Combining global tree cover loss data with historical national forest-cover maps to look at six decades of deforestation and forest fragmentation in Madagascar

Ghislain Vieilledent[1,2,⋆] Clovis Grinand[3]

Fety A. Rakotomalala[3] Rija Ranaivosoa[4] Jean-Roger Rakotoarijaona[4]

Thomas F. Allnutt[5,6] and Frédéric Achard[1]

[1] **Joint Research Center of the European Commission** – Bio-economy Unit, I-21027 Ispra (VA), ITALY
[2] **Cirad** – UPR Forêts et Sociétés, F-34398 Montpellier, FRANCE
[3] **ETC Terra**, F-75020 Paris, FRANCE
[4] **Office National pour l'Environnement**, 101 Antananarivo, MADAGASCAR
[5] **Wildlife Conservation Society**, 101 Antananarivo, MADAGASCAR
[6] **GreenInfo Network**, Oakland, California, USA

[⋆] **Corresponding author:** \E-mail: ghislain.vieilledent@cirad.fr \Phone: +39.033.278.3516

Running headline: *Six decades of deforestation in Madagascar*

Abstract

1. The island of Madagascar has an unparalleled biodiversity, mainly located in the tropical forests of the island, which is highly threatened by anthropogenic deforestation. Scattered forest maps from past studies at national level with substantial gaps (due to presence of cloud cover on satellite imagery) prevent the analyzis of long-term deforestation trends in Madagascar.

2. In this study, we propose a new approach combining historical (1953-2000) national forest-cover maps with recent (2001-2014) global annual tree cover loss data to look at six decades (1953-2014) of deforestation and forest fragmentation in Madagascar. We produced new forest-cover maps at 30 m resolution over the full territory of Madagascar for the year 1990, and annually from 2000 to 2014.

3. We estimated that Madagascar has lost 44% of its natural forest cover over the period 1953-2014 (including 37% over the period 1973-2014). Natural forests cover 8.9 Mha in 2014 (15% of the national territory) which are divided into 4.4 Mha (50%) of moist forests, 2.6 Mha (29%) of dry forests, 1.7 Mha of spiny forests (19%) and 177,000 ha (2%) of mangroves. Since 2005, the annual deforestation rate has progressively increased in Madagascar to reach 99,000 ha/yr during 2010-2014 (corresponding to a rate of 1.08%/yr). This increase is probably due to rapid population growth (close to 3%/yr) and to poor law enforcement in the country. Around half of the forest (46%) is now located at less than 100m from the forest edge.

4. *Policy implications*: Accurate forest-cover change maps can be used to assess the effectiveness of past and current conservation programs and implement new strategies for the future. In particular, forest maps and estimates can be used in the framework of the REDD+ ("Reducing Emissions from Deforestation and Forest Degradation") initiative and for optimizing the current protected area network.

Keywords: biodiversity, climate-change, deforestation, Madagascar, tropical forest

1 Introduction

Separated from the African continent and the Indian plate about 165 and 88 million years ago respectively (Ali & Aitchison, 2008), the flora and fauna of Madagascar followed its own evolutionary path. Isolation combined with a high number of micro-habitats (Pearson & Raxworthy, 2009) has led to Madagascar's exceptional biodiversity both in term of number of species and endemism in many taxonomic groups (Crottini *et al.*, 2012; Goodman & Benstead, 2005). Most of the biodiversity in Madagascar is concentrated in the tropical forests of the island which can be divided into four types: the moist forest in the East, the dry forest in the West, the spiny forest in the South and the mangroves on the West coast (Vieilledent *et al.*, 2016). This unparalleled biodiversity is severely threatened by deforestation (Harper *et al.*, 2007; Vieilledent *et al.*, 2013) associated with human activities such as slash-and-burn agriculture and pasture (Scales, 2011). Tropical forests in Madagascar also store a large amount of carbon (Vieilledent *et al.*, 2016) and high rates of deforestation in Madagascar are responsible for large CO_2 emissions in the atmosphere (Achard *et al.*, 2014). Deforestation threatens species survival by directly reducing their available habitat (Brooks *et al.*, 2002; Tidd *et al.*, 2001). Forest fragmentation can also lead to species extinction by isolating populations from each other and creating forest patches too small to maintain viable populations (Saunders *et al.*, 1991). Fragmentation also increases forest edge where ecological conditions (such as air temperature, light intensity and air moisture) can be dramatically modified, with consequences on the abundance and distribution of species (Murcia, 1995). Forest fragmentation can also have substantial effects on forest carbon storage capacity, as carbon stocks are much lower at the forest edge than under a closed canopy (Brinck *et al.*, 2017). Moreover, forest carbon stocks vary spatially due to climate or soil factors (Saatchi *et al.*, 2011; Vieilledent *et al.*, 2016). As a consequence, accurate and spatially explicit maps of forest-cover and forest-cover change are necessary to monitor biodiversity loss and carbon emissions from deforestation and forest fragmentation, assess the efficiency of present conservation strategies (Eklund *et al.*, 2016), and implement new strategies for the future (Vieilledent *et al.*, 2016, 2013). Simple time-series of forest-cover estimates, such as those provided by the FAO Forest Resource Assessment report (Keenan *et al.*, 2015) are not sufficient.

