

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

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## Abstract

The island of Madagascar has a unique biodiversity, mainly located in the tropical forests of the island. This biodiversity is highly threatened by anthropogenic deforestation. Existing historical forest maps at national level are scattered and have substantial gaps which prevent an exhaustive assessment of long-term deforestation trends in Madagascar. In this study, we combined historical national forest cover maps (covering the period 1953-2000) with a recent global annual tree cover loss dataset (2001-2014) to look at six decades of deforestation and forest fragmentation in Madagascar (from 1953 to 2014). We produced new forest cover maps at 30 m resolution for the year 1990 and annually from 2000 to 2014 over the full territory of Madagascar. 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) and include 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 1.1%/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 100 m from the forest edge. 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 REDD+ framework which aims at “Reducing Emissions from Deforestation and forest Degradation” and for optimizing the current protected area network.

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

## 27 1 Introduction

28 Separated from the African continent and the Indian plate about 165 and 88 million years  
29 ago respectively (Ali & Aitchison, 2008), the flora and fauna of Madagascar followed its  
30 own evolutionary path. Isolation combined with a high number of micro-habitats (Pearson  
31 & Raxworthy, 2009) has led to Madagascar's exceptional biodiversity both in term of num-  
32 ber of species and endemism in many taxonomic groups (Crottini *et al.*, 2012; Goodman  
33 & Benstead, 2005). Most of the biodiversity in Madagascar is concentrated in the tropical  
34 forests of the island which can be divided into four types: the moist forest in the East, the  
35 dry forest in the West, the spiny forest in the South and the mangroves on the West coast  
36 (Vieilledent *et al.*, 2016). This unparalleled biodiversity is severely threatened by defor-  
37 estation (Harper *et al.*, 2007; Vieilledent *et al.*, 2013) associated with human activities such  
38 as slash-and-burn agriculture and pasture (Scales, 2011). Tropical forests in Madagascar  
39 also store a large amount of carbon (Vieilledent *et al.*, 2016) and high rates of deforestation  
40 in Madagascar are responsible for large CO<sub>2</sub> emissions in the atmosphere (Achard *et al.*,  
41 2014). Deforestation threatens species survival by directly reducing their available habitat  
42 (Brooks *et al.*, 2002; Tidd *et al.*, 2001). Forest fragmentation can also lead to species ex-  
43 tinction by isolating populations from each other and creating forest patches too small to  
44 maintain viable populations (Saunders *et al.*, 1991). Fragmentation also increases forest  
45 edge where ecological conditions (such as air temperature, light intensity and air moisture)  
46 can be dramatically modified, with consequences on the abundance and distribution of  
47 species (Murcia, 1995). Forest fragmentation can also have substantial effects on forest  
48 carbon storage capacity, as carbon stocks are much lower at the forest edge than under a  
49 closed canopy (Brinck *et al.*, 2017). Moreover, forest carbon stocks vary spatially due to  
50 climate or soil factors (Saatchi *et al.*, 2011; Vieilledent *et al.*, 2016). As a consequence,  
51 accurate and spatially explicit maps of forest cover and forest cover change are necessary

52 to monitor biodiversity loss and carbon emissions from deforestation and forest fragmen-  
53 tation, assess the efficiency of present conservation strategies (Eklund *et al.*, 2016), and  
54 implement new strategies for the future (Vieilledent *et al.*, 2016, 2013). Simple time-series  
55 of forest cover estimates, such as those provided by the FAO Forest Resource Assessment  
56 report (Keenan *et al.*, 2015) are not sufficient.

57 Unfortunately, accurate and exhaustive forest cover maps are not available for Mada-  
58 gascar after year 2000. Harper *et al.* (2007) produced maps of forest cover and forest  
59 cover changes over Madagascar for the years 1953, 1973, 1990 and 2000. The 1953 forest  
60 map is a vector map derived from the visual interpretation of aerial photographs. Forest  
61 maps for the years 1973, 1990, and 2000 were obtained from the supervised classification  
62 of Landsat satellite images and can be used to derive more accurate estimates of forest  
63 cover than those from the FAO Forest Resource Assessment report. Nonetheless, maps  
64 provided by Harper *et al.* (2007) are not exhaustive (due to the presence of clouds in the  
65 satellite imagery), e.g. 11 244 km<sup>2</sup> are mapped as unknown cover type for the year 2000.  
66 Using a similar supervised classification approach as in Harper *et al.* (2007), more recent  
67 maps have been produced for the periods 2000-2005-2010 by national institutions, with the  
68 technical support of international environmental NGOs (MEFT *et al.*, 2009; ONE *et al.*,  
69 2013). Another set of recent forest cover maps using an advanced statistical tool for clas-  
70 sification, the Random Forest classifier (Grinand *et al.*, 2013; Rakotomala *et al.*, 2015),  
71 was produced for the periods 2005-2010-2013 (ONE *et al.*, 2015). However, these maps are  
72 either too old to give recent estimates of deforestation (MEFT *et al.*, 2009; ONE *et al.*,  
73 2013), include large areas of missing information due to images with high percentage of  
74 cloud cover (ONE *et al.*, 2013), or show large mis-classification in specific areas, especially  
75 in the dry and spiny forest domain for which the spectral answer has a strong seasonal  
76 behavior due to the deciduousness of such forests (overall accuracy is lower than 0.8 for  
77 the dry and spiny forests for the maps produced by ONE *et al.* (2015)). Moreover, the

78 production of such forest maps from a supervised classification approach requires signifi-  
79 cant resources, especially regarding the image selection step (required to minimize cloud  
80 cover) and the training step (visual interpretation of a large number of polygons needed to  
81 train the classification algorithm) (Rakotomala *et al.*, 2015). Most of this work of image  
82 selection and visual interpretation would need to be repeated to produce new forest maps  
83 in the future using a similar approach.

