*Environmental Conservation* **34** (4): 325–333 © 2007 Foundation for Environmental Conservation doi:10.1017/S0376892907004262

# Fifty years of deforestation and forest fragmentation in Madagascar

GRADY J. HARPER[1]*, MARC K. STEININGER[1], COMPTON J. TUCKER[2], DANIEL JUHN[1] AND FRANK HAWKINS[1,3]

[1]*Conservation International, 2011 Crystal Drive suite 500, Arlington VA 22202, USA,* [2]*Code 923 NASA/GSFC, Greenbelt, Maryland 20771, USA, and* [3]*Conservation International, BP 5178, Antananarivo 101, Madagascar*

Date submitted: 29 June 2006 Date accepted: 26 September 2007 First published online: 21 December 2007

## SUMMARY

**Tropical deforestation is a key contributor to species extinction and climate change, yet the extent of tropical forests and their rate of destruction and degradation through fragmentation remain poorly known. Madagascar's forests are among the most biologically rich and unique in the world but, in spite of longstanding concern about their destruction, past estimates of forest cover and deforestation have varied widely. Analysis of aerial photographs (*c.* 1953) and Landsat images (*c.* 1973, *c.* 1990 and *c.* 2000) indicates that forest cover decreased by almost 40% from the 1950s to *c.* 2000, with a reduction in 'core forest' > 1 km from a non-forest edge of almost 80%. This forest destruction and degradation threaten thousands of species with extinction. Country-wide coverage of high-resolution validated forest cover and deforestation data enables the precise monitoring of trends in habitat extent and fragmentation critical for assessment of species' conservation status.**

*Keywords*: deforestation, forest, fragmentation, Madagascar, remote sensing

## INTRODUCTION

### Tropical forests and deforestation

Tropical forests cover less than 10% of Earth's terrestrial surface (Mayaux *et al.* 2005), yet they are thought to host at least 50% of terrestrial species (Lovejoy 1997) and contain 45% of the above-ground carbon in vegetation (Watson *et al.* 2000). The annual global deforestation rate of humid tropical forests is estimated to have been 0.5% between 1990 and 1997, with regional annual rates of up to 5.9% (Achard *et al.* 2002). However, large uncertainties still exist, with a range of ±24% at the 95% confidence level for the global estimate, and ±56% for Latin America. Achard *et al.*'s (2002) estimate for annual deforestation of humid tropical forests at the global level from 1990–1997 is 23% less than that of the United Nation's Food and Agriculture Organization (FAO 2000) from 1990–2000, and 41% less for Africa. Uncertainties aside, much forest data produced to date is of limited utility. FAO forest studies do not produce spatially explicit maps, which are essential for forest fragmentation analysis, and for analyses incorporating other spatial datasets. Maps of 1 km resolution are an improvement, but are still of limited use for fragmentation analysis and are on a scale that misses much detail relevant to biodiversity conservation. More precise and detailed information on the extent and distribution of tropical forests and their rate of clearing are essential to estimating threats to biological diversity and carbon emissions.

Deforestation threatens species survival and diminishes biodiversity by destroying forest habitat, creating forest fragments too small to maintain viable populations and increasing 'edge effects' at forest/non-forest interfaces (Harris 1984). Edge effects due to fragmentation typically affect an area several times larger than the forest destruction itself (Harris 1984; Skole & Tucker 1993), affecting micro-meteorology over short distances (Kapos 1989), and increasing exposure to damaging winds (Ferreira & Laurance 1997), fire frequency (Cochrane 2001), and access for livestock, other non-forest animals and hunters (Enserink 1999; Cullen *et al.* 2000). To assess the impact of tropical deforestation on biological diversity, not only the area deforested, but also the isolation of forest patches and the area of edge habitat must be determined.

### Madagascar

Madagascar's separation from Africa approximately 165 million years ago, and from India 70 million years ago (Rakotosamimanana 2003) is reflected in extremely high biological endemism (Table 1). More than 90% of Madagascar's endemic animal species live exclusively in forest or woodland (Dufils 2003). The tropical forests of Madagascar are among the highest priority areas in the world for biodiversity conservation (Myers *et al.* 2000).

Estimates of forest and woodland cover prior to human arrival between the fourth and seventh centuries AD have varied widely, with some arguing that forest covered 90% or more of the island (Humbert & Cours Darne 1965), while others argue that it was less (Kull 2000). By 1600 AD, deforestation was reportedly already advanced in the central highlands, with the use of fire in zebu cattle grazing and slash-and-burn agriculture playing an important role (Gade 1996). By the late 19th century, concern about forest destruction had led to enactment of laws against agricultural

*Correspondence: Grady Harper Tel: +1 703 341 2761 Fax: +1 703 979 2514 e-mail: gharper@conservation.org

**Table 1** Species richness and endemism in Madagascar.

| *Taxon* | *No. of species* | *% Endemic* | *Source* |
|---|---|---|---|
| Plants | 12 000 | 85% | Gautier & Goodman (2003) |
| Birds | 209 (breeding) | 51% | Hawkins & Goodman (2003) |
| Mammals | 117 | 90% | Garbutt (1999) |
| Reptiles | 346 | >90% | Raxworthy (2003) |
| Amphibians | 199 | 99% | Glaw & Vences (2003) |