Unfortunately, accurate and exhaustive forest-cover maps are not available for Madagascar for the last fifteen years (2000-2015). Harper *et al.* (2007) produced maps of forest cover and forest cover changes over Madagascar for the years *c.* 1953, *c.* 1973, 1990 and 2000. The *c.* 1953 forest map was derived from the visual interpretation of aerial photography at coarse scale (1/1,000,000). Forest maps for the years *c.* 1973, 1990, and 2000 were obtained from supervised classification of Landsat satellite images at 60 m resolution (for the year 1973) or 30 m resolution (for years 1990 and 2000) and can be used to derive more accurate estimates of forest cover (89.5% accuracy reported for the forest/non-forest map of year 2000). Nonetheless, maps provided by Harper *et al.* (2007) are not exhaustive (due to the presence of clouds in the satellite imagery), e.g. 11 244 km2 are mapped as unknown cover type for the year 2000. Using a similar supervised classification approach as in Harper *et al.* (2007), more recent maps have been produced for the periods 2000-2005-2010 by national institutions, with the technical support of international environmental NGOs (MEFT, USAID, and CI, 2009; ONE, DGF, FTM, MNP, and CI, 2013). Another set of recent forest-cover maps using an advanced statistical tool for classification, the Random Forest classifier (Grinand *et al.*, 2013; Rakotomala *et al.*, 2015), was produced for the periods 2005-2010-2013 (ONE, DGF, MNP, WCS, and Etc Terra, 2015). However, these maps are either too old to give recent estimates of deforestation (MEFT, USAID, and CI, 2009; ONE, DGF, FTM, MNP, and CI, 2013), include large areas of missing information due to images with high percentage of cloud cover (ONE, DGF, FTM, MNP, and CI, 2013), or show large mis-classification in specific areas, especially in the dry and spiny forest domain for which the spectral answer has a strong seasonal behavior due to the deciduousness of such forests (overall accuracy is lower than 0.8 for the dry and spiny forests for the maps produced by ONE, DGF, MNP, WCS, and Etc Terra (2015)). Moreover, the production of such forest maps from a supervised classification approach requires significant resources, especially regarding the image selection step (required to minimize cloud cover) and the training step (visual interpretation of a large number of polygons needed to train the classification algorithm) (Rakotomala *et al.*, 2015). Most of this work of image selection and visual interpretation would need to be repeated to produce new forest maps in the future using a similar approach.

Global forest or tree cover products have also been published recently and can be tested at the national scale for Madagascar. Kim *et al.* (2014) produced a global forest-cover change map from 1990 to 2000 (derived from Landsat imagery). This product was updated to cover the period 1975-2005 (`http://glcf.umd.edu/data/landsatFCC/`) but forest-cover maps after 2005 were not produced. Moreover, the approach used in Kim *et al.* (2014) did not accurately map the forests in the dry and spiny ecosystems of Madagascar (see Fig. 8 in Kim *et al.* (2014)). Hansen *et al.* (2013) mapped tree cover percentage, annual forest loss and forest gain from 2000 to 2012 at global scale at 30 m resolution. This product has since been updated and is now available up to the year 2014 (Hansen *et al.*, 2013). To map forest cover from the Hansen *et al.* (2013) product, a tree cover threshold must be selected (that defines forest cover). Selecting such a threshold is not straightforward as the accuracy of the global tree cover map strongly varies between forest types, and is substantially lower for dry forests than for moist forests (Bastin *et al.*, 2017). Moreover, the Hansen *et al.* (2013) product does not provide information on land-use. In particular the global tree cover map does not separate tree plantations such as oil palm or eucalyptus plantations from natural forests (Tropek *et al.*, 2014). Thus, the global tree cover map from Hansen *et al.* (2013) cannot be used alone to produce a map of forest cover

(Tyukavina *et al.*, 2017). In complement to the tree cover percentage provided in Hansen *et al.* (2013), a layer of annual tree cover loss is also provided (i.e. complete loss of tree cover from a value higher than 10% to zero) for the period 2001-2014.

In this study, we present a simple approach which combines the maps from Harper *et al.* (2007) and products from Hansen *et al.* (2013) to derive annual wall-to-wall forest-cover change maps over the period 2000-2014 for Madagascar. We use the forest-cover map provided by Harper *et al.* (2007) for the year 2000 (defining the land-use) with the tree cover loss product provided by Hansen *et al.* (2013) that we apply only inside forest areas identified by Harper *et al.* (2007). Similar to the approach of Harper *et al.* (2007), we also assess trends in deforestation rates and forest fragmentation from *c.* 1953 to 2014. The approach described in this study can help assess the effectiveness of current conservation strategies, and assist the implementation of future strategies. Our approach could be easily extended to other tropical countries that have at least one forest-cover map between 2000 and 2014. This approach can easily be repeated in the future when the Hansen *et al.* (2013) products are updated.

2 Materials and Methods

2.1 Creation of new forest-cover maps of Madagascar from 1953 to 2014

We produced annual forest/non-forest maps at 30 m resolution for the full territory of Madagascar for the period 2000-2014 by combining the forest map of year 2000 from Harper *et al.* (2007), and the tree cover percentage and annual forest cover loss maps over the period 2000-2014 from Hansen *et al.* (2013). The 2000 Harper's forest map includes 208,000 ha of unclassified areas due to the presence of clouds on satellite images, mostly (88%) within the moist forest domain which covered 4.17 Mha in total in 2000. To provide a label (forest or non-forest) to these unclassified pixels, we used the 2000 tree cover percentage map of Hansen *et al.* (2013) by selecting a threshold of 75% tree cover to define forest cover as recommended by other studies for the moist domain (Achard *et al.*, 2014). We thus obtained a forest-cover map for the year 2000 covering the full territory of Madagascar. We then combined this forest-cover map of the year 2000 with the annual tree cover loss maps from 2001 to 2014 provided by Hansen *et al.* (2013) to create annual forest-cover maps from 2001 to 2014 at 30 m resolution. We also completed the Harper's forest map of year 1990 by filling unclassified areas (due to the presence of clouds on satellite images) using our forest-cover map of year 2000. To do so, we assumed that if forest was present in 2000, the pixel was also forested in 1990. The remaining unclassified pixels were limited to a relatively small total area of *c.* 8,000 ha. We labeled these residual pixels as non-forest as for the year 2000. Similarly we completed the Harper's forest map of year 1973 by filling unclassified areas using our forest-cover map of the year 1990 assuming that if forest was present in 1990, it was also present in 1973. Contrary to the year 1990, the remaining unclassified pixels for year 1973 corresponded to a significant total area of 3.32 million ha. We also reprojected the forest-cover map of year 1953 to a common projection in order to compare the forest-cover area in 1953 with forest-cover areas at the following dates. This map was produced by scanning a paper map derived from aerial photos, and thus could not be perfectly aligned with the other maps produced through digital processing of satellite imagery (Harper *et al.*, 2007). Finally for all forest-cover maps from 1973, the isolated single non-forest pixels (i.e. fully surrounded by forest pixels) were removed, assuming that single non-forest pixels inside a forest patch were not corresponding to deforestation (they might correspond to selective logging activities). This allowed us to avoid counting very small scale events (<0.1 ha such as selective logging) as forest fragmentation. All the resulting maps are freely available at `https://bioscenemada.cirad.fr/forestmaps`.