84 Global forest or tree cover products have also been published recently and can be  
85 tested at the national scale for Madagascar. Kim *et al.* (2014) produced a global forest  
86 cover change map from 1990 to 2000 (derived from Landsat imagery). This product was  
87 updated to cover the period 1975-2005 (<http://glcf.umd.edu/data/landsatFCC/>) but  
88 forest cover maps after 2005 were not produced. Moreover, the approach used in Kim *et al.*  
89 (2014) did not accurately map the forests in the dry and spiny ecosystems of Madagascar  
90 (see Fig. 8 in Kim *et al.* (2014)). Hansen *et al.* (2013) mapped tree cover percentage,  
91 annual tree cover loss and gain from 2000 to 2012 at global scale at 30 m resolution.  
92 This product has since been updated and is now available up to the year 2014 (Hansen  
93 *et al.*, 2013). To map forest cover from the Hansen *et al.* (2013) product, a tree cover  
94 threshold must be selected (that defines forest cover). Selecting such a threshold is not  
95 straightforward as the accuracy of the global tree cover map strongly varies between forest  
96 types, and is substantially lower for dry forests than for moist forests (Bastin *et al.*, 2017).  
97 Moreover, the Hansen *et al.* (2013) product does not provide information on land-use. In  
98 particular the global tree cover map does not separate tree plantations such as oil palm  
99 or eucalyptus plantations from natural forests (Tropek *et al.*, 2014). Thus, the global tree  
100 cover map from Hansen *et al.* (2013) cannot be used alone to produce a map of forest cover  
101 (Tyukavina *et al.*, 2017).

102 In this study, we present a simple approach which combines the historical forest maps  
103 from Harper *et al.* (2007) and more recent global products from Hansen *et al.* (2013) to

104 derive annual wall-to-wall forest cover change maps over the period 2000-2014 for Mada-  
105 gascar. We use the forest cover map provided by Harper *et al.* (2007) for the year 2000  
106 (defining the land-use) with the tree cover loss product provided by Hansen *et al.* (2013)  
107 that we apply only inside forest areas identified by Harper *et al.* (2007). Similar to the  
108 approach of Harper *et al.* (2007), we also assess trends in deforestation rates and forest  
109 fragmentation from 1953 to 2014. We finally discuss the possibility to extend our approach  
110 to other tropical countries or repeat it in the future for Madagascar. We also discuss how  
111 our results could help assess the effectiveness of past and current conservation strategies  
112 in Madagascar, and implement new strategies in the future.

## 113 2 Materials and Methods

### 114 2.1 Creation of new forest cover maps of Madagascar from 1953 115 to 2014

116 Original 1990-2000 forest cover change map for Madagascar from Harper *et al.* (2007) is a  
117 raster map at 28.5 m resolution. It was derived from the supervised classification of Landsat  
118 TM (Thematic Mapper) and ETM+ (Enhanced Thematic Mapper Plus) satellite images.  
119 For our study, this map has been resampled at 30 m resolution using a nearest-neighbor  
120 interpolation and reprojected in the WGS 84/UTM zone 38S projected coordinate system.

121 The 2000 Harper's forest map includes 208,000 ha of unclassified areas due to the  
122 presence of clouds on satellite images, mostly (88%) within the moist forest domain which  
123 covered 4.17 Mha in total in 2000. To provide a label (forest or non-forest) to these  
124 unclassified pixels, we used the 2000 tree cover percentage map of Hansen *et al.* (2013)  
125 by selecting a threshold of 75% tree cover to define forest cover as recommended by other  
126 studies for the moist domain (Achard *et al.*, 2014; Aleman *et al.*, 2017). To do so, the  
127 Hansen's 2000 tree cover map was resampled on the same grid as the original Harper's  
128 map at 30 m resolution using a bilinear interpolation. We thus obtained a forest cover  
129 map for the year 2000 covering the full territory of Madagascar.

130 We then combined the forest cover map of the year 2000 with the annual tree cover loss  
131 maps from 2001 to 2014 from Hansen *et al.* (2013) to create annual forest cover maps from  
132 2001 to 2014 at 30 m resolution. To do so, Hansen's tree cover loss maps were resampled  
133 on the same grid as the original Harper's map at 30 m resolution using a nearest-neighbor  
134 interpolation. We also completed the Harper's forest map of year 1990 by filling unclassified  
135 areas (due to the presence of clouds on satellite images) using our forest cover map of year  
136 2000. To do so, we assumed that if forest was present in 2000, the pixel was also forested in  
137 1990. Indeed, there is little evidence of natural forest regeneration in Madagascar (Grouzis

138 *et al.*, 2001; Harper *et al.*, 2007), especially over such a short period of time. The remaining  
139 unclassified pixels were limited to a relatively small total area of about 8,000 ha. We labeled  
140 these residual pixels as non-forest, as for the year 2000.

141 The 1973 forest cover map for Madagascar from Harper *et al.* (2007) is a raster map at  
142 57 m resolution derived from the supervised classification of Landsat MSS (Multispectral  
143 Scanner System) satellite images. We resampled this map at 30 m resolution using a  
144 nearest-neighbor interpolation on the same grid as the forest cover maps for years 1990  
145 and 2000. We completed the Harper's forest map of year 1973 by filling unclassified areas  
146 using our forest cover map of the year 1990 assuming that if forest was present in 1990, it  
147 was also present in 1973. Contrary to the year 1990, the remaining unclassified pixels for  
148 year 1973 corresponded to a significant total area of 3.3 millions ha which was left as is.

149 The 1953 forest cover map from Harper *et al.* (2007) is a vector map produced by  
150 scanning the paper map of Humbert *et al.* (1965) which was derived from the visual inter-  
151 pretation of aerial photographs. We reprojected the forest cover map of year 1953 in the  
152 WGS 84/UTM zone 38S projected coordinate system. Because of the methodology used to  
153 derive the 1953 forest cover map, it was not possible to perfectly aligned this map with the  
154 forest cover maps of later years which were produced through digital processing of satellite  
155 imagery. As a consequence, the 1953 cannot be merged with the map of later years to  
156 identify precisely the location of the deforested areas. Nonetheless, the 1953 forest cover  
157 map can be used to have a rough estimate of the forest cover and forest fragmentation at  
158 this date. To do so, the map was rasterized at 30 m resolution on the same grid as the  
159 forest cover maps for years 1973, 1990 and 2000.

160 Finally for all forest cover maps from 1973, isolated single non-forest pixels (i.e. fully  
161 surrounded by forest pixels) were recategorized as forest pixels. Doing so, forest cover  
162 increased from about 95,000 ha for year 1953 to about 600,000 ha for year 2010. This  
163 allowed us to avoid counting very small scale events (<0.1 ha, such as selective logging



164 or windthrow) as deforestation. It also prevents us from underestimating forest cover and  
165 overestimating forest fragmentation. All the resulting maps have been made permanently  
166 and freely available on the Zenodo research data repository at [https://doi.org/10.5281/  
167 zenodo.1145785](https://doi.org/10.5281/zenodo.1145785).

