Sensors **2008**, *8*, 2104-2117

sensors

ISSN 1424-8220

www.mdpi.org/sensors

Full Research Paper

Mangrove Forest Distributions and Dynamics in Madagascar (1975–2005)

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Received: 14 February 2008 / Accepted: 25 March 2008 / Published: 27 March 2008

Abstract: Mangrove forests of Madagascar are declining, albeit at a much slower rate than the global average. The forests are declining due to conversion to other land uses and forest degradation. However, accurate and reliable information on their present distribution and their rates, causes, and consequences of change have not been available. Earlier studies used remotely sensed data to map and, in some cases, to monitor mangrove forests at a local scale. Nonetheless, a comprehensive national assessment and synthesis was lacking. We interpreted time-series satellite data of 1975, 1990, 2000, and 2005 using a hybrid supervised and unsupervised classification approach. Landsat data were geometrically corrected to an accuracy of ± one-half pixel, an accuracy necessary for change analysis. We used a postclassification change detection approach. Our results showed that Madagascar lost 7% of mangrove forests from 1975 to 2005, to a present extent of ~2,797 km^2. Deforestation rates and causes varied both spatially and temporally. The forests increased by 5.6% (212 km^2) from 1975 to 1990, decreased by 14.3% (455 km^2) from 1990 to 2000, and decreased by 2.6% (73 km^2) from 2000 to 2005. Similarly, major changes occurred in Bombekota Bay, Mahajamba Bay, the coast of Ambanja, the Tsiribihina River, and Cap St Vincent. The main factors responsible for mangrove deforestation include conversion to agriculture (35%), logging (16%), conversion to aquaculture (3%), and urban development (1%).

Keywords: Mangrove, Madagascar, Change analysis, Landsat, Aster

1. Introduction

Mangrove forests are found in the intertidal zone in the tropical and subtropical regions of the world. The present extent is estimated between 160,000 and 180,000 km^2, covering about one quarter of world's tropical and subtropical coastlines [1-2]. The forests have been declining at an alarming rate—perhaps greater than or equal to adjacent coral reefs or tropical forests [3]—and much of what remains is in degraded condition [2,4]. Data obtained from 80 countries around the world showed a 35% decline of mangrove forests since 1980 [5].

Mangrove forests in Madagascar, covering an approximate area between 3,000 to 4,000 km^2, are found almost exclusively on the western coast [6]. Only 2% of the forests are found on the northeastern coasts. The forests are species poor; only nine species are found in Madagascar compared to more than 45 species in Southeast Asia and about 17 species in sub-Saharan Africa [7-8]. Following the global trends, mangrove forests in Madagascar are declining due to conversion to other land uses and forest degradation.

These forests provide important ecological and societal goods and services to local communities. For example, mangrove forests provide wood and forest products to numerous coastal communities and contribute to the national economy [9-10]. Mangrove wood is used extensively for making fishing traps and canoes, and also for domestic use such as fencing, housing, and fuel for cooking [11]. Similarly, a mangrove forest protects riverbanks and shorelines from erosion, filters pollutants, and provides nursery grounds and refuge for several fish species. They also provide a significant carbon sink due to year-round physiologically active foliage [12]. Mangrove vegetation also serves as a barrier to protect lives and property from natural disasters such as tsunami and hurricanes [13].

In spite of this importance and usefulness, accurate and reliable information on the distribution rates, causes, and consequences of mangrove forest change in Madagascar has not been available. Earlier studies [14-17] used remotely sensed data to map and, in some cases, to monitor mangrove forests at a local scale. However, national assessment and synthesis of the mangrove forest distribution and dynamics of Madagascar was not attempted. The objective of our study is to quantify the spatial and temporal dynamics and distribution of mangrove forests and to identify the proximate causes of change from 1975 to 2005 using remotely sensed data.