2.2 Computing forest-cover areas and deforestation rates

From these new forest-cover maps, we calculated the total forest-cover area for seven available years (1953-1973-1990-2000-2010-2005-2014), and the annual deforested area and annual deforestation rate for the corresponding six time periods between 1953 and 2014. The annual deforestation rates were calculated as follows (Puyravaud, 2003; Vieilledent *et al.*, 2013):

$$\theta = 100 \times [1 - (1 - (F_{t_2} - F_{t_1})/F_{t_1})^{(1/(t_2-t_1))}$$

where θ is the annual deforestation rate (in %/yr), F_{t_2} and F_{t_1} are the forest cover free of clouds at both dates t_2 and t_1, and $t_2 - t_1$ is the time-interval (in years) between the two dates.

Because of the large unclassified area (3.32 million ha) in 1973, the annual deforestation areas and rates for the two periods 1953-1973 and 1973-1990 are only indicative estimates. For these two periods the annual deforestation rates are computed as the ratio $(F_{t_2} - F_{t_1})/F_{t_1}$ considering only the mapped forest pixels. Area and rate estimates are produced at the national scale and for the four forest ecosystems present in Madagascar: moist forest in the East, dry forest in the West, spiny forest in the South, and mangroves on the Western coast (Fig. 1). To define the forest domains, we used a map from the MEFT (*"Ministère de l'Environnement et des Forêts à Madagascar"*) with the boundaries of the four ecoregions in Madagascar. Ecoregions were defined on the basis of climatic and vegetation criteria using the climate classification by Cornet (1974) and the vegetation classification from the 1996 IEFN national forest inventory (Ministère de l'Environnement, 1996). Because mangrove forests are highly dynamic ecosystems that can expand or contract on decadal scales depending on changes in environmental factors (Armitage *et al.*, 2015), a fixed delimitation of the mangrove ecoregion on six decades might not be fully appropriate. As a consequence, our estimates of the forest-cover and deforestation rates for mangroves in Madagascar must be considered with this limitation.

2.3 Comparing our forest-cover and deforestation rate estimates with previous studies

We compared our estimates of forest-cover and deforestation rates with estimates from the three existing studies at the national scale for Madagascar: (i) (Harper *et al.*, 2007), (ii) (MEFT, USAID, and CI, 2009) and (iii) (ONE, DGF, MNP, WCS, and Etc Terra, 2015). Harper *et al.* (2007) provides forest-cover and deforestation estimates for the periods c. 1953-c. 1973-1990-2000. MEFT, USAID, and CI (2009) provides estimates for the periods 1990-2000-2005 and ONE, DGF, MNP, WCS, and Etc Terra (2015) provides estimates for the periods 2005-2010-2013. To compare our forest-cover and deforestation estimates over the same time periods, we consider an additional time-period in our study (2010-2013) by creating an extra forest-cover map for the year 2013. We computed the Pearson's correlation coefficient and the root mean square error (RMSE) between our forest-cover estimates and forest-cover estimates from previous studies for all the dates and forest types (including also the total forest cover estimates). For previous studies, the computation of annual deforestation rates (in %/yr) is not always detailed and might slightly differ from one study to another (see Puyravaud, 2003). Harper *et al.* (2007) also provide total deforested areas for the two periods 1973-1990 and 1990-2000. We converted these values into annual deforested area estimates. When annual deforested areas were not reported (for 1953-1973 in Harper *et al.* (2007) and in MEFT, USAID, and CI (2009) and ONE, DGF, MNP, WCS, and Etc Terra (2015)), we computed them from the forest-cover estimates in each study. These estimates cannot be corrected from the potential bias due to the presence of residual clouds. Forest-cover and deforestation rates were then compared between all studies for the whole of Madagascar and the four ecoregions. The same ecoregion boundaries as in our study were used in ONE, DGF, MNP, WCS, and Etc Terra (2015) but this was not the case for Harper *et al.* (2007) and MEFT, USAID, and CI (2009), which can explain part of the differences between the estimates.

2.4 Fragmentation

We also conducted an analysis of changes in forest fragmentation for the years 1953, 1973, 1990, 2000, 2005, 2010 and 2014. We applied the method developed by Riitters *et al.* (2000) which uses a moving window to characterize the fragmentation around each forested pixel. Computations were done using the function `r.forestfrag` of the GRASS GIS software (Neteler & Mitasova, 2008). Six categories of fragmentation were identified from the amount of forest and its occurrence as adjacent forest pixels: "interior", "perforated", "edge", "transitional", "patch", and "undetermined". We used a moving window of 7x7 pixels (4.4 ha). Using this window size, forest edge had a width of about 90m (Riitters *et al.*, 2000). The "interior" category can be interpreted as the most intact forest (Potapov *et al.*, 2017). The "patch" and "transitional" categories correspond to isolated small forest patches. We reported the area of forest in each fragmentation category for the six years and analyzed the dynamics of fragmentation over the six decades. We also computed the distance to forest edge for all forest pixels for the years 1953, 1973, 1990, 2000, 2005, 2010 and 2014. For that, we used the function `gdal_proximity.py` of the GDAL software (http://www.gdal.org/). We computed the mean and 90% quantiles (5% and 95%) of the distance to forest edge and looked at the evolution of these values with time.

