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**The feasibility of mangrove REDD+
projects in the Western Indian Ocean:
Linking mangrove conservation and
climate change adaptation to the
global carbon markets.**

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1. Introduction

Of all the biological carbon (i.e., green carbon) captured in the world, >50% is captured by marine living organisms (i.e., blue carbon). Mangroves, salt marshes and seagrasses form much of the earth's blue carbon sinks and store comparable amounts of carbon per year to all other plant biomass on land. Blue carbon habitats will play a critical role in mitigating climate change, not only because of the size of the pools which they lock-up, but also because they provide a wealth of other ecosystem goods (e.g., food; fuel; construction material; medicine) and services (e.g., storm protection; barriers to erosion; breeding grounds and nurseries; water filtration) essential to the long-term well-being and climate change adaptability of increasingly vulnerable coastal communities. The significant role that coastal habitat loss has on global greenhouse gas emissions and the important role these habitats play in climate change adaptation are becoming increasingly recognized at an international level (Laffoley *et al.*, 2009; Nellemann *et al.*, 2009; Gordon *et al.* 2011; Pendleton *et al.* 2012; Ullman *et al.* 2012). There is a growing international movement to establish a REDD+ (Reducing Emissions from Deforestation and Degradation plus other measures to restore, enhance, and conserve carbon stocks) mechanism for blue carbon habitats similar to that existing for terrestrial forests. There is also an urgent need to include coastal, marine carbon in National Inventory Submissions – the mandatory national accounting of greenhouse gas emissions that countries must submit under the United Nations Framework Convention on Climate Change (UNFCCC) (Thompson, 2009).

With an estimated 2,800 km² of mangroves in 2005 (Giri and Muhlhausen, 2008), Madagascar is seemingly blessed with significant blue carbon assets. The generation of carbon credits through the conservation and restoration of such habitats could make a critical contribution to poverty alleviation and biodiversity conservation in coastal areas. However, following global trends, these forests are being rapidly degraded and deforested. In particular, Madagascar's mangroves are threatened by over-exploitation for charcoal and timber, conversion for agriculture and hyper-sedimentation from upstream deforestation.

In Madagascar, as elsewhere, there is a critical lack of technical capacity to quantify mangrove carbon, as well as to establish projects that will conserve them for the generation of carbon credits. The accurate quantification of carbon sequestration by mangroves is fundamental to establishing carbon offsetting projects based on their conservation, restoration and sustainable-use, and ultimately in placing financial value on them. The true value of mangroves needs to be accounted for and weighed against alternative uses, such as conversion for agriculture.

The exact nature of carbon fluxes between mangroves and their surrounding environment is complex and remains an active subject of research (Kristensen *et al.*, 2008). While the sequestration of carbon in mangroves can vary greatly from site to site, relatively few studies of carbon have been undertaken in the WIO in comparison to other major mangrove regions in the world (e.g., Indonesia, Malaysia). While numerous studies have measured above-ground biomass in mangrove trees (Twilley *et al.*, 1992; Saenger, 2002; Komiyama *et al.*, 2005; Alongi, 2009; Kauffman & Cole, 2010), few have quantified both above- and below-ground pools (i.e., Adame *et al.* 2013; Chen *et al.* 2012; Donato *et al.*, 2011; Kauffman *et al.*, 2011; Donato *et al.*, 2012; Matsui *et al.* 2012; Ray *et al.* 2011). However, it is the deep, organic-rich soils (i.e., below-ground pools) that are thought to contain the vast majority of C stocks (Golley *et al.*, 1962; Matsui, 1998; Fujimoto *et al.*, 1999).

Carbon offset project developers must adhere to methodologies approved by issuers of carbon credits to establish the net CO₂ sequestered by a project. This must be done to provide *ex ante* (pre-project) and *ex poste* (actual) CO₂ reductions.

Existing approved methodologies are designed for terrestrial forests and are not entirely appropriate for the development of mangrove carbon offsetting projects. Therefore, the development and validation of baseline and monitoring methodologies that take into account the unique characteristics of mangroves is critical for effective long-term conservation, restoration and sustainable-use.

2. Proposed goals and objectives

This project aimed to quantify the net above- and below-ground CO₂ sequestration of an extensive Malagasy mangrove forest experiencing deforestation and provide the science necessary to assess the feasibility of and work towards establishing mangrove REDD+ projects. In the long-term this project aims to contribute towards poverty alleviation, biodiversity conservation and climate change adaptation in coastal areas. The research comprised five objectives:

2.1 Contribute to the development of REDD methodologies specific to mangroves

Existing REDD methodologies do not address some of the unique characteristics of mangrove CO₂ sequestration. This research aimed to assess the applicability of existing and approved REDD methodologies to mangroves and site conditions within the WIO.

2.2 Build local capacity to undertake ecological and carbon stock measurements and establish REDD+ projects

In Madagascar, conservationists and coastal managers rely largely on foreign, costly consultants to design and undertake the ecological and carbon stock measurements necessary to establish REDD+ projects. This research aimed to build Malagasy capacity in the design, implementation and analysis of mangrove carbon stock measurements, ecological assessments and eventual long-term monitoring required for REDD+ projects.

2.3 Demonstrate the value of Madagascar's mangroves in mitigating climate change

Despite terrestrial CDM reforestation/afforestation and REDD receiving a great deal of donor support in recent years, the importance of blue carbon has only begun to be recognized internationally (e.g., Gordon *et al.* 2011; Pendleton *et al.* 2012; Ullman *et al.* 2012). This research aimed to demonstrate the financial and climate change mitigation value of mangroves.

2.4 Assess the feasibility of establishing mangrove REDD+ projects within the Western Indian Ocean region

While it is possible to implement mangrove carbon offsetting projects within the existing frameworks, and there are examples of mangrove restoration projects being established elsewhere in the world, their successful registration and generation of actual income as blue carbon projects remains to be seen. To date, no mangrove reforestation projects have been submitted for CDM registration and there are no published assessments on the feasibility of mangrove REDD+ projects. This research aimed to contribute to the scarce literature documenting the feasibility of mangrove forests, and provide the first such assessment in Madagascar.

2.5 Catalyse the development of a mangrove REDD+ project

This research aimed to provide the scientific information needed to develop an actual pilot mangrove REDD+ project that could eventually finance the conservation of the particular large-scale mangrove site researched. In addition, this goal would form a valuable case study that would provide lessons for the establishment of other such projects.

3. Methods

3.1 Selection of the pilot area

Owing to the expense and effort of measuring mangrove carbon stocks, as well as the high cost of fine spatial resolution satellite imagery, this research initially assessed feasibility on a national-level in order to select a pilot site for further in depth research and to serve as a REDD+ pilot project site. The preliminary national-level analysis involved multiple criteria to determine optimal areas of interest (AOI) to further assess REDD+ feasibility. The primary criteria considered included the extent of primary mangrove forest (circa 1990, 2000 and 2010), mangrove forest cover dynamics (1990-2000 and 2000-2010), drivers of loss (i.e., anthropogenic versus natural), operational logistics, and the availability of remotely sensed data, resulting in the selection of Ambaro-Ambanja as our AOI. Details of site selection criteria are elaborated in relevant sections of the document.

3.2 REDD+ development

We compiled and consulted appropriate literature to ensure compliance with documented methods and standards for developing REDD+ projects and the IPCC guidelines for estimating GHG emissions. VCS approved methodologies were pre-selected and compared taking into consideration how the key methodological components (applicability conditions, project boundaries, baseline, leakage, monitoring, uncertainty, quantification of GHG emission reductions) applied to mangroves. The project narrowed the possibilities to two: the VM0015 version 1 “Methodology for Avoided Unplanned Deforestation” and the VM0009 version 2.1 “Methodology for Avoided Deforestation” based on the characteristics summarized in Table 1 below. Of these, the VM0009 was selected as the most appropriate methodology for developing a REDD+ mangrove pilot project because of the greater flexibility it offers at several levels:

1. The VM0009 allows for several baseline types within a single project, using one reference area and one project accounting area for each baseline identified. This allows for coping with the potentially wide variety of ecosystems, socioeconomic systems and associated diversity of deforestation agents, drivers and underlying causes of deforestation met along the littoral forests in the context of a large-scale mangrove REDD+ project.
2. The distinction between different optional classes of below-ground and dead wood classes makes it easy for project proponents to account for one and not the other, based on their relevancy and ease of data collection.
3. The methodology employs a unique “cumulative deforestation model” that is developed from historic deforestation trends observed from sample points across the reference region. This “sampling for deforestation” approach permits modeling without wall-to-wall coverage of the reference region, and therefore the approach is very useful for regions subject to variable and often substantial cloud cover – such as mangroves. The approach is also well suited to modeling market-driven deforestation; in Ambanja-Ambaro deforestation is driven by urban market demand for charcoal and timber.
4. The methodology is also unique in that the baseline model is not spatially explicit and in that it does not require monitoring of forest cover change in the project area.

5. Unlike the other REDD methodologies, explicit Project Description (PD) requirements are provided to facilitate project development and validation.
6. Lastly, the VM0009 allows for carrying out the analysis of agents, drivers and underlying causes of deforestation through a participatory rural appraisal, a methodology most adapted to the context of the pilot site for which official literature and expertise is scarce.

Table 1. Characteristics used to compare the VM0015 v1 and the VM0009 v2.1.

Specifications		VM0015	VM0009
Baseline types permitted		Unplanned Avoided Deforestation (UAD) Mosaic, Frontier or a transition between the two	Avoided Planned Deforestation (APD) Avoided Unplanned Deforestation and Degradation (AUDD) – Mosaic or Frontier
Spatial domains	Project Area	Area (or areas) under the control of the project participants in which the AUD project activity will be implemented and GHG emission reductions accounted. Only one, located within the reference area	Area (or areas) under control of the project proponent and is where the project activities may be implemented to address the agents and drivers of deforestation, thus preventing emissions from the project accounting area(s). Only one
	Project Accounting Area(s)	None	The project accounting area is an area within the project area that is subject to deforestation under the baseline scenario and is associated with a baseline type One for each baseline type A forested area within the project area that is subject to deforestation in the baseline scenario
	Reference Area (s)	Analytical domain from which information on historical deforestation is extracted and projected into the future to spatially locate the area that will be deforested in the baseline case Only one	The reference area is located in the same region as the project area and similar to the project accounting area in most respects. One for each baseline type
	Leakage Belt	Area where any deforestation above the baseline projection will be considered leakage.	None
	Proxy Area(s)	None	The area where residual carbon stocks are estimated for each baseline scenario One for each baseline type, located within the corresponding reference area
	Leakage Management Area(s)	Area (or areas) specifically designed to implement activities that reduce the risk of activity displacement leakage	Activity-shifting leakage Area(s) The area where leakage resulting from the activities of the agent of deforestation would likely occur due to the project activity(ies). One for each baseline type

Specifications		VM0015	VM0009
Spatial domains			Market-effects Leakage Area(s) The area where leakage would likely occur resulting from a change in the supply of wood products due to the project activity(ies). One if the baseline scenario includes commercial logging
Carbon pools considered	Above ground merchantable tree	Yes (no distinction)	Yes if baseline scenario or project activity(ies) include the harvest of long-lived wood products, otherwise No
	Above ground other (non-merchantable) tree		Yes
	Above ground non-tree	Optional (Yes, if the baseline scenario includes perennial tree crop)	Optional (Yes, if the baseline scenario includes perennial tree crop)
	Below ground merchantable tree	Optional (no distinction)	Optional
	Below ground other (non-merchantable) tree		Optional
	Belowground non-tree		Optional
	Litter	No	No
	Dead wood	Not accounted for	Yes, if Above Ground Merchantable Tree is selected
	Standing dead wood		Optional
	Lying dead wood		Optional
	Soil organic carbon	Optional	Optional
	Long-lived (harvested) wood products	Yes	Yes, if Above Ground Merchantable Tree is selected
Method to identify agents, drivers and underlying causes of deforestation		Existing studies, historical land-use and land-cover change maps, expert-consultations, field-surveys and other verifiable sources of information, as needed.	A Participatory Rural Appraisal can be used

3.3 Contemporary classification and further stratification of mangroves

A Landsat ETM+ satellite image was acquired from the United States Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center (<http://glovis.usgs.gov>) to provide comprehensive coverage of the target AOI from June, 2010. The image was then atmospherically corrected to estimate the effects of absorption by atmospheric gases, remove systematic haze, and convert image units to at-surface reflectance. Factoring in observed maximum heights of Malagasy mangrove forests, high-lying areas (i.e., >30 m) were removed using a mask created from a Shuttle Radar Topography

Mission (SRTM) digital elevation model to exclude areas where mangrove habitat and associated ecosystems cannot exist. Unsupervised classification of the Landsat scene was then used to group image pixels into clusters representing dominant land-cover types. Existing national-scale land-cover and mangrove maps and high spatial resolution imagery were referenced to combine and label clusters based on dominant mangrove and other land-cover types. Sub-mangrove type labels were based on broad categories driven by relatively homogenous levels of canopy cover (Table 2).

In contrast to mangrove deforestation, which is relatively reliable to map using single-date Landsat data, and thus is a class in our scheme, preliminary image analysis coupled with the field-observed extent and intensity of degradation confirmed the challenge of accurately detecting mangrove degradation. Whether naturally-induced or resulting from anthropogenic exploitation, the subtle modification of forest canopy-cover is difficult to accurately measure using remotely sensed data of moderate spatial resolution (i.e., Landsat). Our preliminary analysis confirmed the ability to accurately map broadly defined mangrove canopy-cover classes, including deforested, but problematically, open-canopy categories included mangrove stands that were comprised of lower stature (i.e., young) trees, and of naturally open and/or heavily degraded higher stature (i.e., mature) trees. In addition, and despite degradation, given that transitions between mangrove types are subtle, there are instances where our mangrove classes can overlap. As such, our scheme provides no definitive indication of mangrove degradation and is based on the status of a mangrove stand's canopy (i.e., closed vs. open vs. absent (i.e., deforested)). However, correlations between canopy-cover and carbon stocks are established in the literature (e.g., Plugge et al. 2010). Typically, well developed, closed canopies are indicative of forest stands comprised primarily of higher stature trees, which due their comparatively larger stature sequester and store significantly larger amounts of carbon than open-canopy stands.

Table 2. Mangrove and other surrounding land-cover type classes and definitions.

Level V (full class description)
1: savannah (mosaic of dry grass, exposed soil and scattered trees/shrubs (canopy <30% closed)) (also includes senesced rice; reeds)
2: woodland (mosaic of grass and scattered trees/shrubs (canopy <30% closed)) (also includes orchard-agricultural mosaics)
3: active cultivation (e.g., sugar cane, rice, reeds (agri/aquaculture in bloom))
4: closed canopy terrestrial forest (canopy >60% closed)
5: open canopy terrestrial forest (canopy 30-60% closed)
6: closed-canopy mangrove (crowns >60% closed)
7: open canopy mangrove I (relatively sparse mangrove ecosystems intermixed with tanne/mudflats) (crowns 30-70% closed)
8: open canopy mangrove II (very sparse mangrove ecosystems intermixed with tanne/mudflats: often appears as non-vegetation) (crowns ≥10, <40% closed)
9: deforested mangrove (mosaic of stumps, scattered trees, exposed soil/mud, variable regeneration) (crowns < 30% closed)
10: exposed soil (inactive agri/aquacultural fields; extremely patchy savannah)
11: exposed mud (low tides (ocean frontage; rivers; inactive aquaculture ponds))
12: clear water
13: turbid water
14: extremely turbid water
15: shadow
16: cloud

While there are promising techniques being researched for assessing mangrove degradation, degradation classes went beyond the scope and resources of this project. To date there are no proven techniques for mapping mangrove degradation using Landsat data, and the use of finer spatial resolution imagery remains problematic due to cost and limited wall-to-wall coverage. Moreover, even if finer spatial resolution data were available and used over multiple time-steps with an aim to

precisely map subtle modifications in canopy-cover (i.e., degradation), confident distinguishing between natural and human influence would remain problematic. As such, broad canopy-cover classes do provide a reliable representation of different dominant mangrove types and have proven to be associated with statistically distinct carbon-densities in terrestrial forests (e.g., Plugge et al. 2010), but these classes are not without their limitations. There remains much room for improvement with mangrove stratification for carbon-densities and further research in to alternative and/or more refined stratification approaches is required. That said, in designing our mapping and sampling schemes, we concluded that these broad classes were ecologically rational and more importantly, could be associated with unique carbon stocks.