## 168 2.2 Computing forest cover areas and deforestation rates

169 From these new forest cover maps, we calculated the total forest cover area for seven  
170 available years (1953-1973-1990-2000-2005-2010-2014), and the annual deforested area and  
171 annual deforestation rate for the corresponding six time periods between 1953 and 2014.  
172 The annual deforestation rates were calculated using Eq. 1 (Puyravaud, 2003; Vieilledent  
173 *et al.*, 2013):

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

174 In Eq. 1,  $\theta$  is the annual deforestation rate (in %/yr),  $F_{t_2}$  and  $F_{t_1}$  are the forest cover  
175 free of clouds at both dates  $t_2$  and  $t_1$ , and  $t_2 - t_1$  is the time-interval (in years) between  
176 the two dates.

177 Because of the large unclassified area (3.3 millions ha) in 1973, the annual deforestation  
178 areas and rates for the two periods 1953-1973 and 1973-1990 are only partial estimates  
179 computed on the basis of the available forest extent. Area and rate estimates are produced  
180 at the national scale and for the four forest types present in Madagascar: moist forest in  
181 the East, dry forest in the West, spiny forest in the South, and mangroves on the Western  
182 coast (Fig. 1). To define the forest types, we used a map from the MEFT (*“Ministère de  
183 l’Environnement et des Forêts à Madagascar”*) with the boundaries of the four ecoregions  
184 in Madagascar. Ecoregions were defined on the basis of climatic and vegetation criteria

185 using the climate classification by [Cornet \(1974\)](#) and the vegetation classification from  
186 the 1996 IEFN national forest inventory ([Ministère de l'Environnement, 1996](#)). Because  
187 mangrove forests are highly dynamic ecosystems that can expand or contract on decadal  
188 scales depending on changes in environmental factors ([Armitage \*et al.\*, 2015](#)), a fixed  
189 delimitation of the mangrove ecoregion on six decades might not be fully appropriate. As  
190 a consequence, our estimates of the forest cover and deforestation rates for mangroves in  
191 Madagascar must be considered with this limitation.

## 192 **2.3 Comparing our forest cover and deforestation rate estimates** 193 **with previous studies**

194 We compared our estimates of forest cover and deforestation rates with estimates from  
195 the three existing studies at the national scale for Madagascar: (i) [Harper \*et al.\* \(2007\)](#),  
196 (ii) [MEFT \*et al.\* \(2009\)](#) and (iii) [ONE \*et al.\* \(2015\)](#). [Harper \*et al.\* \(2007\)](#) provides forest  
197 cover and deforestation estimates for the periods c. 1953-c. 1973-1990-2000. [MEFT \*et al.\*](#)  
198 [\(2009\)](#) provides estimates for the periods 1990-2000-2005 and [ONE \*et al.\* \(2015\)](#) provides  
199 estimates for the periods 2005-2010-2013. To compare our forest cover and deforestation  
200 estimates over the same time periods, we consider an additional time-period in our study  
201 (2010-2013) by creating an extra forest cover map for the year 2013. We computed the  
202 Pearson's correlation coefficient and the root mean square error (RMSE) between our  
203 forest cover estimates and forest cover estimates from previous studies for all the dates  
204 and forest types (including also the total forest cover estimates). For previous studies,  
205 the computation of annual deforestation rates (in %/yr) is not always detailed and might  
206 slightly differ from one study to another (see [Puyravaud, 2003](#)). [Harper \*et al.\* \(2007\)](#) also  
207 provide total deforested areas for the two periods 1973-1990 and 1990-2000. We converted  
208 these values into annual deforested area estimates. When annual deforested areas were not

209 reported (for 1953-1973 in Harper *et al.* (2007) and in MEFT *et al.* (2009) and ONE *et al.*  
210 (2015)), we computed them from the forest cover estimates in each study. These estimates  
211 cannot be corrected from the potential bias due to the presence of residual clouds. forest  
212 cover and deforestation rates were then compared between all studies for the whole of  
213 Madagascar and the four ecoregions. The same ecoregion boundaries as in our study were  
214 used in ONE *et al.* (2015) but this was not the case for Harper *et al.* (2007) and MEFT  
215 *et al.* (2009), which can explain a part of the differences between the estimates.

## 216 **2.4 Fragmentation**

217 We also conducted an analysis of changes in forest fragmentation for the years 1953, 1973,  
218 1990, 2000, 2005, 2010 and 2014 at 30 m resolution. We used a moving window of 51 ×  
219 51 pixels centered on each forest pixel to compute the percentage of forest pixels in the  
220 neighborhood. We used this percentage as an indication of the forest fragmentation. The  
221 size of the moving windows was based on a compromise: a sufficiently high number of cells  
222 (here 2601) had to be considered to be able to compute a percentage and a reasonably  
223 low number of cells had to be chosen to have a local estimate of the fragmentation.  
224 Computations were done using the function `r.neighbors` of the GRASS GIS software  
225 (Neteler & Mitasova, 2008). Using the density of forest in the neighborhood, we defined  
226 five forest fragmentation classes: 0-20% (highly fragmented), 21-40%, 41-60%, 61-80%  
227 and 81-100% (lowly fragmented). We reported the percentage of forest falling in each  
228 fragmentation class for the six years and analyzed the dynamics of fragmentation over the  
229 six decades.

230 We also computed the distance to forest edge for all forest pixels for the years 1953,  
231 1973, 1990, 2000, 2005, 2010 and 2014. For that, we used the function `gdal_proximity.py`  
232 of the GDAL library (<http://www.gdal.org/>). We computed the mean and 90% quantiles  
233 (5% and 95%) of the distance to forest edge and looked at the evolution of these values with

234 time. Previous studies have shown that forest micro-habitats were mainly altered within  
235 the first 100 m of the forest edge (Brinck *et al.*, 2017; Broadbent *et al.*, 2008; Gibson *et al.*,  
236 2013; Murcia, 1995). Consequently, we also estimated the percentage of forest within the  
237 first 100 m of the forest edge for each year and looked at the evolution of this percentage  
238 over the six decades.