2. Study Area

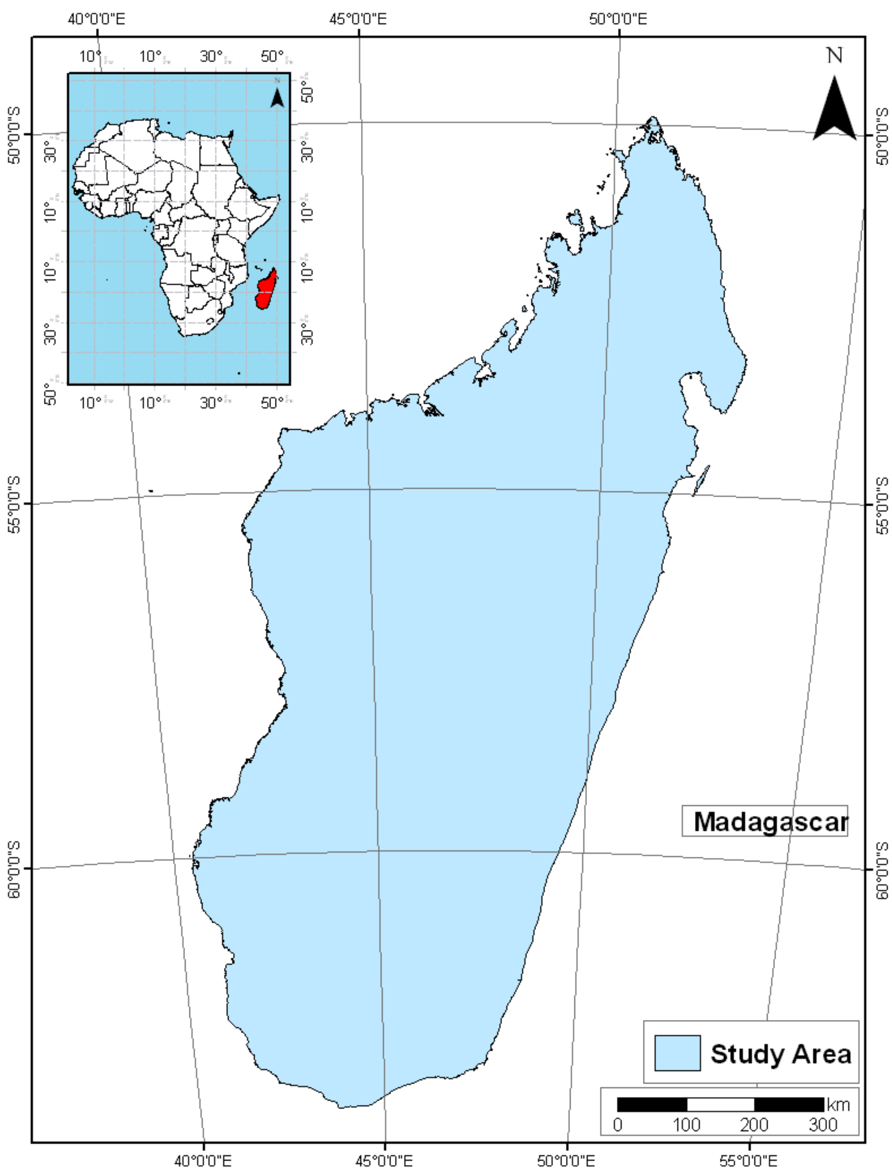
Our study area covers the whole country of Madagascar (Figure 1). Madagascar, the largest island in the Indian Ocean, is one of the biodiversity "hot spot" areas of the world. The island is home to 5% of the world's plant and animal diversity, more than 80% of which are endemic (Table 1). Mangrove forests occupy 25% of the 4,000-km coastline of Madagascar. The majority of the mangrove areas can be found in Mahajamba Bay, Bombetoka, South Mahavavy and Salala, and Maintrirano [1]. The Mahajamba Bay mangrove forests represent more than 10% of the mangrove forests in Madagascar.

Table 1. Species richness and endemism in Madagascar (adapted from [25]).

Taxon	No. of Species	% Endemic
Plants	12,000	85
Birds	209 (breeding)	51
Mammals	117	90
Reptiles	346	90
Amphibians	199	90

Madagascar's mangrove forests occupy diverse environmental and climatic conditions: mostly wet season in the northwest and mostly dry season in the southwest. Forests in the northwest are more diverse and taller compared to the southwest possibly due to lower rainfall and the absence of abundant freshwater.

Figure 1. Location of study area.



3. Data and Methodology

3.1 Data

We used GeoCover satellite data for 1975, 1990, and 2000 and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data for 2005. These data were acquired from the U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center (http://glovis.usgs.gov). GeoCover is a collection of Landsat data that provides near-global coverage with generally cloud-free images collected for three eras: 1) the 1975 edition, with imagery collected from 1973 to 1983, 2) the 1990s edition, with imagery collected from 1989 to 1993, and 3) the 2000s edition, with imagery collected between 1997 and 2000 (referred to hereafter as the 1975, 1990, and 2000 data, respectively). Additional Multispectral Scanner (MSS), Thematic Mapper (TM), and Enhanced Thematic Mapper Plus (ETM+) data were acquired to cover cloud-covered areas. We also acquired ASTER Visible and Near Infra-Red (VNIR) satellite data for 2005 (collected from 2005 to 2006) from EROS. About 13 MSS, 14 TM, 16 ETM+, and 39 ASTER VNIR scenes were used. Ideally, same-year data is recommended, but the unavailability of cloud-free data of the region necessitated the use of multiyear and multiseason data.

GeoCover data, available in GeoTiff format with a Universal Transverse Mercator (UTM) projection and World Geodetic System – 84 (WGS-84) datum, is orthorectified to less than 50-m Root Mean Square (RMS) error. The ASTER L1B data used in the study was geometrically and radiometrically corrected data. To avoid problems associated with multiple zones, we reprojected all the images into Lambert Azimuthal Equal Area projection.

In addition, very high-resolution satellite data such as IKONOS and QuickBird were also acquired for selected areas to validate classification results. Secondary data such as mangrove forest maps, forest classification maps, and land use/land cover maps obtained from various sources were also collected and used for training data collection and visual comparison.