To confirm class definitions and guarantee that representative classification reference data would be employed, a preliminary field survey was conducted in February, 2012. Examples of dominant mangrove and other land-cover types were located using a stratified random sampling design. In total, 22 100x100 m (i.e., hectare sized) plots were established within different dominant mangrove types (Table 2: classes 6-8); within them, numerous qualitative and quantitative measurements were recorded to characterize the forest. One hundred plots were also set-up within seven non-mangrove classes (Table 2: classes 1-5; 10-11), within these, measurements were not taken, but field notes and photographs recorded variability and confirmed representativeness. The locations of all plots were recorded using a Garmin GPSmap 62sc GPS unit. Through viewing imagery in Google Earth, 100 additional areas were located to augment field-collected reference data for mangrove and other land-cover types (Figure 1). The Maximum Likelihood (ML) classification algorithm was employed for traditional pixel-based image classification using atmospherically corrected Landsat ETM+ bands 1-5 and 7 as input. Numerous studies support ML as an effective and robust algorithm for classifying mangrove habitat with medium spatial resolution remotely sensed data (Aschbacher *et al.*, 1995; Gao, 1998; Green *et al.*, 1998; Rasolofoharino *et al.*, 1998; Gao, 1999; Saito *et al.*, 2003; Tong *et al.*, 2004). Accuracy was quantitatively assessed using a confusion matrix to cross-tabulate mapped classes against independent validation data. Adopting an approach described by Giri & Muhlhausen (2008) and Giri *et al.*, (2011), an enhanced version of Google Earth was also used to divide the classified map into a geographically explicit grid, facilitating qualitative comparisons with existing maps and higher spatial resolution satellite imagery to locate “gross” classification errors. In addition, the number of hectares (ha) occupied by each mapped class was calculated.

To explore an alternative classification approach involving partitioning the landscape in to meaningful ecological units, the Landsat image was also segmented using eCognition Developer version 8.0.1 (Definiens, 2010). After image segmentation, the classification reference data were used to nominate certain objects as representatives of target map classes, and all other objects were assigned membership to mangrove and surrounding land-cover classes based on their inherent spectral, geometric and textural properties, and by their location and position relative to each other. As with the pixel-based classification, map accuracy was assessed using a standard confusion matrix and further assessed through Google Earth. The results of both classification approaches were compared quantitatively and qualitatively. In addition, the results of these detailed, localized mapping efforts were compared to national-level contemporary mangrove data (i.e., Giri and Muhlhausen, 2008).

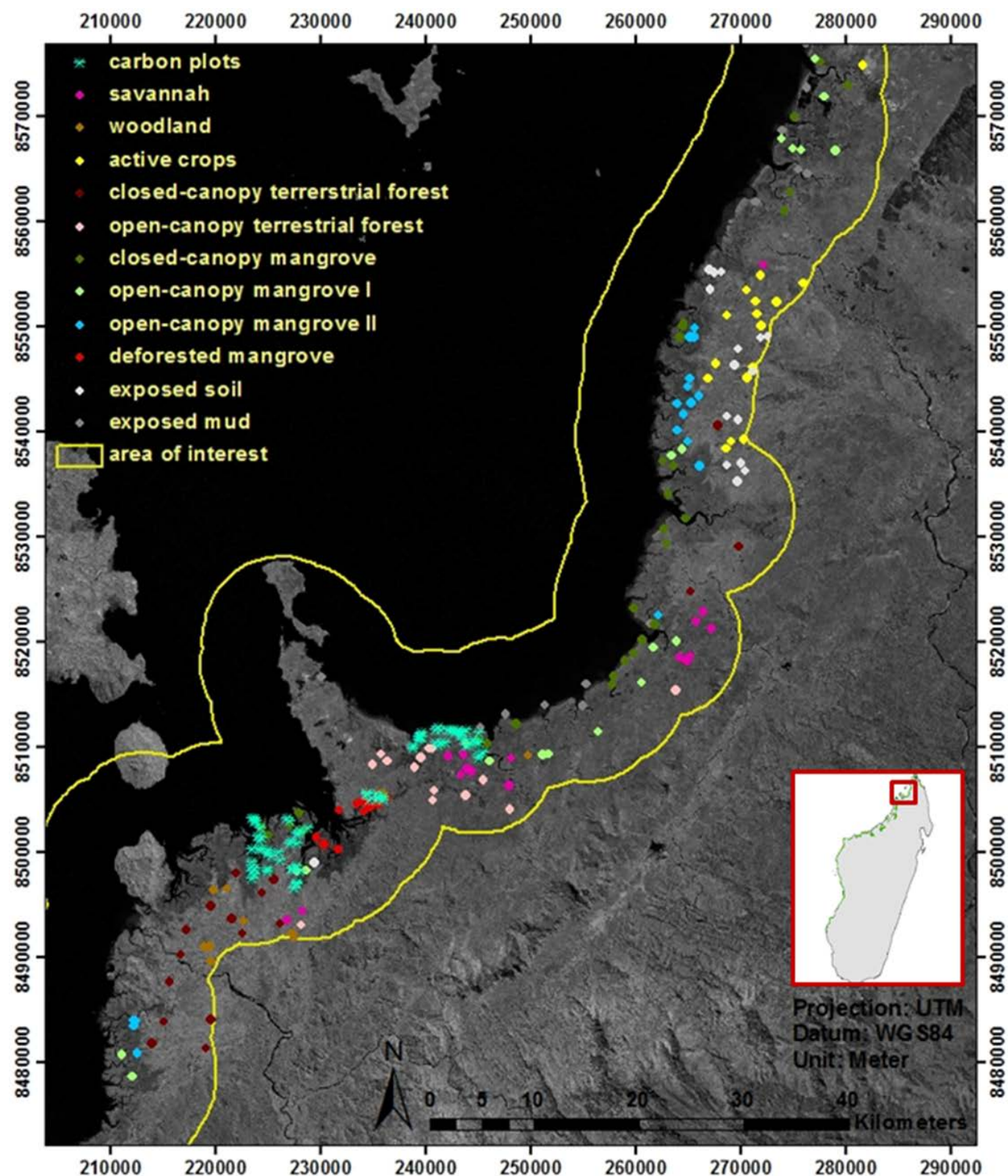


Figure 1. The location of satellite image classification reference data for mangrove and other land-cover categories (as described in Table 1) and the location of mangrove carbon plots.

3.4 Analysis of historical land-cover and land-use dynamics

To meet the historical reference period requirements for a VCS REDD+ project, long-term mangrove dynamics were assessed from 2000-2010. In addition to that of June 2010, two Landsat ETM+ satellite images were acquired from the USGS EROS Center to provide comprehensive historic coverage for September 2000 and August 2006. The spectral, geometric and textural properties of image objects associated with specific mangrove and surrounding land-cover types established during the contemporary object-based 2010 classification were used to assign membership to historic image objects. The Idrisi Land Change Modeler was subsequently used to calculate the losses, gains and persistence associated with each mapped category from 2000-2006 and 2006-2010. In addition, from-to transitions were determined for all mapped classes. Finer spatial resolution SPOT, Quickbird, IKONOS and Worldview data were used to assess the validity of the extent and location of mangrove and other land-cover type transitions; however, as is often the case, their extent, historical coverage, and usefulness (e.g., cloud-cover) was often limited.

3.5 Identification and analysis of agents, drivers and underlying causes of deforestation

Understanding the socioeconomic context of deforestation is a critical step for defining future REDD+ project activities and establishing the feasibility of REDD+ project scenarios. In April through May of 2012, participative appraisals were made in two communes of the Ambaro-Ambanja Bay area using key informant interviews (n = 30) and focus group discussions (n = 40), as per the methodologies stipulated in the *Social and Biodiversity Impact Assessment (SBIA) Manual for REDD+ Projects, Part 1 - Core Guidance for Project Proponents* (Richards and Panfil 2011) and *Part 2 – Social Impact Assessment Toolbox* (Richards 2011). Results of surveys in these two communes showed that charcoal making, timber exploitation for local needs, timber exploitation for commerce and land conversion to agriculture are the most common drivers of deforestation in the two communes studied. However, more information across the broader area of interest is required to create a full understanding of the agents, drivers, and underlying causes of deforestation across the project area.

The analysis of agents, drivers and underlying causes of deforestation is therefore presently an ongoing process that needs to be expanded. It builds on the research already undertaken in 2012 using a methodology entailing the following four steps:

1: Identification of agents of deforestation / degradation

2: Identification of deforestation drivers

For each identified agent, the research was designed to analyse the factors that drive land-use decisions. This involved assessing two sets of driver variables:

- a) Driver variables explaining the quantity (ha) of deforestation, such as: Prices of agricultural products; Costs of agricultural inputs; Population density; and Rural wages;
- b) Driver variables explaining the location of deforestation, such as: Access to forests (such as vicinity to existing roads, navigable channels); Proximity to markets; Proximity to forest edges; Proximity to existing settlements; Spatial variables indicating availability within the forest of land with good ecological conditions to expand agricultural activities; Management category of the land (e.g. national park, community reserve, etc.);

3: Identification of underlying causes of deforestation

The broader forces that determine the agents' characteristics and decisions, such as: Land-use policies and their enforcement; Population pressure; Poverty and wealth; Property regimes

4: Analysis of chain of events leading to deforestation

To carry out these steps, our socioeconomic research makes use of existing studies, the LU/LC-change maps derived through multi-date Landsat classification, consultations with local experts, participatory appraisals with local communities as well as an ongoing analysis of the meta-production and forest use systems. After validation by communities, the typology of forestry, agriculture and fishery-based production systems that will be based on the analysis of the chain of events leading to deforestation will serve as the socioeconomic baseline for the project and provide a useful monitoring tool.

In addition, the implementation of mangrove REDD+ could very well have distinct gender, economic, health, or other social impacts. As such, we plan to complement our analysis of production and forest use systems with a social impact assessment involving local communities. This will provide a case study of social impacts specific to mangrove REDD; thus providing information for the design of future projects that would ensure positive social impacts. This social impact assessment methodology was designed in close consultation with the *SBIA Manual for REDD+ Projects, Part 1 - Core Guidance for Project Proponents* (Richards and Panfil 2011) and *Part 2 – Social Impact Assessment Toolbox* (Richards 2011) which details cost-effective and scientifically credible methods for assessing and monitoring the community impacts of land-based carbon projects. Our socioeconomic research aims to use these methods to carry out the social impact assessment to increase stakeholder engagement and, in turn, contribute to project sustainability and permanence of carbon stocks. In addition, the social impact assessment will contribute to the currently limited body of understanding on the socioeconomic impacts of forest carbon projects.

3.6 Estimation of above- and below-ground carbon stocks

To measure mangrove biomass and estimate carbon stocks, plots were established through field surveys that were conducted between April-September, 2012 using adaptations of methodologies described in Kauffman and Donato (2012). Plots had a default size of 10x10 m, but were expanded to 20x20 if this was required to adequately represent variability at a given location. Regardless of size, all plots consisted of an inner plot within the main plot (i.e., nested design). Within the inner plot (5x5 or 10x10 m, depending on plot size), all trees with a diameter < 5 cm were measured. Throughout the entire plot (10x10 or 20x20 m, depending on plot size), all trees with a diameter > 5 cm were measured. Tree measurements included species type, tree height, dbh (at 130 or 30 cm depending on tree height), and quality of lead stem; from which plot-level tree density, tree stature, biomass and dominant species were derived. Information on geomorphology (i.e., location, topography) and site conditions (e.g., salinity) were also collected for each plot. In all plots, canopy cover was systematically estimated to confirm and refine mangrove class type labels. For standing dead trees and stumps, heights and diameters were measured to document levels of degradation. Regeneration (i.e., seeds and saplings), lying-dead wood, leaf-litter, epiphytes and understory were also inventoried; but their potential carbon pools were considered negligible and not quantitatively sampled (Kauffman *et al.*, 2011). Soil depth was measured randomly in each plot quadrat with a 3 m metal rod. Soil samples were extracted at plot-center using a soil corer at 0-15, 15-30, 30-50, 50-100, and 100-150 cm. Plot locations were recorded

at plot center using Garmin GPSmap 62sc GPS unit. In addition to within mangrove strata, carbon plots were targeted in areas that were or could once again become mangrove ecosystems (e.g., deforested areas; tannes; agricultural/aquacultural areas). Potential plot locations centered on a stratified systematic sampling design wherein candidate plots were systematically located along regularly-spaced intervals. The accessibility of all plots was considered in advance using finer spatial resolution satellite imagery viewable in Google Earth and whilst in the field, several plots were determined not representative and eliminated from consideration. In total, 91 rectangular plots were established in a range of mangrove forest and non-forest areas.

Following field work, the strong allometric relationships between tree height, diameter at breast height and above-ground biomass were used to estimate the above-ground carbon of mangrove trees (Fromard *et al.*, 1998; Smith & Whelan, 2006). The equations used were selected following a thorough review of the literature and consultation with J. Boone Kauffman (Oregon State University) (Table 3). Below-ground biomass of trees was calculated using a generalized equation developed by Komiyama *et al.* (2005). The biomass of standing dead wood calculated using equations found in Kauffman and Donato (2012). The bulk density (i.e., oven dry sample mass(g)/volume of sample (cm³) and organic carbon of soil samples were determined by the Laboratoire des Radio Isotopes (LRI) of the University of Antananarivo in Antananarivo, Madagascar. For bulk density, the LRI placed wet soil samples in a ventilated oven at 105°C for 24 hours. The weight of each sample was recorded before and after oven-drying, and each oven-dried sample's mass was divided by the sample's volume. We determined soil organic carbon using a modified Walkley-Black method: soil organic matter is oxidized without external heat using an H₂SO₄ solution and potassium dichromate (K₂Cr₂O₇). Further details on the Walkley-Black approach are available in Schumacher (2002).

Table 3. Allometric equations employed for calculation of above-ground biomass. Wood density values are from Simpson (1996).

Species	Allometric equation	Wood density	Reference
<i>Avicennia marina</i>	$B=0.1848*dbh^{2.3524}$	0.661	Dharmawan and Siregar (2008)
<i>Bruguiera gymnorrizha</i> (leaves)	$B=0.0679*dbh^{1.4914}$	0.741	Chave et al. (2005)
<i>Bruguiera gymnorrizha</i> (stem)	$B=0.464*(dbh^{2*H})^{0.94275*p}$	0.741	Chave et al. (2005)
<i>Ceriops tagal</i> (dbh 2-18cm)	$B=10^{(-0.7247)*dbh^{2.3379}}$	0.803	Clough and Scott (1989)
<i>Ceriops tagal</i> (18<dbh<25cm)	$B=10^{(-0.494)*dbh^{2.056}}$	0.803	Clough and Scott (1989)
<i>Heritiera littoralis</i> (leaves)	$B=0.0679*dbh^{1.4914}$	1.074	Chave et al. (2005)
<i>Heritiera littoralis</i> (stem)	$B=0.464*(dbh^{2*H})^{0.94275*p}$	1.074	Chave et al. (2005)
<i>Lumnitzera racemosa</i>	$B=0.0214*(dbh^{2*H})^{1.05655*p}$	0.565	Kauffman and Cole (2010)
<i>Rhizophora mucronata</i> (leaves)	$B=0.0139*D^{2.1072}$	0.867	Clough and Scott (1989)
<i>Rhizophora mucronata</i> (root)	$B=0.0068*DBH^{3.1353}$	0.867	Clough and Scott (1989)
<i>Rhizophora mucronata</i> (stem)	$B=0.0311*(dbh^{2*H})^{1.00741*p}$	0.867	Kauffman and Cole (2010)
<i>Sonneratia alba</i>	$B=0.0825*(dbh^{2*H})^{0.89966*p}$	0.78	Kauffman and Cole (2010)
<i>Xylocarpus granatum</i>	$B=0.0830*(dbh^{2*H})^{0.89806*p}$	0.7	Kauffman and Cole (2010)

3.7 Calculation of net greenhouse gas sequestration

The establishment of land-use and land-cover changes over the historical reference period allows the description of a business-as-usual scenario and the projection of future (without-project) deforestation rates and the associated GHG emissions. A preliminary assessment of the net GHG sequestration was carried out in keeping with the procedures laid out in the approved VCS methodology VM0015. The projected deforestation (based on prior knowledge of the drivers of loss and historical deforestation) was compared to the potential with-project scenario to quantify the avoided deforestation and GHG emissions that the project will achieve using conservative assumptions. Projected *ex ante* GHG emission reductions are calculated on the principal of the following basic formula:

GHG emission reduction credits issued =

Baseline emissions minus

Project emissions minus

Leakage minus

Non-permanence Risk Buffer withholding.