3 Results

3.1 Dynamics of forest cover and deforestation intensity

Natural forests in Madagascar covered 16.0 Mha in 1953, about 27% of the national territory of 587,041 km2. In 2014, the forest cover dropped to 8.9 Mha, corresponding to about 15% of the national territory (Fig. 2 and Tab. 1). Madagascar has lost 44% and 37% of its natural forests between 1953 and 2014, and between 1973 and 2014 respectively (Fig. 2 and Tab. 1). In 2014 the remaining 8.9 Mha of natural forest were distributed as: 4.4 Mha of moist forest (50% of total forest cover), 2.6 Mha of dry forest (29%), 1.7 Mha of spiny forest (19%) and 0.18 Mha (2%) of mangrove forest (Fig. 1 and Tab. 2). Regarding the deforestation trend, we observed a progressive decrease of the deforestation rate after 1990 from 205,000 ha/yr (1.63%/yr) over the period 1973-1990 to 44,300 ha/yr (0.43%/yr) over the period 2000-2005 (Tab. 1). Then from 2005, the deforestation rate has progressively increased and has more than doubled over the period 2010-2014 (98,700 ha/yr, 1.08%/yr) compared to 2000-2005 (Tab. 1). The deforestation trend characterized by a progressive decrease of the deforestation rate over the period 1990-2005 and a progressive increase of the deforestation after 2005 is valid for all four ecoregions (Tab. 3), with the exception of the spiny forest domain for which the deforestation rate during the period 2010-2013 was lower than during 2005-2010 (Tab. 3).

3.2 Comparison with previous forest-cover change studies in Madagascar

Forest-cover maps provided by previous studies over Madagascar were not exhaustive (unclassified areas) due to the presence of clouds on satellite images used to produce such maps. In Harper *et al.* (2007), the maps of years 1990 and 2000 include 0.5 and 1.12 Mha of unknown cover type respectively. Proportions of unclassified areas are not reported in the two other existing studies by MEFT, USAID, and CI (2009) and ONE, DGF, MNP, WCS, and Etc Terra (2015). With our approach, we produced wall to wall forest-cover change maps from 1990 to 2014 for the full territory of Madagascar (Tab. 1). This allowed us to produce more robust estimates of forest-cover and deforestation rates over this period. Our forest-cover estimates over the period 1953-2013 (considering forest cover estimates at national level and by ecoregions for all the available dates) were well correlated (Pearson's correlation coefficient = 0.99) to estimates from the three previous studies (Tab. 2) with a RMSE of 300,000 ha (6% of the mean forest cover of 4.8 Mha when considering all dates and forest types together). These small differences can be partly attributed to differences in ecoregion boundaries. Despite significant differences in deforestation estimates (Tab. 3), a similar deforestation trend was observed across studies with a decrease of deforestation rates over the period 1990-2005, followed by a progressive increase of the deforestation after 2005.

3.3 Evolution of forest fragmentation with time

In parallel to the dynamics of deforestation, forest fragmentation has progressively increased since 1953 in Madagascar. We observed a continuous decrease of the mean distance to forest edge from 1953 to 2014 in Madagascar. The mean distance to forest edge has decreased to *c.* 300 m in 2014 while it was previously *c.* 1.5 km in 1973 (Fig. 3). Moreover, a large proportion (73%) of the forest was located at a distance greater than 100 m in 1973, while almost half of the forest (46%) was at a distance lower than 100 m from forest edge in 2014 (Fig. 3). The percentage of forest that can be considered intact in Madagascar has continuously decreased since 1953. The percentage of forest belonging to the "interior" category (most intact forests) has fallen from 68% in 1973 to 50% in 2014. In 2014, more than 16% of the forest belonged to the "patch" and "transitional" categories (isolated small forest patches) compared to 9.5% in 1973 (Tab. 4).

4 Discussion

4.1 Benefits of the combined use of recent global annual tree cover loss data with historical national forest-cover maps

In this study, we combined recent (2001-2014) global annual tree cover loss data (Hansen *et al.*, 2013) with historical (1953-2000) national forest-cover maps (Harper *et al.*, 2007) to look at six decades (1953-2014) of deforestation and forest fragmentation in Madagascar. We produced annual forest-cover maps at 30 m resolution covering Madagascar for the period 2000 to 2014. Our study extends the forest-cover monitoring on a six decades period (from 1953 to 2014) while harmonizing the data from previous studies (Harper *et al.*, 2007; MEFT, USAID, and CI, 2009; ONE, DGF, MNP, WCS, and Etc Terra, 2015). We propose a generic approach to solve the problem of forest definition which is needed to transform the 2000 global tree cover dataset from Hansen *et al.* (2013) into a forest/non-forest map (Tropek *et al.*, 2014). We propose to use a historical national forest-cover map, based on a national forest definition, as a forest cover mask. This approach could be easily extended to other regions or countries for which an accurate forest-cover map is available at any date within the period 2000-2014, but preferably at the beginning of the period to profit from the full record and derive long-term estimates of deforestation. Moreover, this approach can be repeated in the future if and when the global tree cover product is updated. We have made the R/GRASS code used for this study freely available in a GitHub repository (see Data availability statement) to facilitate application to other study areas or repeat the analysis in the future for Madagascar.

