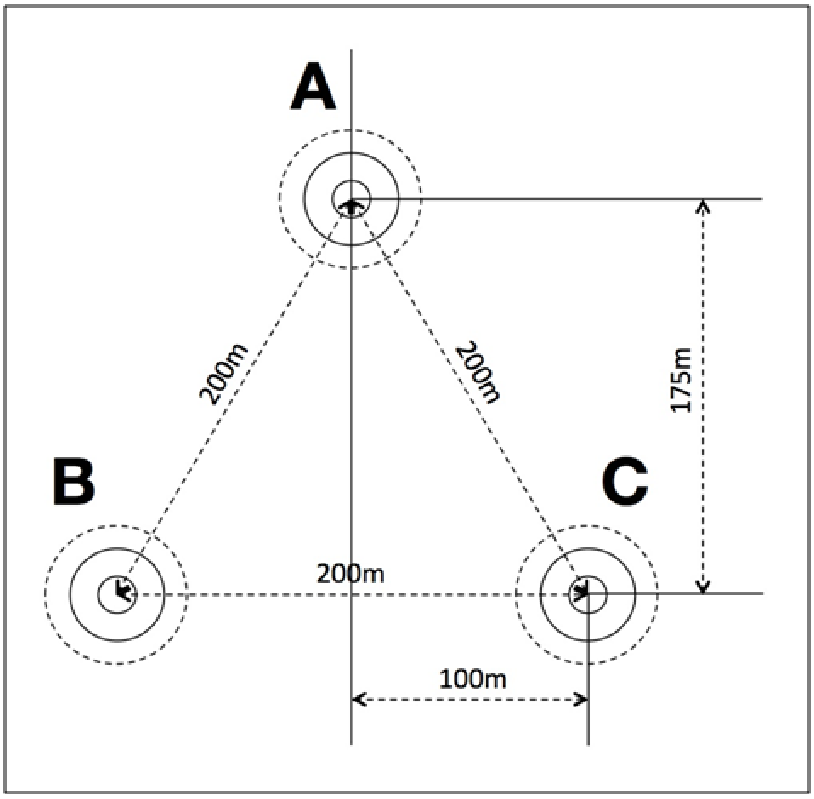
5.1.2 PERR-FH Forest Inventory in 2014

PERR-FH forest inventory was conducted in 2014 over the whole eastern humid forest eco-region. The objective was to determine emission factors to use with activity data for deforestation in order to quantify the FREL over this ecoregion. This inventory also allowed developing a map of aboveground and soil carbon stocks.

The methodological framework for this inventory can be summarize as follows: (i) use of existing data, (ii) stratification based on IEFN, (iii) sampling method (with a precision of 10% at 95% of confidence level), (iv) carbon pools measured, (v) type of data to collect, (vi) samples and plots, (vii) data processing (allometric model, software for inventory data treatment).

Concerning the field data collection method: carbon pools measured are above ground biomass and dead standing wood. Inventory arrangements has two levels of organization: (i) inventory clusters with 3 samples (A, B and C) and organized as an equilateral triangle with 200m per side, (ii) inventory plots regrouping 4 nested plots (1, 2, 3 and 4) for the measurement of large trees, medium size trees, small trees and natural regeneration.

Graphic 12 show a cluster with 3 plots defined by geographic coordinates in their center. Centers of plots are identified with GPS and located with a steel rod. Each plot is pictured at 10 m downstream from the plot center (Geotagging)



Graphic 12: Clusters arrangement in PERR-FH inventory

Each plot is divided into 4 nested plots (cf. Graphic 13) :

1-Large trees:

Trees with DBH≥ 30 cm ; Identified from the plot center using a Relaskop with factor 2.

2-Medium size trees:

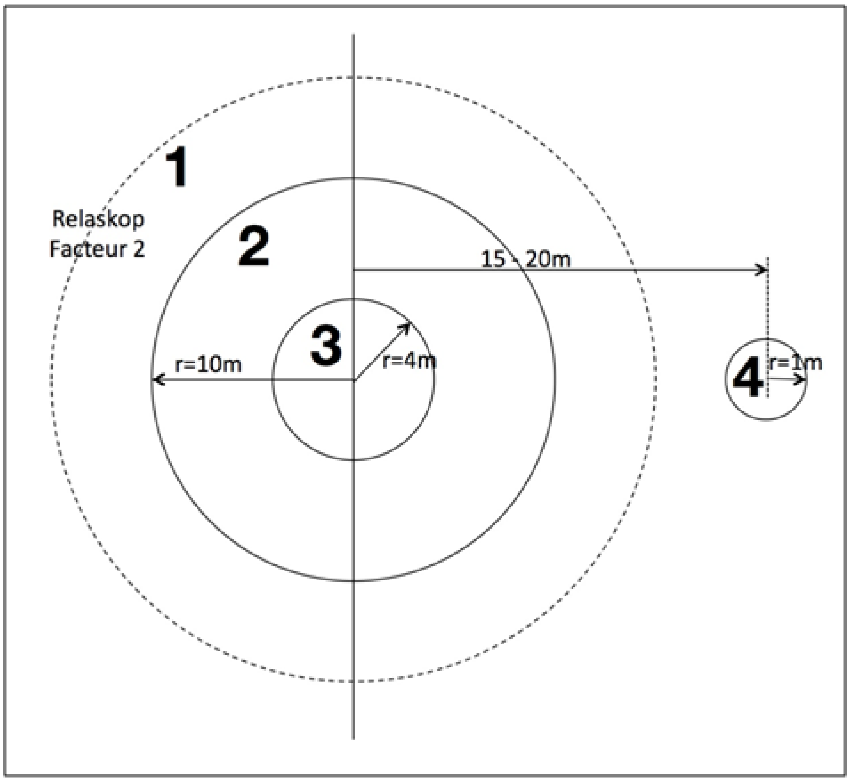
Trees with DBH≥ 15 cm and DBH< 30 cm ; Identified within a 10m radius circle.

3-Small trees:

Trees with DBH≥ 5 cm and DBH< 15 cm ; Identified in a 4m radius circle.

4-Natural regeneration:

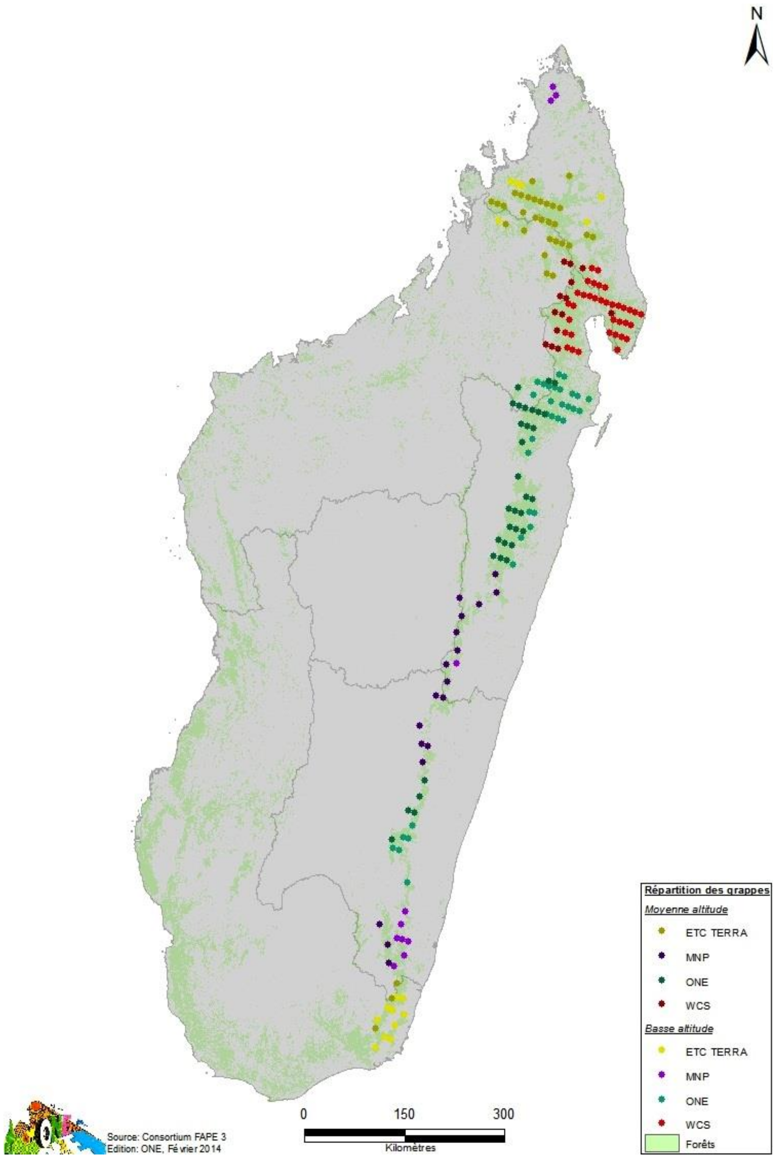
Trees with DBH < 5 cm ; Identified within a 1 m radius circle, moved from 15 to 20 m.



Graphic 13 : Plots arrangements in PERR-FH inventory

The type of data collected are: general information, dendrometric and dendrologic parameters (DBH, height, etc..).

Through this inventory, 567 plots or 189 clusters were inventoried according to the following map:



Graphic 14 : PERR-FH clusters map

5.2 ABOVE GROUND BIOMASS

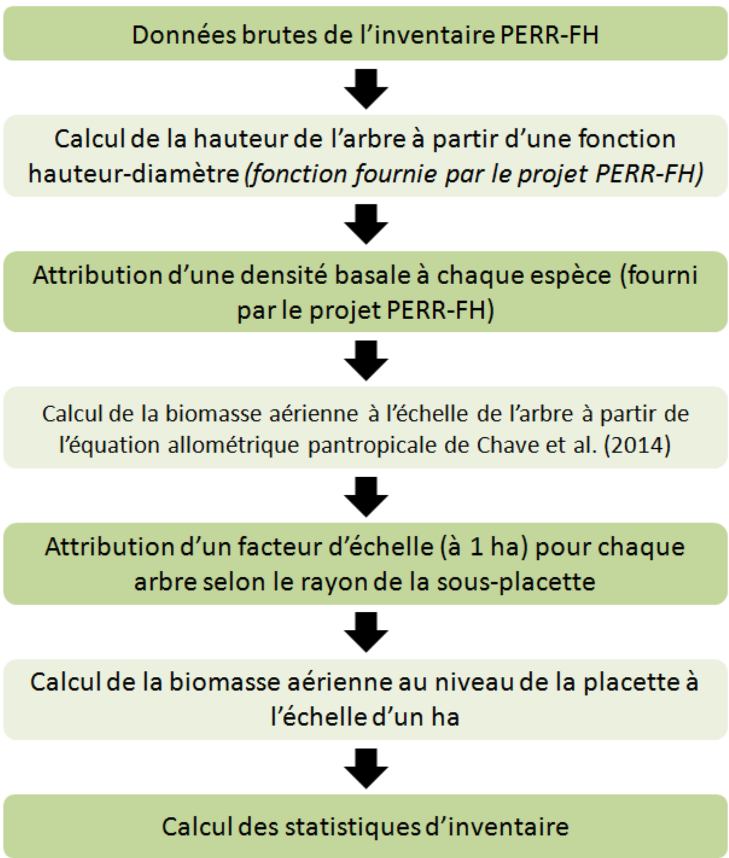
5.2.1 Humid forest

The calculation of above ground biomass in this forest ecoregion is based on 567 ground inventory plots grouped in 189 clusters (grappes) from the PERR-FH project (see subsection 5.1.2 for a short summary or Livrable 2 of the PERR-FH report annexed as a separate file to this report). Each cluster is considered as the sampling unit.

The PERR-FH inventory data was processed as described in

Graphic 15.

Graphic 15: PERR-FH inventory data processing workflow



The PERR-FH inventory raw data was provided by the PERR-FH project "as is". This data and all subsequent processing steps are annexed to this report as a separate file (PERR-FH_inventory_biomass_estimation.xlsx).