The result of this first estimate is that the project could offset around 205,600 t CO₂eq over 30 years, about 7,000 t CO₂eq annually. While interpreting this result, one must bear in mind that this preliminary assessment used extremely conservative assumptions, and in particular a flat rate of deforestation over the period, resulting in a likely underestimate of the project's real carbon potential. The preliminary results of the analysis of the agents, drivers and underlying causes of deforestation as well as the 2013 imagery obtained for the project area both indicate that the deforestation rate is accelerating. The project hopes to carry out a more robust, in depth estimation using the VM0009 methodology, which is better suited to the project, in October 2013 after completion of the full analysis of the agents, drivers and underlying causes of deforestation. Undertaking this research depends on gaining further funding.

3.8 Assessment of REDD methodologies and feasibility

The outputs of the full feasibility assessment, due in October 2013, will demonstrate whether a mangrove REDD project is feasible and could properly fulfil the requirements of the Voluntary Carbon Standard, as well as those of the Climate, Community and Biodiversity Standard. Since these are the current benchmark standards for the development of REDD projects that generate carbon credits for sale on forest carbon markets, the project would clearly show how mangrove conservation/restoration can be used to generate carbon revenues. The combination of the carbon measurements and socioeconomic research will provide the necessary information to fully assess the feasibility of mangrove REDD against the current carbon market standards. In doing so, the results will clearly demonstrate to potential investors the viability of this mangrove REDD project.

4. Results

4.1 Selection of mangrove forest

According to Landsat satellite-derived mangrove-cover maps produced by Chandra Giri (USGS) and analyzed by Blue Ventures, Madagascar had approximately 213,000 hectares (ha) (circa 2010) of mangrove forest ecosystems distributed primarily along the west coast. Considered independently, there are nearly 100 distinct, non-contiguous mangrove forest ecosystems; however, just 31 sites represent over 200,000 ha. These 31 distinct sites, each greater than 1,000 ha, are defined here as Madagascar's primary mangrove forest ecosystems (Table 4). Of these units, Mahajamba Bay has the greatest extent (26,678 ha), followed by Ambaro-Ambanja bay (25,900 ha).

Table 4. The area (in hectares) and ecological type of Madagascar's major mangrove forest ecosystems. Extents are ordered from largest to smallest using 2010 values. Mangrove ecosystem type was defined for all major sites based on definitions in Hughes *et al.* 1992; Taylor *et al.* 2003, and visual interpretation in Google Earth.

Mangrove ecosystem	Ecosystem type	1990	2000	2010
Mahajamba	bay	27778	27578	26678
Ambaro-Ambanja	bay	32632	30617	25901
Antsohihy	estuary	17081	16065	13838
Tambohorano	oceanic	21140	12781	13418
Tsiribihina	delta	20595	16374	12197
Sahamalaza	bay	12107	11063	10956
Mahavavy su Sud	oceanic	10615	10870	10654
Mahajanga	bay	12375	11814	9574
Mangoky	delta	14684	12247	9431
Manambolo	delta	12259	8277	8045
Morondava-Bosy	oceanic	8743	7500	6123
Kamendriky-Tsilambana	oceanic	6102	6102	5924
Mahabo-Andramy	oceanic	4721	5939	5905
Maintirano	oceanic	8937	4644	5900
Boeny	bay	3870	3888	3867
Baly-Soalala	bay	3687	3683	3507
Besalampy	estuary	6247	5097	3287
Rigny-Irody	bay	3224	3232	3231
Morombe	lagoon	3652	2952	3035
Mariarano	estuary	2472	2412	2330
Narinda	bay	2249	2058	2036
Sohany	estuary	2470	1984	2025
Belo sur Mer	estuary	2603	2387	1917
Vilamatsa	estuary	1881	1881	1847
Kabatomena	delta	2458	1882	1529
Reharaka	oceanic	2229	1528	1406
Assassins	bay	1720	1296	1360
Manampatra	oceanic	1405	1404	1327
Morovasa	Bay	1253	1199	1199
Mangolovo	Estuary	1415	981	1172
Ambondrombe	Estuary	1462	1349	1109

The mangrove dynamics of each of Madagascar's primary mangrove units derived by this analysis are shown in Tables 5 (1990 - 2000) and 6 (2000 - 2010). According to Giri's maps, from 1990 to 2010 Madagascar experienced a net loss of approximately 21% of its mangroves; a total of 2,868 ha a year. Mangrove losses and gains were driven by a range of natural and anthropogenic causes and differ markedly according to the time period, geographic region, and ecosystem type. Differentiating 1990 - 2010 into two temporal increments, from 1990 - 2000 there was a net-loss of nearly 12% (34,418 ha) of mangroves country-wide, with the most substantial loss in Tambohorano (8,359 ha/39.5%), Maintirano (4,293 ha/48%), Tsiribihina (4,220 ha/20.5%), Manambolo (3,981 ha/32.5%), Mangoky (2,437 ha/16.6%), Ambaro/Ambanja (2,008 ha/6.2%), and Morondava-Bosy (1243 ha/14.3%). In contrast, from 2000-2010, there was a net loss of 8.6% (i.e., 22,941 ha), with largest net losses in Ambaro/Ambanja (4,717 ha/15.4%), Tsiribihina (4,177 ha/25.5%), Mangoky (2,816 ha/23%), Mahajanga (2,240 ha/19%), Antsohihy (2,227 ha/13.9%), and Besalampy (1,810 ha/35.5%). While Tambohorano and Maintirano exhibited the greatest net loss from 1990-2000, from 2000 - 2010 they experienced net gains. Manambolo still experienced net loss from 2000 - 2010, but substantially less (i.e., 232 ha/2.8%). Tsiribihina, Mangoky, Ambaro/Ambanja and Morondava-Bosy all exhibited substantial loss (i.e., >1,200 ha) between 1990 - 2000 and 2000 - 2010.

Table 5. Dynamics from 1990-2000 for Madagascar's primary mangrove ecosystems.

Mangrove ecosystem	loss		Persistence		gain		net loss	
	ha	%	ha	%	ha	%	ha	%
Tambohorano	10349	49	10790	51	1991	9.4	8359	39.5
Maintirano	4852	54.3	4085	45.7	559	6.3	4293	48
Tsiribihina	5736	27.8	14859	72.2	1515	7.4	4220	20.5
Manambolo	5076	41.4	7183	58.6	1095	8.9	3981	32.5
Mangoky	3478	23.7	11206	76.3	1041	7.1	2437	16.6
Ambaro-Ambanja	2809	8.6	29816	91.4	801	2.5	2008	6.2
Morondava-Bosy	1788	20.4	6955	79.6	545	6.2	1243	14.2
Besalampy	2130	34.1	4117	65.9	980	15.7	1150	18.4
Sahamalaza	1074	8.9	11034	91.1	30	0.2	1044	8.6
Antsohihy	1062	6.2	16019	93.8	45	0.3	1017	6
Morombe	1106	30.3	2546	69.7	406	11.1	701	19.2
Reharaka	931	41.8	1298	58.2	231	10.3	701	31.4
Kabatomena	749	30.5	1708	69.5	172	7	577	23.5
Mahajanga	993	8	11381	92	433	3.5	561	4.5
Sohany	752	30.4	1718	69.6	266	10.8	486	19.7
Mangolovo	517	36.6	897	63.4	84	5.9	434	30.7
Assassins	533	31	1188	69	108	6.3	425	24.7
Belo sur Mer	490	18.8	2112	81.2	275	10.6	215	8.3
Mahajamba	201	0.7	27577	99.3	1	0	200	0.7
Narinda	253	11.3	1996	88.7	62	2.7	192	8.5
Ambondrombe	122	8.3	1341	91.7	8	0.6	113	7.8
Mariarano	59	2.4	2412	97.6	0	0	59	2.4
Morovasa	54	4.3	1199	95.7	0	0	54	4.3
Baly-Soalala	56	1.5	3631	98.5	52	1.4	4	0.1
Manampatra	1	0.1	1404	99.9	0	0	1	0.1
Vilamatsa	0	0	1881	100	0	0	0	0
Kamendriky-Tsilambana	0	0	6102	100	1	0	0	0
Rigny-Irody	14	0.4	3210	99.6	22	0.7	-9	-0.3
Boeny	0	0	3870	100	18	0.5	-18	-0.5
Mahavavy su Sud	82	0.8	10533	99.2	337	3.2	-254	-2.4

Table 6. Dynamics from 2000-2010 for Madagascar's primary mangrove ecosystems.

Mangrove ecosystem	loss		persistence		gain		net loss	
	ha	%	ha	%	ha	%	ha	%
Ambaro-Ambanja	5357	17	25260	83	641	2	4716	15.4
Tsiribihina	6366	38.9	10009	61.1	2189	13.4	4177	25.5
Mangoky	4280	34.9	7967	65.1	1464	12	2816	23
Mahajanga	2422	20.5	9393	79.5	181	1.5	2240	19
Antsohihy	2302	14.3	13763	85.7	75	0.5	2227	13.9
Besalampy	3283	64.4	1815	35.6	1472	28.9	1810	35.5
Ambanja	1918	20.8	7289	79.2	122	1.3	1796	19.5
Morondava-Bosy	2255	30.1	5245	69.9	878	11.7	1378	18.4
Mahajamba	1050	3.8	26528	96.2	150	0.5	900	3.3
Belo sur Mer	798	33.4	1589	66.6	327	13.7	470	19.7
Kabatomena	593	31.5	1288	68.5	241	12.8	352	18.7
Ambondrombe	240	17.8	1109	82.2	0	0	240	17.8
Manambolo	3678	44.4	4599	55.6	3446	41.6	232	2.8
Mahavavy su Sud	245	2.3	10624	97.7	29	0.3	216	2
Kamendriky-Tsilambana	267	4.4	5835	95.6	89	1.5	178	2.9
Baly-Soalala	187	5.1	3497	94.9	11	0.3	176	4.8
Reharaka	715	46.8	814	53.2	592	38.8	122	8
Sahamalaza	110	1	10953	99	3	0	107	1
Mariarano	85	3.5	2327	96.5	3	0.1	82	3.4
Manampatra	77	5.5	1327	94.5	0	0	77	5.5
Vilamatsa	34	1.8	1847	98.2	0	0	34	1.8
Mahabo-Andramy	44	0.7	5895	99.3	10	0.2	34	0.6
Narinda	27	1.3	2031	98.7	6	0.3	21	1
Boeny	27	0.7	3861	99.3	7	0.2	21	0.5
Rigny-Irody	26	0.8	3206	99.2	25	0.8	2	0.1
Morovasa	0	0	1199	100	0	0	0	0
Sohany	427	21.5	1557	78.5	468	23.6	-41	-2.1
Assassins	307	23.7	989	76.3	370	28.6	-64	-4.9
Morombe	713	24.2	2238	75.8	797	27.0	-84	-2.8
Mangolovo	215	22	766	78	406	41.4	-191	-19.5
Tambohorano	5378	42.1	7404	57.9	6014	47.1	-637	-5
Maintirano	2173	46.8	2471	53.2	3429	73.8	-1256	-27

Mangrove ecosystems exhibiting the highest amounts of net loss (i.e., Ambaro-Ambanja, Tsiribihina, Mangoky and Mahajanga) were targeted as potential areas to assess REDD feasibility. For these areas, the drivers of loss were investigated. This process involved collating and extracting information from >100 published journal articles, books, graduate theses, institutional and/or organizational documents and reports, tabular and digital socioeconomic and biophysical data-sets. Based on these information sources, data on the agents, drivers and underlying causes of dynamics were sometimes specific to individual mangrove ecosystems (e.g., proximity to roads; access to alternative (terrestrial) forested resources), but often represented broad, regional characteristics (e.g., cyclone frequency/extent; population pressure). Documented anthropogenic activities in these units included logging, slash and burn, charcoal production, grazing, and impacts associated with migration (Rasolofo 1997; Rasolofoharinoro et al. 1998; Andriamalala 2007; Guillet et al. 2008; Hajanarina 2010; Schwartz 2007; WWF 2010). The principal natural pressures included tropical storms (e.g., cyclones), sedimentation and hydrological dynamics, and the influence of/proximity to gullies (Rasolofoharinoro et al. 1998;

Andriamalala 2007; Hajanarina 2010). Analysis of cyclone data indicated that, of the areas under consideration, cyclones were likely to be a primary driver of mangrove loss in Tsiribihina and Mangoky from 1990 - 2000, which experienced seven and five cyclones, respectively. In contrast, Ambaro-Ambanja and Mahajanga experienced two or less. From 2000 - 2010, cyclones seemingly played a less prominent role in mangrove dynamics for the areas under consideration. Analysis of population data indicated a strong relationship between population density and mangrove loss in all areas except Mangoky from 2000 - 2010. Table 7 provides a summary of anthropogenic and natural pressures and threats posed to some of Madagascar's primary mangrove ecosystems.

Table 7. Anthropogenic and natural pressures for Madagascar's primary mangrove ecosystems. Information compiled from Rasolofo (1997); Rasolofoharino et al. (1998); Andriamalala (2007); Guillet et al. (2008); Schwartz (2007); Hajanirina (2007); UNEP (2007); Rakotomavo et al. (2009); Rakotomavo and Fromard (2010); WWF (2010)

Site	Anthropogenic pressures						Natural pressure		
	logging	slash/burn	migration	charcoal	grazing	aquaculture	cyclones	sedimentation	hydrological dynamics
Mangoky	x	x	x	--	x	--	x	x	x
Tsiribihina	x	--	--	x	--	x	--	--	--
Mahajanga	x	x	x	x	--	--	x	x	--
Mahajamba	x	--	x	--	--	x	--	x	--
Ambanja/ Ambaro	x	--	x	x	--	--	x	--	--

Comparisons of mangrove loss with surrounding terrestrial forest loss (defined based on analysis presented in Harper et al. 2007) (including the extent of communes which include portions of a particular mangrove ecosystem) indicate that from 1990 - 2000, with the exception of Tsiribihina, mangrove loss exceeded terrestrial forest loss in Madagascar's largest mangrove ecosystems. For Mangoky, this is most likely explained by the impact of cyclones during that period. Similarly, from 2000 - 2010, excepting Tsiribihina, mangrove loss exceeded terrestrial forest loss (Figure 2). This relationship must be viewed cautiously though, as terrestrial forest loss data are only from 2000 - 2005.

Given the rate of loss from 1990 - 2000, but particularly from 2000 - 2010, the documented drivers of loss, the comparative lack of impact from cyclones, the contemporary relationship between mangrove loss and population, and that deforestation in mangroves seemingly out-paced loss in terrestrials forests over the past twenty years, Ambaro-Ambanja and Mahajanga were targeted for further field studies. Given a much higher net loss (Figure 3), Ambaro-Ambanja was visited first in February, 2011. The initial visit trip confirmed that not only was deforestation widespread in the past 20 years, but that it was in large part driven by anthropogenic overexploitation for charcoal production. In addition, the field study confirmed that field missions in the area would be practicable. Furthermore, a thorough review of available remotely sensed data confirmed the availability of mostly cloud free Landsat and SPOT coverage. As such, Ambaro-Ambanja was chosen as the most suitable area to assess the feasibility of mangrove REDD in Madagascar.