The accuracy of the derived forest-cover change maps depends directly on the accuracies of the historical forest-cover maps and the tree cover loss dataset. The reported global accuracy of the tree cover loss dataset is 99.6% (see Tab. S5 in Hansen *et al.* (2013)). Verhegghen *et al.* (2016) have compared deforestation estimates derived from the global tree cover loss dataset (Hansen *et al.*, 2013) with results derived from semi-automated supervised classification of Landsat satellite images (Achard *et al.*, 2014) for six countries in Central Africa and they found a good agreement between these two sets of estimates. Consistent with Harper *et al.* (2007), we did not consider potential forest regrowth in Madagascar (although Hansen *et al.* (2013) provided a tree cover gains layer for the period 2001-2013) for several reasons. First, the tree gain layer of Hansen *et al.* (2013) includes and catches more easily tree plantations than natural forest regrowth (Tropek *et al.*, 2014). Second, there is little evidence of natural forest regeneration in Madagascar (Grouzis *et al.*, 2001; Harper *et al.*, 2007). This can be explained by several ecological processes following burning practice such as soil erosion (Grinand *et al.*, 2017) and reduced seed bank due to fire and soil loss (Grouzis *et al.*, 2001). Moreover, in areas where forest regeneration is ecologically possible, young forest regrowth are more easily re-burnt for agriculture and pasture. Third, young secondary forests provide more limited ecosystem services compared to old-growth natural forests in terms of biodiversity and carbon storage.

4.2 Dynamics of forest-cover in Madagascar from 1953 to 2014

We estimated that natural forests in Madagascar cover 8.9 Mha in 2014 (corresponding to 15% of the country) and that Madagascar has lost 44% of its natural forest since 1953 (37% since 1973). There is ongoing scientific debate about the extent of the "original" forest cover in Madagascar, and the extent to which humans have altered the natural forest landscapes since their large-scale settlement around 800 CE (Burns *et al.*, 2016; Cox *et al.*, 2012). Early French naturalists stated that the full island was originally covered by forest (Humbert, 1927; Perrier de La Bâthie, 1921), leading to the common statement that 90% of the natural forests have disappeared since the arrival of humans on the island (Kull, 2000). More recent studies counter-balanced that point of view saying that extensive areas of grassland existed in Madagascar long before human arrival and were determined by climate, natural grazing and other natural factors (Virah-Sawmy, 2009; Vorontsova *et al.*, 2016). Other authors have questioned the entire narrative of extensive alteration of the landscape by early human activity which, through legislation, has severe consequences on local people (Klein, 2002; Kull, 2000). Whatever the original proportion of natural forests and grasslands in Madagascar, our results demonstrate that human activities since the 1950s have profoundly impacted the natural tropical forests and that conservation and development programs in Madagascar have failed to stop deforestation in the recent years. Deforestation has strong consequences on biodiversity and carbon emissions in Madagascar. Around 90% of Madagascar's species are forest dependent (Allnutt *et al.*, 2008; Goodman & Benstead, 2005) and Allnutt *et al.* (2008) estimated that deforestation between 1953 and 2000 led to an extinction of 9% of the species. The additional deforestation we observed over the period 2000-2014 (around 1Mha of natural forest) worsen this result. Regarding carbon emissions, using the 2010 aboveground forest carbon map by Vieilledent *et al.* (2016), we estimated that deforestation on the period 2010-2014 has led to 40.2 Mt C of carbon emissions in the atmosphere (10 Mt C /yr) and that the remaining aboveground forest carbon stock in 2014 is 832.8 Mt C. Associated to deforestation, we showed that the remaining forests of Madagascar are highly fragmented with 46% of the forest being at less than 100m of the forest edge. Small forest fragments do not allow to maintain viable populations and "edge effects" at forest/non-forest interfaces have impacts on both carbon emissions (Brinck *et al.*, 2017) and biodiversity loss (Gibson *et al.*, 2013; Murcia, 1995).

4.3 Deforestation trend and impacts on conservation and development policies

In our study, we have shown that the progressive decrease of the deforestation rate on the period 1990-2005 was followed by a continuous increase in the deforestation rate on the period 2005-2014. In particular, we showed that deforestation rate has more than doubled on the period 2010-2014 compared to 2000-2005. Our results are confirmed by previous studies (Harper *et al.*, 2007; MEFT, USAID, and CI, 2009; ONE, DGF, MNP, WCS, and Etc Terra, 2015) despite differences in the methodologies regarding (i) forest definition (associated to independent visual interpretations of observation polygons to train the classifier), (ii) classification algorithms, (iii) deforestation rate computation method, and (iv) correction for the presence of clouds. Our deforestation rate estimates from 1990 to 2014 have been computed from wall to wall maps at 30 m resolution and can be considered more accurate in comparison with estimates from these previous studies. Our forest-cover and deforestation rate estimates can be used as source of information for the next FAO Forest Resources Assessment project (Keenan *et al.*, 2015). Current rates of deforestation can also be used to build reference scenarios for deforestation in Madagascar and contribute to the implementation of deforestation mitigation activities in the framework of REDD+ (Olander *et al.*, 2008).

The increase of deforestation rates after 2005 can be explained by population growth and political instability in the country. Nearly 90% of Madagascar's population relies on biomass for their daily energy needs (Minten *et al.*, 2013) and the link between population size and deforestation has previously been demonstrated in Madagascar (Gorenflo *et al.*, 2011; Vieilledent *et al.*, 2013). With a mean demographic growth rate of about 2.8%/yr and a population which has increased from 16 to 24 million people on the period 2000-2015 (United Nations, 2015), the increasing demand in wood-fuel and space for agriculture is likely to explain the increase in deforestation rates. The political crisis of 2009 (Ploch & Cook, 2012), followed by several years of political instability and weak governance could also explain the increase in the deforestation rate observed on the period 2005-2014 (Smith *et al.*, 2003). These results show that despite the conservation policy in Madagascar (Freudenberger, 2010), deforestation has dramatically increased at the national level since 2005. Results of this study, including recent spatially explicit forest-cover change maps and forest-cover estimates, should help implement new conservation strategies to save Madagascar natural tropical forests and their unique biodiversity.

5 Author's contribution

All authors conceived the ideas and designed methodology; GV analysed the data and wrote the **R**/GRASS script; GV drafted the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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7 Data accessibility

All the data and codes used for this study are made publicly available in the `deforestmap` GitHub repository (`https://github.com/ghislainv/deforestmap.git`). The results are fully reproducible running the **R** script `deforestmap.R` located inside the `deforestmap` repository.