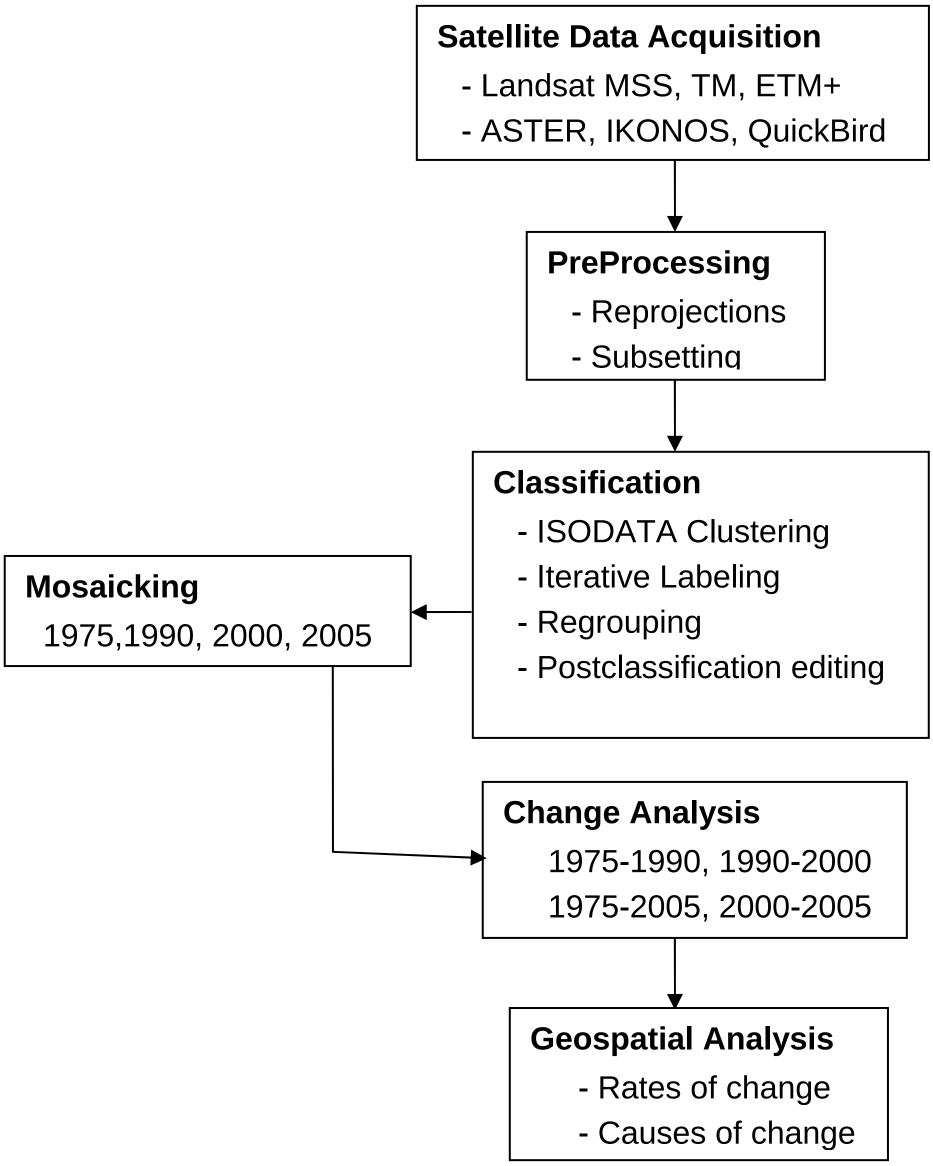
3.2 Methods

A schematic diagram of the methodology used for the study is presented in Figure 2. Prior to classification, images were checked and corrected for georeferencing errors inherent in the multidate images. Errors might have arisen because not all images were georectified with the same level of accuracy. Significant discrepancies were observed particularly in the case of MSS. To address this problem, we reprojected the problem images using image-to-image registration with RMS error of ± one-half pixel (15 m for TM). Images were resampled with cubic convolution, which has better spatial accuracy over the more commonly used nearest neighbor resampling [18-19].

ISODATA unsupervised classification was performed for each image. Initially, a total of 26 clusters were generated, which were then grouped into mangrove and non-mangrove classes.

The classified images were then manually edited to remove obvious errors using secondary data and very high resolution satellite imageries such as IKONOS and QuickBird. Each classified image was resampled to 50 m to be consistent with MSS data. However, this resampling did not improve the spatial details of MSS data. Finally, four classification images were produced, one each for 1975, 1990, 2000, and 2005. Once the editing was satisfactory, a mosaic for the whole country was prepared. In mosaicking, overlap function was set to a minimum to retain the mangrove pixels from both the images.

Figure 2. Analysis process flow diagram.



Following classification of images from each time period, a postclassification change analysis was performed for the change analysis. Change areas were reclassified to identify major causes. This approach is probably the most common and intuitive change detection method. Among the principal advantages of this approach is that it provides "from-to" change information. However, the approach may have three sources of uncertainty: (1) semantic differences in class definitions between maps, (2) positional errors, and (3) classification errors. To minimize the semantic differences in class definitions, we used the same number of classes for all four dates. To minimize positional errors, additional GCPs were selected and RMS was reduced to ± one-half pixel. Finally, postclassification editing using secondary data minimized classification errors. However, there might still be few minor errors associated with positional errors and classification errors.