**Table 2** Historical estimates of Madagascar's forest cover. *Secondary and degraded forest classes not included in cover estimates from Humbert and Cours Darne (1965), Faramalala (1988) and the IEFN (1996). †Estimates include plantations. ‡Estimate does not include plantations.

| *Source* | *Time of data collection* | *Total forest area (km²)* | *Data source* |
|---|---|---|---|
| Blasco (1965), Humbert & Cours Darne (1965)* | 1949–1957 | 159 959 | 1:40 000 to 1:50 000 aerial photographs |
| Faramalala (1988)* | 1972–1979 | 106 370 | Landsat MSS photo interpretation (10% cloud cover) |
| Green & Sussman (1990) | 1984–1985 | 38 000 (humid forest only) | Partial Landsat MSS photo coverage of eastern forests |
| IEFN (1996)* | 1990–1994 | 103 010 | Landsat TM5, visual interpretation |
| Mayaux *et al.* (2000) | 1998–1999 | 101 041 | SPOT-4 Vegetation 1-km digital analysis |
| FAO (2000)† | 1990 | 129 010 | Interview |
| FAO (2000)† | 2000 | 117 270 | Interview |
| FAO (2000)‡ | 2000 | 113 770 | Interview |

burning (Jarosz 1993), to little effect. A human population of 17.9 million, growing at 2.8% $yr^{-1}$ (UNPF [United Nations Population Fund] 2004), coupled with widespread dependence on subsistence agriculture and fuelwood cutting, makes deforestation in Madagascar difficult to slow. Recent field studies have confirmed negative effects of deforestation and forest fragmentation in all of Madagascar's forested regions (Langrand & Wilmé 1997; Vallan 2000; Watson *et al.* 2004).

The first systematic forest map of Madagascar, produced by F. Blasco based on visual interpretation of aerial photography from 1949–1957 (Blasco 1965; Humbert & Cours Darne 1965), reported 159 959 $km^2$ of forest and mangrove suffering little or no degradation (Table 2). Faramalala (1988) estimated forest cover in *c*. 1973 to be 106 400 $km^2$ (see also IEFN [Inventaire Ecologique et Forestier National] 1996) based on visual interpretation of 1:1 000 000 scale Landsat image prints. A national forest inventory based on visual interpretation of Landsat 5 images, indicated 103 000 $km^2$ of 'little- to non-degraded' forest in 1994 (IEFN 1996). The FAO (2000) reported total forest cover (including natural forest and plantations) in 1990 to be 129 010 $km^2$ and cover in 2000 of 117 270 $km^2$; they estimated natural forest cover in 2000 to be 113 770 $km^2$ (FAO 2000). Using 1-km SPOT Vegetation data, Mayaux *et al.* (2000) estimated there was 101 000 $km^2$ of primary forest in 1999.

The differences among these estimates are caused by differences in definitions of forest, mapping techniques and resolution of data used. Work in other regions has demonstrated that forest cover, fragmentation and clearance estimates are most accurate when produced from digital analysis of high-resolution images covering the entire study area, used in conjunction with ground or aerial verification (Townshend & Justice 1988; Tucker & Townshend 2000; Steininger *et al.* 2001).

## METHODS

### Overview

For this study, we used orthorectified Landsat images from NASA's Geocover project (Tucker *et al.* 2004) for the 1970s, *c.* 1990 and *c.* 2000, and we digitized the Humbert and Cours Darne (1965) map from the 1950s. We mapped humid and dry forest, spiny forest and woodland, mangrove, non-forest, water cloud/cloud shadow. Similar to previous studies of tropical forest cover (see for example Skole & Tucker 1993, Steininger *et al.* 2001), we defined 'forest' as areas of primary vegetation dominated by tree cover at least seven metres in height, with neighbouring trees crowns touching or overlapping when in full leaf. In practice, this means that the canopy is at least 80% closed. 'Spiny forest and woodland' is primary vegetation dominated by closed-canopy trees or shrubs in the arid southern and south-western regions of Madagascar, sometimes as low as two metres in height in the extreme south. We did not include open-canopy areas, secondary formations or plantations in our estimates of forest and woodland areas. Lightly degraded primary forest and mature secondary forest may be indistinguishable from primary forest in Landsat imagery. However, we saw little evidence of forest regeneration in Madagascar. Thus, the forest classes include virtually all natural forest habitat upon which 90% of Madagascar's fauna depend.

### Mapping methods

For the 1970s, we used Landsat Multispectral Scanner (MSS) data from the period 1972–1979, predominantly 1973; for *c.* 1990, we used Landsat Thematic Mapper (TM) data from 1989–1996, predominantly 1990; and for *c.* 2000, we used Landsat Enhanced Thematic Mapper Plus (ETM+) data from 1999–2001, predominantly 2000. All dates of satellite imagery were co-registered to sub-pixel precision to minimize false change caused by locational inconsistency between dates. Our analyses were conducted at a 57-m spatial resolution for the 1970s and at a 28.5-m spatial resolution for *c.* 1990 and *c.* 2000.

The *c.* 1990 and *c.* 2000 data were classified together in a single multi-date image to produce a direct estimate of change. Classification of multi-date images, rather than classifying single-date images individually and then combining them to derive change estimates, reduces false-change errors caused by differences between image dates in vegetation phenology, illumination conditions and atmospheric interference.