Data on total height were collected for a subsample of trees (2,519 arbres) and they were used for calibrating a H-DBH relation similar to the formula type proposed by Chave et al. (2014):

$$H_{est} = 1{,}389036*\exp(0{,}980517*\ln(D))*\exp(-\,0{,}07032031*(\ln(D))^2) \qquad (1)$$

Application of this diameter-height function to the measured tree dataset shows that height is on average overestimated by approx. 15.7%. However, when estimating biomass for this dataset using the pantropical allometric equation with height of Chave et al. (2014) using both measured and estimated heights, total biomass is overestimated by only 1.4%.
The wood densities for each tree in the inventory had already been assigned by the PERR-FH project. According to Clovis Grinand (2016, personal communication), wood densities were assigned based on the 2006 IPCC guidelines for GHG inventories and the global wood density database (Chave et al. 2009; Zanne et al. 2009). In cases where a wood density value was not available for a particular species, the mean wood density value of the genus or family was assigned. If neither was available or known then a conservative default wood density value of 0.5 was assigned.
Then tree level biomass was calculated based on the following pantropical allometric equation provided by Chave et al. (2014).

$$AGB_{est} = 0{,}0673*(\rho*D^2*H_{est})^{0{,}976} \qquad (2)$$

With :

AGB_{est} : *Above-Ground Biomass* per tree estimated, in tdm

ρ : Wood density, from IPCC list and the list per kind from Rakotovao et al. 2011 and based on vernacular name inventoried on the field

D : Diameter at Breist Height (DBH)

H_{est} : Tree estimated height

Since no height was measured for all trees, three different methods were tested: a) using the H-DBH relation presented previously and the allometric equation from Chave et al. (2014); b) the allometric equation from Chave 2014 without height; and c) calculating mean measured tree height by diameter class and then using these mean tree heights to calculate biomass using the allometric equation of Chave with height. The method a) generates an estimate that is 6% higher in average than b) et 2% lower than method c). Therefore, it is method a) that has been retained in the calculations.

Following the calculation of tree-level biomass, a scaling factor was assigned to each tree to scale the biomass estimate to the 1 ha scale. As each sample plot featured 4 nested plots (see Graphic 13 in section 5.1.2), different scaling factors were assigned based on the DBH of the tree (see Table 13 for fixed area subplots).

Table 13: Scaling factor for fixed area subplots - 2014 PERR-FH forest inventory

DBH OF TREE [CM]	RADIUS OF SAMPLE PLOT [M]	AREA OF SAMPLE PLOT [SQM]	SCALING FACTOR TO 1 HA
≥15<30	10	314,16	31,83
≥5<15	4	50,27	198,94
<5cm	1	3,14	3 183,10

For trees with a DBH ≥30 cm which were measured with the Relascope (basal area factor 2), the scaling factor was calculated as follows:

$$SF = RCV * \frac{10{,}000}{\pi * c^2 * D^2} \qquad (4)$$

Avec:

SF is the scaling factor, dimensionless

RCV: is the relascope counting value, dimensionless (0, 0.5 or 1)

c is the c-value for basal area factor 2, dimensionless (here 35.352)

D: DBH, in m

The scaling factor was then used to calculate biomass at the 1 ha scale for each tree. Then, above ground biomass was summarized by plot to calculate the inventory statistics (see Table 14).

Table 14: PERR-FH inventory statistics

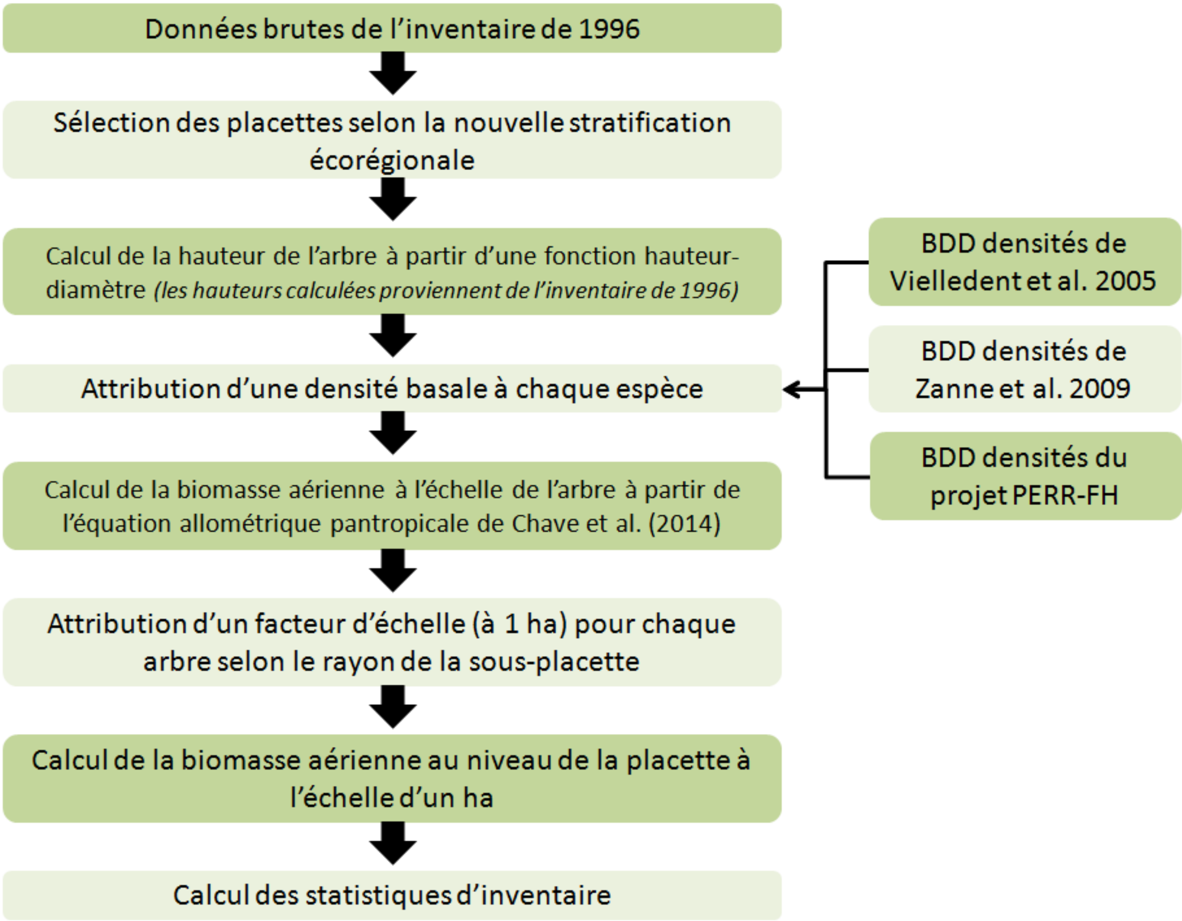
PARAMETER	VALUE
Mean AGB [tdm/ha]	271.58
Min [tdm/ha]	75.01
Max [tdm/ha]	544.43
STD [tdm/ha]	89.99
N	189
90% confidence interval [tdm/ha]	+/- 10.77
90% confidence interval [%]	+/- 3.96%
Lower bound 90% CI [tdm/ha]	260.81
Upper bound 90% CI [tdm/ha]	282.34

5.2.2 Dry and spiny forests

The calculation of above ground biomass in these two forest ecoregions is based on 187 (dry forest) and 106 (spiny forest) ground inventory clusters (3 plots per cluster) from the 1996 national forest inventory (see subsection 5.1.1 for a short summary or the 1996 national forest inventory report annexed as a separate file to this report).

As the distance in between plot centres within one cluster is only 40m (compared to 200 m in the PERR-FH inventory), inventory statistics are calculated at the cluster level.

The 1996 forest inventory data was processed as described in Graphic 16.



Graphic 16 : 1996 inventory data processing workflow

The 1996 forest inventory raw data was provided "as is". This data and all subsequent processing steps are annexed to this report as a separate file (1996_inventory_biomass_estimation.xlsx).

Since the 1996 forest inventory sampling plan was based on a different vegetation stratification (see section 2.2), the first step was to select only those plots for analysis which fell within the current boundaries of the eco-regions for dry forest and spiny forest. Since coordinates were only available for the "camps" (the center of 5 clusters, each cluster being 1km away from the camp), the selection was made on the location of the camps (even if 1 or 2 clusters would be situated in the other eco-region). In the dry forest eco-region, 1 camp (i.e. 5 clusters) was excluded because they were originally attributed to the humid forest eco-region and thus a different sampling technique was used (9 plots per cluster, different relascope factor).

For the majority of trees, height data was available in the raw data. It was however not possible to determine whether the height was measured or calculated. For a small fraction of trees height was calculated based on the following diameter-height functions.

For dry forest:

$$H_{est} = e^{2.9920-\frac{9.0579}{D}} \qquad (5)$$

For spiny forest :

$$H_{est} = e^{2.4798-\frac{9.9758}{D}} \qquad (6)$$

With :

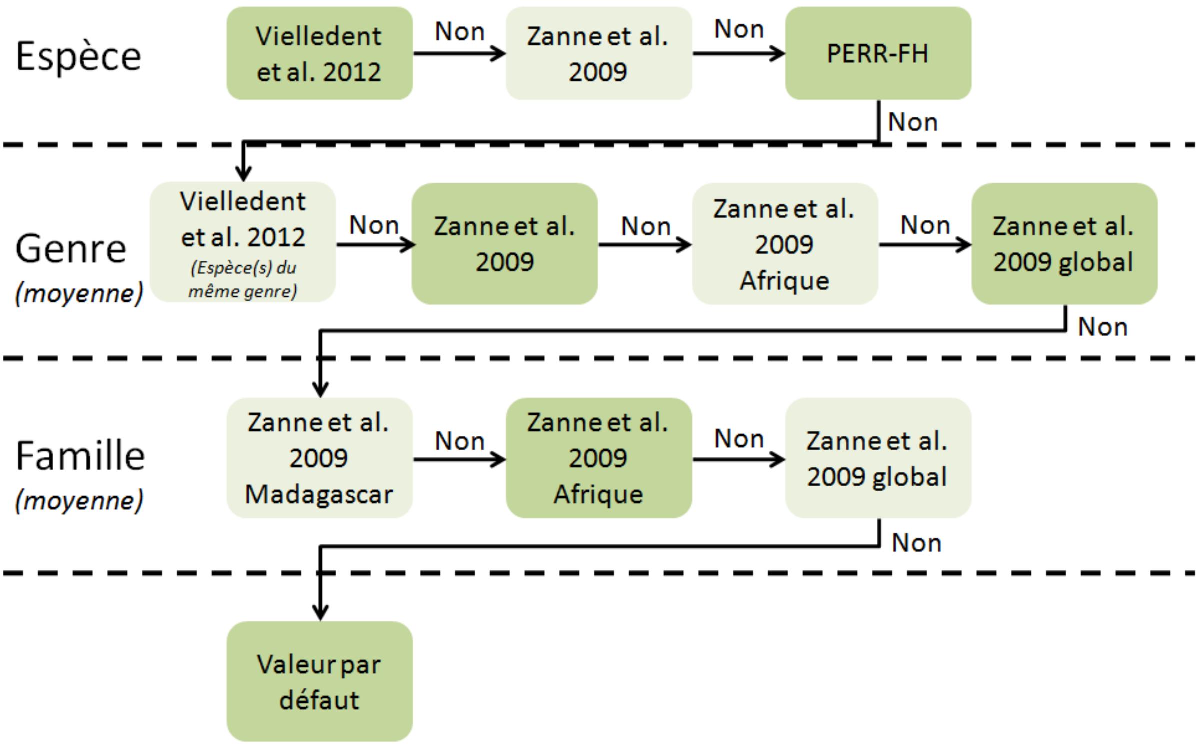
H_{est} Estimated tree height, in m

D DBH in cm

The wood densities for each tree were assigned according to the decision tree in

Graphic 17.

Graphic 17 : Arbre de décision pour attribuer les densités spécifiques



Wood densities were assigned based on the following 3 main databases:

1. A wood density database compiled by Vielledent et al. (2012) as part of its research related to the development of allometric equations;
2. The global wood density database compiled by Zanne et al. 2009;
3. The PERR-FH wood density database compiled by the PERR-FH project for the purpose of the PERR-FH inventory.

The first database was given the priority as it is based on country-specific data.

In the order to assign basic densities, these 3 databases were searched for a WD value at the species level. If no WD value was found or only the genus of the tree was known, then WD values were assigned based on the genus in the following order of priority:

1. WD value from a species of the same genus from the database of Vielldent et al. (2012)
2. Mean WD across the genus for species found in Madgascar from the database of Zanne et al. 2009
3. Mean WD across the genus for species found in Africa from the database of Zanne et al. 2009
4. Mean WD across the genus from the entire database of Zanne et al. 2009

In cases where only a single species of the same genus was found, the WD of this species was assigned.