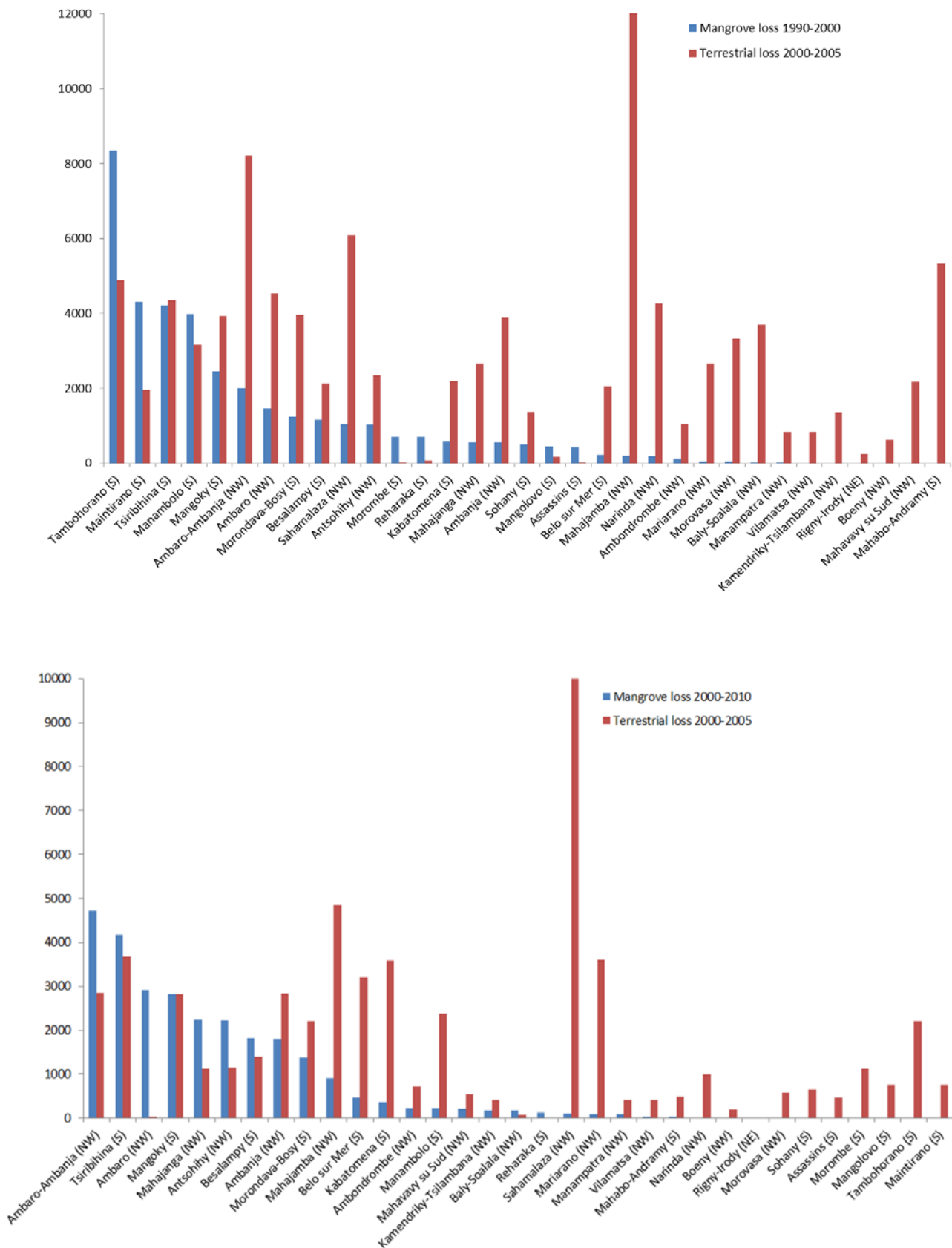
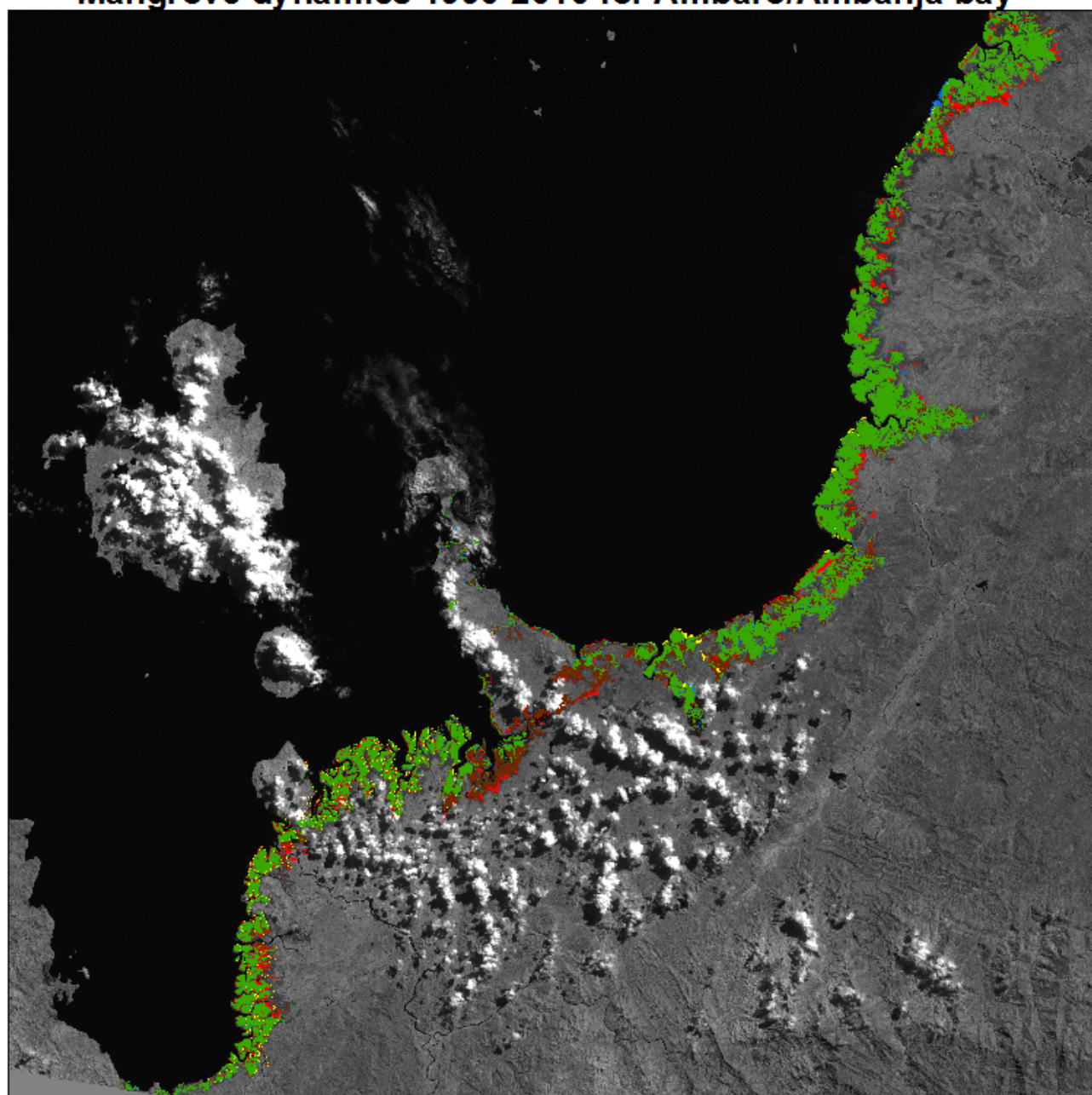


Figure 2. Net loss in mangroves and terrestrial forest from 1990 - 2000 (top) and 2000 - 2005/2010 (bottom). Mangrove forest loss based on analysis of maps produced by Chandra Giri (USGS). Terrestrial forest loss defined based on methods described in Harper et al. (2007).

Mangrove dynamics 1990-2010 for Ambaro/Ambanja bay



Projection: Laborde
Datum: Tananarive 1925
Unite: Metre



Kilometre
0 5 10 20 30 40

- loss 1990-2000 (2809 ha/8.6%)
- gain 1990-2000 (801 ha/2.5%)
- loss 2000-2010 (5357 ha/17.5%)
- gain 2000-2010 (641 ha/2.1%)
- persistent 1990-2010 (24579 ha/75.3%)

Mangrove dynamics 1990-2010 for Ambaro/Ambanja bay

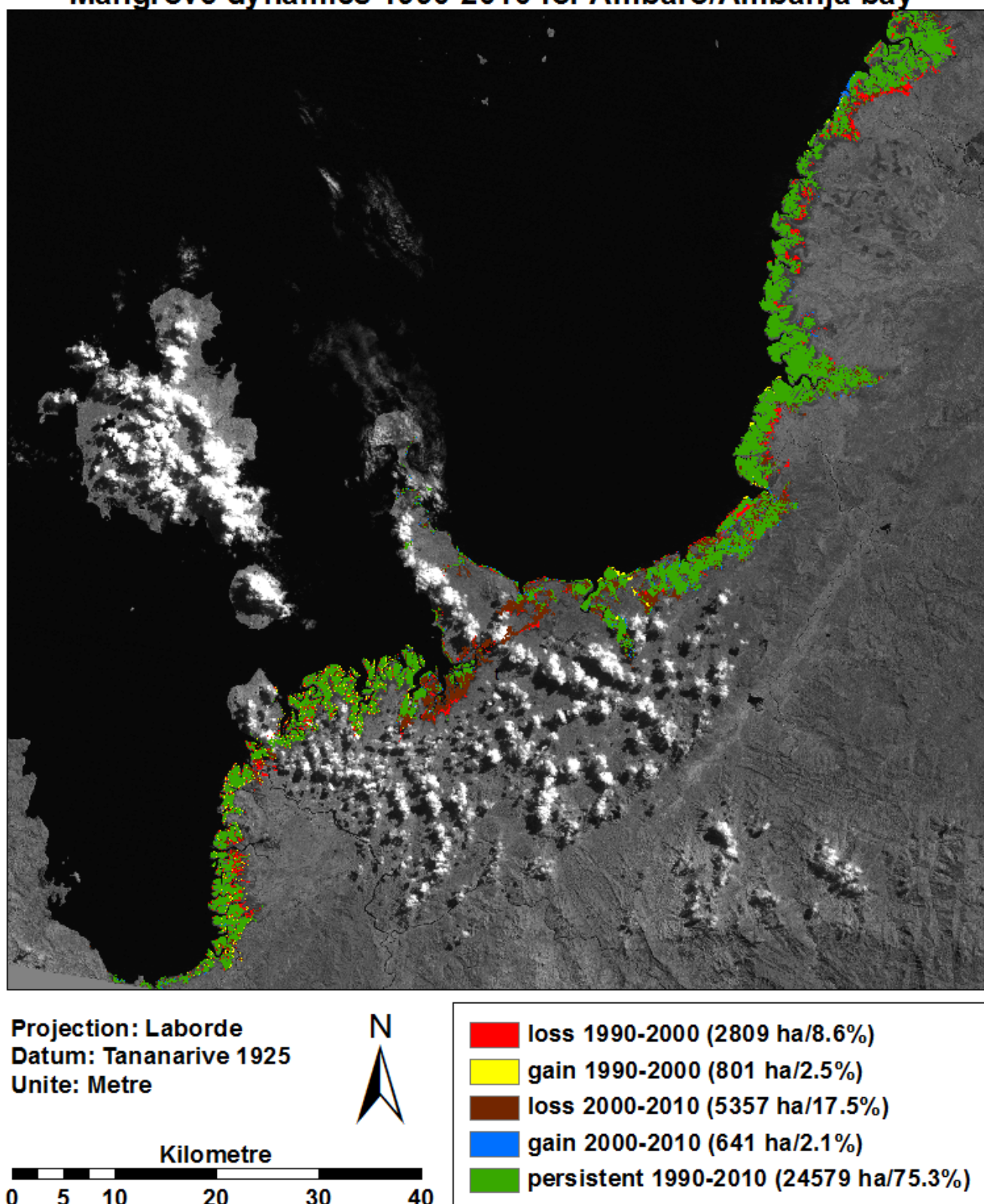


Figure 3. Mangrove dynamics from 1990 - 2000 and 2000 - 2010 in Ambaro/Ambanja bay. During 1990 - 2000, this area exhibited amongst the highest rates of mangrove loss in Madagascar. From 2000 - 2010, it had the largest amount of net mangrove loss in Madagascar, driven mainly by overexploitation for charcoal production.

4.2 REDD development, methodological assessment and feasibility

The project team has started to collect data to fulfil project requirements under the VM0009 methodology. The project spatial, temporal and carbon boundaries have been defined and land-use and land-cover types within all project areas were defined through participatory mapping done in April-May 2013 (Figure 4). The detailed analysis of deforestation agents, drivers and underlying causes is currently being undertaken. The results of this analysis will feed into a final Project Idea Note to be issued in October 2013 at the same time as the feasibility study.

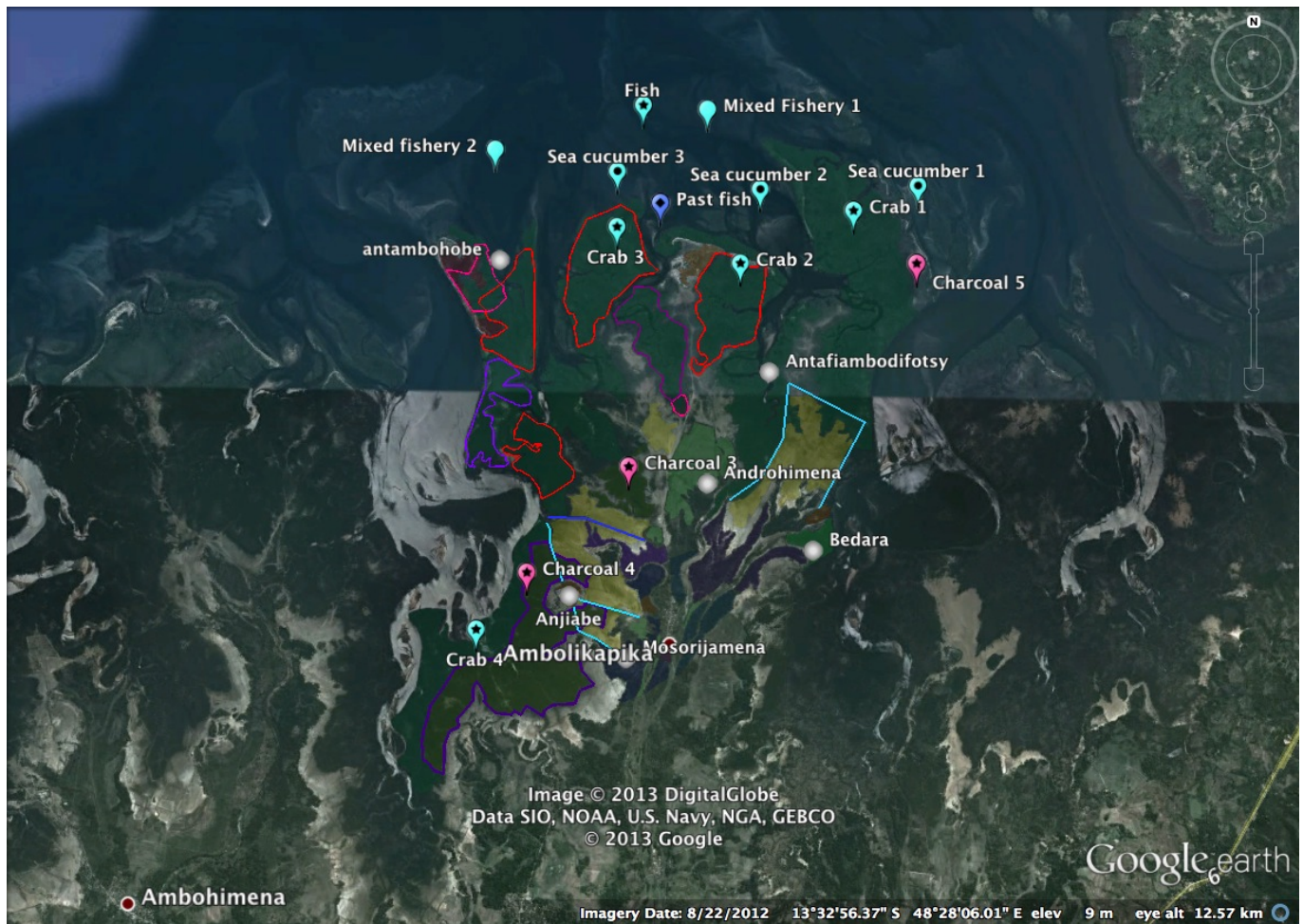


Figure 4. Example of land-use and land-cover maps in one of the project area villages digitised from participatory maps created in April-May 2013. Mangroves appear in dark to light green, rice fields in light blue, cocoa/coffee/coconut plantations in purple. Areas outlined in red and purple correspond to mangrove forests used for charcoal or timber production. Place markers indicate important sites for crab, sea cucumber, and fish capture.