A supervised methodology was used to classify each two-date 'image pair'. Our classification was based on a simple set of classes: forest, non-forest, water, cloud/shade (no data), and mangrove. Because we classified two-date images, we had to train the classification for all observed combinations of these basic classes (for example forest to forest, forest to non-forest, non-forest to cloud). For these 'basic class combinations' it was often necessary to create multiple sub-classes or 'signatures', in order to capture the full range of spectral variation in an image pair. Each of these signatures, in turn, consisted of a number of polygonal training sites drawn on top of the satellite image by the classifier. These training sites were identified through visual interpretation of the satellite imagery informed by literature research, consultation with biologists familiar with Madagascar's landscape, purchased aerial photos and five days of overflights.

The process of classification was iterative. A set of signatures representing all observed combinations of basic classes was created; the classification was run and the resulting thematic image was inspected for errors with reference to both dates of the satellite image pair; errors were corrected by editing the training sites of existing signatures and/or creating additional signatures. This iterative process continued until visual inspection of the classification revealed no further obvious errors. The sub-classes of the final classifications were recoded into the general classes of the final product. The recoded classifications were filtered using two passes of a three-by-three orthogonal neighbourhood majority filter, followed by a 2-ha 'eliminate' function in Erdas Imagine 8.4. The filtered classifications were then joined to produce a seamless country mosaic.

We classified the 1970s images separately because of their lower spatial resolution, and different spectral bands and radiometric sensitivity. This imagery was analysed with reference to the *c.* 1990–*c.* 2000 images and classifications to minimize the aforementioned sources of error. The 1970s analysis was merged with the *c.* 1990–*c.* 2000 analysis to create a three-date map of forest cover and deforestation.

We used a number of rules in combining the 1970s data with the *c.* 1990–*c.* 2000 data in order to minimize errors in the cover and change estimates. For example, areas that were seen to be forest on either date in the *c.* 1990–*c.* 2000 map, but as non-forest or water in the 1970s map, were recoded to be forest in the 1970s, because the superior quality of the later imagery made it more reliable.

Internal geometric differences between the 1950s photo-based data and the Landsat data of later years made it impractical to merge the 1950s map with the Landsat-based map. Thus, only an aggregate numeric forest change estimate could be made for the 1950s–1970s period, versus the spatially explicit forest change estimates for the 1970s–*c.* 1990 and *c.* 1990–*c.* 2000 periods.

A bioclimatic mask was used to separate the mapped forest into humid forest, dry forest and spiny forest; mangrove forest was already a distinct class (Fig. 1). The bioclimatic mask is based in part on the Missouri Botanical Gardens 'Bioclimate 5' product (Schatz & Lescot 2003), the humid zone being a combination of the 'humid', 'sub-humid' and 'montane' zones in Bioclimate 5. We defined the spiny forest and woodland zone using local expertise, and defined the dry forest zone as the remainder of the country.

### Calculation of deforestation rates

The extent and rate of forest loss in each forest class was calculated for each two-date time period using only pixels that were cloud-free in both dates in question. Forest extent and fragmentation indices were calculated for each of these four forest classes for each date.

We calculated average annual deforestation rates from the mosaic map, based on change intervals of 20 years (*c.* 1953–*c.* 1973), 17 years (*c.* 1973–*c.* 1990), and 10 years (*c.* 1990–*c.* 2000). Using these average intervals instead of the actual dates of each image pair classified decreases the temporal precision of the calculations. But, given the large study area and the large number of images, we believe the impact on the accuracy of our figures is small, especially for the *c.* 1990–*c.* 2000 period when most image dates were tightly clustered around the target dates of 1990 and 2000.

### Fragmentation

Fragmentation was represented by two variables: forest patch size and proximity of forest to non-forest edge. The presence