If no WD value was available at the genus level or only the family of the tree was known, then WD values were assigned based on the family in the following order of priority:

1. Mean WD across the family for species found in Madgascar from the database of Zanne et al. 2009
2. Mean WD across the family for species found in Africa from the database of Zanne et al. 2009
3. Mean WD across the family from the entire database of Zanne et al. 2009

Finally, if no wood density could be assigned through the above process either because no WD data was available or the tree could not be identified then a conservative WD default value of 0.5 was assigned (this value was chosen because it corresponds to the default value used in the PERR-FH project).

Then tree level biomass was calculated based on the following pantropical allometric equation provided by Chave et al. (2014).

$$AGB_{est} = 0{,}0673*(\rho*D^2*H_{est})^{0{,}976} \quad (7)$$

With :

AGB_{est} : *Above-Ground Biomass* estimated, in tdm

ρ : Wood density, from IPCC list and the list per kind from Rakotovao et al. 2011 and based on vernacular name inventoried on the field

D : Diameter at Breist Height (DBH)

H_{est} : Tree estimated height

Following the calculation of tree-level biomass, a scaling factor was assigned to each tree to scale the biomass estimate to the 1 ha scale. As each sample plot featured 4 nested plots (see Graphic 13 in section 5.1.2), different scaling factors were assigned based on the DBH of the tree. See Table 15 for the scaling factor for fixed area subplots.

Table 15: Scaling factor for fixed area subplots - 1996 forest inventory

DBH of tree [cm]	Radius of sample plot [m]	Area of sample plot [sqm]	Scaling factor to 1 ha
≥3<15	3.75	44.18	226.35
<3cm	1	3.14	3,183.10

For trees with a DBH ≥15 cm which were measured with the Relascope (basal area factor 4), the scaling factor was calculated as follows:

$$SF = RCV * \frac{10{,}000}{\pi * c^2 * D^2} \tag{8}$$

Avec:

SF is the scaling factor, dimensionless

RCV: is the relascope counting value, dimensionless (0, 0.5 or 1)

c is the c-value for basal area factor 4, dimensionless (here 24.995)

D: Diamètre à Hauteur de Poitrine (DHP), in m

The scaling factor was then used to calculate biomass at the 1 ha scale for each tree. Then, above ground biomass was summarized by plot to calculate the inventory statistics (see Table 16).

Table 16 : 1996 forest inventory statistics

Parameter	Value Spiny forest	Value Dry forest
Mean AGB [tdm/ha]	22.19	69.82
Min [tdm/ha]	2.10	0.00
Max [tdm/ha]	78.08	234.41
STD [tdm/ha]	16.60	48.76
N	106	187
90% confidence interval [tdm/ha]	+/- 2.65	+/- 5.86
90% confidence interval [%]	+/- 11.95%	+/- 8.40%
Lower bound 90% CI [tdm/ha]	19.53	42.89

PARAMETER	Value Spiny forest	Value Dry forest
Upper bound 90% CI [tdm/ha]	27.65	54.62

5.2.3 Mangrove

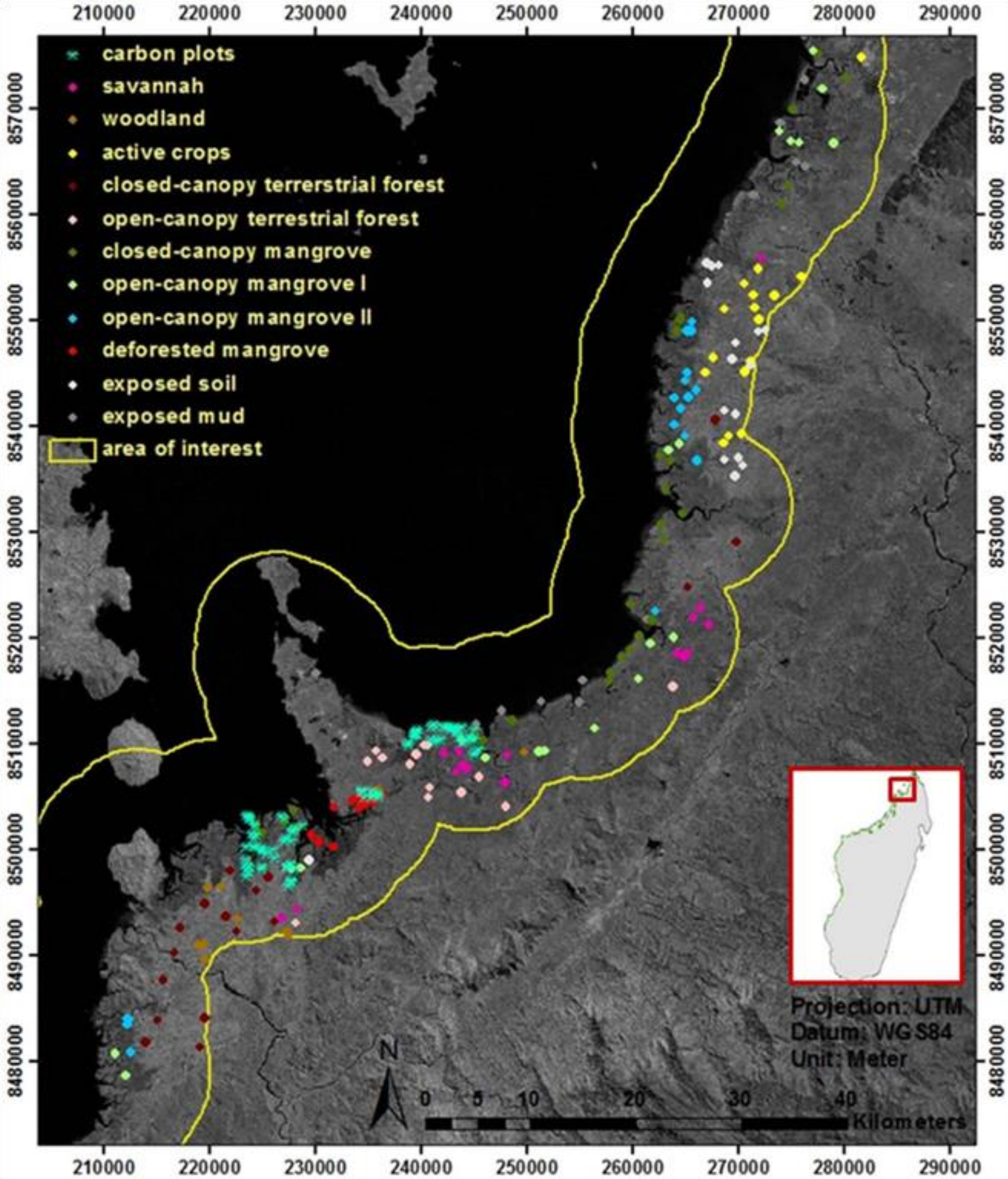
A biomass estimation of mangrove forests is included in this first FREL submission for the sake of completeness, i.e. to provide a FREL for all major forest types in Madgascar. Biomass values for mangrove forests were derived from a peer-reviewed paper from Jones et al. (2014). While the biomass estimates are considered to be robust, there are several issues which limit their applicability for the national FREL.

- The biomass measurements are from a small study area in Northwestern Madagascar, i.e. the sample is not representative
- The sample size is comparatively small
- The biomass values provided contain deadwood, a carbon pool which is not included in the FREL
- Even though Jones et al. (2014) mapped deforested mangrove sites, no biomass estimation was made on these post-deforestation sites

Nevertheless, this study currently provides the best available data for estimating emissions from mangrove deforestation. In order to take the above limitations into account, mangrove emission calculations are made rather conservatively.

The biomass measurements stem from 55 10mx10m (in some cases 20mx20m) ground inventory plots located in Northwestern Madgascar. The study area contained approx. 26,000 ha of mangrove forest (Graphic 18).

Graphic 18 : Mangrove biomass study area (source: Jones et al. 2014)



Prior to biomass sampling, mangroves (and other forest and non-forest ecosystems) were mapped and classified. Mangroves were divided into 4 classes (see Table 17).

Table 17 : Mangrove classes (source: adapted from Jones et al. 2014)

CLASS	DESCRIPTION OF TYPICAL CONSTITUENTS	CLASS CAN ALSO INCLUDE
Closed-canopy mangrove	tall, mature stands; canopy >60% closed	extremely dense younger stands
Open-canopy mangrove 1	young, short-medium trees; canopy 30%–60% closed; influenced by background soil/mud	naturally open; very degraded tall
Open-canopy mangrove 2	stunted short trees, very sparse; canopy ≥10% closed; dominated by background soil/mud	
Deforested mangrove	mosaic of stumps, scattered trees; canopy <30% closed; greatly influenced by exposed soil/mud	

Aboveground biomass (including deadwood), belowground biomass and soil organic carbon was measured in the first three classes. Biomass was estimated using the allometric equations and wood densities shown in Table 18 (dbh and height was measured). Allometric equations were obtained from Clough et al. (1989), Comley et al. (2005) and Kauffman et al. 2010, while wood densities were obtained from Dharmawan et al (2008; all as cited in Jones et al. 2014).

Table 18 : Allometric equations and wood densities used in biomass estimation (source: adapted from Jones et al. 2014)

Species	Allometric equation	Wood density
Avicennia marina	$B = 0.1848 \times dbh^{2.3524}$	0.661
Bruguiera gymnorrhiza (leaves)	$B = 0.0679 \times dbh^{1.4914}$	0.741
Bruguiera gymnorrhiza (stem)	$B = 0.464 \times (dbh^2 \times H)^{0.94275} \times p$	0.741
Ceriops tagal (dbh 2–18 cm)	$B = 10^{-0.7247} \times dbh^{2.3379}$	0.803
Ceriops tagal (dbh 18–25 cm)	$B = 10^{-0.494} \times dbh^{2.056}$	0.803
Heritiera littoralis (leaves)	$B = 0.0679 \times dbh^{1.4914}$	1.074
Heritiera littoralis (stem)	$B = 0.464 \times (dbh^2 \times H)^{0.94275} \times p$	1.074
Lumnitzera racemosa	$B = 0.0214 \times (dbh^2 \times H)^{1.05655} \times p$	0.565

Rhizophora mucronata (leaves)	$B = 0.0139 \times D^{2.1072}$	0.867
Rhizophora mucronata (root)	$B = 0.0068 \times dbh^{3.1353}$	0.867
Rhizophora mucronata (stem)	$B = 0.0311 \times (dbh^2 \times H)^{1.00741} \times p$	0.867
Sonneratia alba	$B = 0.0825 \times (dbh^2 \times H)^{0.89966} \times p$	0.78
Xylocarpus granatum	$B = 0.0830 \times (dbh^2 \times H)^{0.89806} \times p$	0.7

Note: dbh refers to diameter at breast height; D represents diameter; H stands for height; p = wood density.

The results from Jones et al. (2014) for above ground biomass are shown in Table 19 (please note that the results are provided in tC/ha and not in tdm/ha as before, because the carbon fraction used by Jones et al. 2014 could not be determined.

Table 19 : Mangrove carbon stock estimates (source: based on Jones et al. 2014)

Class	Mean carbon in above and below ground biomass (including deadwood) [tC/ha]	N	90% Confidence interval [tC/ha]	90% Confidence interval [%]
Closed-canopy	146.8	23	+/- 17.52	+/- 12%
Open-canopy 1	42.9	28	+/- 9.88	+/- 23%
Open-canopy 2	20.8	4	+/- 10.83	+/- 52%

Since activity data for mangroves is not available with the above stratification, the following assumptions are made for the calculation of the FREL:

- 50% of mangrove deforestation occurs in the closed canopy class, 50% of mangrove deforestation occurs in the open canopy class 1 (effectively this means that the mean carbon value of both classes is used);
- the biomass estimate from the open canopy class 2 is used for the residual carbon stock in post-deforestation mangroves for the calculation of emission factors.

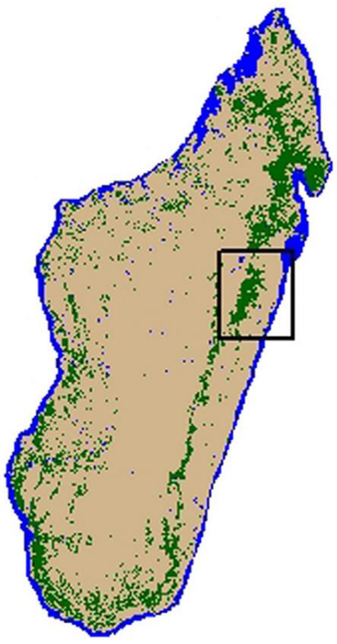
5.2.4 Non-forest

In order to estimate emission from land use change in general and deforestation in particular, one needs to also consider the long-term biomass remaining in the post-deforestation land use / land cover.