## 239 **3 Results**

### 240 **3.1 Forest cover change and deforestation rates**

241 Natural forests in Madagascar covered 16.0 Mha in 1953, about 27% of the national ter-  
242 ritory of 587,041 km<sup>2</sup>. In 2014, the forest cover dropped to 8.9 Mha, corresponding to  
243 about 15% of the national territory (Fig. 2 and Tab. 1). Madagascar has lost 44% and  
244 37% of its natural forests between 1953 and 2014, and between 1973 and 2014 respectively  
245 (Fig. 2 and Tab. 1). In 2014 the remaining 8.9 Mha of natural forest were distributed as  
246 follow: 4.4 Mha of moist forest (50% of total forest cover), 2.6 Mha of dry forest (29%),  
247 1.7 Mha of spiny forest (19%) and 0.18 Mha (2%) of mangrove forest (Fig. 1 and Tab. 2).  
248 Regarding the deforestation trend, we observed a progressive decrease of the deforestation  
249 rate after 1990 from 205,000 ha/yr (1.6%/yr) over the period 1973-1990 to 42,000 ha/yr  
250 (0.4%/yr) over the period 2000-2005 (Tab. 1). Then from 2005, the deforestation rate  
251 has progressively increased and has more than doubled over the period 2010-2014 (99,000  
252 ha/yr, 1.1%/yr) compared to 2000-2005 (Tab. 1). The deforestation trend, characterized  
253 by a progressive decrease of the deforestation rate over the period 1990-2005 and a pro-  
254 gressive increase of the deforestation after 2005, is valid for all four forest types except  
255 the spiny forest (Tab. 3). For the spiny forest, the deforestation rate during the period  
256 2010-2013 was lower than on the period 2005-2010 (Tab. 3).

### 257 **3.2 Comparison with previous forest cover change studies in** 258 **Madagascar**

259 Forest cover maps provided by previous studies over Madagascar were not exhaustive  
260 (unclassified areas) due to the presence of clouds on satellite images used to produce such  
261 maps. In Harper *et al.* (2007), the maps of years 1990 and 2000 include 0.5 and 1.12 Mha

262 of unknown cover type respectively. Proportions of unclassified areas are not reported in  
263 the two other existing studies at the national level by MEFT *et al.* (2009) and ONE *et al.*  
264 (2015). With our approach, we produced wall-to-wall forest cover change maps from 1990  
265 to 2014 for the full territory of Madagascar (Tab. 1). This allowed us to produce more  
266 robust estimates of forest cover and deforestation rates over this period. Our forest cover  
267 estimates over the period 1953-2013 (considering forest cover estimates at national level  
268 and by ecoregions for all the available dates) were well correlated (Pearson's correlation  
269 coefficient = 0.99) to estimates from the three previous studies (Tab. 2) with a RMSE of  
270 300,000 ha (6% of the mean forest cover of 4.8 Mha when considering all dates and forest  
271 types together). These small differences can be partly attributed to differences in ecoregion  
272 boundaries. Despite significant differences in deforestation estimates (Tab. 3), a similar  
273 deforestation trend was observed across studies with a decrease of deforestation rates over  
274 the period 1990-2005, followed by a progressive increase of the deforestation after 2005.

### 275 **3.3 Evolution of forest fragmentation with time**

276 In parallel to the dynamics of deforestation, forest fragmentation has progressively in-  
277 creased since 1953 in Madagascar. We observed a continuous decrease of the mean distance  
278 to forest edge from 1953 to 2014 in Madagascar. The mean distance to forest edge has  
279 decreased to about 300 m in 2014 while it was of about 1.5 km in 1973 (Fig. 3). Moreover,  
280 a large proportion (73%) of the forest was located at a distance greater than 100 m in 1973,  
281 while almost half of the forest (46%) is at a distance lower than 100 m from forest edge in  
282 2014 (Fig. 3). The percentage of lowly fragmented forest in Madagascar has continuously  
283 decreased since 1953. The percentage of forest belonging to the lowly fragmented class has  
284 fallen from 57% in 1973 to 44% in 2014. In 2014, 22% of the forest belonged to the two  
285 highest fragmented forest classes (less than 40% of forest cover in the neighborhood) while  
286 only 15% of the forest belonged to these two fragmentation classes in 1973 (Tab. 4).

## 287 4 Discussion

### 288 4.1 Advantages of combining recent global annual tree cover loss 289 data with historical national forest cover maps

290 In this study, we combined recent (2001-2014) global annual tree cover loss data (Hansen  
291 *et al.*, 2013) with historical (1953-2000) national forest cover maps (Harper *et al.*, 2007) to  
292 look at six decades (1953-2014) of deforestation and forest fragmentation in Madagascar.  
293 We produced annual forest cover maps at 30 m resolution covering Madagascar for the  
294 period 2000 to 2014. Our study extends the forest cover monitoring on a six decades  
295 period (from 1953 to 2014) while harmonizing the data from previous studies (Harper *et al.*,  
296 2007; MEFT *et al.*, 2009; ONE *et al.*, 2015). We propose a generic approach to solve the  
297 problem of forest definition which is needed to transform the 2000 global tree cover dataset  
298 from Hansen *et al.* (2013) into a forest/non-forest map (Tropek *et al.*, 2014). We propose  
299 to use a historical national forest cover map, based on a national forest definition, as a  
300 forest cover mask. This approach could be easily extended to other regions or countries for  
301 which an accurate forest cover map is available at any date within the period 2000-2014, but  
302 preferably at the beginning of the period to profit from the full record and derive long-term  
303 estimates of deforestation. Moreover, this approach could be repeated in the future with  
304 the release of updated tree cover loss data. We have made the **R**/GRASS code used for this  
305 study freely available in a GitHub repository (see Data availability statement) to facilitate  
306 application to other study areas or repeat the analysis in the future for Madagascar.