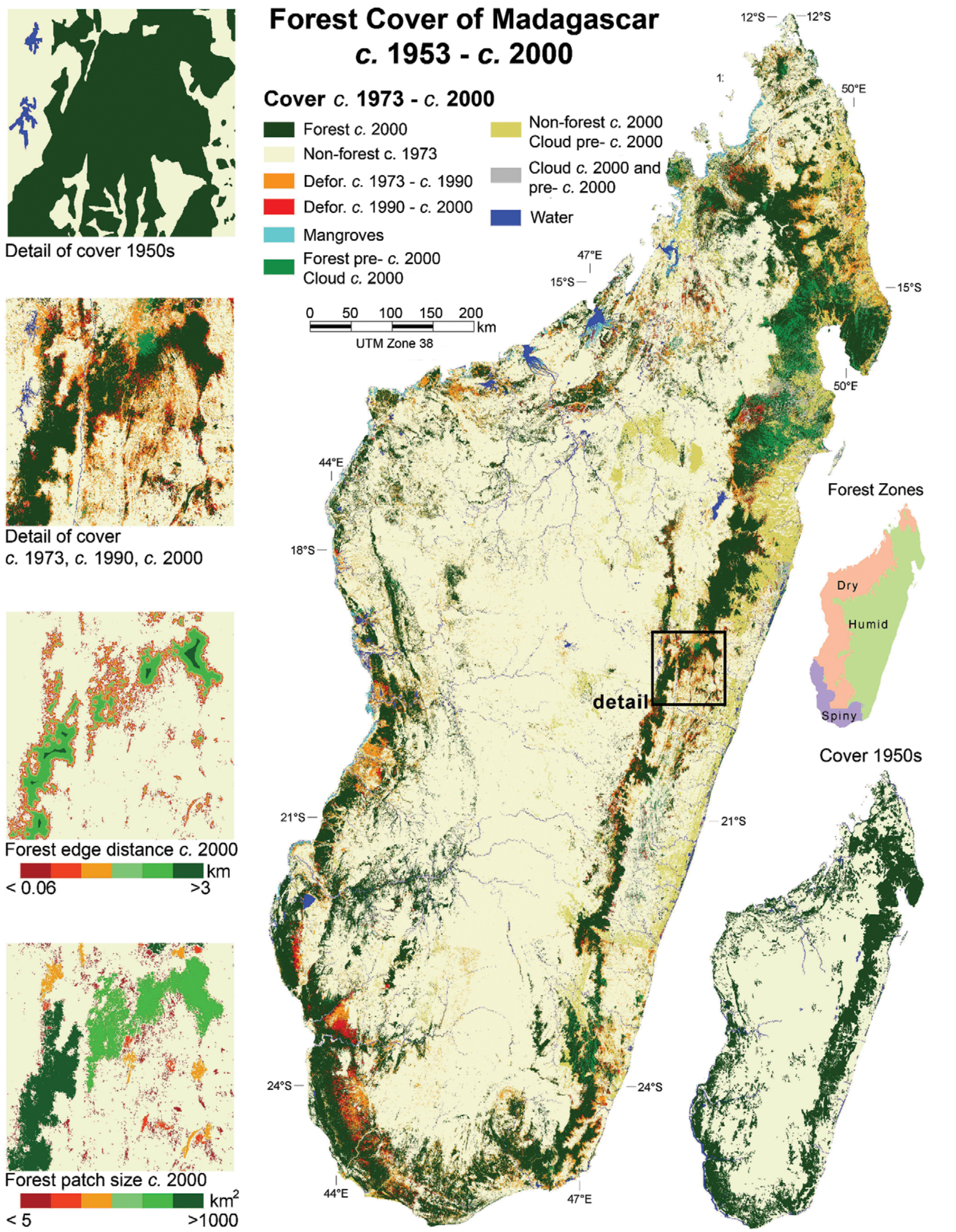


**Figure 1** Madagascar forest cover from the 1950s to *c*. 2000. Forest cover changes from the 1970s to *c*. 2000 are shown in the main figure, and forest cover in the 1950s is shown in the lower-right inset.

https://doi.org/10.1017/S0376892907004262 Published online by Cambridge University Press

**Table 3** Madagascar's known forest cover 1950s–*c*. 2000. *Known forest cover is visible forest plus cloud- or shade-obscured areas that were visible forest at a later date. †Unknown indicates an area obscured by cloud or shadow at a given date, whose land cover type cannot be deduced with certainty from data from earlier or later dates. n/a = not available. The increase in spiny forest cover from the 1950s to the 1970s seems likely to have been due to differences in forest definition and mapping methods.

| *Forest cover type* | *1950s aerial photographs* | *1970s MSS data* | *c. 1990 TM data* | *c. 2000 ETM data* |
|---|---|---|---|---|
| Humid (km$^2$) | 87 656 | 68 760 | 52 343 | 41 668 |
| Dry (km$^2$) | 42 521 | 40 277 | 27 118 | 24 570 |
| Spiny (km$^2$)† | 29 782 | 30 298 | 24 200 | 21 322 |
| Mangrove (km$^2$) | n/a | n/a | 2396 | 2261 |
| Total known forest (km$^2$)* | 159 959 | 141 731 | 106 057 | 89 821 |
| Total known forest (%)* | 27.0 | 23.9 | 17.9 | 15.1 |
| Total area of unknown cover type (km$^2$)† | 0 | 34 433 | 5003 | 11 244 |
| Total area of unknown cover type (%)† | 0 | 5.8 | 0.8 | 1.9 |

Table 4 Madagascar's deforestation 1950s–*c*. 2000. Deforestation rates were calculated over average time periods of 20, 17 and 10 years. Figures for the actual area deforested in the 1950s–1970s are omitted because deforestation was not directly observed for this time range; percent deforestation rates are calculated from aggregate forest areas. n/a = not available.

| *Forest cover type* | *1950s–1970s* | *1970s–c. 1990* | *c. 1990–c. 2000* |
|---|---|---|---|
| Observed deforestation over time interval (km$^2$) | | | |
| Humid | – | 14 822 | 3220 |
| Dry | – | 13 116 | 1982 |
| Spiny | – | 6097 | 2817 |
| Mangroves | – | n/a | 55 |
| Total | – | 34 035 | 8074 |
| Observed deforestation (% yr$^{-1}$) | | | |
| Humid | 0.6 | 1.7 | 0.8 |
| Dry | 0.2 | 1.9 | 0.7 |
| Spiny | -0.1 | 1.2 | 1.2 |
| Mangroves | n/a | n/a | 0.2 |
| Total | 0.3 | 1.7 | 0.9 |

of clouds required us to make a number of assumptions in order to provide the most realistic estimates of fragmentation. Cloud cover can make a large forest patch appear like two or more smaller patches. To minimize this effect, for a given date, any areas of cloud cover that were forested in the most recent previous cloud-free date were counted as forest. This was done only for the assessment of fragmentation and thus the total areas for forest and woodland in Tables 3 and 4 differed from those in Table 5. We defined forest and woodland edge habitat as areas within a specified distance from non-forest patches >5 ha.