4.3 Contemporary classification and further stratification of mangroves

The quantitative accuracy assessments (i.e., confusion matrices) indicated that both object- and pixel-based maps had high overall (>93%) and per-class (>80%) accuracy. Qualitative accuracy assessments conducted through comparisons with imagery viewable in Google Earth helped to further highlight instances of misclassification in both maps, which were then manually edited. It is clear that both maps provide a much more detailed and comprehensive representation of the AOI than

the single-class estimates of mangrove coverage made previously by the USGS, which provided no indication as to surrounding land-cover types (Figure 5). In addition, the Giri maps, while providing an unprecedented, multi-date national-level dataset for mangrove coverage, failed to map the full extent of mangrove ecosystems, seemingly leaving out vast stretches of relatively sparse habitat. Given no representation of sparser mangroves, this resulted in overestimations of mangrove loss, as transitions from closed, higher stature mangroves to more open-canopy and/or lower stature mangroves were not represented. While both pixel- and object-based maps are superior to the level of detail offered by the Giri maps, in terms of their representation of the AOI, an object-based approach more easily facilitates historical classification of the study area, and therefore served as contemporary representation of the study area in Ambanja (Figure 6) and facilitated historical mapping.

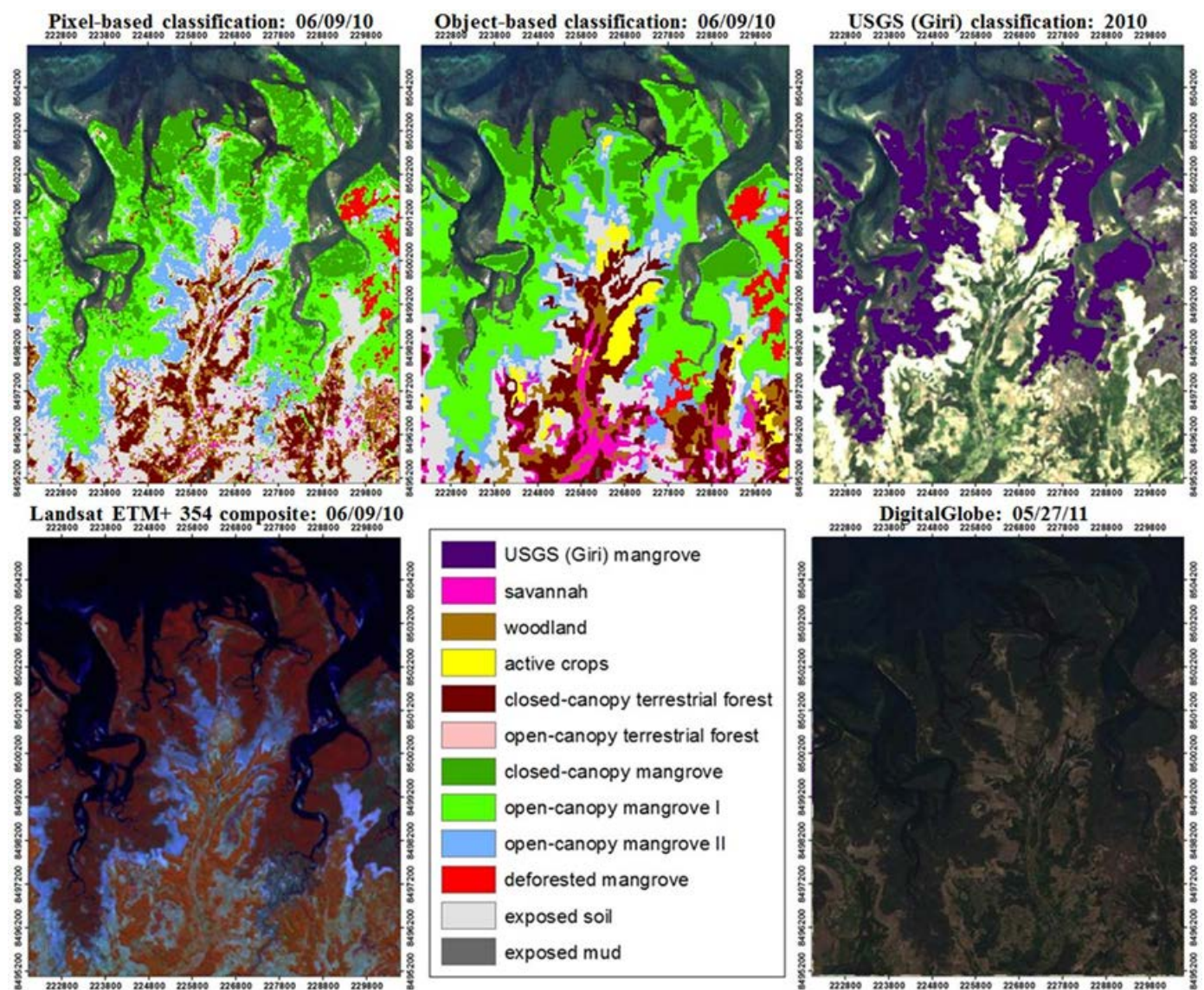


Figure 5. The results of contemporary pixel-based (top-left) and object-based (top-center) satellite image classifications, as compared with national-level mangrove data produced by the USGS (top-right). The bottom-left shows the unclassified Landsat satellite imagery, whereas the bottom-right shows finer spatial resolution satellite imagery viewable in Google Earth.

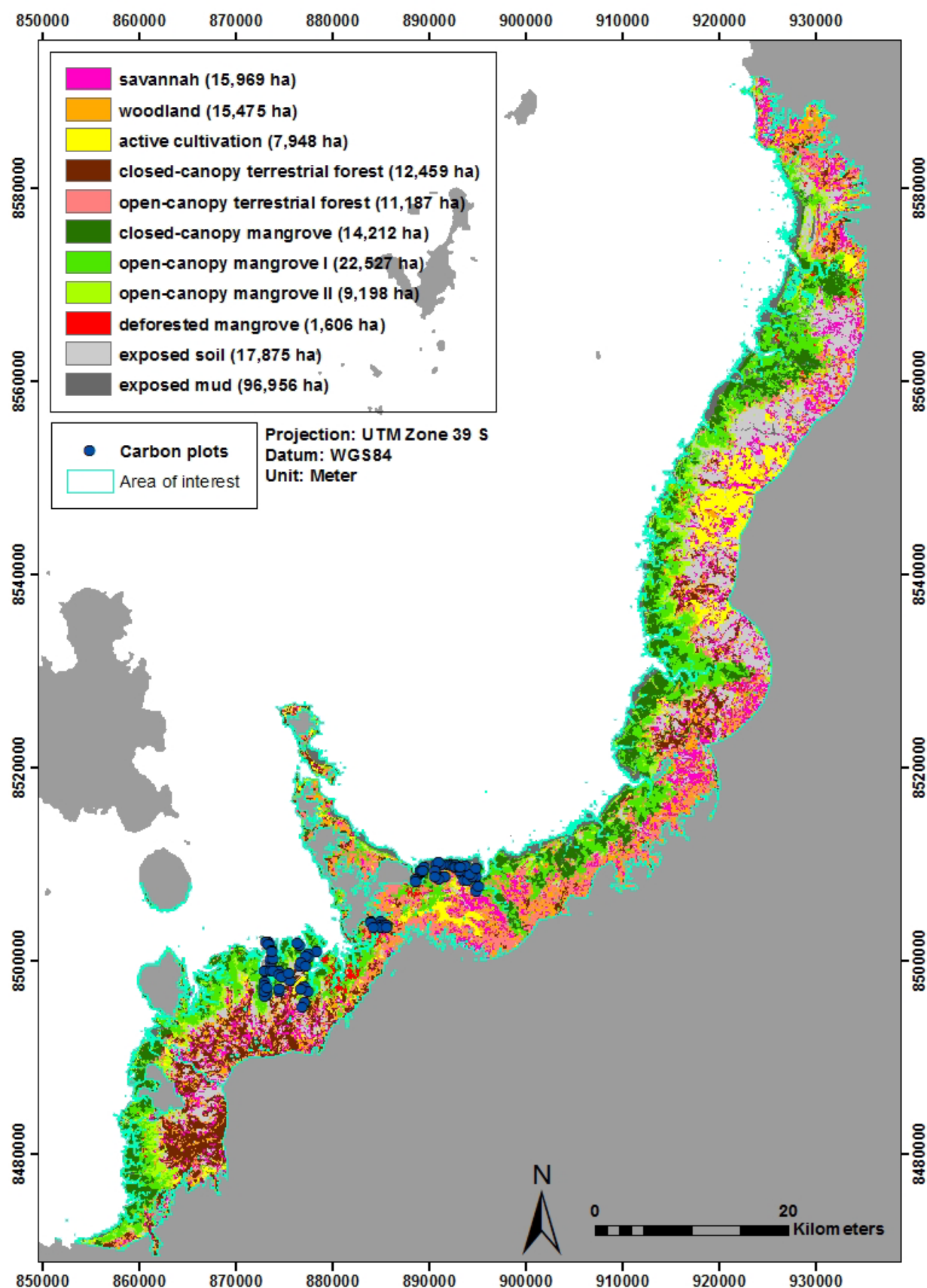


Figure 6. The results of contemporary object-based satellite image classification for the full extent of the AOI, including the location and size in hectares (ha) for all mapped classes for both Ambanja and Ambaro bays. Class descriptions are provided in Table 1. Blue points represent the locations of carbon stock plots established during 2012.

4.4 Analysis of historical land-cover and land-use dynamics

The suite of historical maps allowed us to quantify the amount of, and pinpoint the location of, change (Figure 7). In addition, analysing these maps revealed specific mangrove and other land-cover type transitions (i.e. from-to). Analysis of mangrove and surrounding land-cover type dynamics confirmed that during 2000 - 2006, closed-canopy mangroves experienced a net loss of ~1100 ha. During this same time period, open-canopy mangrove I experienced a loss of 4,149 ha, but a net gain of over 800 ha. This is explained by transitions from closed-canopy to open-canopy mangrove I, resulting from a thinning of the canopy due to tree harvest. Similarly, open-canopy II exhibited a loss (i.e., >2,700 ha), but also had a net gain (i.e. 170 ha), which is likely attributable to transitions from closed-canopy and open-canopy I mangrove to open-canopy mangrove II due to tree harvest. The amount of formerly forested mangrove (i.e., deforested mangrove) land had a net gain of nearly 400 ha (Figure 8). While not able to detect subtle modifications in mangrove stands, these findings confirm the ability of broad mangrove classes to map transitions in canopy-cover due to degradation, in this case known to be primarily caused by over-harvesting.

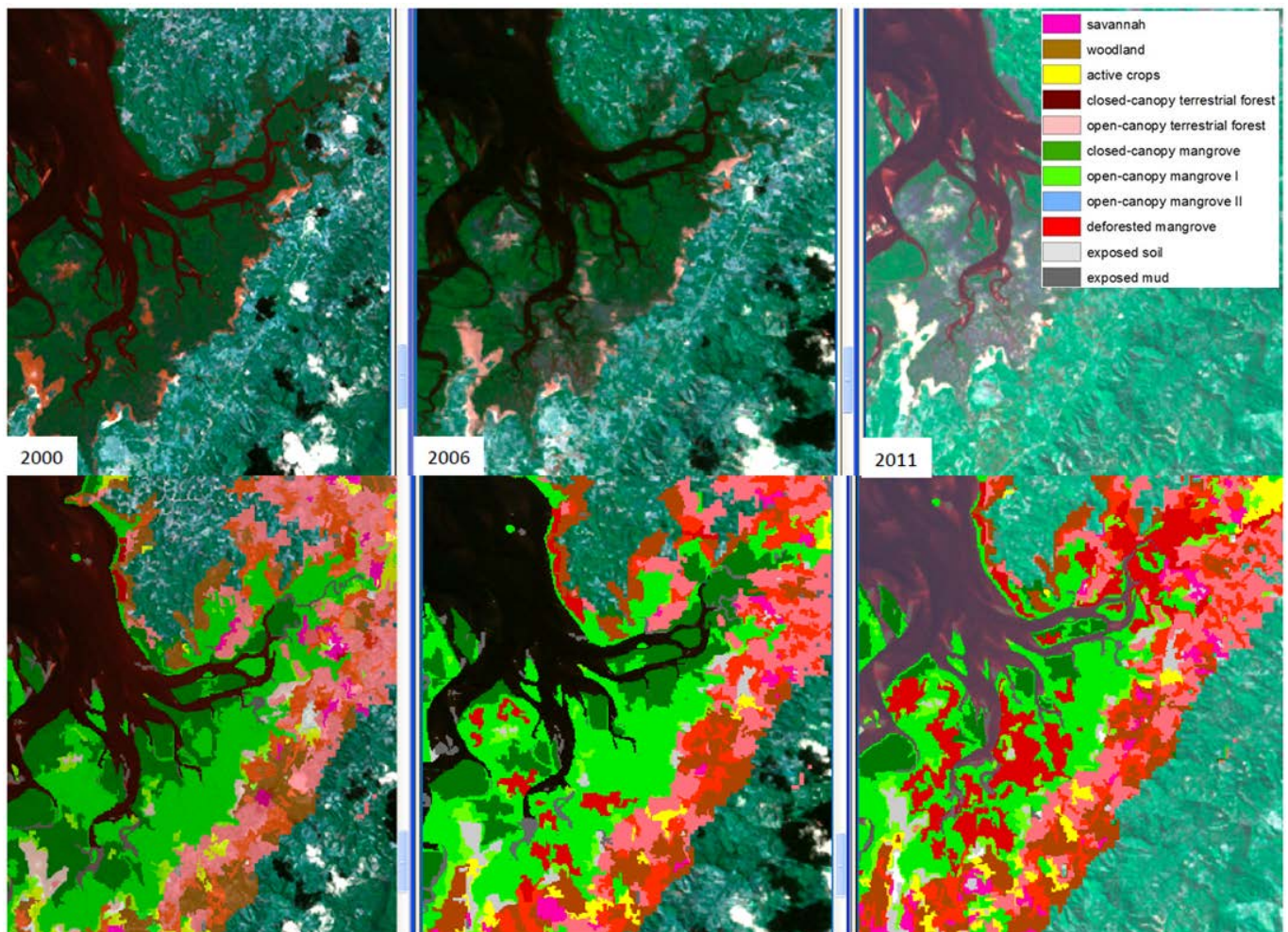


Figure 7. A sub-set of mangrove and land-cover type dynamics from 2000 - 2006 and 2000 - 2011. Maps were made for and dynamics assessed for the entire AOI, comprised of Ambaro and Ambanja bays.

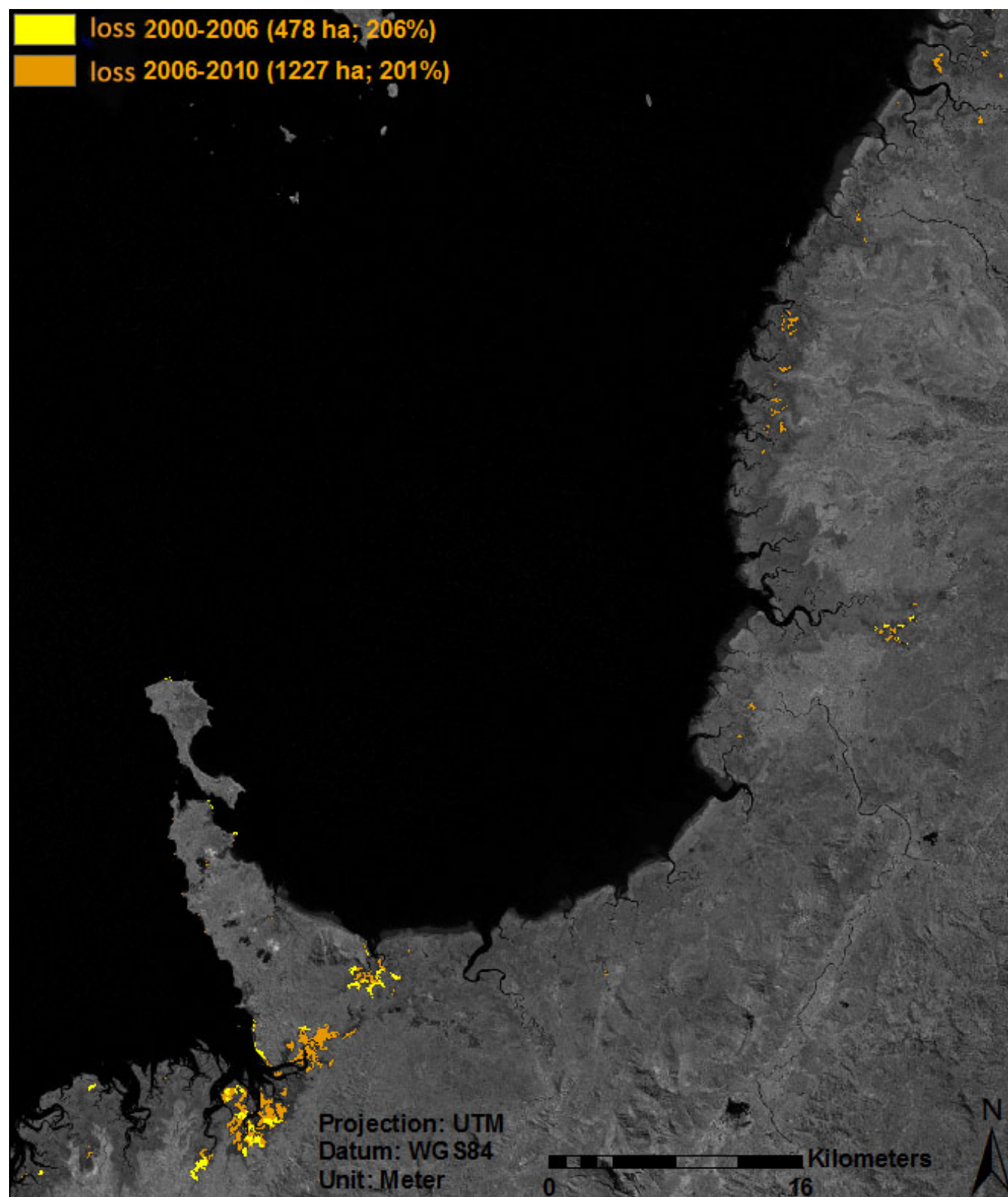


Figure 8. Mangrove deforestation (i.e., mangrove forest loss) in Ambanja Bay from 2000 - 2006 (478 ha) and 2006 - 2010 (i.e., 1,227 ha).