Change maps were generated subtracting the classification maps, 1975s–1990s, 1975s–2000s, 1975s–2005s, 1990s–2000s, 1990s–2005s, and 2000s–2005s. The change areas were interpreted visually to identify the factors responsible for the change. Once the mangrove/nonmangrove areas were calculated for each period, the rate of change r was calculated by using the following equation [20]:

$$\text{Rate of change (r)} = \left(\frac{1}{t2 - t1}\right)\ln\left(\frac{Ai2}{Ai1}\right)$$

where,

R = rate of deforestation (area/year)

A_1= area at an initial time t_1

A_2= area at a later time t_2

Qualitative validation was performed with the help of local experts and high-resolution satellite data such as QuickBird and IKONOS. We divided the entire area into 500 x 500 grids and checked each grid visually to identify and correct "gross" errors inherent in the classified maps.

Accuracy assessment of the mangrove classification map of 2005 was performed using 176 randomly selected points consisting of 88 sample points for mangrove classes and 88 sample points for nonmangrove classes. Google Earth™ mapping service images were used to determine the classification accuracy. A 3 x 3 pixel window was used to avoid errors due to misregistration. Accuracy assessments of mangrove classification maps of 1975, 1990, and 2000 were not performed due to the unavailability of reference data for the entire country covering these time periods.

4. Results and Discussion

4.1 Mangrove Forest Assessment

We prepared a wall-to-wall map of the mangrove forests of Madagascar for 2005 (Figure 3). With this new map, we assessed the present status and delineated the spatial distribution of the mangrove forests at a national scale. We estimated that the aerial extent of the mangrove forests of Madagascar in 2005 was 2,797 km^2. Overall classification accuracy of the 2005 map is 94.89% with a Kappa Coefficient of 0.90. Major mangrove forest areas are located at Mahajamba Bay, Bombekota Bay, Cap St Vincent, and Mahavavy. Small patches of mangrove forests can be found in other areas along the west coast and in the northeast. The mangrove areas in western Madagascar are still vast and luxuriant. Mangroves in the northwest are taller and matured compared to the rest of the country [11].

Earlier estimations of total mangrove forest area of Madagascar varied widely (Figure 4), ranging from 2,170 km^2 to 4,530 km^2. The majority of these studies, obtained from literature and field survey, provide total mangrove forest area of the country but do not provide information on their spatial distribution. Among those studies which mapped the mangrove areas, discrepancies might have arisen due to various mapping techniques, and type and resolutions of source data used for the estimation. For example, our estimates classified water bodies and barren areas inside the mangrove forests as a separate class, but some studies combined those classes with the mangrove class.

Figure 3. Mangrove forest distribution of Madagascar for 2005.