307 The accuracy of the derived forest cover change maps depends directly on the accu-  
308 racies of the historical forest cover maps and the tree cover loss dataset. Using visual-  
309 interpretation of aerial images in 342 areas distributed among all forest types, Harper  
310 *et al.* (2007) estimated an overall 89.5% accuracy in identifying forest/non-forest classes  
311 for the year 2000. The accuracy assessment of the tree cover loss dataset for the tropical

312 biome reported 13% of false positives and 16.9% of false negatives (see Tab. S5 in Hansen  
313 *et al.* (2013)). These numbers rise at 20.7% and 20.6% respectively for the subtropical  
314 biome. In the subtropical biome, the lower density tree cover canopy makes it difficult to  
315 detect change from tree cover to bare ground. For six countries in Central Africa, with  
316 a majority of moist dense forest, Verhegghen *et al.* (2016) have compared deforestation  
317 estimates derived from the global tree cover loss dataset (Hansen *et al.*, 2013) with results  
318 derived from semi-automated supervised classification of Landsat satellite images (Achard  
319 *et al.*, 2014) and they found a good agreement between the two sets of estimates. There-  
320 fore, our forest cover change maps after 2000 might be more accurate for the dense moist  
321 forest than for the dry and spiny forest. In another study assessing the accuracy of the  
322 tree cover loss product across the tropics (Tyukavina *et al.*, 2015), authors reported 4%  
323 of false positives and 48% of false negatives in Sub-Saharan Africa. They showed that  
324 85% of missing loss occurred on the edges of other loss patches. This means that tree cover  
325 loss might be underestimated in Sub-Saharan Africa, probably due to the prevalence of  
326 small-scale disturbance which is hard to map at 30 m, but that areas of large-scale defor-  
327 estation are well identified and spatial variability of the deforestation is well represented.  
328 A proper accuracy assessment of our forest cover change maps should be performed to  
329 better estimate the uncertainty surrounding our forest cover change estimates in Madagas-  
330 car from year 2000 (Olofsson *et al.*, 2014, 2013). Despite this limitation, we have shown  
331 that the deforestation trend we observed for Madagascar, with a doubling deforestation on  
332 the period 2010-2014 compared to 2000-2005, was consistent with the other studies at the  
333 national scale (MEFT *et al.*, 2009; ONE *et al.*, 2015).

334 Consistent with Harper *et al.* (2007), we did not consider potential forest regrowth in  
335 Madagascar (although Hansen *et al.* (2013) provided a tree cover gains layer for the period  
336 2001-2013) for several reasons. First, the tree gain layer of Hansen *et al.* (2013) includes  
337 and catches more easily tree plantations than natural forest regrowth (Tropek *et al.*, 2014).



338 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  
339 burning practice such as soil erosion ([Grinand \*et al.\*, 2017](#)) and reduced seed bank due to  
340 fire and soil loss ([Grouzis \*et al.\*, 2001](#)). Moreover, in areas where forest regeneration is  
341 ecologically possible, young forest regrowth are more easily re-burnt for agriculture and  
342 pasture. Third, young secondary forests provide more limited ecosystem services compared  
343 to old-growth natural forests in terms of biodiversity and carbon storage.  
344

## 345 **4.2 Natural forest cover change in Madagascar from 1953 to 2014**

346 We estimated that natural forest in Madagascar covers 8.9 Mha in 2014 (corresponding  
347 to 15% of the country) and that Madagascar has lost 44% of its natural forest since 1953  
348 (37% since 1973). There is ongoing scientific debate about the extent of the “original”  
349 forest cover in Madagascar, and the extent to which humans have altered the natural  
350 forest landscapes since their large-scale settlement around 800 CE ([Burns \*et al.\*, 2016](#); [Cox  
351 \*et al.\*, 2012](#)). Early French naturalists stated that the full island was originally covered by  
352 forest ([Humbert, 1927](#); [Perrier de La Bâthie, 1921](#)), leading to the common statement that  
353 90% of the natural forests have disappeared since the arrival of humans on the island ([Kull,  
354 2000](#)). More recent studies counter-balanced that point of view saying that extensive areas  
355 of grassland existed in Madagascar long before human arrival and were determined by  
356 climate, natural grazing and other natural factors ([Virah-Sawmy, 2009](#); [Vorontsova \*et al.\*,  
357 2016](#)). Other authors have questioned the entire narrative of extensive alteration of the  
358 landscape by early human activity which, through legislation, has severe consequences on  
359 local people ([Klein, 2002](#); [Kull, 2000](#)). Whatever the original proportion of natural forests  
360 and grasslands in Madagascar, our results demonstrate that human activities since the  
361 1950s have profoundly impacted the natural tropical forests and that conservation and  
362 development programs in Madagascar have failed to stop deforestation in the recent years.

363 Deforestation has strong consequences on biodiversity and carbon emissions in Madagascar.  
364 Around 90% of Madagascar’s species are forest dependent ([Allnutt \*et al.\*, 2008](#); [Goodman  
365 & Benstead, 2005](#)) and [Allnutt \*et al.\* \(2008\)](#) estimated that deforestation between 1953 and  
366 2000 led to an extinction of 9% of the species. The additional deforestation we observed  
367 over the period 2000-2014 (around 1 Mha of natural forest) worsen this result. Regarding  
368 carbon emissions, using the 2010 aboveground forest carbon map by [Vieilledent \*et al.\*  
369 \(2016\)](#), we estimated that deforestation on the period 2010-2014 has led to 40.2 Mt C of  
370 carbon emissions in the atmosphere (10 Mt C /yr) and that the remaining aboveground  
371 forest carbon stock in 2014 is 832.8 Mt C. Associated to deforestation, we showed that the  
372 remaining forests of Madagascar are highly fragmented with 46% of the forest being at  
373 less than 100 m of the forest edge. Small forest fragments do not allow to maintain viable  
374 populations and “edge effects” at forest/non-forest interfaces have impacts on both carbon  
375 emissions ([Brinck \*et al.\*, 2017](#)) and biodiversity loss ([Gibson \*et al.\*, 2013](#); [Murcia, 1995](#)).

### 376 **4.3 Deforestation trend and impacts on conservation and devel- 377 opment policies**

378 In our study, we have shown that the progressive decrease of the deforestation rate on the  
379 period 1990-2005 was followed by a continuous increase in the deforestation rate on the  
380 period 2005-2014. In particular, we showed that deforestation rate has more than doubled  
381 on the period 2010-2014 compared to 2000-2005. Our results are confirmed by previous  
382 studies ([Harper \*et al.\*, 2007](#); [MEFT \*et al.\*, 2009](#); [ONE \*et al.\*, 2015](#)) despite differences in  
383 the methodologies regarding (i) forest definition (associated to independent visual inter-  
384 pretations of observation polygons to train the classifier), (ii) classification algorithms, (iii)  
385 deforestation rate computation method, and (iv) correction for the presence of clouds. Our  
386 deforestation rate estimates from 1990 to 2014 have been computed from wall-to-wall maps

387 at 30 m resolution and can be considered more accurate in comparison with estimates from  
388 these previous studies. Our forest cover and deforestation rate estimates can be used as  
389 source of information for the next FAO Forest Resources Assessment (Keenan *et al.*, 2015).  
390 Current rates of deforestation can also be used to build reference scenarios for deforestation  
391 in Madagascar and contribute to the implementation of deforestation mitigation activities  
392 in the framework of REDD+ (Olander *et al.*, 2008).