Since no countrywide inventory data is available, the residual carbon stock in post-deforestation land use is estimated based on a peer-reviewed publication from Andriamananjara et al. (2016) for humid forest and from Raharimalala et al. (2012) for dry and spiny forests.

5.2.4.1 Humid forest

The study assessed aboveground biomass and soil organic carbon in closed canopy forest, tree fallow, shrub fallow and degraded land in the Ankeniheny-Zahamena Corridor situated in the Eastern Humid Forest Ecoregion (see Graphic 19).

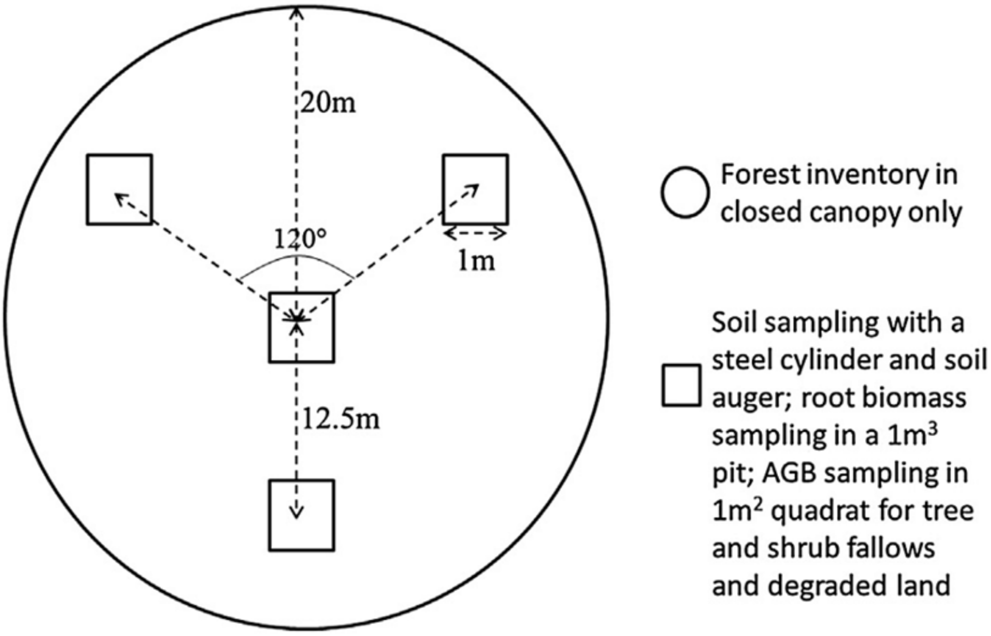


Graphic 19 : Study area (source : Andriamananjara et al. 2016)

The categories tree fallow, shrub fallow and degraded land are of interest here since they constitute post-deforestation land use classes. According to Styger et al. (2007; 2009), these classes represent the typical temporal vegetation gradient following slash and burn agriculture.

A total of 91 post-deforestation sites were sampled by Andriamananjara et al. (2016): 32 tree fallow sites, 29 shrub fallow sites, and 30 degraded land sites. At each plot location, four subplots were established (see

Graphic 20). Within each subplot, all individual plants were inventoried within a 1m x 1m quadrant, cut at ground level and weighed for the AGB assessment. AGB was quantified after oven-drying and weighing of the collected samples within the $1m^2$ quadrant and extrapolated to the hectare scale.



Graphic 20 : Plan d'échantillonnage dans les occupations du sol post-déforestation (source : Andriamananjara et al. 2016)

Le Table 20 shows the aboveground biomass estimates for the three post-deforestation land use classes[2].

Table 20 : Above ground biomass in post-deforestation land use classes

[2] Carbon values were converted back to biomass based on the carbon fraction value provided by Andriamananjara et al. (2016)

Class	AGB (tdm/ha)	N	STD	90% confidence interval [tdm/ha][3]	90% confidence interval [%]
Tree fallow	21.6	32	14.82	+/- 4.31	+/- 19.95%
Shrub fallow	21.8	29	14.95	+/- 4.57	+/- 20.95%
Degraded land	16.6	30	11.39	+/- 3.42	+/- 20.60%

Since the non-forest activity data is not stratified according to the above classes, we use the value from the shrub fallow class for estimating biomass in the post-deforestation land use class for the humid forest ecoregion as it constitutes the highest value and is thus conservative in terms of estimating emissions.

5.2.4.2 Dry and spiny forest

For dry and spiny forest, estimation of post-deforestation biomass from Raharimalala et al. (2012) have been used.

Table 21 : Above ground biomass in post-deforestation located in dry forest eco-region (from Raharimalala et al. (2012)

Period of abandon [years]	Tree and liana biomass [tdm/ha]	n	Standard Error
1-5	0,403	5	+/- 0,401
6-10	1,2	5	+/- 0,7
11-20	2,5	5	+/- 0,3
21-30	17,4	5	+/- 4,2
31-40	41,1	5	+/- 8,4
>40	66,9	5	+/- 9,5

[3] Andriamananjara et al. (2016) only report the range of the coefficient of variation for AGB across all four classes, including closed canopy forest. We conservatively use the highest value to calculate the standard deviation and then the confidence interval.

The "11-20 years" value has been used because it fits better with the default transition period from IPCC guidelines (2006)[4].

According to the section 5.2.3, we uses biomass value for the class "Mangrove with Open-canopy 2" to estimate post deforestation biomass of sites within the mangrove eco-region. Table 22 summarizes biomass values for post-deforestation sites.

Table 22 : Above ground biomasse in "non-forest" per ecoregion

NON-FOREST CLASS	AGB [TDM/HA]	90% CONFIDENCE INTERVAL [TDM/HA]	90% CONFIDENCE INTERVAL [%]
Non-forest in humid forest eco-region	21,80	+/- 4,57	+/- 20,95%
Non-forest in dry forest eco-region	2.50	+/- 0,64	+/- 25,58%
Non-forest in spiny forest eco-region	2.50	+/- 0,64	+/- 25,58%
Non-forest in mangrove eco-region	44,26[5]	+/- 10,83	+/- 54,16%

5.3 BELOW GROUND BIOMASS

Below ground biomass is estimated using root-shoot ratios. We use a peer-reviewed publication from Mokany et al. (2006) to select root-shoot ratios (see Table 23).

[4] Volume 4, Chapitre 2, section 2.3.1.1: [...] The length of time that land remains in a conversion category after a change in land use is by default 20 years (the time period assumed for carbon stocks to come to equilibrium for the purposes of calculating default coefficients [...]

[5] This biomass value in tdm/ha is estimated for the purpose of displaying it in comparison to the other non-forest biomass values. Since Jones et al. (2014) do not provide the carbon fraction, biomass was calculated by dividing the carbon stock by a carbon fraction of 0.47.

Table 23 : Root-shoot ratios

Vegetation category (from Mokany et al. 2006)	Assigned FREL land cover class	Root-shoot ratio	90% confidence interval	90% confidence interval [%]
Tropical moist deciduous forest >125 t.d.m./ha	Humid forest	0.235	+/- 0.08	+/- 36.05%
Tropical moist deciduous forest <125 t.d.m./ha	Humid Forest Non-Forest humid forest eco-region	0.205	+/- 0.02	+/- 9.84%
Tropical/ subtropical dry forest > 20 tdm/ha	Dry forest Spiny forest	0.275	+/- 0.02	+/- 6.89%
Tropical/ subtropical dry forest < 20 tdm/ha	Dry forest Spiny forest Non-forest in dry/spiny forest eco-region	0.563	+/- 0.20	+/- 35.95%

We apply the same root-shoot ratios for both forest and non-forest within a forest ecoregion. The rationale for this is that the predominant driver of deforestation is shifting cultivation, i.e. there is a cyclic regrowth of natural vegetation. This may not be deemed conservative, as the root-shoot ratios for e.g. shrub land or grassland are much higher. However, frequent burning would prevent the built-up of higher belowground biomass and hence this approach is deemed defensible.

Belowground biomass is calculated by multiplying the aboveground biomass estimates from section 5.2 with the root-shoot ratios from Table 23. The belowground biomass estimates are shown in Table 24.

Table 24 : Belowground biomass by land cover class

FREL land cover class	Mean BGB [tdm/ha]	90% confidence interval [tdm/ha]	90% confidence interval [%]
Humid forest	63,73	+/- 24,52	+/- 38,49%
Dry forest	19,85	+/- 3,94	+/- 19,84%
Spiny forest	7,77	+/- 2,35	+/- 30,25%
Mangrove	BB was measured together with AB and thus cannot be displayed separately		

Non-Forest humid forest eco-region	4,47	+/- 1,03	+/- 23,15%
Non-Forest dry forest eco-region	1,41	+/- 0,62	+/- 44,12%
Non-Forest spiny forest eco-region	1,41	+/- 0,62	+/- 44,12%
Non-Forest mangrove forest eco-region	BGB was measured together with AGB and thus cannot be displayed separately		

5.4 EMISSION FACTORS

In order to calculate emission factors, we first calculate total biomass (AGB+BGB) and then convert biomass to carbon and then carbon dioxide, using the conversion factors provided in Table 25. We use the most conservative estimate for carbon fraction and consequently assume the uncertainty of this factor to be zero.

Table 26 shows total carbon stocks in forest and non-forest, Table 27 provides an overview of the emission factors and Table 28 to Table 31 show each emission factor in more detail including key uncertainties.

These data and all process steps are explained and showed in the report in annex (*20170117_emission_calc.xlsx*).

Table 25 : Carbon and CO2 conversion factors

PARAMETER	VALUE	SOURCE
Carbon fraction in biomass [tC/tdm]	0.47	IPCC AFOLU guidelines 2006, table 4.3 (McGroddy et al. 2004)
C to CO2 conversion factor [tCO2/tC]	44/12	Based on the molecular weight of carbon and oxygen

Table 26 : Forest and non-forest carbon stocks

FREL LAND COVER CLASS	CARBON STOCKS [TCO2/HA]	90% CONFIDENCE INTERVAL [TCO2/HA]	90% CONFIDENCE INTERVAL [%]
Humid forest	577.84	+/- 84.02	+/- 14.54%

Dry forest	153.97	+/- 21.76	+/- 14.13%
Spiny forest	51.65	+/- 8.38	+/- 16.22%
Mangrove	347.78	+/- 72.41	+/- 20.82%
Non-Forest humid forest eco-region	45.27	+/- 8.07	+/- 17.83%
Non-Forest dry forest eco-region	6.73	+/- 1.54	+/- 22.81%
Non-Forest spiny forest eco-region	6.73	+/- 1.54	+/- 22.81%
Non-Forest mangrove forest eco-region	76.27	+/- 41.31	+/- 54.16%

Table 27 : Emission factor overview

LAND COVER CHANGE TYPE	EMISSION FACTOR [TCO2/HA]	90% CONFIDENCE INTERVAL [TCO2/HA]	90% CONFIDENCE INTERVAL [%]
Deforestation in Humid forest (D_{FH})	532.57	+/- 84.40	+/- 15.85%
Deforestation in dry forest (D_{FS})	147.24	+/- 21.81	+/- 14.81%
Deforestation in spiny forest (D_{FE})	44.91	+/- 8.52	+/- 18.97%
Deforestation in mangroves (D_M)	271.52	+/- 83.37	+/- 30.70%

Table 28 : Emission factor « Deforestation in Humid Forest»

DESCRIPTION OF THE PARAMETER	DEFORESTATION HUMID FOREST (D_{FH}): CONVERSION OF HUMID FOREST INTO NON-FOREST
Data unit	tCO2/ha
Value for the parameter	532.57
Source of data	**For aboveground forest biomass:** • 567 ground inventory forest plots organized in 189 clusters (DBH and sample height measurements) • Estimated tree heights based on a diameter-height function developed using a dataset of 2.519 measured tree heights

	• Wood densities from PERR-FH (2014) • Allometric equation from Chave et al. (2014) **For aboveground non-forest biomass** 29 ground inventory non-forest plots (Andriamananjara et al. 2016) **For belowground biomass and carbon stock calculation** • Root-shoot ratios from Mokany et al. 2006 • Carbon fraction from IPCC AFOLU guidelines 2006, table 4.3 (McGroddy et al. 2004)
Spatial level	Ecoregional / local
Key uncertainties for this parameter	Sampling error DBH and height measurement errors Error of the diameter height function Error of the wood density estimate Error of the allometric equation Error of the root-shoot ratio
Estimation of uncertainty	Using error propagation, the uncertainty is estimated at +/- 84.40 tCO2/ha (+/- 15.85%) at the 90% confidence level