8 References

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551 # 9 Tables

Year	Forest (ha)	Unmapped (ha)	Annual defor. (ha/yr)	Rate (%/yr)
1953	15968176	0	-	-
1973	14242592	3316531	86279	0.57
1990	10762442	0	204715	1.63
2000	9879031	0	88341	0.85
2005	9667553	0	42296	0.43
2010	9319851	0	69540	0.73
2014	8925246	0	98651	1.08

Table 1: **Evolution of the forest cover and deforestation rates from 1953 to 2014 in Madagascar**. Forest map for the year 1973 has 3.3 Mha of unclassified areas due to the presence of clouds on satellite images. As a consequence, deforestation rates for the periods 1953-1973 and 1973-1990 are indicative. The two last columns indicate the annual deforested areas and annual deforestation rates on the previous time-period (e.g. 1953-1973 for year 1973, 1973-1990 for year 1990, etc.).

Forest type	Source	1953	1973	1990	2000	2005	2010	2013	2014
Total	Harper2007	15995900	14173100	10605700	8982100	-	-	-	-
	MEFT2009	-	-	10650142	9678402	9413218	-	-	-
	ONE2015	-	-	-	-	9451350	8977337	8485509	-
	this study	15968176	14242592	10762494	9879031	9667553	9319851	9051029	8925246
Moist	Harper2007	8765600	6876000	5234300	4166800	-	-	-	-
	MEFT2009	-	-	5270599	4787771	4700430	-	-	-
	ONE2015	-	-	-	-	4555788	4457184	4345093	-
	this study	8578299	6989942	5270169	4872016	4767876	4633104	4470194	4409842
Dry	Harper2007	4252100	4027700	2711800	2457000	-	-	-	-
	MEFT2009	-	-	3320582	3084976	3027505	-	-	-
	ONE2015	-	-	-	-	3223028	2970192	2678640	-
	this study	4761551	4434871	3224917	2940970	2880819	2734639	2642253	2595621
Spiny	Harper2007	2978200	3029800	2420000	2132200	-	-	-	-
	MEFT2009	-	-	2123630	1871735	1756884	-	-	-
	ONE2015	-	-	-	-	1681527	1558533	1466765	-
	this study	2462830	2582880	2054724	1857628	1810704	1744427	1731308	1712731
Mangroves	Harper2007	-	-	239600	226100	-	-	-	-
	MEFT2009	-	-	-	-	-	-	-	-
	ONE2015	-	-	-	-	173564	171220	169877	-
	this study	143412	199853	181226	177708	177492	177149	176890	176718

Table 2: **Comparing our estimates of forest-cover (in ha) for Madagascar with previous studies on the period 1953-2014**. We compared our estimates of forest-cover with the estimates from three previous studies (Harper *et al.*, 2007; MEFT, USAID, and CI, 2009; ONE, DGF, MNP, WCS, and Etc Terra, 2015). We obtained a Pearson's correlation coefficient of 0.99 between our forest-cover estimates and forest-cover estimates from previous studies. The increase in mangrove and spiny forest covers from *c.* 1953 to *c.* 1973 in Harper *et al.* (2007) and our study is most probably due to differences in forest definition and mapping methods between the 1953 aerial-photography derived map and the 1973 Landsat image derived map.

Forest type	Source	1953-1973	1973-1990	1990-2000	2000-2005	2005-2010	2010-2013
Total	Harper2007	91140 (0.30)	200206 (1.70)	80740 (0.90)	-	-	-
	MEFT2009	-	-	97174 (0.83)	53037 (0.53)	-	-
	ONE2015	-	-	-	-	94803 (1.18)	163943 (1.50)
	this study	86279 (0.57)	204712 (1.63)	88346 (0.85)	42296 (0.43)	69540 (0.73)	89607 (0.97)
Moist	Harper2007	94480 (0.60)	87188 (1.70)	32200 (0.80)	-	-	-
	MEFT2009	-	-	48283 (0.79)	17468 (0.35)	-	-
	ONE2015	-	-	-	-	19721 (0.50)	37364 (0.94)
	this study	79418 (1.02)	101163 (1.65)	39815 (0.78)	20828 (0.43)	26954 (0.57)	54303 (1.19)
Dry	Harper2007	11220 (0.20)	77153 (1.90)	19820 (0.70)	-	-	-
	MEFT2009	-	-	23561 (0.67)	11494 (0.40)	-	-
	ONE2015	-	-	-	-	50567 (1.80)	97184 (2.29)
	this study	16334 (0.35)	71174 (1.86)	28395 (0.92)	12030 (0.41)	29236 (1.04)	30795 (1.14)
Spiny	Harper2007	-2580 (-0.10)	35865 (1.20)	28170 (1.20)	-	-	-
	MEFT2009	-	-	25190 (1.19)	22970 (1.23)	-	-
	ONE2015	-	-	-	-	24599 (1.69)	30589 (1.66)
	this study	-6002 (-0.24)	31068 (1.34)	19710 (1.00)	9385 (0.51)	13255 (0.74)	4373 (0.25)
Mangroves	Harper2007	-	-	550 (0.20)	-	-	-
	MEFT2009	-	-	-	-	-	-
	ONE2015	-	-	-	-	469 (0.32)	448 (0.20)
	this study	-2822 (-1.67)	1096 (0.57)	352 (0.20)	43 (0.02)	69 (0.04)	86 (0.05)

Table 3: **Comparing our estimates of annual deforestation rates for Madagascar with previous studies on the period 1953-2014**. Annual deforestation areas (in ha/yr) and annual deforestation rates (second number in parenthesis, in %/yr) are provided. For deforestation rates in %/yr, exact same numbers as in scientific articles and reports from previous studies (Harper *et al.*, 2007; MEFT, USAID, and CI, 2009; ONE, DGF, MNP, WCS, and Etc Terra, 2015) have been reported. The way annual deforestation rates in %/yr have been computed in these previous studies can slightly differ from one study to another, but estimates always correct for the potential presences of clouds on satellite images and unclassified areas on forest maps. Annual deforested areas in ha/yr have been recomputed from forest-cover estimates in Tab. 2 (except for Harper *et al.* (2007) for the periods 1973-1990 and 1990-2000 for which annual deforested areas in ha/yr were derived from numbers reported in the original publication, see methods) and do not correct for the potential presence of clouds.