393 The increase of deforestation rates after 2005 can be explained by population growth  
394 and political instability in the country. Nearly 90% of Madagascar's population relies on  
395 biomass for their daily energy needs (Minten *et al.*, 2013) and the link between popu-  
396 lation size and deforestation has previously been demonstrated in Madagascar (Gorenflo  
397 *et al.*, 2011; Vieilledent *et al.*, 2013). With a mean demographic growth rate of about  
398 2.8%/yr and a population which has increased from 16 to 24 million people on the period  
399 2000-2015 (United Nations, 2015), the increasing demand in wood-fuel and space for agri-  
400 culture is likely to explain the increase in deforestation rates. The political crisis of 2009  
401 (Ploch & Cook, 2012), followed by several years of political instability and weak governance  
402 could also explain the increase in the deforestation rate observed on the period 2005-2014  
403 (Smith *et al.*, 2003). These results show that despite the conservation policy in Madagas-  
404 car (Freudenberger, 2010), deforestation has dramatically increased at the national level  
405 since 2005. Results of this study, including recent spatially explicit forest cover change  
406 maps and forest cover estimates, should help implement new conservation strategies to  
407 save Madagascar natural tropical forests and their unique biodiversity.

## 408 **5 Author's contribution**

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

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## 422 **7 Data accessibility**

423 All the data and the script used for this study have been made permanently and publicly  
424 available on the Zenodo research data repository so that the results are entirely repro-  
425 ducible:

- 426 • Input data: <https://doi.org/10.5281/zenodo.1118955>
- 427 • Script: <https://doi.org/10.5281/zenodo.1118484>
- 428 • Output data: <https://doi.org/10.5281/zenodo.1145785>

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## 605 9 Tables

Table 1: **Evolution of natural forest cover and deforestation rates from 1953 to 2014 in Madagascar.** Areas are provided in thousands of hectares (Kha). 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, partial deforestation rates for the periods 1953-1973 and 1973-1990 are computed based on the available forest extent. The last two 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.).

| Year | Forest (Kha) | Unmap (Kha) | Annual defor. (Kha/yr) | Rate (%/yr) |
|------|--------------|-------------|------------------------|-------------|
| 1953 | 15,968       | 0           | -                      | -           |
| 1973 | 14,243       | 3,317       | 86                     | 0.6         |
| 1990 | 10,762       | 0           | 205                    | 1.6         |
| 2000 | 9,879        | 0           | 88                     | 0.8         |
| 2005 | 9,668        | 0           | 42                     | 0.4         |
| 2010 | 9,320        | 0           | 70                     | 0.7         |
| 2014 | 8,925        | 0           | 99                     | 1.1         |

**Table 2: Comparing Madagascar forest cover estimates 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 *et al.*, 2009; ONE *et al.*, 2015). Areas are provided in thousands of hectares (Kha). 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 1953 to 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   | 1990   | 2000  | 2005  | 2010  | 2013  | 2014  |
|-------------|------------|--------|--------|--------|-------|-------|-------|-------|-------|
| Total       | Harper2007 | 15,996 | 14,173 | 10,606 | 8,982 | -     | -     | -     | -     |
|             | MEFT2009   | -      | -      | 10,650 | 9,678 | 9,413 | -     | -     | -     |
|             | ONE2015    | -      | -      | -      | -     | 9,451 | 8,977 | 8,486 | -     |
|             | this study | 15,968 | 14,243 | 10,762 | 9,879 | 9,668 | 9,320 | 9,051 | 8,925 |
| Moist       | Harper2007 | 8,766  | 6,876  | 5,234  | 4,167 | -     | -     | -     | -     |
|             | MEFT2009   | -      | -      | 5,271  | 4,788 | 4,700 | -     | -     | -     |
|             | ONE2015    | -      | -      | -      | -     | 4,556 | 4,457 | 4,345 | -     |
|             | this study | 8,578  | 6,990  | 5,270  | 4,872 | 4,768 | 4,633 | 4,470 | 4,410 |
| Dry         | Harper2007 | 4,252  | 4,028  | 2,712  | 2,457 | -     | -     | -     | -     |
|             | MEFT2009   | -      | -      | 3,321  | 3,085 | 3,028 | -     | -     | -     |
|             | ONE2015    | -      | -      | -      | -     | 3,223 | 2,970 | 2,679 | -     |
|             | this study | 4,762  | 4,435  | 3,225  | 2,941 | 2,881 | 2,735 | 2,642 | 2,596 |
| Spiny       | Harper2007 | 2,978  | 3,030  | 2,420  | 2,132 | -     | -     | -     | -     |
|             | MEFT2009   | -      | -      | 2,124  | 1,872 | 1,757 | -     | -     | -     |
|             | ONE2015    | -      | -      | -      | -     | 1,682 | 1,559 | 1,467 | -     |
|             | this study | 2,463  | 2,583  | 2,055  | 1,858 | 1,811 | 1,744 | 1,731 | 1,713 |
| Mangroves   | Harper2007 | -      | -      | 240    | 226   | -     | -     | -     | -     |
|             | MEFT2009   | -      | -      | -      | -     | -     | -     | -     | -     |
|             | ONE2015    | -      | -      | -      | -     | 174   | 171   | 170   | -     |
|             | this study | 143    | 200    | 181    | 178   | 177   | 177   | 177   | 177   |

**Table 3: Comparing Madagascar annual deforestation rates with previous studies on the period 1953-2014.** Annual deforested areas (in thousands of hectares per year, Kha/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 *et al.*, 2009; ONE *et al.*, 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 Kha/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 Kha/yr were derived from numbers reported in the original publication, see methods) and do not correct for the potential presence of clouds.

