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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). Around half of the forest (46%) is now located at less than 100 m from the forest edge. Our approach could be replicated to other developing countries with tropical forest. 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.

1. Introduction

Separated from the African continent and the Indian plate about 165 and 88 million years ago respectively (Ali and Aitchison, 2008), the flora and fauna of Madagascar followed its own evolutionary path. Isolation combined with a high number of micro-habitats (Pearson and 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 and 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 (136 MgC/ha in the moist forest, Vieilledent et al., 2016) and high rates of deforestation in Madagascar (1.4–4.7%/yr, Achard et al., 2002) are responsible for large CO_2 emissions in the atmosphere. 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

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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 (Broadbent et al., 2008; Gibson et al., 2013; Murcia, 1995). Forest fragmentation can also have substantial effects on forest carbon storage capacity, as carbon stocks are about 50% 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., 2013, 2016). 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 after year 2000. Harper et al. (2007) produced maps of forest cover and forest cover changes over Madagascar for the years 1953, 1973, 1990 and 2000. The 1953 forest map is a vector map derived from the visual interpretation of aerial photographs. Forest maps for the years 1973, 1990, and 2000 were obtained from the supervised classification of Landsat satellite images and can be used to derive more accurate estimates of forest cover than those from the FAO Forest Resource Assessment report. 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 km^2 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 et al., 2009; ONE et al., 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 et al., 2015). However, these maps are either too old to give recent estimates of deforestation (MEFT et al., 2009; ONE et al., 2013), include large areas of missing information due to images with high percentage of cloud cover (ONE et al., 2013), or show large mis-classification in specific areas, especially in the dry and spiny forest domain, for which the spectral signal shows strong seasonal variations 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 et al., 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 tree cover loss and 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 this study, we present a simple approach which combines the historical forest maps from Harper et al. (2007) and the more recent global 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 1953 to 2014. We finally discuss the possibility to extend our approach to other tropical countries or repeat it in the future for Madagascar. We also discuss how our results could help assess the effectiveness of past and current conservation strategies in Madagascar, and implement new strategies in the future.

2. Materials and methods

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

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

The 2000 Harper's forest map includes 208 000 ha of unclassified areas due to the presence of clouds on satellite images. Unclassified areas were mostly (88%) present within the moist forest domain which covered 4.17 Mha 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) and selected a tree cover threshold of 75% to define the forest (Achard et al., 2014; Aleman et al., 2017). This threshold allows to characterize properly the moist forest in Madagascar as 90% of the moist forest in 2000 in Harper et al. (2007) has a tree cover greater than 75% (Fig. A1). For this step, the Hansen's 2000 tree cover map was resampled on the same grid as the original Harper's map at 30 m resolution using a bilinear interpolation. We thus obtained a forest cover map for the year 2000 covering the full territory of Madagascar.

We then combined the forest cover map of the year 2000 with the annual tree cover loss maps from 2001 to 2014 from Hansen et al. (2013) to create annual forest cover maps from 2001 to 2014 at 30 m resolution. To do so, Hansen's tree cover loss maps were resampled on the same grid as the original Harper's map at 30 m resolution using a nearest-neighbor interpolation. 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. Indeed, there is little evidence of natural forest regeneration in Madagascar (Grouzis et al., 2001; Harper et al., 2007), especially over such a short period of time. The remaining unclassified pixels were limited to a relatively small total area of about 8000 ha. We labeled these residual pixels as non-forest, as for the year 2000.

The 1973 forest cover map for Madagascar from Harper et al. (2007) is a raster map at 57 m resolution derived from the supervised classification of Landsat MSS (Multispectral Scanner System) satellite images. We resampled this map at 30 m resolution using a nearest-