Table 29 : Emission factor « Deforestation in dry forest»

Description of the parameter	Deforestation in dry forest (D_{FS}): Conversion of dry forest into non-forest
Data unit	tCO2/ha
Value for the parameter	147.24
Source of data	**For aboveground forest biomass calculation:** • 187 ground forest inventory cluster plots (1996 national forest inventory; (DBH and sample height measurements) • Estimated tree heights based on a diameter-height function developed) • Wood densities from Zanne et al. (2009), Vielledent et al. (2012), PERR-FH (2014) • Allometric equation from Chave et al. (2014) **For aboveground non-forest biomass calculation** 29 ground inventory non-forest plots (Andriamananjara et al. 2016) **For belowground biomass and carbon stock calculation** • Root-shoot ratios from Mokany et al. 2006 • Carbon fraction from IPCC AFOLU guidelines 2006, table 4.3 (McGroddy et al. 2004)
Spatial level	Ecoregional / local
Key uncertainties for this parameter	Sampling error DBH and height measurement errors Error of the diameter height function Error of the wood density estimate Error of the allometric equation Error of the root-shoot ratio
Estimation of uncertainty	Using error propagation, the uncertainty is estimated at +/- **21.81** tCO2/ha (+/-**14,81**%) at the 90% confidence level

Table 30 : Emission factor « Deforestation in spiny forest»

DESCRIPTION OF THE PARAMETER	DEFORESTATION SPINY FOREST (D_{FE}): CONVERSION OF SPINY FOREST INTO NON-FOREST
Data unit	tCO2/ha
Value for the parameter	44.91
Source of data	**For aboveground forest biomass calculation:** • 122 ground forest inventory cluster plots (1996 national forest inventory; (DBH and height measurements) • Estimated tree heights based on a diameter-height function developed) • Wood densities from Zanne et al. (2009), Vielledent et al. (2012), PERR-FH (2014) • Allometric equation from Chave et al. (2014) **For aboveground non-forest biomass calculation** • 29 ground inventory non-forest plots (Andriamananjara et al. 2016) **For belowground biomass and carbon stock calculation** • Root-shoot ratios from Mokany et al. 2006 • Carbon fraction from IPCC AFOLU guidelines 2006, table 4.3 (McGroddy et al. 2004)
Spatial level	Ecoregional / local
Key uncertainties for this parameter	Sampling error DBH and height measurement errors Error of the diameter height function Error of the wood density estimate Error of the allometric equation Error of the root-shoot ratio
Estimation of uncertainty	Using error propagation, the uncertainty is estimated at +/- **8.52** tCO2/ha (+/-**18.97** %) at the 90% confidence level

Table 31 : Facteur d'émissions « Deforestation of Mangrove »

Description of the parameter	**Deforestation of Mangroves (D_M): Conversion of mangrove into non-forest**
Data unit	tCO2/ha
Value for the parameter	271.52
Source of data	• 55 ground mangrove forest inventory plots (Jones et al. 2014; DBH and height measurements) • Wood densities from Dharmawan et al (2008; as cited in Jones et al. 2014) • Allometric equations from Clough et al. **(1989), Comley et al. (2005) and Kauffman et al.** (2010; as cited in Jones et al. (2014)
Spatial level	Local
Key uncertainties for this parameter	Sampling error DBH and height measurement errors Error of the wood density estimate Error of the allometric equation
Estimation of uncertainty	Using error propagation, the uncertainty is estimated at +/- **83.37** tCO2/ha (+/-**30.70**%) at the 90% confidence level

6 QUANTIFICATION OF FREL

Based on the activity data described in section 4 the emission factors in section5, we calculate the annual emissions by eco-regional stratum and then summarize them to calculate the total annual GHG emissions over the reference period that is equivalent to the annual Forest Reference Emission Level (see table Table 32).

Table 32 : Emissions par écorégion et calcul du NERF

STRATUM	EMISSIONS [TCO2/YEAR]	90% CONFIDENCE INTERVAL [TCO2/YEAR]	90% CONFIDENCE INTERVAL [%]
Deforestation in Humid (D_{FH})	11 139 292	+/- 2 842 546	+/- 25.52%
Deforestation en dry forest (D_{FS})	8 286 042	+/- 2 062 294	+/- 24.89%
Deforestation en spiny forest (D_{FE})	1 119 455	+/- 308 554	+/- 27.56%
Deforestation in Mangroves (D_{M})	117 660	+/- 43 115	+/- 36.64%
Forest Reference Emission Level	**20 662 448**	**+/- 3 525 647**	**+/- 17.06%**

7 EVALUATION OF FREL UNCERTAINTY

7.1 IDENTIFICATION AND ASSESSMENT OF SOURCES OF UNCERTAINTY

This section summarizes the approach to identify, minimize and quantify uncertainty following the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Chapter 3).

The methodology used to estimate average annual GHG emissions in the reference period is based on the provisions of the 2006 IPCC GL, which is equivalent to the Activity Data x Emission Factor (ADxEF) method indicated in Chapter 3.2.3 of the GFOI MGD 2[6] as shown in section 6. Since the multiplication does not have uncertainty by itself, uncertainties may be grouped in uncertainties linked to the Activity Data (AD) and uncertainties linked to the Emission Factors (EF).

7.1.1 Sources of uncertainty of Activity Data

The uncertainties of the activity data come from the uncertainties associated to the Land Cover classification in each of the epochs interpreted. Per the GOFC-GOLD REDD Sourcebook the possible sources of uncertainty would be the quality of satellite data, interoperability of the different sensors, image processing, cartographic and thematic standards, location and co-registration, the interpreting procedure, and the post-processing:

7.1.1.1 Quality of the satellite data

Satellite imagery used is Landsat TM, ETM+ and Landsat 8, which are suitable for land cover interpretation and land cover change interpretation in terms of spatial, spectral and temporal resolution7. However, there are two sources of error related to the data availability. Landsat 7 ETM+ lost its Scan Line Corrector (SLC) in April 2003, compromising data quality in the form of data gaps outside of the central portion of each image bands. Moreover, the tropical rainforest eco-region is characterized by its high and persistent cloud cover, so shadows and cloud coverage also comprises quality as it generates data gaps.

Considering these two sources, as well as the corrections conducted for humid forests described above, the data gaps amount to 0.01% of the total area. The land cover classifications affected by clouds are listed in the table below.

---

[6] GFOI (in press). Integrating remote-sensing and ground-based observations for estimation of emissions and removals of greenhouse gases in forests: Methods and Guidance from the Global Forest Observations Initiative – Version 2. Chapter .2.3

[7] GOFC-GOLD. (2015). REDD Sourcebook. 2.7.3.1.1 Sources of uncertainty.

CODE	LAND USE IN 2005	LAND USE IN 2010	LAND USE IN 2013	LAND USE CHANGE	ACRONYMS	NB OF PIXELS	AREA (IN HA)
228	Dry forest	Dry forest	Clouds / Shadow	Intact dry forest	SSO	73 693	6 632
288	Dry forest	Clouds / Shadow	Clouds / Shadow	Intact dry forest	SOO	1 567	141
778	Mangroves	Mangroves	Clouds / Shadow	Mangroves	MMO	6 558	590
778	Mangroves	Mangroves	Clouds / Shadow	Mangroves	MMO	6 558	590
888	Clouds / Shadow	Clouds / Shadow	Clouds / Shadow	Clouds / Shadow	OOO	2 024	182
Total						90 400	8 136

7.1.1.2 Interoperability of the different sensors

Although three different sensors are used (Landsat 5 TM, Landsat 7 ETM+ and Landsat 8 OLI), these have similar spatial and spectral resolutions. The main difference is the higher quality in Landsat 8 OLI due to its high signal-to-noise ratio, which is three times higher than Landsat ETM+, and the different spectral resolutions as Landsat 8 OLI contain additional bands and the SWIR and NIR do not have the same spectral range as Landsat 7 ETM+. This potential source of error must be mitigated through pre-processing and when training the classification algorithm as part of the interpreting procedure. The error is estimated to be negligible but any potential error stemming from the use of different sensors would also be reflected through the accuracy assessment.

7.1.1.3 Location and co-registration

Landsat imagery is co-registered with a geolocation accuracy < 1 pixel, which is a good practice as defined in the GOFC-GOLD REDD Sourcebook[8]. Therefore, this source of error is considered to be negligible.

[8] GOFC-GOLD (2015). REDD Sourcebook. Section 2.1.2.2

7.1.1.4 Interpreting procedure

The change detection was conducted using semi-automated /supervised classification. This may lead to the misclassification of stable pixels as undergoing change to other land uses, or the misclassification of pixels undergoing change as being stable. This is likely to be most significant source of error.

7.1.1.5 Post-processing procedure

Post classification comprises the filtering steps using the MMU as well as filtering for 2 x 2 deforestation pixels. It is assumed that this process does not create any uncertainties.

7.1.2 Sources of uncertainties on emission factors

Emission factors are calculated as the difference between two mean biomass estimates (see section 5.4). Therefore the uncertainty of EFs is directly related to the uncertainty of the mean biomass estimates of the different forest and non-forest strata considered.

According to Cunia (1987)[9] aboveground biomass measurements are related to three sources of errors: the measurement errors (biometric variables such as DBH, Total height or basic densities, for instance), the prediction error of the allometric model used (i.e. uncertainty of the model parameters), and the sampling error (i.e. sampling design, spatial heterogeneity of the forest).

However, more recent research such as Picard et al. (2015)[10], Van Breugel et al. (2011)[11] and Chave et al. (2004) add an additional uncertainty that is due to the selection of the allometric model (i.e. different models have different predictions).

A further error related to the aboveground biomass estimation here is the error of the diameter-height function. Since tree height was not measured for all trees, a diameter height function was developed both by the 1996 national forest inventory and the PERR-FH project. This function was used to calculate tree height for the purpose of using it with the allometric equation to estimate aboveground biomass.

This FREL considers belowground biomass. Belowground biomass is calculated using root-shoot ratios. Consequently, the error related to the root-shoot ratio needs to be considered in the uncertainty estimation.

[9]Cunia, T. 1987. Error of forest inventory estimates: its main components. *In* E.H. Whraton& T. Cunia, eds., *Estimating tree biomass regressions and their error. Proceedings of the workshop on tree biomass regression functions and their contribution to the error offorest inventory estimates, May 26–30, 1986, Syracuse, N.Y. – Part E*. Broomall, PA, USA,USDA Forest Service, Northeastern Forest Experiment Station, General Technical Reportno. NE-117, pp. 1–14. 34, 39, 46, 184

[10] Picard et al. 2015. Error in the estimation of emission factors for forest degradation in central Africa. Introduction.

[11]Van Breugel et al. (2011) - Estimating carbon stock in secondary forests Decisions and uncertainties associated with allometric biomass models

7.1.2.1 Ground inventory plots for aboveground biomass

7.1.2.1.1 Measurement errors

Measurement errors are the errors of the predictors of the allometric model. DBH measurement error may be systematic or random. The former is assumed to be negligible since measurements of DBH were done by experimental cruisers following SOPs, while the latter may occur due to random errors that propagate a zero bias. Picard et al. (2015) assumed in its analysis of uncertainties for emission factors assumed this error to be a 2%. Total tree height is another predictor which is measured and which has a random error associated (assuming that there are no systematic errors). According to Chave et al. (2004), who measured 1000 trees, estimated tree height to be c.a 10% of the estimated a value. Finally, another predictor which is commonly used in allometric equations is the Wood Specific Gravity (WGS). Since this predictor cannot be measured, usually it is sourced from research studies and global databases. Chave et al. (2004) assumed that the error of this predictor was 10% of the estimated values. Chave et al. (2004) found that the propagated error of these three predictors was 16.5% of total tree biomass. However, as indicated by this study, errors at the tree level would be averaged and cancelled at the stand level. However, Picard et al. (2015), considering only the DBH measurement error, concluded that this error was negligible with respect to the other sources of error.

7.1.2.1.2 Error in the diameter height function

Both the 1996 national forest inventory and the PERR-FH project developed a diameter-height function for use with an allometric equation. Applying the function developed for the PERR-FH project to trees of the 1996 forest inventory (humid forest ecoregion) for which measured height is available, then the estimated tree height has a bias of + 16%. However, application of the Chave et al. (2014) pantropical equation without height gives 6% higher mean biomass estimate across all plots. Consequently, while the diameter height function overestimates height, the mean biomass estimation using this estimated height is still lower than using an allometric equation without height. While the error is not quantified it is still considered as part of the total error to estimate biomass at the plot level (see section 7.2).