4.5 Characteristics of mapped mangrove types

Tree measurements summed at the plot-level allowed for summarizing the primary forest characteristics associated with mapped mangrove classes (Table 8). Open-canopy II plots were comprised of extremely sparse and stunted low stature trees with very open canopies. Open-canopy I plots were primarily comprised of moderate-dense stands of medium stature trees with relatively open canopies. Closed-canopy plots were typified by high stature trees exhibiting variable density but with well-formed closed canopies. Exceptions to the typical forest characteristics described in Table 8 include forest stands dominated by mature trees which were either very naturally open and/or highly degraded. Given their relatively open appearance, these types of stands appeared as open-canopy I in the classified maps. In addition, extremely dense medium/near-tall stands at times appeared as closed-canopy in the classified maps. These exceptions confirm the difficulty in distinguishing subtle degradation from otherwise distinct forest types. At the landscape-level, there was negligible difference in spectral appearance between areas comprised of relatively open-canopy medium stature trees and those comprised of tall trees which were naturally open, or had been heavily harvested and/or naturally degraded. Regardless, and encouragingly, more often than not, observations in forest plots confirmed that the broad canopy-cover classes employed are typified by dominant forest characteristics.

Table 8. Species (spp.) dominance, average height in meters (m) (± 1 standard deviation (stdev)), average trees per hectare (ha) (± 1 stdev) and average diameter (d) in centimeters (cm) (± 1 stdev) for mapped mangrove categories.

class	spp. dominance	height (m) (± 1 stdev)	trees/ha (± 1 stdev)*	d (cm) (± 1 stdev)
open-canopy II	<i>Avicennia marina</i>	1.6 (± 0.4) (n=7)	1300 (± 638) (n=7)	4.6 (± 0.2) (n=4)
open-canopy I	<i>Ceriops tagal</i>	2.6 (± 0.4) (n=12)	2780 (± 750) (n=5)	5.1 (± 0.9) (n=9)
	<i>Ceriops tagal</i>	4.5 (± 0.7) (n=8)	3300 (± 849) (n=2)	7.5 (± 1.6) (n=7)
	<i>Rhizophora mucronata</i>	4.2 (± 0.6) (n=6)	2160 (± 498) (n=5)	7.3 (± 1.3) (n=6)
closed-canopy	<i>Avicennia marina</i>	8.6 (n=1)	1250 (n=1)	14.9 (n=1)
				10.1 (± 0.5)
	<i>Ceriops tagal</i>	7.3 (± 1.2) (n=3)	2625 (± 318) (n=2)	(n=3)
	<i>Rhizophora mucronata</i>	7.3 (± 1.4) (n=18)	4719 (± 1133) (n=12)	11 (± 3.2) (n=18)
				15.6 (± 7.1)
	<i>Sonneratia alba</i>	6.3 (± 1) (n=2)	3170 (± 3000) (n=2)	(n=2)

4.6 Estimation of above- and below-ground carbon stocks

Following the estimation of biomass for individual trees in each plot, plot-level carbon stocks were scaled up to hectare level estimates applicable to the distinct mangrove type classes (**Figure 9**). Closed-canopy mangrove was estimated to have average above-ground carbon (C) stocks of 87.5 Mg/ha (± 8.8 (i.e., 1 standard error) for live trees and 3.3 Mg/ha (± 1.1) for dead trees (n=20). Average below-ground C stocks for closed-canopy were 57.5 Mg/ha (± 4.1) for live roots, 2.8 (± 0.8) for dead roots, and 451.2 Mg/ha (± 33) for soil (i.e., 0-150 cm) (n=20). In contrast, open-canopy mangrove I was estimated to have average above-ground C stocks of 21.8 Mg/ha (± 3.7) for live trees and 1.7 (± 0.6) for dead trees (n=25). Average below-ground C stocks for open-canopy I were 16.0 Mg/ha (± 2.3) for live trees, 1.4 Mg/ha (± 0.5) for dead trees, and 365.7 Mg/ha (± 33.3) for soil (n=21). Open-canopy II mangroves were estimated to have average above-ground C stocks of 7.3 Mg/ha (± 1.8) for live trees and 5.6 (± 1.5) for dead trees (n=4). Below-ground C stocks for open-canopy II were 4.4 Mg/ha (± 1.1) for live roots, 3.5 Mg/ha (± 0.9) for dead roots, and 517.1 Mg/ha (± 76) for soil (n=4).

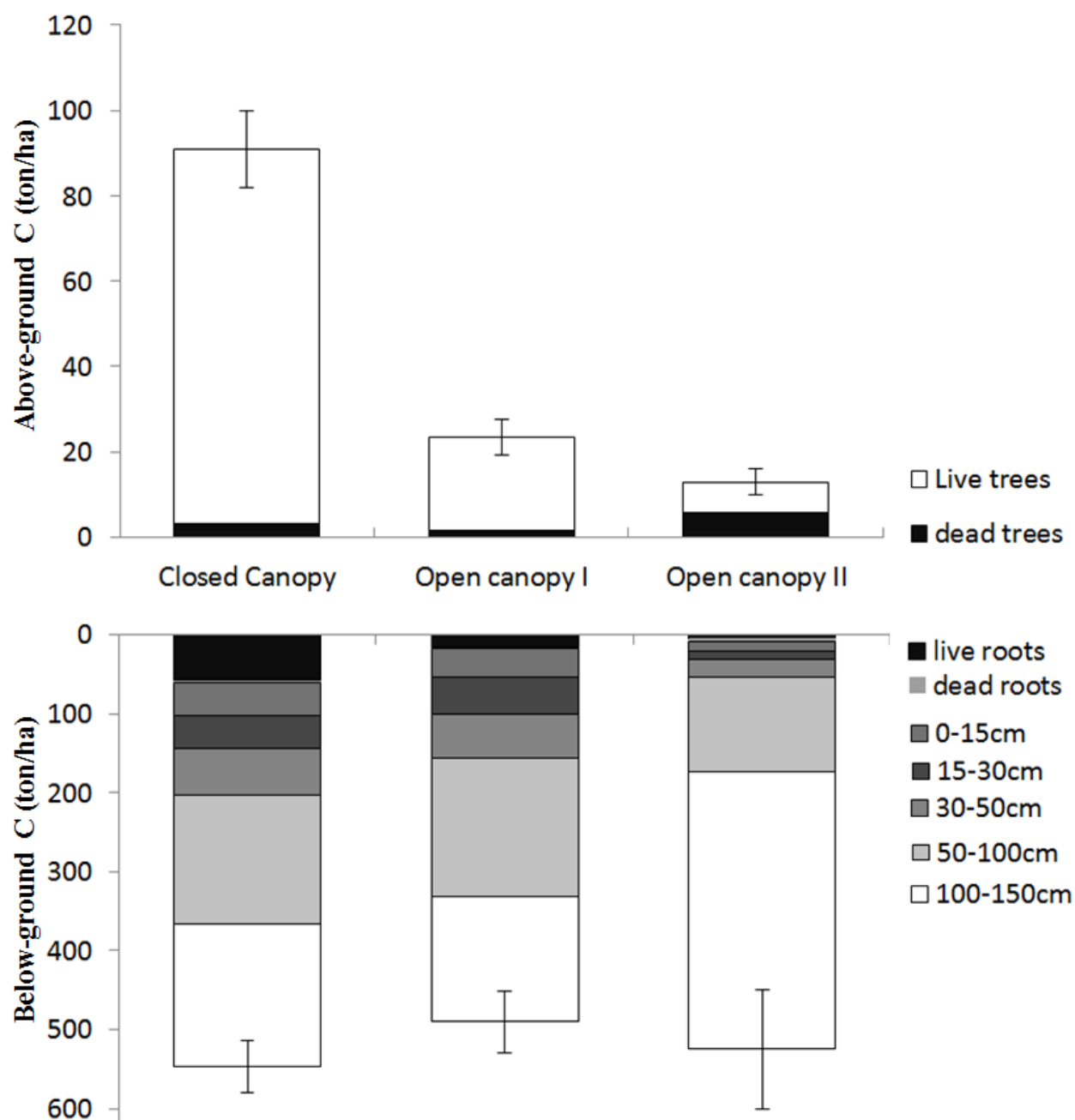


Figure 9. Estimated above- and below-ground carbon (C) stocks (ton/hectare (ha) for mapped mangrove classes (see table 1) in Ambanja/Ambaro bay.

To assess the impact of degradation on hectare-level C stocks estimates, within each mapped mangrove type, plots were partitioned based on whether they represented intact or degraded forest (**Figure 10**). Intact closed-canopy mangrove was estimated to have average above-ground carbon (C) stocks of 90.7 Mg/ha (± 10) for live trees and 2.7 Mg/ha (± 1.1) for dead trees ($n=17$), whereas degraded closed-canopy forest exhibited average C stocks of 69.5 Mg/ha (± 14) for live trees and 6.6 Mg/ha (± 4) for dead trees ($n=3$). The average below-ground C stock (i.e., live roots; dead roots; soil (1-150cm) for intact

closed-canopy forest was 472 Mg/ha (± 29 , $n=17$) versus 605 Mg/ha (± 176) for degraded ($n=3$). In contrast, intact open-canopy I mangroves had average above-ground carbon (C) stocks of 24.7 Mg/ha (± 6.2) for live trees and 2.5 Mg/ha (± 1.2) for dead trees ($n=13$), whereas degraded closed-canopy forest exhibited average C stocks of 19.9 Mg/ha (± 4.3) for live trees and 1 Mg/ha (± 0.5) for dead trees ($n=12$). The average below-ground C stock (i.e., live roots; dead roots; soil (1-150cm) for intact open-canopy I forest was 463 Mg/ha (± 59) ($n=10$) versus 465 Mg/ha (± 56) for degraded ($n=11$). No open-canopy II plots contained enough stumps to be considered degraded.

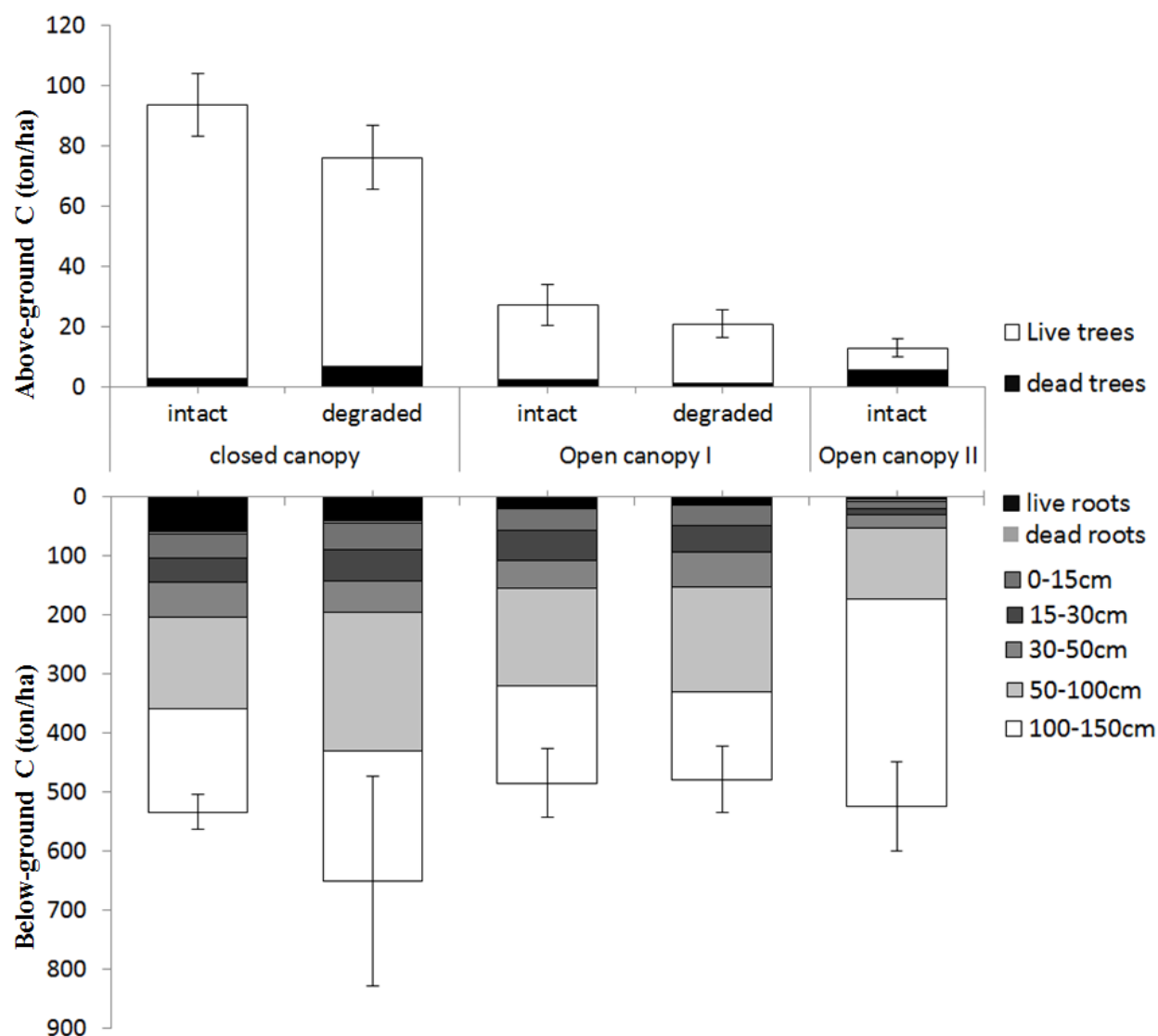


Figure 10. Estimated above- and below-ground carbon (C) stocks (ton/hectare (ha)) for mapped mangrove classes (see table 1) in Ambanja/Ambaro bay. C stocks are partitioned by plots comprised of intact vs. degraded forest.

C stocks sampled throughout the Indo-Pacific as described in Donato *et al.* (2011) were on average 1,023 Mg/ha, 49-98% of which was in the organic-rich soils. In western Micronesia, specifically Yap state (Federated States of Micronesia) and the

Republic of Palau, mangrove C storage ranged from 479 (seaward)-1,385 (landward) Mg/ha with 70% of storage in soils (Kauffman *et al.*, 2011). Mangroves in Madagascar are not nearly as high in stature as those in the Indo-Pacific, which explains their lower C stocks. However, while much less than the mangroves of the Indo-Pacific, in comparison to other terrestrial forest types (e.g., boreal, temperate, tropical upland (Donato *et al.* 2011)), these preliminary results indicate that Madagascar's mangroves are still very carbon-dense (Figure 11). This is in large part because of the high amount of carbon in the soil, not in the tree biomass – an important caveat. As such, these results support a growing body of evidence that mangroves are amongst the most carbon-dense forests in the tropics, with equal or greater above- and typically larger below-ground stocks than terrestrial systems (Fujimoto *et al.*, 1999; Donato *et al.*, 2011; Kauffman *et al.*, 2011; Ray *et al.* 2011; Chen *et al.* 2012; Donato *et al.*, 2012; Matsui *et al.* 2012; Adame *et al.* 2013).