| Forest type | Source     | 1953-1973 | 1973-1990 | 1990-2000 | 2000-2005 | 2005-2010 | 2010-2013 |
|-------------|------------|-----------|-----------|-----------|-----------|-----------|-----------|
| Total       | Harper2007 | 91 (0.3)  | 200 (1.7) | 81 (0.9)  | -         | -         | -         |
|             | MEFT2009   | -         | -         | 97 (0.8)  | 53 (0.5)  | -         | -         |
|             | ONE2015    | -         | -         | -         | -         | 95 (1.2)  | 164 (1.5) |
|             | this study | 86 (0.6)  | 205 (1.6) | 88 (0.9)  | 42 (0.4)  | 70 (0.7)  | 90 (1.0)  |
| Moist       | Harper2007 | 94 (0.6)  | 87 (1.7)  | 32 (0.8)  | -         | -         | -         |
|             | MEFT2009   | -         | -         | 48 (0.8)  | 17 (0.4)  | -         | -         |
|             | ONE2015    | -         | -         | -         | -         | 20 (0.5)  | 37 (0.9)  |
|             | this study | 79 (1.0)  | 101 (1.6) | 40 (0.8)  | 21 (0.4)  | 27 (0.6)  | 54 (1.2)  |
| Dry         | Harper2007 | 11 (0.2)  | 77 (1.9)  | 20 (0.7)  | -         | -         | -         |
|             | MEFT2009   | -         | -         | 24 (0.7)  | 11 (0.4)  | -         | -         |
|             | ONE2015    | -         | -         | -         | -         | 51 (1.8)  | 97 (2.3)  |
|             | this study | 16 (0.4)  | 71 (1.9)  | 28 (0.9)  | 12 (0.4)  | 29 (1.0)  | 31 (1.1)  |
| Spiny       | Harper2007 | -3 (-0.1) | 36 (1.2)  | 28 (1.2)  | -         | -         | -         |
|             | MEFT2009   | -         | -         | 25 (1.2)  | 23 (1.2)  | -         | -         |
|             | ONE2015    | -         | -         | -         | -         | 25 (1.7)  | 31 (1.7)  |
|             | this study | -6 (-0.2) | 31 (1.3)  | 20 (1.0)  | 9 (0.5)   | 13 (0.7)  | 4 (0.3)   |
| Mangroves   | Harper2007 | -         | -         | 1 (0.2)   | -         | -         | -         |
|             | MEFT2009   | -         | -         | -         | -         | -         | -         |
|             | ONE2015    | -         | -         | -         | -         | 0 (0.3)   | 0 (0.2)   |
|             | this study | -3 (-1.7) | 1 (0.6)   | 0 (0.2)   | 0 (0.0)   | 0 (0.0)   | 0 (0.0)   |

Table 4: **Evolution of the forest fragmentation from 1953 to 2014 in Madagascar.** Five forest fragmentation classes, based on the percentage of forest in the neighborhood, are defined: 0-20% (highly fragmented), 21-40%, 41-60%, 61-80% and 81-100% (lowly fragmented). The percentage of forest falling in each forest fragmentation class is reported for each year. Forest areas are provided in thousands of hectares (Kha).

| Year | Forest (Kha) | 0-20 | 21-40 | 41-60 | 61-80 | 81-100 |
|------|--------------|------|-------|-------|-------|--------|
| 1953 | 15,968       | 0    | 1     | 8     | 12    | 78     |
| 1973 | 14,243       | 6    | 9     | 12    | 16    | 57     |
| 1990 | 10,762       | 7    | 10    | 13    | 17    | 53     |
| 2000 | 9,879        | 7    | 11    | 14    | 17    | 51     |
| 2005 | 9,673        | 8    | 11    | 14    | 18    | 49     |
| 2010 | 9,320        | 8    | 12    | 15    | 18    | 47     |
| 2014 | 8,925        | 9    | 13    | 16    | 19    | 44     |

606 **10 Figures**

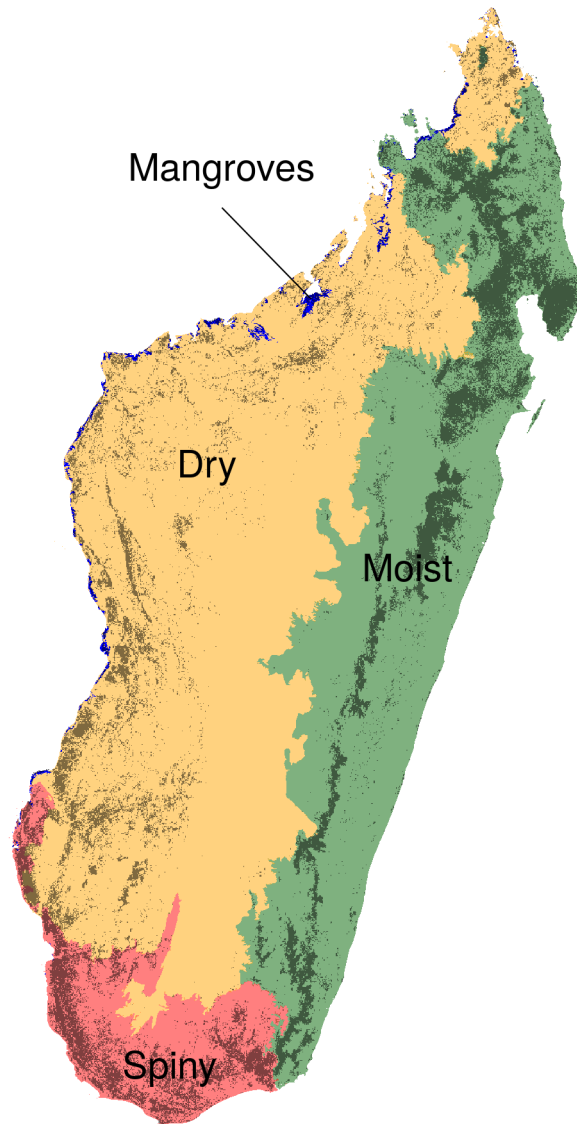


Figure 1: **Ecoregions and forest types in Madagascar.** Madagascar can be divided into four climatic ecoregions with four forest types: the moist forest in the East (green), the dry forest in the West (orange), the spiny forest in the South (red), and the mangroves on the West coast (blue). Ecoregions 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. Forest types are defined on the basis of their belonging to one of the four ecoregions.