Year	Forest (ha)	patch (%)	transitional (%)	edge (%)	perforated (%)	interior (%)	NA (%)
1953	15962870	0.01	1.12	4.46	0.58	93.83	0.00
1973	14228217	2.21	7.25	19.81	2.86	67.87	0.01
1990	10749572	3.00	8.17	21.28	3.81	63.73	0.01
2000	9866145	3.09	8.37	22.13	3.92	62.49	0.01
2005	9659861	3.51	8.88	22.56	6.44	58.59	0.02
2010	9306528	4.28	9.72	22.94	8.52	54.52	0.02
2014	8911481	5.18	10.72	23.25	10.58	50.24	0.03

Table 4: **Evolution of the forest fragmentation from 1953 to 2014 in Madagascar**. Six categories of fragmentation were identified from the amount of forest and its occurrence as adjacent forest pixels: "interior", "perforated", "edge", "transitional", "patch", and "undetermined" (Riitters *et al.*, 2000). We used a moving window of 7x7 pixels (4.4 ha). Using this window size, forest edge had a width of about 90 m. The "interior" category can be interpreted as the most intact forest. The "patch" and "transitional" categories correspond to isolated small forest patches.

552 # 10 Figures

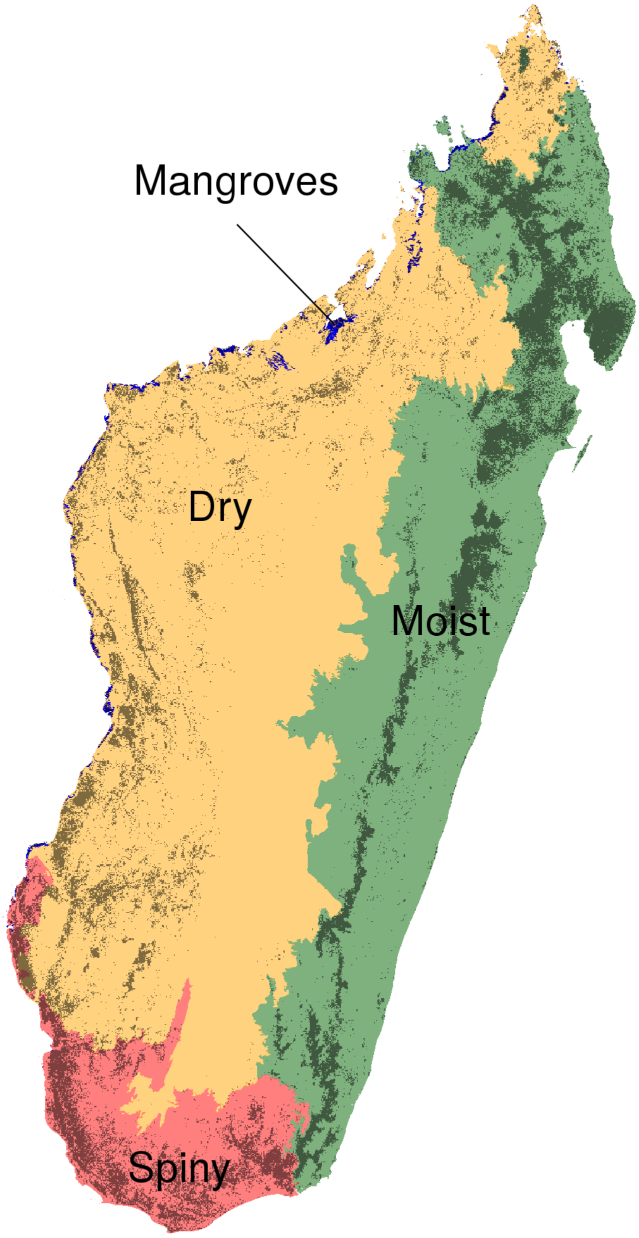

Figure 1: **Ecoregions and forest types in Madagascar.** Madagascar can be divided into four climatic ecoregions with four forest types: the moist forest in the East (green), the dry forest in the West (orange), the spiny forest in the South (red), and the mangroves on the West coast (blue). Ecoregions were defined following climatic (Cornet, 1974) and vegetation (Ministère de l'Environnement, 1996) criteria. The dark grey areas represent the remaining natural forest cover for the year 2014.