7.1.2.1.3 Allometric model error

The allometric model error can be divided in the following sources.

a) the error due to the uncertainty of the model's coefficients;
b) the error linked to the residual model error;
c) the selection of the allometric model.

According to Picard et al. (2015) the largest uncertainty is due to the selection of the allometric model which may be 77% of the average estimate. Van Breugel et al. (2011) estimated that the errors linked to the allometric equation could vary from 5 and 35% depending on the model selected. Regarding the first and second errors, these are expected to be negligible as the parameter's uncertainty and the residual model error of Chave et al. (2014) are very low. Therefore, it is expected that the main source of error will be the selection of the allometric equation, which is relevant.

7.1.2.1.4 Sampling error

The sampling error must be added to the measurement and prediction errors mentioned above; this one is used to perform the inference to estimate the biomass/carbon at the level of the area of interest. This error depends on: a) the sampling design; b) the size of the sampling; c) the type of estimator used; d) the variability inherent between the sampling units. The sampling error is considered to be significant.

7.1.2.2 Belowground biomass estimation

7.1.2.2.1 Error of the root-shoot ratio

To estimate belowground biomass, the aboveground biomass is multiplied with a root-shoot ratio. We use mean root-shoot ratios provided by Mokany et al. (2006), who provides a review of published root-shoot ratios across a range of vegetation types. Some of the errors related to AGB estimation would also be applicable here, such as measurement and sampling errors. However, the only error available from Mokany et al. (2006) is the sampling error for the range of studies analyzed.

7.1.2.3 Synthesis

As explained above, the main sources of uncertainty, which are significant for the estimation of emission factors, are:

Ground inventory plots for aboveground biomass estimation

- **Measurement error:** random errors linked to the measurement of predictors. As described above, this could be between 10-16.5% in total, yet it is expected that this error will be compensated to a certain extent as these are random errors.
- **Allometric model error**: the main source is the selection of the allometric equation. The choice of the allometric equation (Chave et al. 2014 with height) is deemed conservative, as it provides a slightly lower value (- 1.6%) than the allometric equation developed by Vielledent et al. 2012 specifically for Madagascar. Compared to the allometric equation of Chave et al. (2014) without height, it provides a 4.7% lower biomass value. Consequently, for the purpose of this FREL estimation this error is assumed to be zero.
- **Error of the diameter-height function:** As mentioned above, this error is accounted for in the aggregated error estimate for aboveground biomass estimation at the plot level when using an allometric equation (see below). To account for these errors, we use an aggregated error of 15% that accounts for the measurement error (DBH and height), the error in wood density estimation and the error of the diameter height function. The value is the upper end of an estimate provided by Chave et al. (2014), who estimated the total uncertainty in biomass estimation at up to 15% for ground plots of 0.25ha size.
- **Sampling error**: The sampling error for the different forest types is provided in Table 33.

Table 33 : Biomass sampling error for the different forest and non-forest types

LAND COVER TYPE	SAMPLING ERROR [%] (90% CONFIDENCE INTERVAL)
Humid Forest	+/- 3,96%
Dry Forest	+/- 8,30%
Spiny Forest	+/- 12,06%
Mangrove	+/- 14,44%
Non-forest, humid forest eco-region	+/- 20,95%
Non-forest, dry forest eco-region	+/- 25,58%
Non-forest, spiny forest eco-region	+/- 25,58%
Non-forest, mangroves	+/- 52,05%

7.2 UNCERTAINTY QUANTIFICATION

Where uncertainty could not be reduced to zero or close to zero (e.g. by applying conservative values), we have quantified uncertainty for all activity data and emission factors. We use the 'simple error propagation' method (IPCC 2006), calculating uncertainties in all activity data and emission factors before aggregating them to estimate average annual GHG emissions. Per IPCC (2006), to quantify uncertainty using the simple propagation of error method, estimates of the mean and the standard deviation for each input are required, as well as the equation through which all inputs are combined to estimate an output. The following approach was applied:

- Where the mean, standard deviation and sample size is available, we calculate the 90% confidence interval. Where they are not available, we follow the guidance provided by the IPCC (2006) and use expert judgment to directly derive a confidence interval (relative).
- In all cases, we assume that the confidence interval is symmetrical.

Uncertainty is then calculated using the formulas from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (i.e. equations 3.1 and 3.2).

7.2.1 Calculation of uncertainty

The PERR-FH project carried out accuracy assessments for the change detection in all 4 main forest ecoregions.

A confusion matrix was developed on the basis of photo interpretation of points (10,000 points for the ecoregion of the humid forests and 3,578 points for the other ecoregions) taken from the validation images, independent from those used for the classification and corresponding more or less to the second period of the studies (2010-2013). These points are spread over deforestation hot spot and according to a mesh of points ranging from 5 to 1 km depending on the rate of the deforestation.

This step focuses on a statistical comparison of the result of the previous classification (from the LANDSAT images) with the result of the observation of satellite images at sampling points and for two historical dates (2010 and 2013). The sampling was carried out on high-resolution images: SPOT 5 at 10 m resolution and on LANDSAT images at 30 m resolution. The latter were used in the case that such SPOT images might not be available on the studied areas. SPOT images were collected via the "Satellite-Assisted Environmental Monitoring in the Indian Ocean" (SEAS-OI) station in most cases and from the PHCF image database (via Planet Action) In other cases. At least, four regions were covered by high-resolution images and two historical dates (see Graphic 24 and 25 above).

A map of deforestation rates from GFC data (Global Forest Change, Hansen et al., 2013) on a 20 x 20 km square grid was produced. A regular sampling on this grid was then carried out according to the importance of deforestation (rate of deforestation). Three levels of classification were defined in order to improve validation observations in hot spots of deforestation (see Table 34).

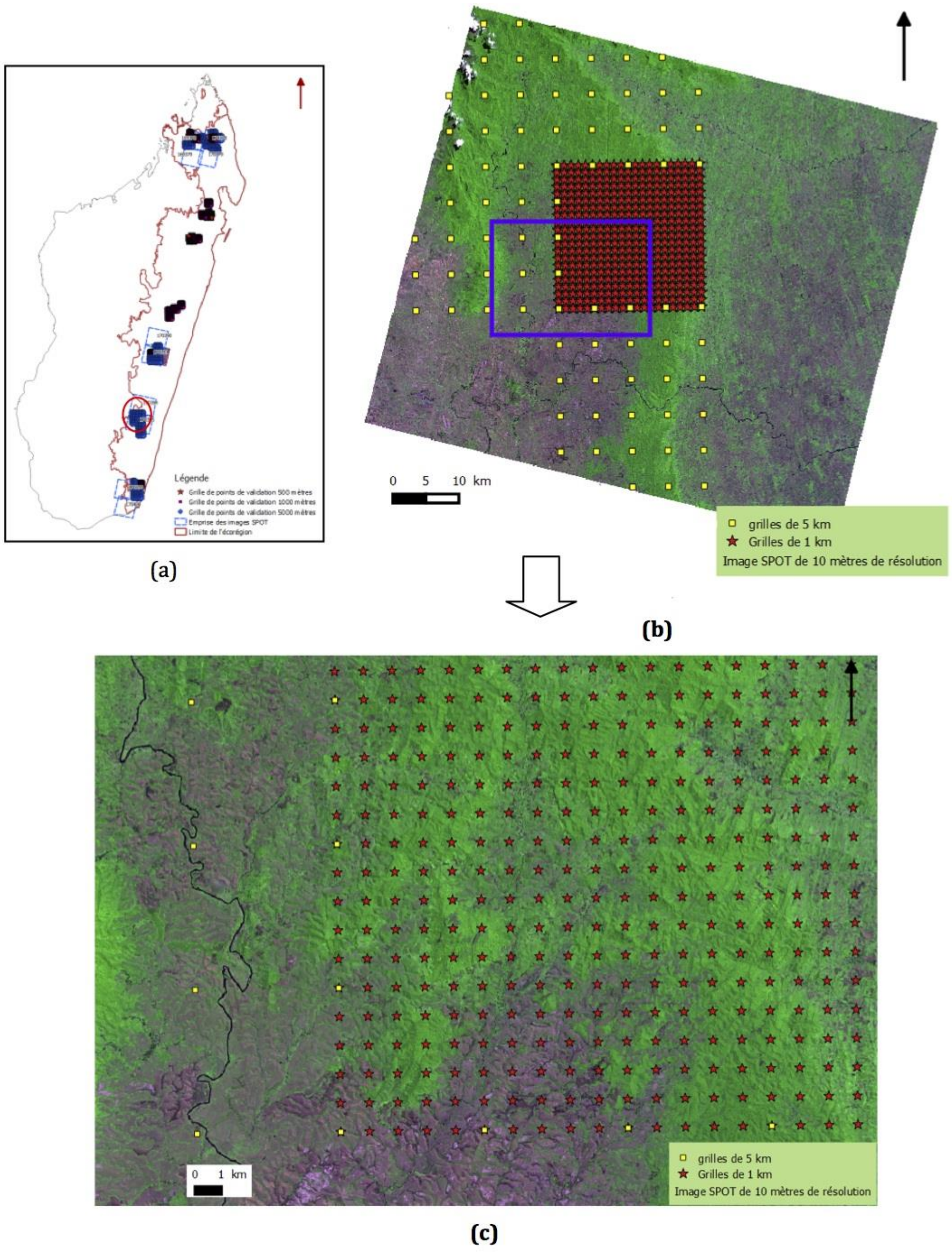
Table 34 : Regular point sowing spacing according to deforestation intensity

Deforestation pressure per grid of 20 by 20 km (ha / year)	Intensity of deforestation	Spacing of points [Km]
<20	Low	5 x 5
20 - 50	Average	1 x 1
> 50	Strong	0,5 x 0,5

Table 35 below shows the different dates and references of the SPOT 5 image scenes used for external validation of the results.

Table 35 : Dates and reference of SPOT 5 images used for external validaiton over humid forests

<table>
<tr><th rowspan="3">Zone</th><th rowspan="3">Referenc of the scene SPOT (K-J)</th><th colspan="2">Sources</th></tr>
<tr><th>Archives PHCF</th><th>SEAS-OI</th></tr>
<tr><th>Date - 2010</th><th>Date - 2013</th></tr>
<tr><td rowspan="4">COMATSA</td><td>169 - 378</td><td>15/05/2009</td><td>11/09/2013</td></tr>
<tr><td>169 - 379</td><td>24/03/2009</td><td>11/09/2013</td></tr>
<tr><td>170 - 378</td><td>05/05/2009</td><td>12/08/2013</td></tr>
<tr><td>170 - 379</td><td>05/05/2009</td><td>08/12/2013</td></tr>
<tr><td rowspan="4">COFAV-COFAM</td><td>170 - 390</td><td>24/03/2009</td><td>14/10/2013</td></tr>
<tr><td>170 - 391</td><td>24/03/2009</td><td>14/10/2013</td></tr>
<tr><td>170 - 394</td><td>29/04/2009</td><td>14/10/2013</td></tr>
<tr><td>170 - 395</td><td>29/04/2009</td><td>14/10/2013</td></tr>
<tr><td rowspan="5">Fort-Dauphin</td><td rowspan="4">170 - 399</td><td>29/03/2009</td><td rowspan="4">12/05/2013</td></tr>
<tr><td>22/02/2009</td></tr>
<tr><td>18/01/2008</td></tr>
<tr><td>14/03/2009</td></tr>
<tr><td>170 - 400</td><td>18/01/2008</td><td>12/05/2013</td></tr>
</table>



Graphic 21: Deforestation hot spot and validation and sampling areas

a) Map of location of deforestation hot spots (b) Validation zones, (b) Extract of the sampling grids on SPOT 5 images at the COFAV level (Images distributed by SEAS-OI © CNES Distribution Astrium Services / Spot image SA, France, all rights reserved).