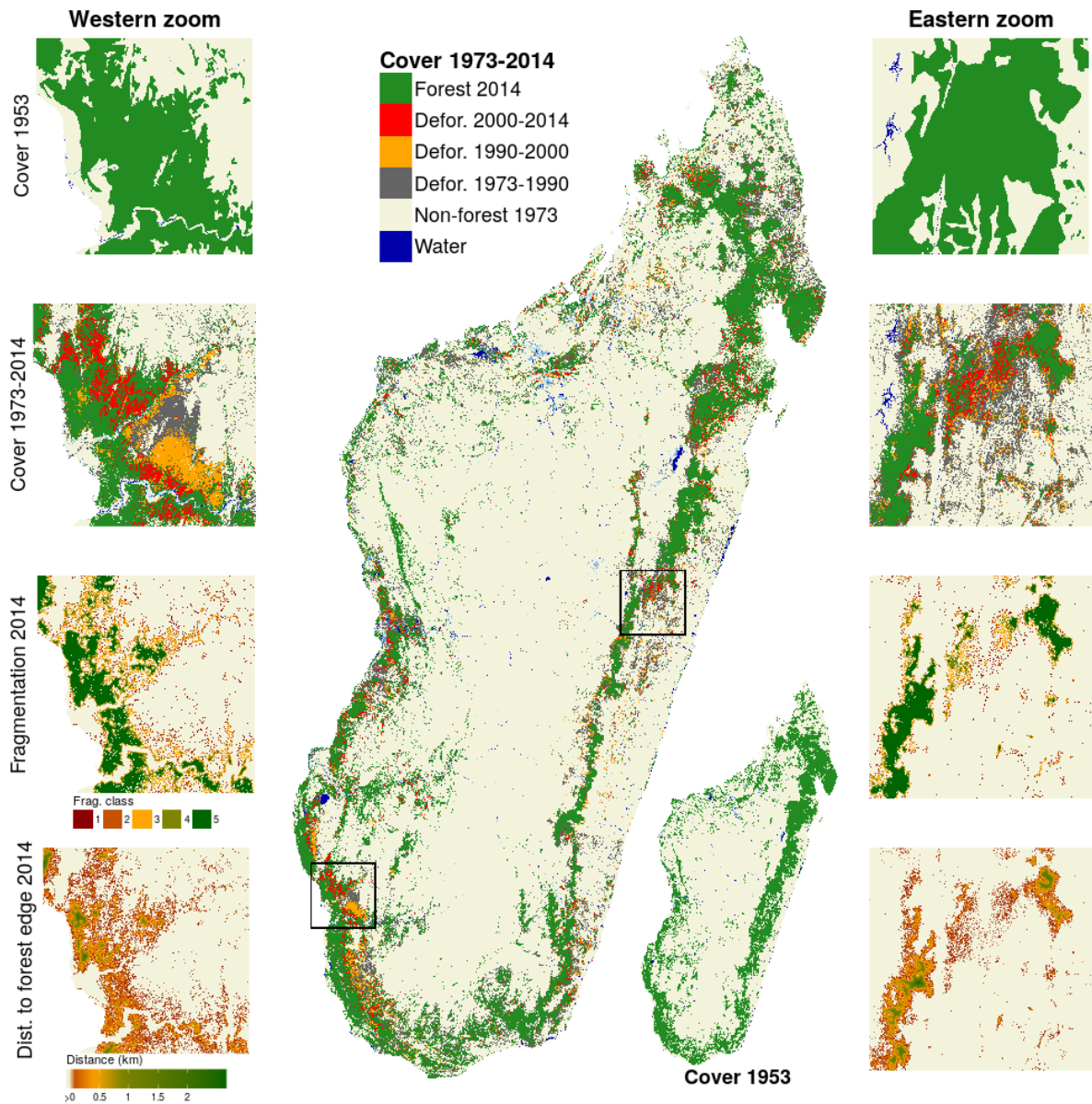


Figure 2: **Forest cover change on six decades from 1953 to 2014 in Madagascar.** forest cover changes from 1973 to 2014 are shown in the main figure, and forest cover in 1953 is shown in the bottom-right inset. Two zooms in the western dry (left part) and eastern moist (right part) ecoregions present more detailed views of (from top to bottom): forest cover in 1953, forest cover change from 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).



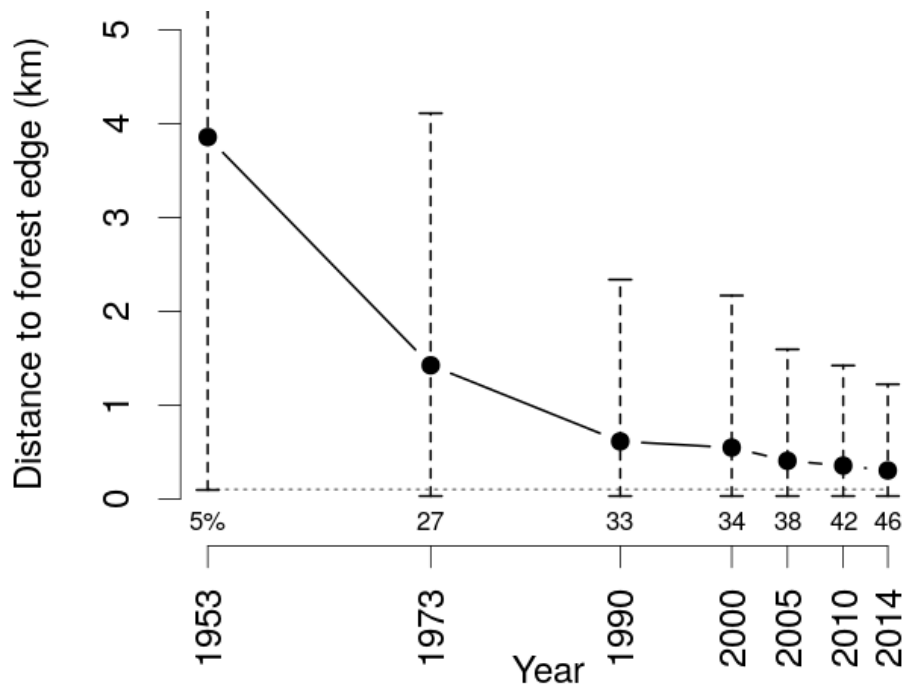


Figure 3: **Evolution of the distance to forest edge from 1953 to 2014 in Madagascar.** Black dots represent the mean distance to forest edge for each year. Vertical dashed segments represent the 90% quantiles (5% and 95%) of the distance to forest edge. Horizontal dashed grey line indicates a distance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