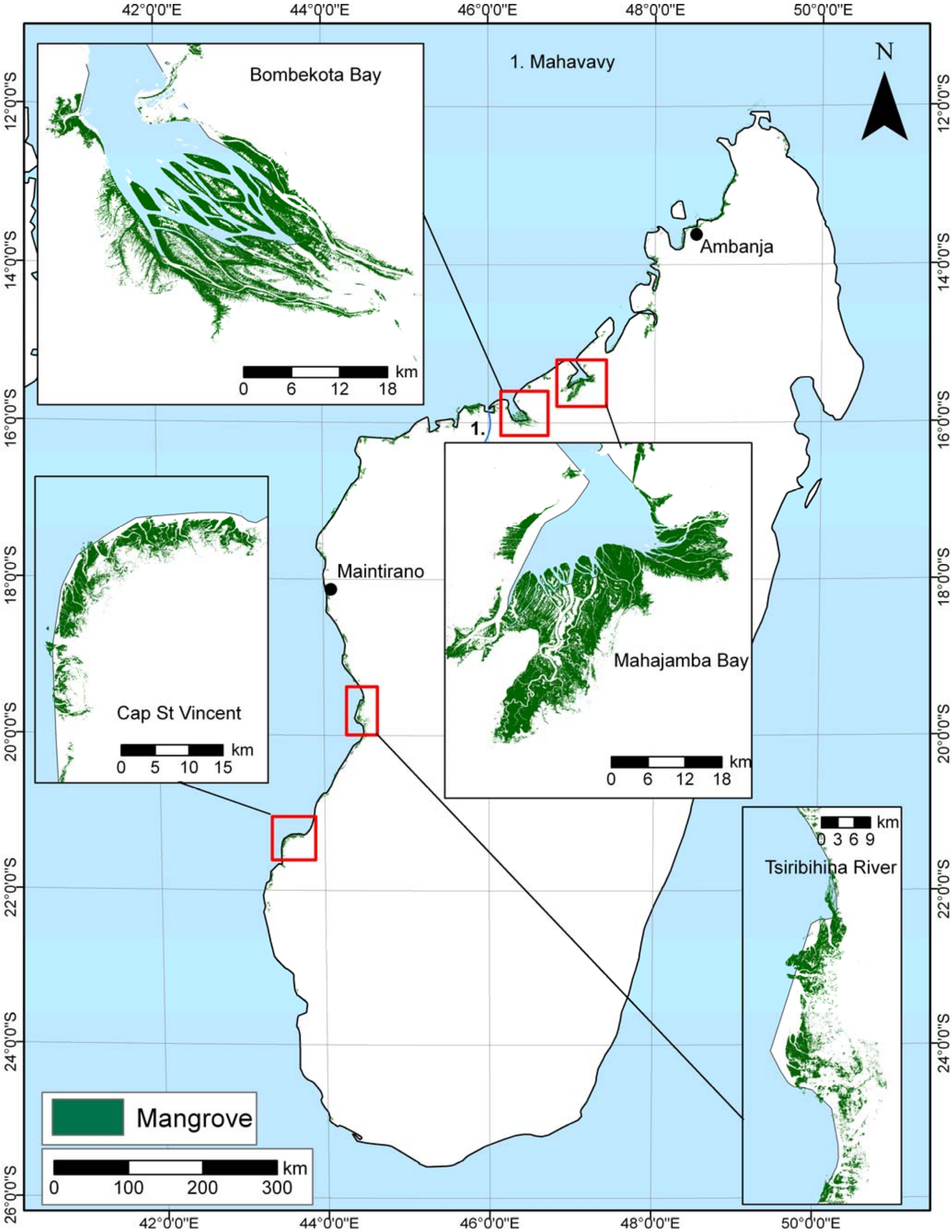
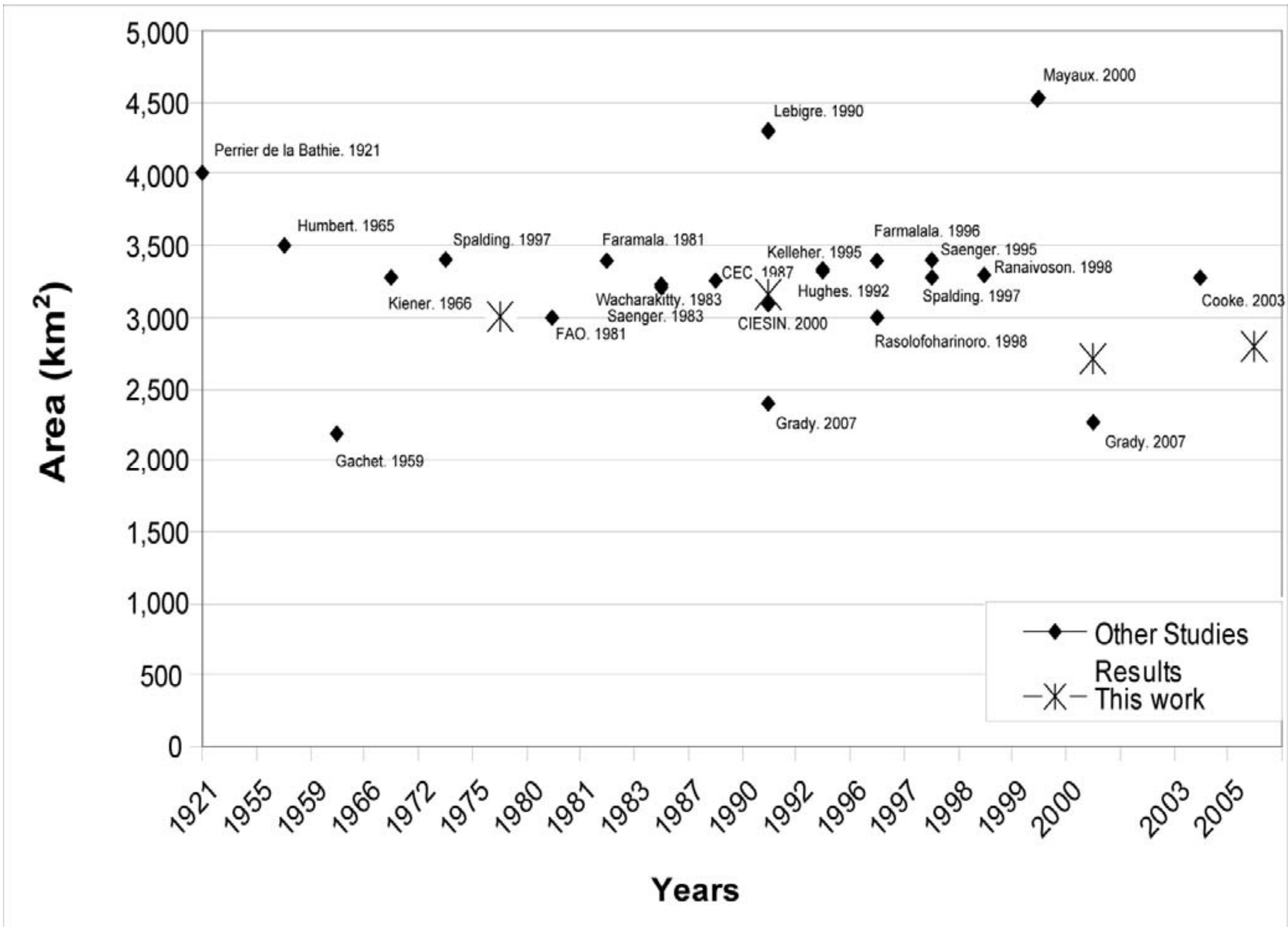