Table 36: External confusion matrix for humid forests classification

		Reference of Classification				User accuracy	Omission error
		FF	**FP**	**PP**			
User Classification	FF	**5 154**	145	4 286 756	5 841	**88,2%**	11,8%
	FP	34	**273**	91 515	365	**74,8%**	25,2%
	PP	372	53	15 790 969	4 648	**90,9%**	9,1%
	Total	5 560	471	20 169 240	10 854		
	Producer's accuracy	**92,7%**	**58%**	**88%**			

Table 37 : External confusion matrix for dry and spiny forest, and mangroves

		Reference of Classification				User accuracy	Omission error
		FF	**FP**	**PP**	**Total**		
User	FF	**882**	77	130	1 089	**81,0%**	19,0%
	FP	92	**222**	66	380	**58,4%**	41,6%
	PP	344	162	**1 603**	2 109	**76,0%**	24,0%
	Total	1 318	461	1 799	3 578		
	Producer's accuracy	**66,9%**	**48%**	**89%**			

7.2.2 Discussion on results

Confusion matrix shows an overall accuracy of about 88.9% for humid forests ecoregion while 75.7% for the other ecoregions.

It's important to note that for estimating the uncertainty of the FREL what matters is the uncertainty of change. Here, the user's accuracy is 74.8% for humid forests ecosystem and 58.4% for the other ecoregions.

According to Olofsson et al (2014), it is crucial to use the 'stratified estimators' with the statistically unbiased estimates. Thus, it would finally allow determining the confidence interval and uncertainty.

This approach was not possible to be applied since the accuracy analysis was conducted on the hot spots of deforestation. Using these estimates as proxies of the so called adjusted areas would cause an over-estimation as suggested by the comparison between adjusted areas and map estimates (388% for humid forest and 846% for other ecoregions).

Considering that estimations based on maps didn't have their confidence interval, we suppose that uncertainty of these estimations is ± 20%.

7.2.3 Calculation of uncertainty related to emission factors

The Methodological Framework of the FCPF Carbon Fund does not clearly indicate what errors must be considered in the assessment of the accuracy of the emission factors. IPCC 2006 guidelines, on the other hand, contain a description of good practices in the calculation and consideration of the uncertainties, but do not include either a clear requirement of what sources of uncertainties should be considered.

As mentioned above, the aggregate or propagation of uncertainties was done by following Method 1 of the IPCC guidelines. In this case, the estimate of uncertainties was made by following the IPCC guidelines (Chapter 2, Volume 1 of IPCC GL 2006). The uncertainties described in the different publications or determined from the different data sources, and in case of the combination of values from different sources, the error spread was made following Method 1 of the IPCC guidelines for the spreading of uncertainties. This means, in the case of a sum of two parameters x and y, it was considered that their uncertainties σx and σy would be combined with the root of the sum of the squares:

Uncertainty $(x+y)$ = $\sqrt{\sigma_x + \sigma_y}$.

In case of a multiplication of parameters x and y, it was considered that their uncertainties σx and σ, would be combined with the following equation:

Uncertainty $(x * y)$ = $\sqrt{\left[\frac{\partial f}{\partial x}\sigma_x\right] + \left[\frac{\partial f}{\partial y}\sigma_y\right]}$

These equations are equivalent to those indicated in Chapter 2 of Volume 1 of IPCC GL 2006.

The following Table 38, Table 39, Table 40, Table 41 and Table 42 provide the uncertainty for aboveground biomass, belowground biomass, carbon stocks and emission factors.

Table 38: Component and aggregated uncertainty for the Aboveground biomass estimate

Land cover type	Mean AGB [tdm/ha]	Sampling error (90% CI) [tdm/ha]	Sampling error (90% CI) [%]	Chave allometry error (90% CI) [tdm/ha]	Chave allometry error(90% CI) [%]	Total AGB error (90% CI) [tdm/ha]	Total AGB error (90% CI) [%]
Humid Forest	271.58	+/- 10.77	+/- 3.96%	+/- 40.74	+/- 15%	+/- 42.14	+/- 15.52%
Dry Forest	69.82	+/- 5.86	+/- 8.40%	+/- 10.47	+/- 15%	+/- 12.00	+/- 17.19%
Spiny Forest	22.19	+/- 2.65	+/- 11.95%	+/- 3.33	+/- 15%	+/- 4.26	+/- 19.18%
Mangrove	Not displayed here because Jones et al. (2014) only provide total biomass values						
Non-forest. humid forest eco-region	21.80	+/- 4.57	+/- 20.95%	+/- 0.00	+/- 0%	+/- 4.57	+/- 20.95%
Non-forest. dry forest eco-region	2.50	+/- 0.64	+/- 25.58%	+/- 0.00	+/- 0%	+/- 0.64	+/- 25.58%
Non-forest. spiny forest eco-region	2.50	+/- 0.64	+/- 25.58%	+/- 0.00	+/- 0%	+/- 0.64	+/- 25.58%
Non-forest. mangroves	Not displayed here because Jones et al. (2014) only provide total biomass values						

Table 39: Composition and aggregation of uncertainty on mangrove carbon stock estimation

Land-use	Average AB + BB (including dead wood) [tC/ha]	Sampling error (IC 90%) [tC/ha]	Sampling error (IC 90%) [%]	Allometric error (IC 90%) [tC/ha]	Allometric error (IC 90%) [%]	Total biomass error (IC 90%) [tC/ha]	Total error biomass (IC 90%) [%]
Mangrove	94.85	13.70	14.44%	14.23	15%	19.75	20.82%
Non-forest. Mangroves eco-region	20.80	10.83	52.05%	3.12	15%	11.27	54.16%

Table 40 : Uncertainty of the BGB estimates

FREL land cover class	Mean BGB [tdm/ha]	90% confidence interval [tdm/ha]	90% confidence interval [%]
Humid Forest	63.73	+/- 24.52	+/- 38.49%
Dry Forest	19.52	+/- 3.91	+/- 20.04%
Spiny Forest	7.78	+/- 2.35	+/- 30.21%
Mangrove	Not displayed here because Jones et al. (2014) only provide total biomass values		
Non-forest, humid forest eco-region	4.47	+/- 1.03	+/- 23.15%
Non-forest, dry forest eco-region	1.41	+/- 0.62	+/- 44.12%
Non-forest, spiny forest eco-region	1.41	+/- 0.62	+/- 44.12%
Non-forest, mangroves	Not displayed here because Jones et al. (2014) only provide total biomass values		

Table 41 : Uncertainty of the carbon stocks estimates

FREL LAND COVER CLASS	CARBON STOCKS [TCO2/HA]	90% CONFIDENCE INTERVAL [TCO2/HA]	90% CONFIDENCE INTERVAL [%]
Humid Forest	577.84	+/- 84.02	+/- 14.54%
Dry Forest	153.97	+/- 21.76	+/- 14.13%
Spiny Forest	51.65	+/- 8.38	+/- 16.22%
Mangrove	347.78	+/- 72.41	+/- 20.82%
Non-forest, humid forest eco-region	45.27	+/- 8.07	+/- 17.83%
Non-forest, dry forest eco-region	6.73	+/- 3.04	+/- 22.81%
Non-forest, spiny forest eco-region	6.73	+/- 0.86	+/- 22.81%
Non-forest, mangroves	76.27	+/- 41.31	+/- 54.16%

Table 42 : Uncertainties related to the emission factors

LAND COVER CHANGE TYPE	EMISSION FACTOR [TCO2/HA]	90% CONFIDENCE INTERVAL [TCO2/HA]	90% CONFIDENCE INTERVAL [%]
Deforestation in Humid (D_{FH})	532.57	+/- 84.40	+/- 15.85%
Deforestation en dry forest (D_{FS})	147.24	+/- 21.81	+/- 14.81%
Deforestation en spiny forest (D_{FE})	44.91	+/- 8.52	+/- 18.97%
Deforestation in Mangroves (D_M)	271.52	+/- 83.37	+/- 30.70%

7.2.4 Calcul de l'incertitude du niveau de référence

Based on the uncertainties of the activity data and the emission factors, the uncertainty of the emissions over the reference period and finally the uncertainty of the forest reference emission level are calculated using error propagation (see Table 43). The total uncertainty of the forest reference emission level is estimated at approx. +/- 3.5 million tCO2/year or approx. 17%

Table 43 : FREL uncertainties of emissions by ecoregion

Stratum	Annual emissions [tCO2/year]	90% confidence interval [tCO2/year]	90% confidence interval [%]
Deforestation in Humid (D_{FH})	11 139 292	+/- 2 842 546	+/- 25.52%
Deforestation en dry forest (D_{FS})	8 286 042	+/- 2 062 294	+/- 24.89%
Deforestation en spiny forest (D_{FE})	1 119 455	+/- 308 554	+/- 27.56%
Deforestation in Mangroves (D_M)	117 660	+/- 43 115	+/- 36.64%
FREL	**20 662 448**	**+/- 3 525 647**	**+/- 17,06%**

8 DISCUSSION, CONCLUSION AND ACTION PLAN FOR FREL IMPROVEMENT

This section briefly discusses the FREL, in particular the data gaps, the validity of assumptions and methodological shortcomings. Furthermore, it provides recommendations on how these issues will be addressed in the upcoming revisions of the national FREL and an action plan for its implementation.

The forest reference emission level presented here is based on the best available data to date. It was the objective to submit a forest reference emission level that is as complete as possible in terms of geographical coverage. This FREL covers all of the four principal forest eco-regions of Madagascar. As such completeness was prioritized over data quality and gaps which in part are filled with - what we believe realistic or conservative - assumptions. These assumptions and in part also technical insufficiencies are discussed further below.

This FREL has benefitted greatly from the recently finalized PERR-FH project, which provided all the activity data and also the biomass data for the Eastern humid forest eco-region. It has also benefitted from the 1996 national forest inventory as well as from scientific research carried out in mangrove forest ecosystems (Jones et al. 2014) and post-deforestation land use systems (Andriamananjara et al. 2016).

It is also important to mention that Madagascar has launched two processes which are very relevant to this FREL submission.

1. The first one is a national process to improve both activity data and emission factors and set-up a national MRV system. A new country-wide land cover change analysis will be carried out from 2005 to 2015. Further, additional forest inventories will be carried out in 2017 and 2018 to provide better biomass estimates for dry forest, spiny forest and mangrove and different post-deforestation land uses.
2. The second one is a subnational process covering the entire Eastern humid forest eco-region. BCN-REDD will submit an application to the FCPF to register part of this eco-region as a subnational Emission-Reduction Program (ER-Program) under the FCPF Carbon Fund. As part of this process a more differentiated land cover classification is being elaborated in order to also include forest degradation and enhancement of forest carbon stock in GHG reporting. It is envisaged that this more differentiated land cover classification will also be applied to the other forest eco-regions at the national level. To better estimate biomass in degraded forests in this eco-region, an inventory has already been carried out in 2016 providing >450 plots with biomass estimates for 5 different degradation strata (it remains to be seen if these strata will be kept though).

Taking this into consideration, most if not all of the data and some of the methods contained in this first FREL submission will be replaced or at least supplemented within a time period of 1 to 2 years. Consequently, most of the shortcomings contained in this first FREL will be addressed by these efforts. This is described in section **Error! Reference source not found.** below

8.1 DATA GAPS, VALIDITY OF ASSUMPTIONS AND METHODOLOGICAL ISSUES REDD+ ACTIVITIES

This FREL only accounts for gross deforestation. Emissions from forest degradation are assumed to be significant though, in particular in the ecoregions of dry forest and spiny forest. No data is available yet to quantify degradation for any of the ecoregions. As mentioned above, a forest inventory was carried out in 2016 to estimate biomass in 5 different degraded forest strata in the humid forest ecoregion. At present, work is on-going to develop a new forest stratification for the humid forest ecoregion which combined with a new land cover change analysis and the above forest inventory data should allow to quantify emissions from forest degradation at least for the humid forest ecoregion in 2017. In the mid term, degradation will also be estimated for the other forest ecoregions so that degradation can be accounted for the entire country in a revised version of this FREL. Likewise, the new land cover change analysis will also allow to estimate carbon stock enhancements from transitions of "non-forestland to forestland", so that the current gross deforestation estimate can be replaced by a net deforestation estimate.

Carbon stock enhancements on forestland remaining forestland would require frequent re-measurement of permanent sample plots and this is not foreseen at present, even if validation and implementation of the ER-P over Eastern humid forest will allow these measurement (within the MRV system), but only at the scale of this ecoregion.

Carbon pools

This FREL accounts for aboveground and belowground biomass. Data on soil organic carbon (SOC) is available for the humid forest ecoregion, as well as for the mangrove forest ecoregion (Jones et al. 2014) and the non-forest estimates in the humid forest ecoregion (from the PERR-FH project and Andriamananjara et al. 2016). All these datasets show significant amounts of carbon stored in SOC. In particular Jones et al. (2014) found that SOC in mangrove forest in the closed canopy and open canopy class 1 is 300%-750% of aboveground carbon (SOC depth 150 cm). Unfortunately, Jones et al. (2014) did not analyse SOC in deforested mangrove sites, so the loss in SOC cannot be estimated. For the dense humid forest ecoregion, mean SOC (depth 100cm) was estimated at 185.39 tC/ha for forest and 180.76 for non-forest, showing little difference. The SOC estimates (depth 100 cm) from Andriamananjara et al. (2016) are lower and show a slight higher variation between forest and non-forest (149.4 tC/ha for forest and 129 - 136.6tC/ha for non-forest).