### Validation

We collected GPS-linked digital photography and video imagery during five days of low altitude flights in September 2002. We used one subset of these data to assist interpretation and another to estimate the accuracy of our *c*. 2000 classification. Based upon our error analysis of 342 areas distributed among the three forest zones, we estimated 89.5% accuracy in identification of forest and non-forest. To directly estimate the error of our deforestation class would have required two dates of validation data, corresponding to the two dates of satellite imagery in question, but this was unavailable. The error in the deforestation class is not the product of the error for forest and non-forest in the two dates of classification because we conducted a direct multi-temporal classification. We believe it is reasonable to assume that the error rate for the deforestation class was about the same as the error rate for the forest and non-forest classes.

### Supplementary information

A list of image dates used for this analysis, and information on obtaining full-resolution digital files of the forest cover, deforestation and fragmentation maps are available via the internet at http://science.conservation.org/portal/server.pt?open=512&objID=755&&PageID=127564&mode=2&in_hi_userid=124186&cached=true

## RESULTS

In the 1950s, there was 160 000 km$^2$ of forest cover in Madagascar, comprising 55% humid, 26% dry and 19% spiny forest (Table 3). The *c*. 2000 data showed a total 89 800 km$^2$ of forest, with an estimated accuracy of about 90%. An additional area of more than 11 200 km$^2$ was obscured by cloud and of that area, almost 9200 km$^2$ were forested in the

**Table 5** Fragmentation of Madagascar's forests, 1950s–*c*. 2000. Fragmentation is measured by distribution of forest area (1) by patch-size, and (2) by distance of forest from a non-forest edge. All forest types are aggregated in these figures.

| | *1950s* | | *1970s* | | *c. 1990* | | *c. 2000* | |
|---|---|---|---|---|---|---|---|---|
| | *km²* | *%* | *km²* | *%* | *km²* | *%* | *km²* | *%* |
| Size class (km²) | | | | | | | | |
| 0–10 | 7971 | 5.0 | 28 072 | 19.8 | 23 321 | 21.7 | 23 372 | 23.6 |
| 10–50 | 12 424 | 7.8 | 8954 | 6.3 | 8442 | 7.8 | 7782 | 7.9 |
| 50–100 | 6078 | 3.8 | 4056 | 2.9 | 3663 | 3.4 | 3820 | 3.9 |
| 100–500 | 16 206 | 10.1 | 11 588 | 8.2 | 8982 | 8.3 | 9978 | 10.1 |
| 500–1000 | 5825 | 3.6 | 5383 | 3.8 | 7392 | 6.9 | 8391 | 8.5 |
| 1000–5000 | 14 780 | 9.2 | 26 733 | 18.9 | 14 219 | 13.2 | 12 293 | 12.4 |
| 5000–10000 | 0 | 0 | 23 308 | 16.4 | 25 135 | 23.3 | 17 778 | 18.0 |
| >10000 | 96 685 | 60.4 | 36 637 | 23.7 | 16 544 | 15.4 | 15 600 | 15.8 |
| Total | 159 969 | 100 | 141 732 | 100 | 107 698 | 100 | 99 015 | 100 |
| Distance from non-forest edge (m) | | | | | | | | |
| 0–57 | 5715 | 3.6 | 30 794 | 21.7 | 25 272 | 23.5 | 24 862 | 25.1 |
| 58–114 | 5660 | 3.5 | 15 454 | 10.9 | 12 723 | 11.8 | 12 373 | 12.5 |
| 115–257 | 12 778 | 8.0 | 19 453 | 13.7 | 15 934 | 14.8 | 15 116 | 15.3 |
| 257–513 | 19 965 | 12.5 | 18 818 | 13.3 | 15 155 | 14.1 | 13 919 | 14.1 |
| 514–998 | 25 447 | 15.9 | 19 118 | 13.5 | 14 705 | 13.7 | 13 012 | 13.1 |
| 998–2993 | 45 217 | 28.3 | 27 305 | 19.3 | 18 441 | 17.1 | 15 494 | 15.6 |
| >2993 | 45 161 | 28.2 | 10 795 | 7.6 | 5471 | 5.1 | 4244 | 4.3 |
| Total | 159 943 | 100 | 141 739 | 100 | 107 703 | 100 | 99 019 | 100 |

most recent previous clear image; the remaining 2100 km² were cloud obscured in all three dates of satellite imagery. Cloud cover was generally associated with the humid forest-covered slopes of the north-eastern mountains. Thus total forest cover in Madagascar in *c*. 2000 was in the range 89 800–101 100 km², with a probable area of around 99 000 km². This forest cover estimate is within 5% of the IEFN (1996) and Mayaux *et al*. (2005) estimates (Table 2). Faramalala's (1988) estimate, based on data from the early 1970s, is closer to our *c*. 1990 estimate than our 1970s estimate.

Average rates of deforestation were 0.3% $yr^{-1}$ from the 1950s to the 1970s, 1.7% $yr^{-1}$ from the 1970s to *c*. 1990, and 0.9% $yr^{-1}$ from *c*. 1990 to *c*. 2000 (Table 4; Fig. 1). The greatest loss occurred in the humid and dry forests, which between the 1950s and *c*. 2000 lost 43% and 41% of their area, respectively. Spiny forest area decreased 28% over the same period, but had the highest clearance rate during the 1990s of almost 1.2% $yr^{-1}$.