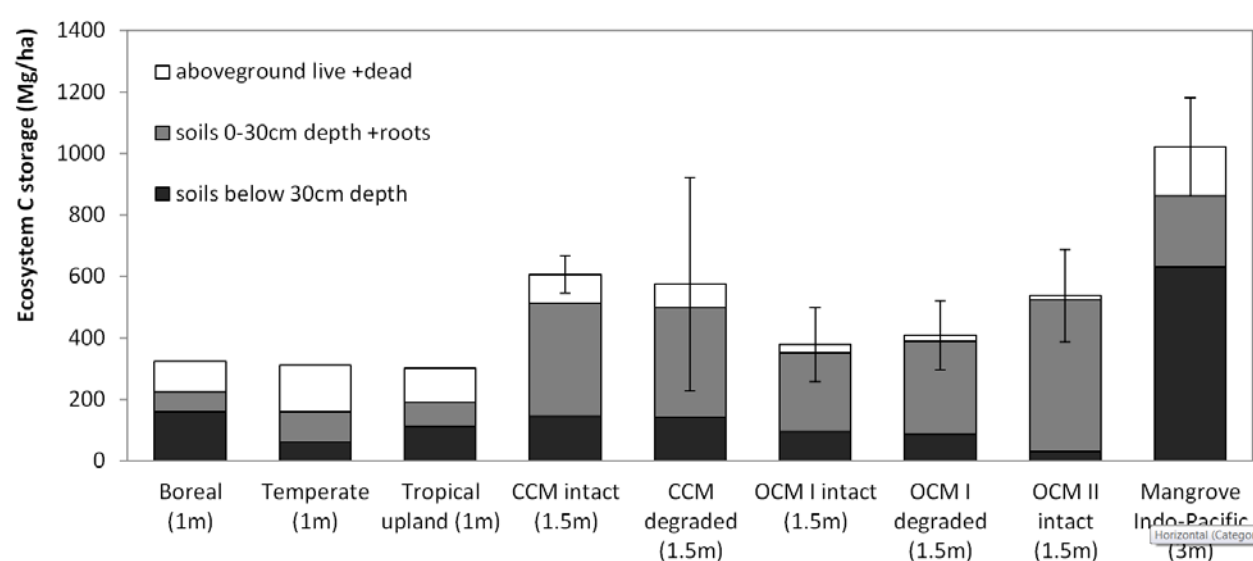


Figure 11. Madagascar's mangrove carbon stocks compared with those in the Indo-Pacific and for other forest types (figure adapted from Donato *et al.* 2011). The depth to which soils were measured is listed under each bar on the x axis.

5. Accomplishment of goals and objectives

5.1 Contribute to the development of the REDD baseline and methodologies specific to mangroves

Our work in the mangroves of Ambondrolava in Madagascar's southwest coast, in partnership with the Belgium-based NGO Honko Mangrove Conservation and Education is on track to fully develop the world's second Plan Vivo project for mangroves, following the work that has been achieved by the project partners, KMFRI, in Gazi Bay, Kenya.

The project continues to participate in a number of global networks and forums which are developing standardized methods for mangrove REDD+ under both the IPCC and VCS AFOLU programme. Key contacts here include: the UNEP-led Blue Forests programme, the United States Forest Service (e.g. Carl Trettin), Oregon State University (e.g. Boone Kauffman), eCoPartners and the VCS. In addition, we attended a number of topical conferences and workshops which facilitate critical knowledge exchange, allowing us to present the results of our work while simultaneously giving us exposure to the work of other leading experts (details under "dissemination of research findings" section below). The project has begun piloting the application of a VCS approved REDD methodology (i.e. VM0009), which will be the first application of a VCS methodology to mangroves. A review of the applicable VCS methodologies showed this particular methodology to be most applicable to the project in northwest Madagascar. We further consulted with the developers of the methodology – ecoPartners – to ensure its applicability.

However, a major stumbling block to the advancement of the project remains the availability of standardised, approved methodologies applicable to mangrove REDD and that specifically take into account what makes these habitats such powerful carbon sinks – the soil organic carbon and the continual accretion of this, year to year, in intact mangroves. The independent development of such a methodology by the project alone is well beyond its technical and financial means. We therefore have begun to collaborate with Silvestrum – a recognised leader in the development of forest and wetland carbon accounting methodologies. Silvestrum is presently developing an approved methodology for the restoration of tidal wetlands and has agreed to collaborate with Blue Ventures in developing a methodology specific to the avoided deforestation and conversion of intact mangrove wetlands. The existence of such a methodology would remove the major barrier preventing this, as well as all other such projects throughout the tropics, from accessing REDD+ finance. The development of a fully approved VCS REDD methodology is a costly undertaking requiring a level of expertise and financial support that has proven to be well beyond the scope of this project.

To overcome this single most important impediment to mangrove REDD+, Blue Ventures has established a partnership with ESSA Foret, ecoPartners, Silvestrum, the Center for Forested Wetlands Research, US Forest Service and WWF Mozambique to try to address the critical need for REDD methodology designed specifically for the conservation of intact wetlands. We have made an application to MASMA to begin this work in 2013.

5.2 Build local capacity to undertake ecological and carbon stock measurements and establish REDD projects

During the period of MASMA funding, our team grew to include more than 10 full time staff members. Of these full time staff, half are Malagasy science graduates. Building on the strong foundations facilitated through the MASMA grant, we have continued to expand our team, which currently is comprised of eight full time Malagasy staff. They were trained in carbon

stock assessment, socioeconomic research and geospatial analysis, and in turn have also themselves been able to train both Malagasy and international graduate student interns. In the coming months, we aim to, pending further funding, hire a full time Malagasy geospatial analyst and several community liaison officers to continue developing the mangrove REDD project in the NW according to VM009. As our partner in this project, input from Dr. James Kairo and graduate students affiliated with KMFRI played an integral role in designing and implementing mangrove carbon stock measurements. Our collaboration with KMFRI also facilitated team-member exchanges between Kenya and Madagascar. Specifically, two students from Kenya, Joseph Langat (PhD) and Lillian Mwihaki (MSc) participated in field campaigns in Madagascar, and several Blue Ventures staff visited Gazi Bay, Kenya, to learn from the carbon project activities undertaken there. In addition, both Malagasy and international graduate student interns have become integral components of our research. During the period of MASMA funding, we designed and supervised theses and internships for:

- four students from the Université d'Antananarivo, Département des Eaux et Forêts (Madagascar) (Diplôme d'Etudes Approfondies)
- two students from Université de Toliara: Institut Halieutique et des Sciences Marines (Madagascar) (Diplôme d'Etudes Approfondies)
- one student from Oxford University: Environmental Change Institute (UK) (MSc thesis)
- one student from King's College London, Geography Department (UK) (MSc thesis)
- three students from King's College London, Conservation Science Department (UK) (MSc internship)
- one student from University of East London (UK) (Master in NGO and Development Management thesis)
- one student from Institut Catholique des Arts et Métiers (France) (MSc internship)
- one student from Katholieke Universiteit Leuven (Belgium) (MSc internship)
- one student from Gettysburg College (USA) (undergraduate independent study project)

What's more, we have trained and benefited from the local knowledge and skills of numerous local community members. These community members have acted as guides and assistants, but have also been trained to take part in and eventually be able to conduct mangrove carbon stock inventories. Such training occurred in five communities during the period of the MASMA grant.

5.3 Demonstrate the value of mangroves to mitigate climate change and their potential financial value

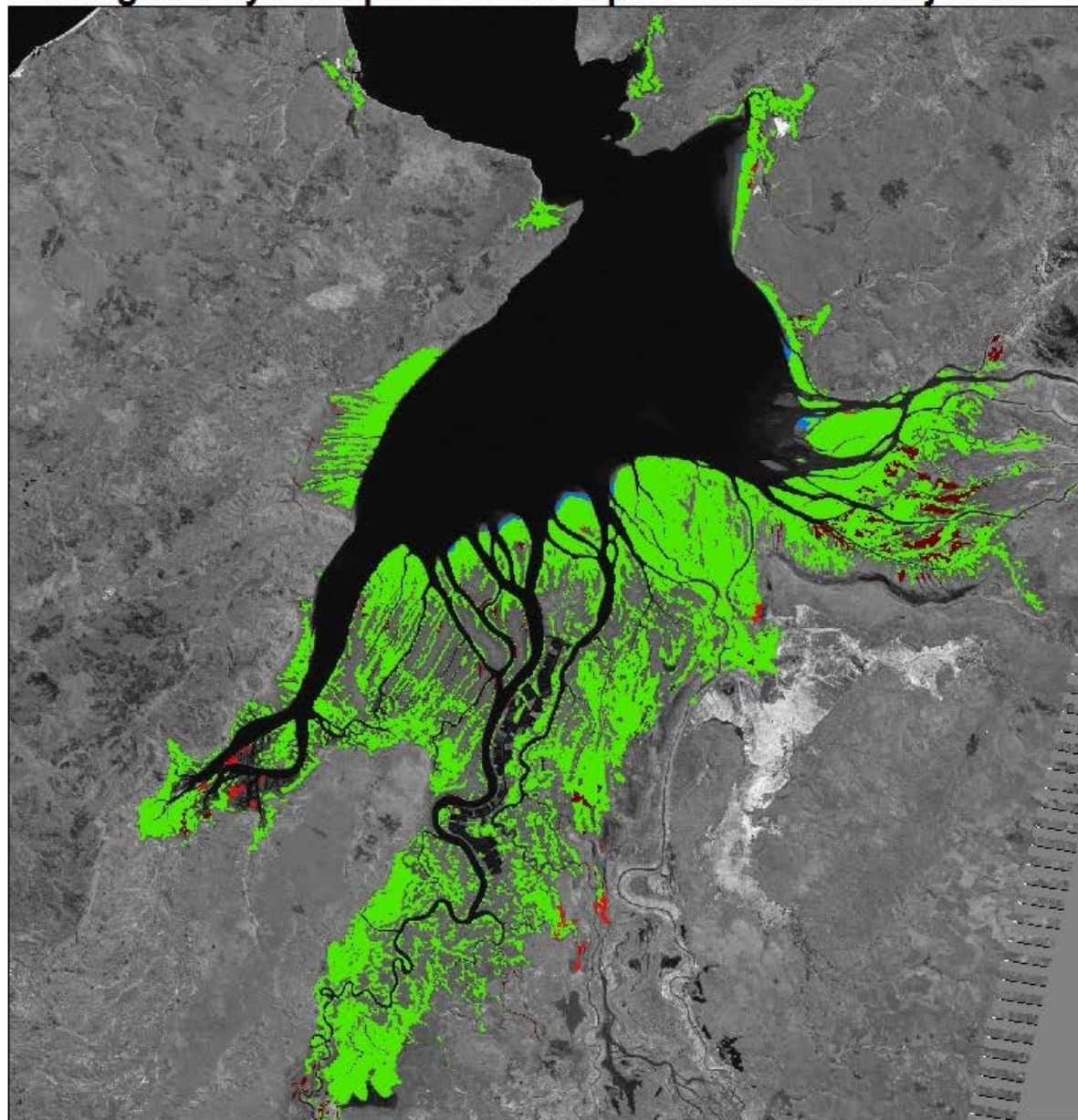
While CDM reforestation/afforestation and terrestrial forest REDD+ projects have received a great deal of donor support and institutional recognition, the importance of blue carbon has only recently begun to be recognized in international forums (e.g., Gordon *et al.* 2011; Pendleton *et al.* 2012; Ullman *et al.* 2012). Within Madagascar, there is a national REDD strategy and a number of relatively advanced upland forest REDD projects. Our project team members regularly attended meetings in the capital city of Antananarivo to work with other key actors in REDD at the national scale, including Madagascar's Designated National Authority and the ONE - the government agency responsible for REDD+ development. Through these national forums, we fully communicated our project progress and disseminated its research results.

As the only organisation measuring mangrove carbon stocks, Blue Ventures is an important member of the national REDD Monitoring, Verification, and Reporting (MRV) group. Notably we have contributed our mangrove carbon stock measurements and historical forest dynamics to the development of a national reference scenario being undertaken by the REDD MRV, so ensuring mangrove carbon is included in national REDD policy. To demonstrate the potential value of mangroves in sequestering CO₂ as well as to identify sites suitable for mangrove REDD+ projects, we:

- Undertook a broad-scale estimate of carbon stock changes in Madagascar's mangrove forests between 1990 - 2000, 2000 - 2010 and 1990 - 2010 using measurements from Maintirano, Belo sur Mer and Velondriake
- Undertook a detailed analysis of dynamics, drivers of change, estimation and valuation of carbon stocks in Madagascar's primary mangrove loss hot-spot (i.e., Ambaro-Ambanja bay)
- Through a partnership with the sustainable aquaculture firm Aqualma, assessed and analysed mangrove dynamics (Figure 12), undertook detailed contemporary and historic classification and estimation of carbon stocks (i.e., over 60 C stock plots) (Figure 13) and assessed primary drivers of loss in Madagascar's largest mangrove ecosystem (i.e., Mahajamba bay)
- Through a partnership with the Belgium-based NGO Honko Mangrove Conservation and Education, assessed and analysed mangrove dynamics, organized and collated extensive community mapping (Figure 14) and undertook a detailed estimation of carbon stocks (i.e., 57 C stock plots, Figure 15) and assessment of primary drivers of loss in the Ambondrolava mangroves of SW Madagascar, all of which works towards establishing one of the world's first registered mangrove forest carbon projects through the UK-based charity, the Plan Vivo Foundation.

Collectively, the results of these efforts have allowed us to quantify carbon stocks, understand drivers and change, and estimate potential financial value in a diverse array of mangrove ecosystems.

Mangrove dynamique 1990-2010 pour Baie de Mahajamba



Projection: Laborde
 Datum: Tananarive 1925
 Unite: Metre



Kilometre
 0 2.5 5 10 15 20

■	perte 1990-2000 (201 ha/0.7%)
■	perte 2000-2010 (1050 ha/3.8%)
■	gain 2000-2010 (150 ha/0.5%)
■	persistant 1990-2010 (26527 ha/95.5%)

blue ventures
 discovery through research

Cartes originales fournies par Chandra Giri (USGS)
 Analyse de changement: Blue Ventures Conservation

Figure 12. Mangrove dynamics from 1990 - 2000 and 2000 - 2010 in Madagascar's largest mangrove ecosystem: Mahajamba bay. Compared with the other main mangrove ecosystems in Madagascar (e.g., Ambaro/Ambanja), Mahajamba has exhibited a small amount of loss; however, loss has increased considerably in recent years and is poised to continue rising due to population increase and economic pressures.