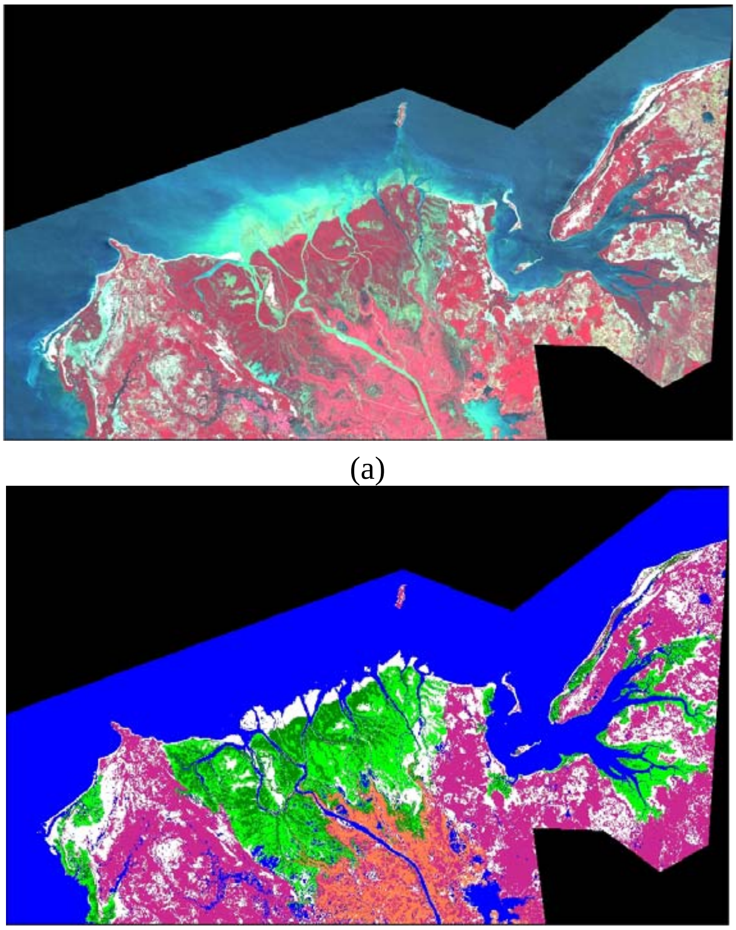
Figure 4. Mangrove forest areas obtained from various studies. Please note that the x-axis is not on a scale; the year followed by author is the publication date, and the date in the x-axis is the actual date of estimation.



Coarse scale mapping based on SPOT VEGETATION 1-km satellite data [15] seems to overestimate the mangrove areas. Landsat-based mangrove estimates for 2000 are much lower than estimates based on SPOT VEGETAION 1-km satellite data. Lebigre (1990) [21] also overestimated the total mangrove areas of Madagascar. In contrast, the estimate by Gachet (1959) [22] seems to underestimate Madagascar mangroves. A recent forest assessment of Madagascar using Landsat data estimated slightly lower mangrove areas compared to our estimates [23]. Our study is the only study focused solely on mangrove forest assessment and monitoring using historical and current Landsat data.

We were able to map mangrove forests larger than 0.01 km^2 because of the resolution of the Landsat data and the minimum mapping unit used for the analysis. This is a significant improvement compared to coarse spatial resolution (i.e., 1-km) mapping. However, we were not able to map very small patches and narrow strips of mangrove forests. We assumed those very small areas have no significance on the total mangrove area of the country. ASTER 15-m data provide better spatial detail compared to Landsat 30-m data. An example of ASTER satellite data and its classification is presented below.

Figure 5. ASTER satellite data (a) and classified map (b) of Cap Tanjona for 2005. Dark red color in (a) is mangrove that is classified into dense mangrove (dark green) and open mangrove (green) in (b).



(a)

(b)