In the 1990s, the greatest clearance of spiny forest occurred in the region centred around the city of Toliara. Two contiguous areas of spiny forest >100 000 ha were cleared to the north and north-east of the city, along with widespread smaller patches of deforestation, primarily to the south. Deforestation rates for the humid and dry forests slowed during the 1990s. Even so, several contiguous patches of 20 000–50 000 ha were cleared in the dry forests of the west-central part of the island during the 1990s. The more general pattern of deforestation in the dry and humid forests was of small-scale clearance at forest edges.

By the 1950s, over 26% of all forest occurred in patches <500 km² and over 43% within 1 km of a non-forest edge. By *c*. 2000, over 45% of all forest was in patches <500 km² and over 80% within 1 km of a non-forest edge. A quarter of the remaining forest in *c*. 2000 was within 57 m of a non-forest edge and nearly a quarter was in isolated forest patches of less than 10 km² (Table 5; Fig. 2). For most parts of the island, with the exception of the eastern humid forest and south-western dry and spiny forest, forest patches were <100 km² (Fig. 1).

Dry forests were by all measures the most fragmented forest type throughout the study period, and increased in fragmentation primarily from the 1950s–*c*. 1990. Despite an overall decrease in humid forest cover, fragmentation of the humid forest increased only slightly from the 1970s–*c*. 2000, whereas spiny forest fragmentation increased continuously over the study period (Fig. 2).

## DISCUSSION

By the 1950s, only 27% of Madagascar was forested and even a conservative estimate of pre-human forest cover suggests it had already lost more than half of its forest cover; the loss may have been as much as two-thirds, or more. Forest cover further declined to approximately 16% in *c*. 2000, a loss of 40% in 50 years. Taking fragmentation into consideration, the impact was even more dramatic. From the 1950s to *c*. 2000, the area of 'core forest' (forest >1 km from a non-forest edge) decreased from >90 000 km² to <20 000 km². The area in patches of >100 km² decreased by more than half. The slowing rate of deforestation in the humid and dry forests after *c*. 1990 is encouraging, but the deforestation rates