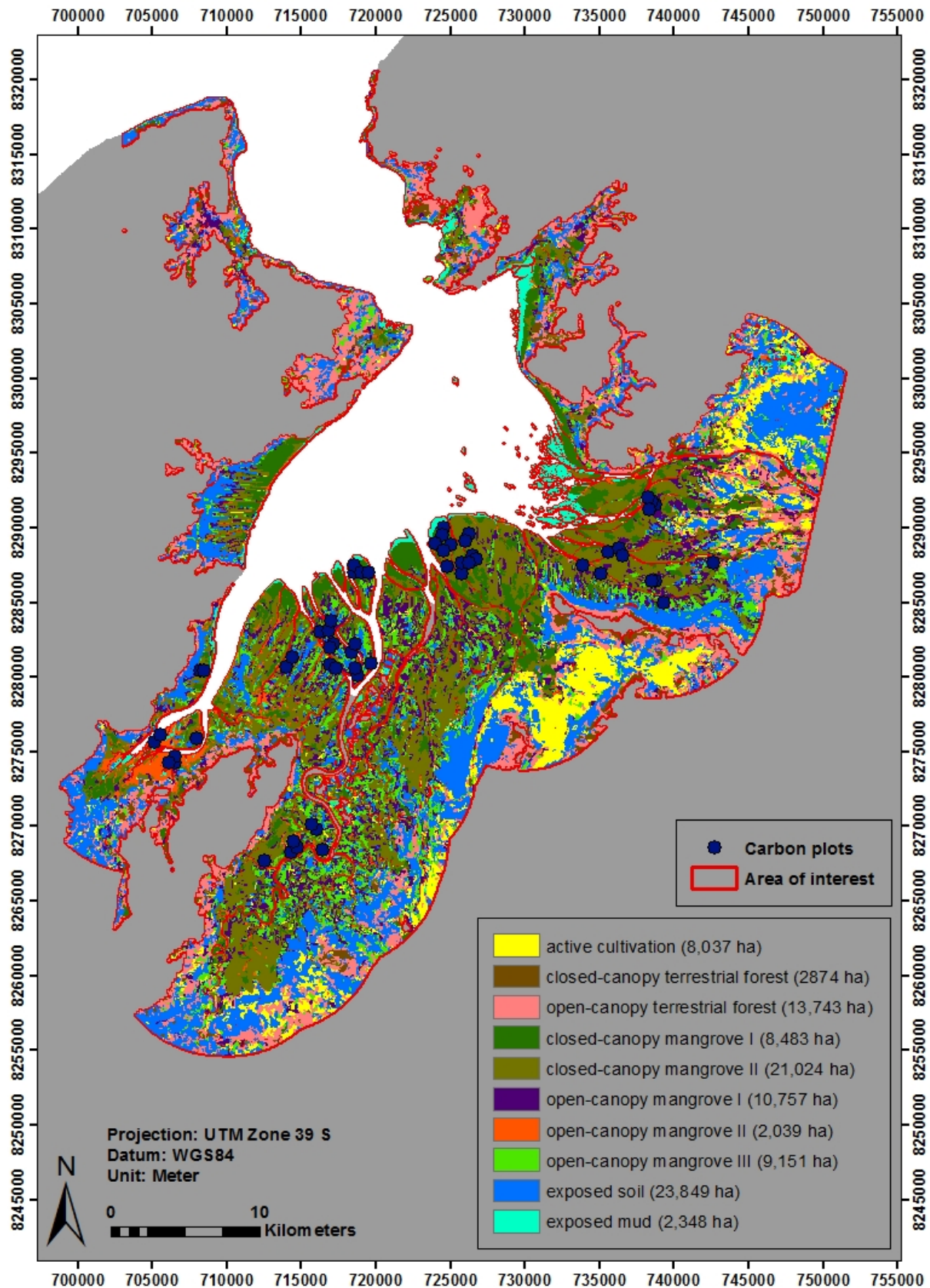


Figure 13. The results of contemporary object-based satellite image classification for the full extent of Madagascar's largest mangrove ecosystem: Mahajamba bay, including the location and size in hectares (ha) for all mapped classes. Blue points represent the locations of over 60 carbon stock plots established during 2012.

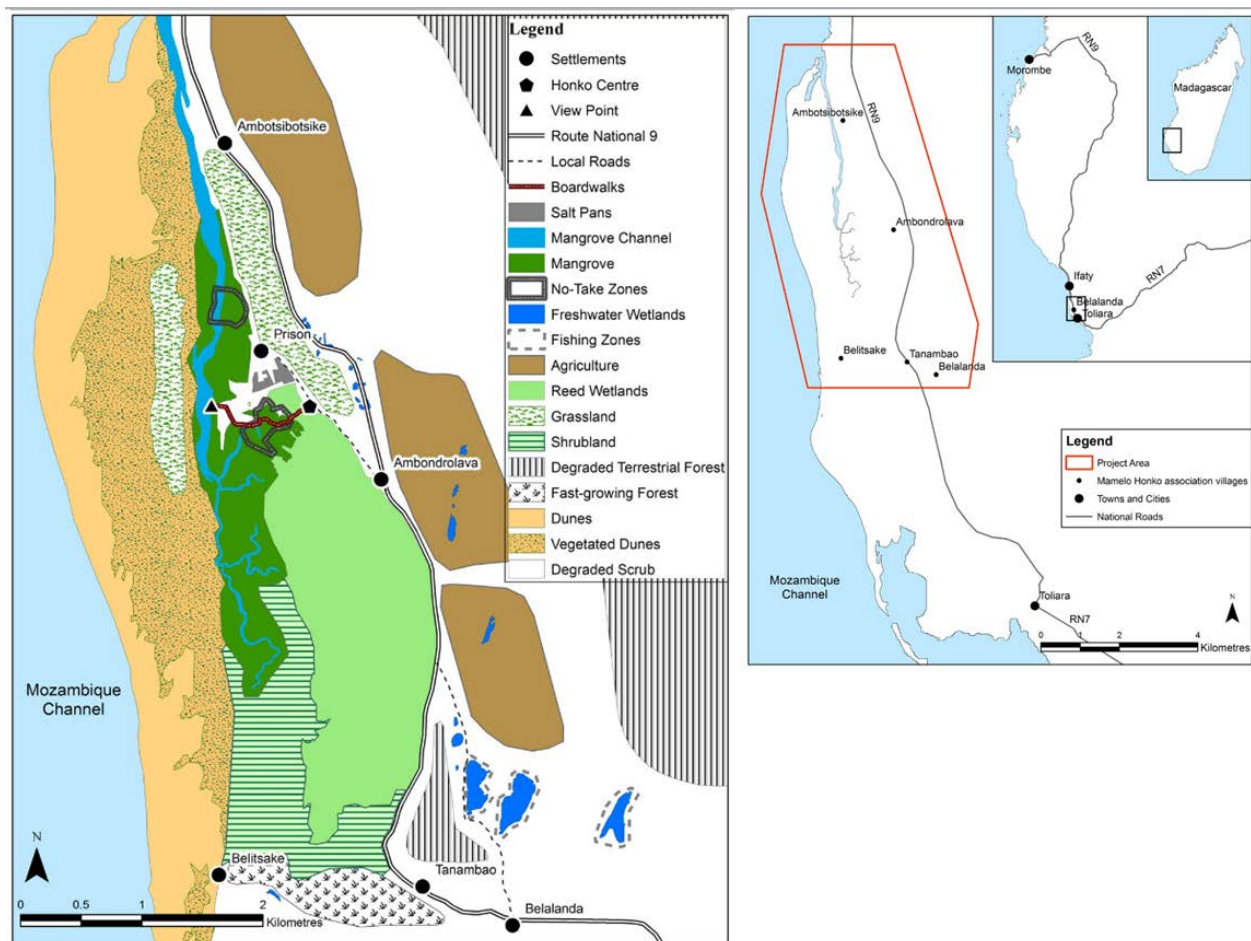


Figure 14. The results of contemporary community mapping for Ambondrolava in southwestern Madagascar. Through our partnership with the Belgian NGO, Honko Mangrove Conservation and Education, we organized and led historic, contemporary and future community mapping sessions. These maps helped provide baseline information for development of a registered Plan Vivo forest carbon project focused on mangroves.

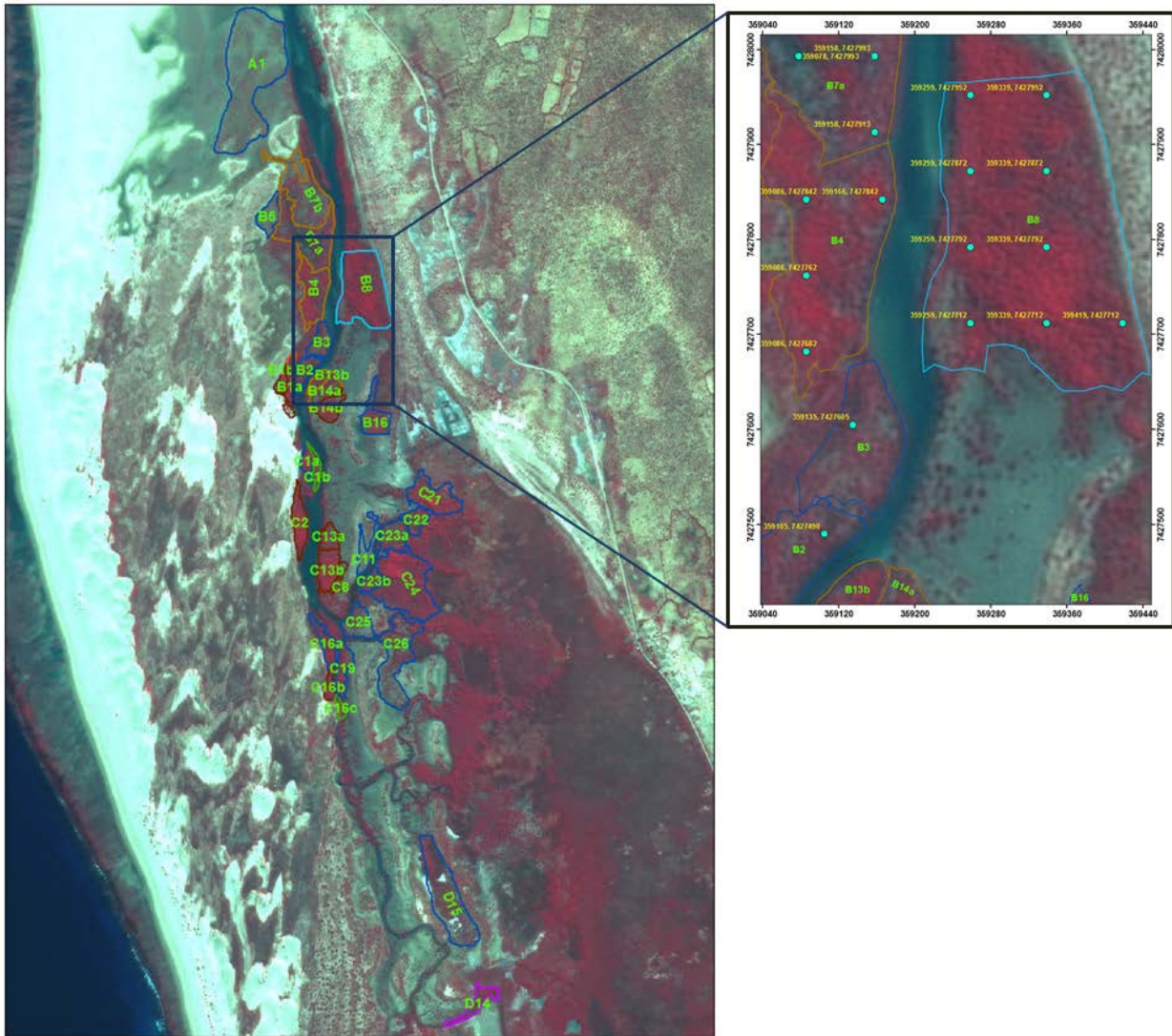


Figure 15. Using SPOT imagery generously donated through Planet Action, and in collaboration with Honko Mangrove Conservation and Education, we stratified the mangroves of Ambondrolava, Madagascar, based on intact, degraded and replanted stands, wherein we established 57 C stock plots.

5.4 Assess the feasibility of establishing mangrove REDD+ projects

A major component of this research was to assess and identify mangrove ecosystems along Madagascar's coast that have high potential for REDD+. Identifying mangrove REDD+ hot-spots included a broad-scale, historical assessment of mangrove forest cover change; analysing the agents, drivers and underlying causes of deforestation; examining natural versus anthropogenic causes of forest loss; and assessing the socioeconomic importance of mangroves in different areas. Building on this work, we identified a primary loss hot-spot (i.e., Ambaro-Ambanja bay) and invested in a further, detailed assessment of the feasibility of establishing mangrove REDD at this location.

5.5 Catalyse the development of mangroves to mitigate climate change and their potential financial value

The results of this research collectively provide the information required to work towards developing an actual pilot mangrove REDD project that could finance conservation, restoration and sustainable use in Ambaro-Ambanja bay. In addition, the recruitment and training of staff, acquisition of field equipment, and experience gained through numerous expeditions allowed us to pursue numerous additional partnerships and projects, including with the Honko Mangrove Conservation and Education in Ambondrolava, Aqualma (part of the UNIMA group) in Mahajamba Bay, WWF - Madagascar & Western Indian Ocean Region in the Tsiribihina Delta, and WWF Mozambique in the Zambezi Delta. Our collective experiences also left us well-positioned to participate in and contribute to the Environment Abu Dhabi-funded and UNEP GEF-organized Abu Dhabi Blue Carbon Demonstration Project in the mangroves of Abu Dhabi, UAE, in January, 2013. Through these ongoing partnerships and collaborations we have become well-positioned to not only secure one of the world's first Plan Vivo projects focused on mangroves and to pilot an existing REDD methodology, but also help develop a REDD methodology specific to mangroves.

5.6 In-country collaboration

We are currently collaborating with two academic institutions (Université d'Antananarivo, Département des Eaux et Forêts and Université de Toliara: Institut Halieutique et des Sciences Marines), the Centre National de Recherches Océanographiques (CNRO) and the sustainable aquaculture firm Aqualma. In addition, our data contributions to the Office National pour l'Environnement (ONE) and the REDD MRV working group will help inform and shape the national REDD readiness strategy, ensuring the inclusion of mangrove forests.

5.7 Dissemination of research findings

To-date, we have shared the results of our ongoing work at the 7th edition of MASMA grantee meeting (Mombasa: October, 2011); the Eyes on the Earth Summit (Abu Dhabi: November, 2011), the Climate Change, Deforestation & the Future of African Rainforests conference (Oxford: January, 2012); the Eyes on the Earth Summit (Abu Dhabi: December, 2011), to School for International Training (SIT) students (Toliara: October, 2012 and March, 2013); and at the regional Carbon Assessment Workshop (Maputo: October, 2012). In January, 2013, we participated in a mangrove carbon demonstration project and workshop in Abu Dhabi, wherein we had the opportunity to present our work to and learn from leading experts in mangrove carbon science. In addition, building on the results of our work thus far, we have prepared several articles for submission to peer-reviewed journals, and are in the process of writing others. The topics of these manuscripts include:

- Structural and biomass analysis of mangroves in WIO – to be carried by KMFRI component of the project
- Mangrove mapping and carbon stock inventory in Ambaro/Ambanja Bay Madagascar (research letter)
- Mangrove mapping and carbon stock inventory in Mahajamba bay, Madagascar (research letter)
- Comparing pixel- and object-based classification approaches for Madagascar's mangroves
- National-level analysis of Madagascar's mangrove dynamics (for submission to Madagascar Conservation & Development)
- REDD+ feasibility for NW Madagascar

6. Conclusions

In summary, during the granting period, the project made significant progress in many areas. We carried out a national analysis of mangrove deforestation and identified areas of high potential for mangrove REDD+. Focussing on key areas of interest identified through our national analysis, we conducted comprehensive historical and contemporary mapping and produced the first localized map of mangroves and surrounding land-cover categories for Ambanja/Ambaro bays. Through these localized mapping efforts we also compared traditional pixel-based with object-based image classification methods, with results supporting the robustness of an object-based approach, particularly for historical dates. Mapping also allowed us to adapt and test mangrove stratification techniques which proved to be ecologically meaningful and represent statistically distinct carbon stocks. To acquire the necessary measurements, we invested in equipment, training and scientific collaborations; the result being that within Madagascar the skills now exist to undertake mangrove carbon measurements in keeping with international protocols. These field measurements have resulted in accurate carbon stock estimations for a range of mangrove types within Madagascar. Through concurrent socio-economic analyses, we have also established the historical dynamics of two of Madagascar's largest mangrove ecosystems (Mahajamba and Ambanja-Ambaro). Our collective experiences have allowed us to begin undertaking the first application of a VCS methodology (i.e. VM0009) to mangroves and lead as technical partner in Plan Vivo projects for mangroves. In addition, we have been able to submit our results to Malagasy officials organizing the national Monitoring Reporting and Verification effort, helping to ensure that blue carbon is given prominence in national REDD+ policy.

Despite the many successes, we have faced and continue to confront numerous challenges. For example, given a need for detailed and accurate characterization of the agents, drivers and underlying causes of degradation and deforestation, our socio-economic team has typically been stretched far too thin. We require expanding our socioeconomic sub-team in order to complete the needed contextual research. In addition, while mapping deforestation has proved possible using existing methods and available remotely sensed data, accurately detecting degradation remains extremely vexing. To best characterize subtle mangrove modification in addition to conversion, finer detail and alternative (e.g., radar, LiDAR) data-sets and alternative image classification approaches (e.g., sub-pixel analysis) must be explored. Furthermore, while thus far our measurements and subsequent calculations have focussed on standing mangrove carbon stocks, it is clear that we need to shift focus to the measurement of GHG emissions and reductions at a landscape level, including the accretion of organic soil carbon and taking into full account the wetland functioning of mangroves. Through overcoming challenges such as those listed through collaboration with other researchers in the WIO, as well as world-leaders in accounting methodologies, we would be better positioned to overcome what still remains perhaps the single most important barrier to mangrove blue carbon projects – an approved methodology for conservation of intact mangrove wetlands.

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