Also, analysis by the PERR-FH project could not conclusively determine how SOC loss occurs over time following deforestation. Existing data couldn’t explain very clearly the transition of SOC from forest plots to non-forest plots. It might be due to the tavy cycle over sites, that move from non-forest, to fallow, then forest and non-forest again. According to IPCC guidelines (2006), it is more important to understand the final step of a transition rather than its process. In this context, these data can be analysed in more details during the REL development for the ER-P on humid forest, and if it provides good results, it could be used at national level.

This FREL does not account for any transfers from the Aboveground and belowground carbon pool to the Dead Organic Matter pool, which may not be conservative at least for emissions from belowground biomass. It seems likely that any root biomass which is not burned decomposes following deforestation and thus the emissions would stretch over a longer period, instead of being released immediately to the atmosphere. The same may hold true for a fraction of the aboveground biomass, if not all biomass is burned or extracted following deforestation. On the other hand, if we consider deforestation to be comparatively stable over the reference period, which is implied in the current "historical average" approach, then transfer to and release from the DOM pool to the atmosphere could be considered to be constant and thus emissions are not overestimated. Yet, more research on transfers to and releases from the DOM pool to the atmosphere may be subject to further research and included in a future version of the FREL.

Greenhouse gases

This FREL only reports CO_2 emissions. Since much of the deforestation in the humid forest ecoregion is caused by slash and burn agriculture, it is assumed that emissions from CH_4 and possibly also N_2O are significant. However, no data is available on the fraction of deforestation that is caused by burning and the fraction of biomass that is fully or partially burned (combustion factor). Since emissions from CH_4 and maybe also N_2O are assumed to be significant, further research will be carried in the future to improve data quality and allow for a comprehensive accounting of GHG.

Forest definition

There is a certain amount of inconsistency between the forest definition and its application to produce activity data. Forest cover was mapped at the Landsat at pixel scale (approx. 0.09 ha). Prior to calculating deforestation, a "filter" of 3x3 Landsat pixels (approx. 0.81 ha) was applied to exclude forested areas that do not qualify according to the minimum area criterion of the forest definition and thus should not count towards deforestation. The same filter was applied to the last land cover map of the reference period to exclude any forested areas falling below the forest definition to estimate the remaining forest area at end of the reference period.

Further, the minimum height criterion was not considered for the activity data, as this would have required the use of ALOS/PALSAR imagery.

Crown cover was not recorded in the forest inventory data and thus the biomass estimates for forest may contain biomass estimates for non-forest sites (which would be conservative).

As a consequence, changes to the forest definition or the minimum mapping unit may be considered in a future version of the FREL.

Activity data

As mentioned above, the current activity data for the humid forest ecoregion will be improved in early 2017 towards including several forest strata. Together with biomass estimates for these strata, emissions estimates for gross deforestation be improved and emissions from degradation and removals from carbon stock enhancements (non-forestland to forestland) will be added to the FREL for the humid forest ecoregion.

Similar efforts will be undertaken to improve the activity data for the other ecoregions.

Biomass estimates and emission factors

There are several issues related to the calculation of biomass and emission factors.

1. Forest inventory for dry forest and spiny forest can be considered out-dated, as it is approx. 20 years old. Assuming that forest degradation in these ecoregions plays a major role, it could well be that the mean biomass for these forest types is considerably lower today than it was in 1996. The application of the pantropical allometric equation of Chave et al. (2014) with height is considered to be appropriate, since it provides the most conservative biomass estimates when compared to Vielledent et al. (2012) and the pantropical allometric equation of Chave et al. (2014) without height (including the bioclimatic variable E). Currently, additional work is in progress to produce a set of national allometric equations in 2017, which will be used for estimating biomass in a revised version of the FREL.
2. For the majority of trees of the PERR-FH inventory (humid forest ecoregion), height was estimated using a diameter height-function, which was derived of a subsample of approx. 2,500 measured tree heights. When applied to trees from the 1996 forest inventory (humid forest ecoregion) for which measured height is available, the function on average overestimates height by approx. 16%. Since the allometric equation with height provides a lower biomass estimate than the one without height, this is not considered to be an issue. Further an overestimation of height by 16% does not imply an overestimation of biomass by the same magnitude. However, an improvement of the diameter-height function may be considered for a future revision of the FREL, which should include the prediction error of the function.
3. For a small fraction of trees in the 1996 inventory (overall <100 trees for dry and spiny forests) height was also calculated using diameter-height functions. These functions are provided in the 1996 national forest inventory report without any further information as to their source. Since they are only applied to a small sample of trees, this is considered to be negligible. However, the source and validity of these functions will be identified and tested and they may be revised for a future version of the FREL as applicable.
4. The assignment process for wood specific gravity values to trees in the two inventories does not follow the same rules. For the PERR-FH inventory dataset, the wood specific gravity values provided by the PERR-FH project were used, since the attribution of scientific names to the popular names recorded by the inventory could not be finalized. For the 1996 forest inventory, the process of attributing scientific names and then wood specific gravity could be more transparently displayed. However, different and in part contradictory datasets were used. To improve this for a revised version of the FREL, a national tree database will be established which will allow a clearer attribution of scientific names to popular names and which will aggregate data for wood specific gravity from different sources.

5. The estimation of biomass in post-deforestation land use is deemed appropriate for the humid forest ecoregion, but not for the dry forest and spiny forest ecoregion. The current approach should be considered a "quick-fix" in the absence of any data. The alternative would have been to report gross biomass loss, which would have lead to overestimation of emission compared to the current approach. A new forest inventory will take place in dry forest and spiny forest in 2017, including the sampling of post-deforestation sites. These values will be used to produce a robust post-deforestation biomass estimate for these ecoregions for a revised version of the FREL.
6. The estimation of biomass of mangroves is derived from a local study and thus the biomass estimates may not be representative for the entire mangrove ecoregion. To address this shortcoming, a mangrove forest inventory is planned for 2018, which will sample biomass across the entire mangrove ecoregion, including degraded and deforested mangrove sites. This will allow producing more differentiated and representative biomass estimates and emission factors for a revised FREL.

Uncertainties

The estimation of uncertainty follows the guidance of the 2006 IPCC guidelines for GHG inventories. At this stage, error propagation is used to aggregate uncertainty and produce a total uncertainty value for the FREL at the 90% confidence level. Most issues related to the uncertainty estimation, in particular of biomass estimation, have already been discussed in chapter **Error! Reference source not found.** From our perspective, the biggest issue with regard to uncertainty estimation of this FREL is the uncertainty related to the choice of the allometric equation and the uncertainty of the change detection. With regard to the allometric equation, we have no means to estimate the error in the biomass prediction at tree and plot level. We anticipate however that the generation of national allometric equations will improve this situation. With regard to the change detection, the accuracy assessment does not follow the best practices as described on Olofsson et al. (2014) and thus the calculation of an adjusted area estimate and the associated confidence interval is not possible. This will be mitigated to some extent by the new land cover change analysis in 2017. Further, BCN-REDD is currently carrying out an additional validation of the change detection using Collect Earth. This should allow to follows the steps described in Olofsson et al. (2014) and replace the map estimates (activity data) with an adjusted area estimate, including a confidence interval to update the uncertainty estimate of the FREL. Finally, it is envisaged to calculate the uncertainty of a revised FREL using a Monte Carlo simulation.

Consistency of the FREL with the national GHG inventory, the INDC and the Emission Reduction Program under the FCPF Carbon Fund

- **FREL and GHG inventory:** Madagascar currently does not operate a national GHG inventory. Emission and removals from the AFOLU sector, including forests, have been published in the national communications. The methods and data as well as the scope of accounting between this FREL and the national communication is at present not consistent. It is anticipated that the national REDD+ process in Madagascar will contribute to improving the data reported in the coming national communications. Care will be given to ensure that consistency is eventually achieved and that any emerging national GHG inventory will take into account the data and methods used in the calculation of this FREL and future versions.

- **FREL and INDC:** Madagascar submitted its INDC to the UNFCCC communicating its aim conditionally to reduce its GHG emissions by 30 Mt CO2e and increase its sink functions by 62 MtCO2e per annum in 2030. This objective is based on a Business as Usual model that assumes a linear trend of emissions and sinks from the period 2000 to 2010 into the future. This model moreover considers that the LULUCF sector is a substantial sink in the range of 215.89 MtCO2e by the year 2020. The current NERF however indicates that the forest sector, being among the most relevant LULUCF sub-sectors is a source. It is important to note, that considering the current design of the NERF; it does not account for regrowth, nor does it quantify the emissions of degradation and the carbon stock enhancement. These sinks and sources will further affect the overall understanding of the overall net emissions from the deforestation and degradation. This would form the basis to further develop and refine Madagascar's nationally determined contribution. However it is important to note, that the current NERF does not pre-judge Madagascar's INDC.
- **FREL and the ER-Program:** The ER-Program and its reference emission level covers the entire humid forest ecoregion and should thus be considered as a subnational component of the national FREL. It is likely that the REL of the ER-Program will have another reference period than the current reference period of the national FREL. Further, the ER-Program may include further carbon pools (e.g. SOC), further REDD+ activities such as forest degradation and may also introduce other methods and data. As such, at least some temporal inconsistencies between the REL of the ER-Program and the FREL can be expected. It is however envisaged to use the ER-Program as a testing ground for wider application at the national level, i.e. that proven approaches will be applied to the other ecoregions in due time to improve the national FREL. In terms of accounting consistency, accounting at the level of the ER-Program should be regarded as being more detailed and so as complementary to the national FREL (ER-Program REL for FH + "national" FREL for FS/FE/FM = new national FREL).

8.2 ACTION PLAN FOR FREL IMPROVEMENT

The following table provides a summary action plan to address the most important issues described in the previous section.

Table 44 : Summary action plan

Issues to be addressed	**Activity**	**Estimated time period**
Exclusion of forest degradation and enhancement of forest carbon stocks, gross deforestation	More detailed land cover change analysis including one or several degraded forest strata is in progress for the humid forest ecoregion. This will allow quantifying emissions from a) net deforestation and b) forest degradation. A more detailed land cover change analysis is planned for	First quarter of 2017 for the humid forest ecoregion Second semester of 2018 for other ecoregions
Exclusion of soil organic carbon	For the ER-Program area (dry forest ecoregion) the inclusion of SOC will be considered. To this end, further analysis will be carried out.	First semester 2017
Exclusion of CH4 and N2O	For the ER-Program area (humid forest ecoregion) the inclusion of SOC will be considered. To this end, further analysis will be carried out.	First semester 2017
Inconsistency of activity data with forest definition	BCN-REDD will assess whether or not a revision of the forest definition will be necessary.	First semester 2017
Activity data Uncertainty estimate for activity data	The activity data for the humid forest ecoregion will be replaced as part of ER-Program activities (see point 1 above) and this will feed into a revised national FREL. Based on the experience in the humid forest ecoregion, a new land cover change analysis for the other ecoregions will be carried out at a later stage. Any new land cover change analysis will be accompanied by an accuracy assessment that allows to estimate the uncertainty of the activity data	First quarter or 2017 for humid forest ecoregion Second semester 2018 for other ecoregions
Out-dated or missing representativeness of forest inventory data Missing non-forest biomass data	New forest inventories for dry and spiny forest, and mangrove are planned, including sampling of post-deforestation land use.	2017-2018

Issues to be addressed	Activity	Estimated time period
Attribution of wood specific gravity	A national tree database will be established, which will include an unambiguous attribution of scientific to popular names and corresponding wood specific gravity values from different sources.	Starting in 2017, ongoing effort
Diameter-height functions	The current diameter-height functions for the different forest ecoregions will be analyzed in more detail and if need be revised	2017
Consistency between FREL and national GH inventory, INDC and ER-Program REL	BCN-REDD, together with the other relevant government bodies will work towards achieving consistency between the national FREL, any emerging national GHG inventory, the INDC and the ER-Program. To this end, a task force / working group will be established which will meet regularly to update each other and initiate - where needed - the necessary steps to align methods and data related to forest GHG accounting	Starting 2017

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