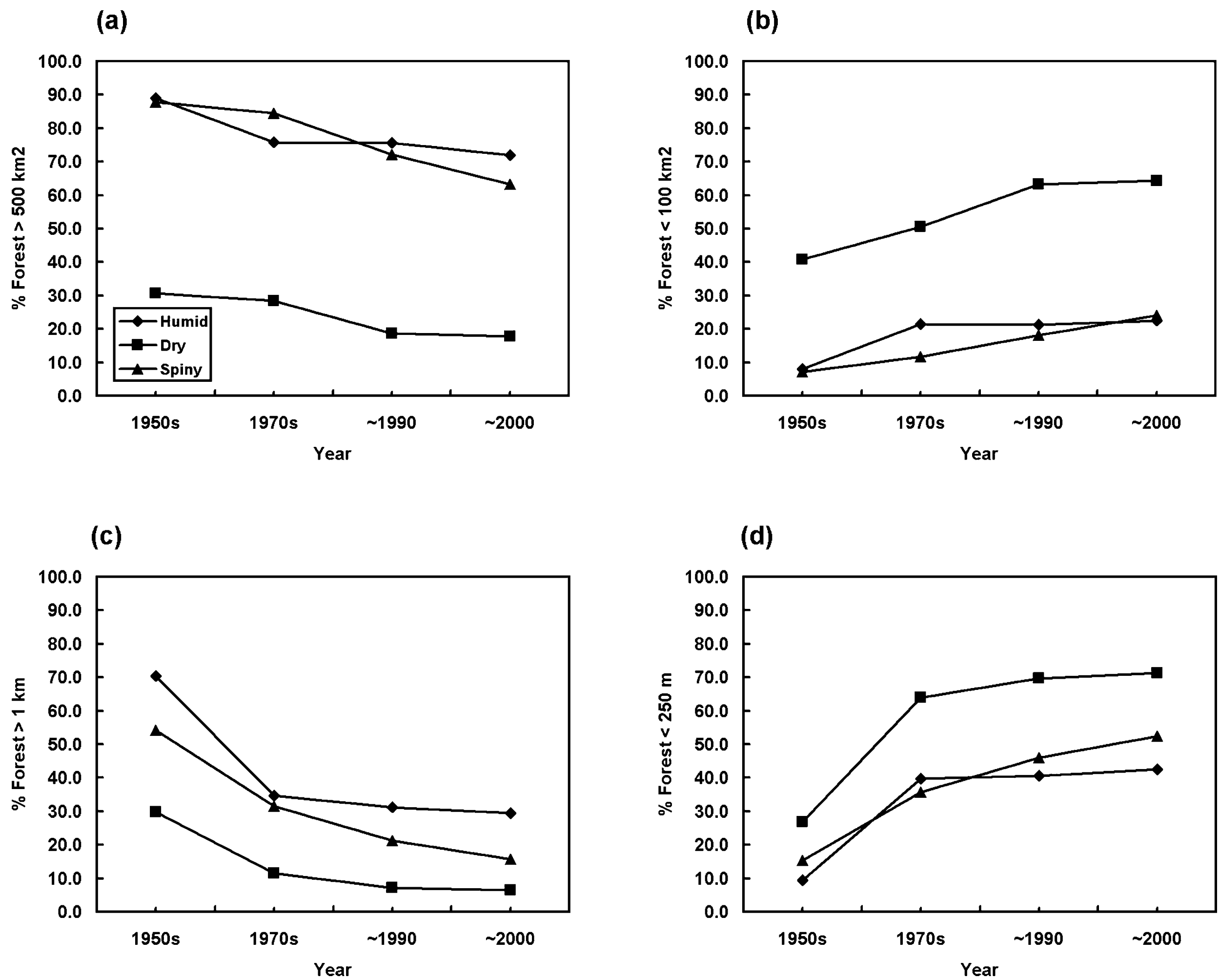


**Figure 2** Trends in fragmentation of Madagascar's forest and woodland from the 1950s to *c*. 2000. Fragmentation is measured by distribution of forest area (1) by patch-size, and (2) by distance of forest from a non-forest edge. (*a*) Percentage of forest in patches > 500 $km^2$ in area. (*b*) Percentage of forest in patches < 100 $km^2$ area. (*c*) Percentage of forest > 1 km from a forest edge. (*d*) Percentage of forest < 250 m from a forest edge.

among all forest types are still disturbing, given their small remaining area and fragmented state.

These results demonstrate extensive loss and degradation of the forest habitat on which 90% of Madagascar's fauna depend. Given the probable lag-time of species extinction following habitat destruction (Brooks *et al*. 1999; Cowlishaw 1999), it is likely that many species are living on 'borrowed time'. These results emphasize the need for redoubled forest conservation efforts in Madagascar. We suggest (1) halting further primary forest clearance as soon as possible, and (2) exploring the potential of strategically located forest restoration efforts for mitigation of species extinctions.

The data here contribute to the goal of halting deforestation by providing precise information necessary to study the causes of deforestation in Madagascar. Only with such understanding may effective policy be formulated. These data may also be used to help prioritize forest conservation activities by identifying forest habitat critical to biodiversity. Critical forest habitat may be identified by combining these forest data with the range polygons of forest-dependent species, protected area polygons, and spatial analyses of levels of endemism and number of threatened species. Similar analysis, with the addition of data on forest fragmentation and secondary forest cover, may be used to identify strategic locations for forest restoration. We do not know how much forest has been lost since 2000. We recommend regular updates to these data to enable more rapid and adaptive response to deforestation threats in Madagascar.

## ACKNOWLEDGEMENTS

This work was supported by Conservation International (CI), the Center for Biological Conservation (CBC) in Madagascar, and NASA's 'Mission to Planet Earth'. We thank the CBC for support for the aerial surveys; François Blasco of the

University of Toulouse for use of the 1950s maps, and Sara Musinsky, Leanne Miller and Minnie Wong of CI for assistance with the work.

## References

Achard, F., Eva, H.D., Stibig, H.J., Mayaux, P., Gallego, J., Richards, T. & Malingreau, J.P. (2002) Determination of deforestation rates of the world's humid tropical forests. *Science* **297**(5583): 999–1002.

Blasco, F. (1965) Notice de la carte de Madagascar. In: *Notice de la carte de Madagascar*, ed. H. Humbert & G. Cours Darne, pp. 4–13. Puducherry, India: Section Scientifique et Technique de L'Institut Francais de Pondichéry.

Brooks, T.M., Pimm, S.L. & Oyugi, J.O. (1999) Time lag between deforestation and bird extinction in tropical forest fragments. *Conservation Biology* **13**(5): 1140–1150.

Cochrane, M.A. (2001) Synergistic interactions between habitat fragmentation and fire in evergreen tropical forests. *Conservation Biology* **15**(6): 1515–1521.

Cowlishaw, G. (1999) predicting the pattern of decline of African primate diversity: an extinction debt from historical deforestation. *Conservation Biology* **13**(5): 1183–1193.

Cullen, L., Bodmer, R.E. & Padua, C.V. (2000) Effects of hunting in habitat fragments of the Atlantic forests, Brazil. *Biological Conservation* **95**(1): 49–56.

Dufils, J.M. (2003) Remaining forest cover. In: *The Natural History of Madagascar*, ed. S.M. Goodman & J.P. Benstead, pp. 88–96. Chicago, IL, USA: University of Chicago Press.

Enserink, M. (1999) Biological invaders sweep in. *Science* **285**(5435): 1834–1836.

FAO (2000) *Global Forest Resources Assessment 2000*. Rome, Italy: Food and Agriculture Organization of the United Nations.

Faramalala, M.H. (1988) Etude de la végétation de Madagascar à l'aide des données spatiales. Doctoral Thesis, L'Universite Paul Sabatier, Toulouse, France.

Ferreira, L.V. & Laurance, W.F. (1997) Effects of forest fragmentation on mortality and damage of selected trees in Central Amazonia. *Conservation Biology* **11**(3): 797–801.

Gade, D.W. (1996) Deforestation and its effects in highland Madagascar. *Mountain Research and Development* **16**(2): 101–116.

Garbutt, N. (1999) *Mammals of Madagascar*. New Haven, CT, USA: Yale University Press.

Gautier, L. & Goodman, S.M. (2003) Introduction to the flora of Madagascar. In: *The Natural History of Madagascar*, ed. S.M. Goodman & J.P. Benstead, pp. 229–250. Chicago, IL, USA: University of Chicago Press.

Glaw, F. & Vences, M. (2003) Introduction to amphibians. In: *The Natural History of Madagascar*, ed. S.M. Goodman & J.P. Benstead, pp. 883–898. Chicago, IL, USA: University of Chicago Press.