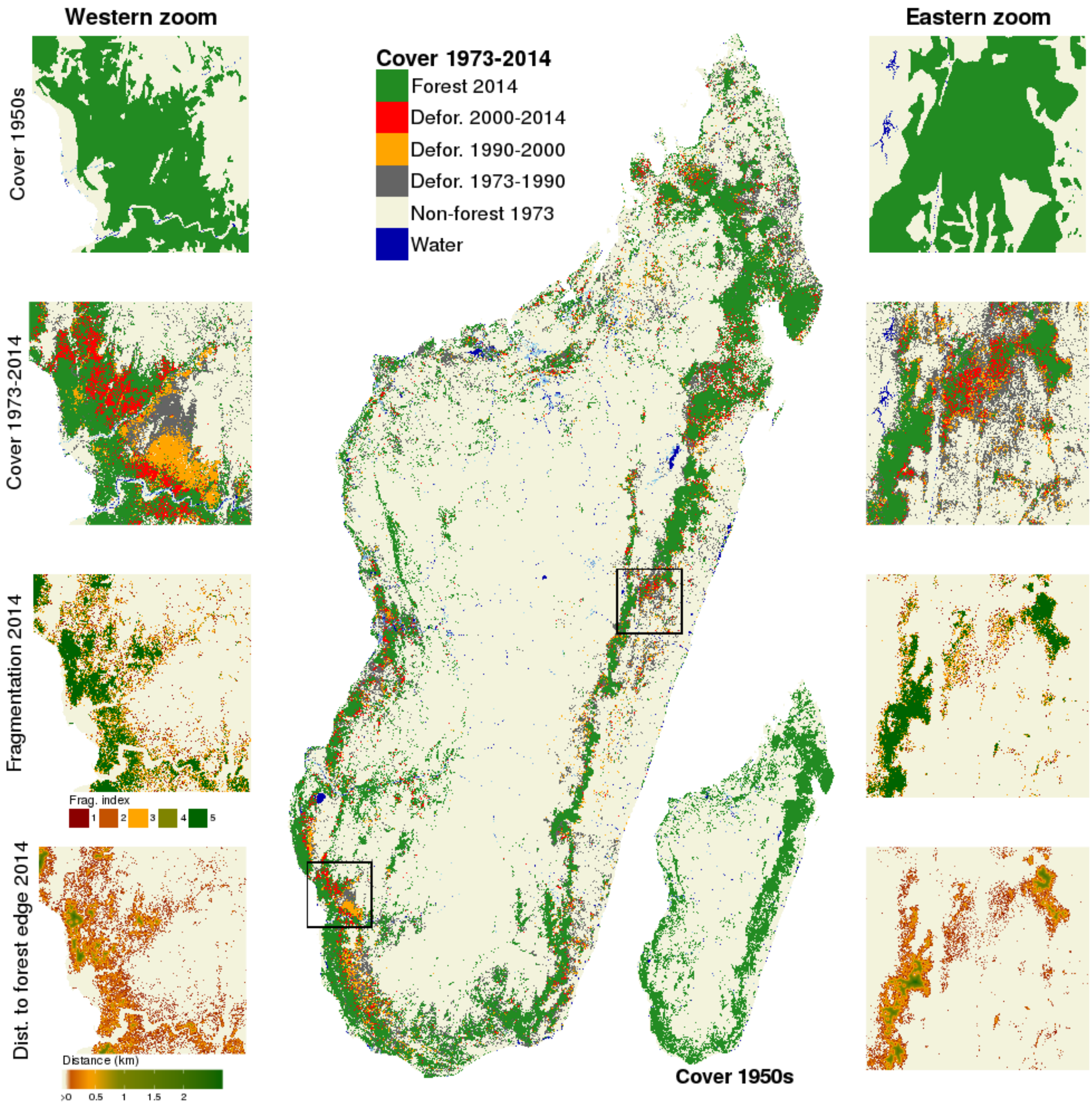

Figure 2: **Forest-cover change on six decades from 1953 to 2014 in Madagascar.** Forest cover changes from *c.* 1973 to 2014 are shown in the main figure, and forest cover in *c.* 1953 is shown in the bottom-right inset. Two zooms in the western dry (left part) and eastern moist (right part) ecoregions present more detailed views of (from top to bottom): forest-cover in 1950s, forest-cover change from *c.* 1973 to 2014, forest fragmentation in 2014 and distance to forest edge in 2014. Data on water bodies (blue) and water seasonality (light blue for seasonal water to dark blue for permanent water) has been extracted from Pekel *et al.* (2016).

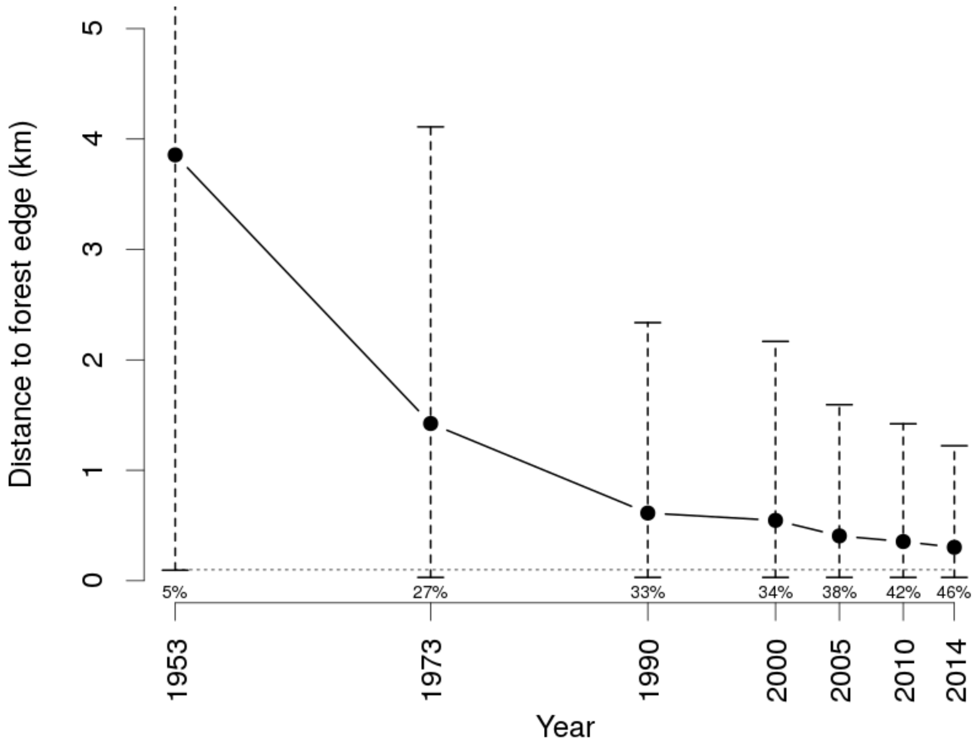

Figure 3: **Evolution of the distance to forest edge from 1953 to 2014 in Madagascar.** Black dots represent the mean distance to forest edge for each year. Vertical dashed segments represent the 90% quantiles (5% and 95%) of the distance to forest edge. Horizontal dashed grey line indicates a distance to forest edge of 100 m. Percentages indicate the percentage of forest at a distance to forest edge lower than 100 m for each year.