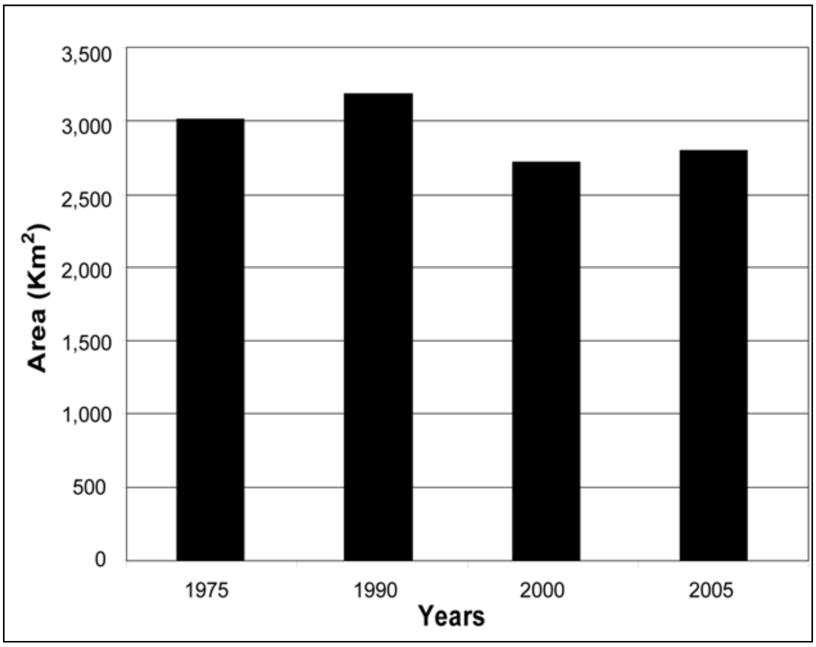
4.2 Mangrove forest cover change

Time-series analysis of satellite data from 1975 to 2005 revealed a net loss of 7% of mangrove forests in Madagascar (Figure 6). This rate is lower compared to mangrove forest loss in many other parts of the world. For example, the tsunami-impacted region of South and Southeast Asia lost about 25% of mangrove forests from 1975 to 2005 [24]. At the global scale, the estimated rate of deforestation varies from 25% to 50%. Loss of mangrove forests due to aquaculture development, quite significant in other parts of the world, is a more recent phenomenon and so far less significant in Madagascar. This is generally true for east Africa and explains the relatively low deforestation rate in Madagascar.

The loss of mangrove forests in Madagascar was found to be lower than overall forest cover loss of the country. According to Harper [25], forest cover of Madagascar decreased by almost 40% from the 1950s to circa 2000. Assuming that Madagascar's mangroves remained generally undistributed prior to 1975 [26], the loss of mangrove forests in Madagascar is substantially lower than overall forest cover loss of the country. Several factors including shifting cultivation, grazing, fuel wood gathering, logging, economic development, cattle ranching, and mining are responsible for the overall deforestation [27].

The rate of deforestation was not uniform through time. For example, the forests increased by 5.6% (170 km^2) from 1975 to 1990, decreased by 14.3 (455 km^2) from 1990 to 2000, and decreased by 2.6% (73 km^2) from 2000 to 2005. Prior to 1975, mangrove forests of Madagascar had little or no degradation [26].

Figure 6. Mangrove forest cover of Madagascar in 1975, 1990, 2000, and 2005.