Green, G.M. & Sussman, R.W. (1990) Deforestation history of the eastern rain forests of Madagascar from satellite images. *Science* **248**(4952): 212–215.

Harris, L.D. (1984) *The Fragmented Forest: Island Biogeographic Theory and the Preservation of Biological Diversity*. Chicago, IL, USA: The University of Chicago Press.

Hawkins, A.F.A. & Goodman, S.M. (2003) In: *The Natural History of Madagascar*, ed. S.M. Goodman & J.P. Benstead, pp. 1019–1044. Chicago, IL, USA: University of Chicago Press.

Humbert H. & Cours Darne G., eds (1965) *Notice de la Carte Madagascar*. Puducherry, India: Section Scientifique et Technique de L'Institut Francais de Pondichéry.

IEFN (1996) *Inventaire Ecologique Forestier National*. Antananarivo, Madagascar: Ministère de l'Environnement.

Jarosz, L. (1993) Defining and explaining tropical deforestation: shifting cultivation and population-growth in colonial Madagascar (1896–1940). *Economic Geography* **69**(4): 366–379.

Kapos, V. (1989) Effects of isolation on the water status of forest patches in the Brazilian Amazon. *Journal of Tropical Ecology* **5**(2): 173–185.

Kull, C.A. (2000) Deforestation, erosion, and fire: degradation myths in the environmental history of Madagascar. *Environment and History* **6**(4): 423–450.

Langrand, O. & Wilmé, L. (1997) Effects of forest fragmentation on extinction patterns of the endemic avifauna on the central high plateau of Madagascar. In: *Natural Change and Human Impact in Madagascar*, ed. S.M. Goodman & B.D. Patterson, pp. 280–308. Washington, DC, USA: Smithsonian Institution Press.

Lovejoy, T.E. (1997) Biodiversity: what is it? In: *Biodiversity II. Understanding and Protecting Our Biological Resources*, ed. M.L. Reaka-Kudla, D.E. Wilson & E.O. Wilson, pp. 7–14. Washington, DC, USA: Joseph Henry Press.

Mayaux, P., Gond, V. & Bartholome, E. (2000) A near-real time forest-cover map of Madagascar derived from SPOT-4 VEGETATION data. *International Journal of Remote Sensing* **21**(16): 3139–3144.

Mayaux, P., Holmgren, P., Achard, F., Eva, H., Stibig, H.-J. & Branthomme, A. (2005) Tropical forest cover change in the 1990s and options for future monitoring. *Philosophical Transactions of the Royal Society of London Series B-Biological Sciences* **360**(1454): 373–384.

Myers, N., Mittermeier, R.A., Mittermeier, C.G., da Fonseca, G.A.B. & Kent, J. (2000) Biodiversity hotspots for conservation priorities. *Nature* **403**(6772): 853–858.

Rakotosamimanana, B. (2003) Foreword. In: *The Natural History of Madagascar*, ed. S.M. Goodman & J.P. Benstead, p. xi. Chicago, IL, USA: University of Chicago Press.

Raxworthy, C.J. (2003) Introduction to the reptiles. In: *The Natural History of Madagascar*, ed. S.M. Goodman & J.P. Benstead, pp. 934–949. Chicago, IL, USA: University of Chicago Press.

Schatz, G.E. & Lescot, M. (2003) Gazetteer to Malagasy botanical collecting localities [www document]. URL http://www.mobot.org/MOBOT/Research/madagascar/gazetteer/

Skole, D. & Tucker, C.J. (1993) Tropical deforestation and habitat fragmentation in the Amazon: satellite data from 1978 to 1988. *Science* **260**(5116): 1905–1910.

Steininger, M.K., Tucker, C.J., Townshend, J.R.G., Killeen, T.J., Desch, A., Bell, V. & Ersts, P. (2001) Tropical deforestation in the Bolivian Amazon. *Environmental Conservation* **28**(2): 127–134.

Townshend, J.R.G. & Justice, C.O. (1988) Selecting the spatial resolution of satellite sensors required for global monitoring of land transformations. *International Journal of Remote Sensing* **9**(2): 187–236.

Tucker, C.J. & Townshend, J.R.G. (2000) Strategies for monitoring tropical deforestation using satellite data. *International Journal of Remote Sensing* **21**(6–7): 1461–1471.

Tucker, C.J., Grant, D.M. & Dykstra, J.D. (2004) NASA's global orthorectified Landsat data set. *Photogrammetric Engineering and Remote Sensing* **70**(3): 313–322.

UNPF (2004) *State of World Population 2004*. New York, NY, USA: United Nations Population Fund.

Vallan, D. (2000) Influence of forest fragmentation on amphibian diversity in the nature reserve of Ambohitantely, highland Madagascar. *Biological Conservation* **96**(1): 31–43.

Watson, J.E.M., Whittaker, R.J. & Dawson, T.P. (2004) Avifaunal responses to habitat fragmentation in the threatened littoral forests of south-eastern Madagascar. *Journal of Biogeography* **31**: 1791–1807.

Watson, R.T., Noble, I.R., Bolin, B., Ravindranath, N.H., Verardo, D.J. & Dokken, D.J., eds (2000) *Land Use, Land-Use Change, and Forestry: Summary for Policy Makers*. Geneva, Switzerland: Intergovernmental Panel on Climate Change.

https://doi.org/10.1017/S0376892907004262 Published online by Cambridge University Press