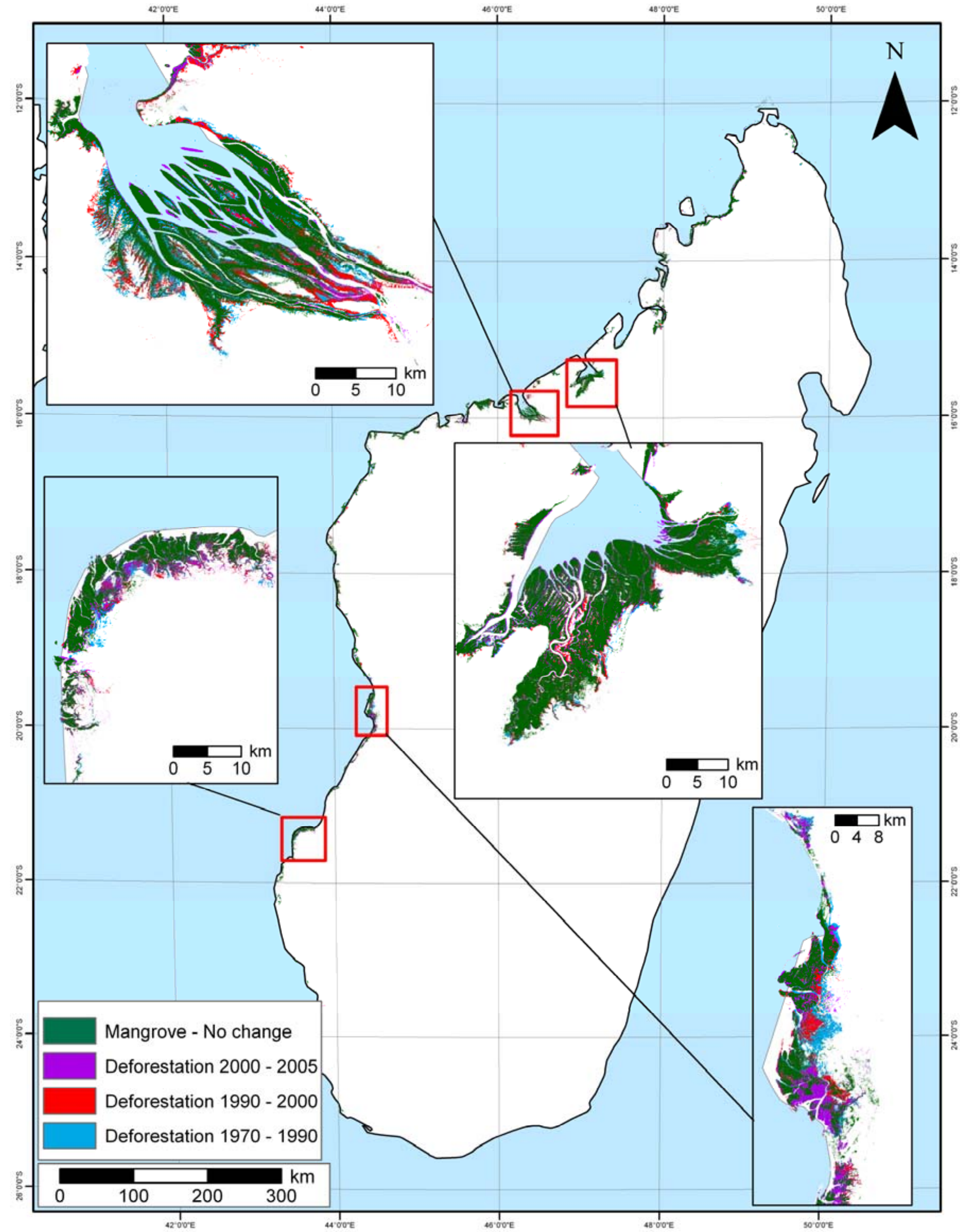


As expected, the rate of deforestation was not uniform across the country (Figure 7). Major changes occurred at Bombekota Bay, Mahajamba Bay, the coast of Ambanja, the Tsiribihina River, and Cap St Vincent that also differed through time periods (table 2). Both positive and negative changes were observed that varied at different time scales. For example, in Bombekota Bay, mangrove forests declined by 20% (66 km^2) from 1975 to 1990, and 34% (87 km^2) from 1990 to 2000. However, the bay gained 49% (85 km^2) of forest area during 2000 to 2005. In all, the bay lost 21% of mangrove forests from 1975 to 2000.

Table 2. Mangrove forest cover change in selected areas during the study period.

Region	Mangrove forest area change in km^2 (% change in parentheses)			
	1975-1990	**1990-2000**	**2000-2005**	**1975-2005**
Bombekota Bay	-66 (20)	-87(34)	+85(49)	-68 (21)
Mahajamba Bay	+1 (0)	-63 (15)	+76 (21)	14 (3)
Coast of Ambanja	+75 (23)	-12(3)	-45 (12)	18 (5)
Cap St Vincent	-8 (6)	-11 (8)	-16 (13)	-35 (25)
Tsiribihina River	-32 (14)	-19 (10)	-32 (20)	-83 (39)

Figure 7. Mangrove forest cover change map from 1975 to 2005.



Even though we tried to minimize classification errors and georeferencing errors, it is expected that change statistics might have been influenced by these factors.

4.3 Causes of the Change

Major causes of mangrove deforestation in Madagascar are conversion to agriculture, conversion to aquaculture, conversion to urban development, logging, and other factors. Other factors include erosion, siltation, and sedimentation. Conversion to agriculture (35%) was the major factor responsible for mangrove deforestation followed by logging (16%), conversion to aquaculture (3%), and urban development (1%). Many thousands of hectares of swamp forest have been cleared for rice cultivation, particularly on the upstream ends of estuarine swamp forests. Some of the mangrove forests have been converted to salt pans.

Conversion of mangrove forest to shrimp farming has become a recent phenomenon, especially in northwest Madagascar. For example, about 600 hectares of shrimp farming areas are established in the Baly Bay region since 1998. Some of the mangrove areas in Mahajamba Bay were also converted for aquaculture development. As a result, shrimp exports have increased significantly in recent years. Similarly, coastal sedimentation, carried by the sediment-laden rivers due to heavy deforestation and over-farming upstream, is a serious problem on the western coast of Madagascar. Sediments suffocate and kill mangroves [28].

5. Conclusions

Quantitative information on the distribution and dynamics of mangrove forests of Madagascar generated from this study will be useful in several ways. First, we have improved the understanding of the spatial distribution of mangrove forests of Madagascar and assessed the rates and causes of deforestation. The geospatiotemporal database generated from this study provides an up-to-date, consistent, and unbiased account of the extent, distribution, and dynamics of mangrove forests of the country with better spatial and temporal details compared to information previously available. Second, unbiased accounts of the status and trends of mangrove forest areas can support countrywide decision making on the distribution of resources for the conservation and rehabilitation of mangrove forests. Third, our country analysis provided essential information on the extent and condition of mangrove forests that can be used to assess the role of mangrove forests in saving lives and property from natural disasters. This issue has become increasingly important in the aftermath of the Asian Tsunami of December 2004 and Hurricane Katrina in the United States in 2005.

Monitoring deforestation at a country level using moderate resolution satellite images over a long period of time requires the processing of large volumes of data. We used simple but efficient methods to analyze these data. Our approach applied semiautomated image analysis techniques to assess present status and to monitor the rates and causes of change over a large area covering the entire country. Our analyses show the potential for producing consistent and timely mangrove forest databases of Madagascar using the historical archive of Landsat data. The full potential of remote sensing technology for identifying mangrove forests, measuring the biophysical properties, and detecting forest cover changes can only be realized through a robust and operational mangrove forest assessment and monitoring program. Future research is needed to map very small mangrove areas that were not able to discern with the Landsat resolution.

Acknowledgements

Work was performed under USGS contract 03CRCN0001.

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