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Decrease of deforestation in Protected Areas of Madagascar during the Covid-19 years

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ABSTRACT
Deforestation poses a significant threat to global biodiversity and ecosystem services. This study focuses on estimating the deforestation within Protected Areas (PAs) in Madagascar over a 21-year period from 2001 to 2022. A novel methodology utilizing remote sensing data and specific thresholds of tree canopy density is employed to estimate annual deforestation rates and identify trends and patterns within PAs. The analysis reveals significant deforestation in the PA network over the last decade, particularly in 2014, 2017, 2018, and 2019. Notably, the lowest annual deforestation rates were estimated during the Covid-19 years of 2020 (0.66%), 2021 (0.62%), and the subsequent year in 2022 (0.67%) when considering the entire network of 103 PAs with natural forests from 2013 to 2022.

RÉSUMÉ
La déforestation constitue une menace importante pour la biodiversité mondiale et les services écosystémiques. Cette étude se concentre sur l'évaluation de l'efficacité des aires protégées (AP) pour lutter contre la déforestation à Madagascar sur une période de 21 ans, de 2001 à 2022. Une méthodologie novatrice utilisant des données de télédétection et des seuils spécifiques de densité du couvert arboré est employée pour estimer les taux annuels de déforestation et identifier les tendances et les modèles au sein des AP. Au cours de la dernière décennie, l'analyse révèle une déforestation significative dans le réseau des AP au cours de certaines années, notamment en 2014, 2017, 2018 et 2019. En revanche, il est intéressant de noter qu'entre 2013 et 2022, les taux annuels de déforestation les plus bas ont été estimés pendant les années de Covid-19 en 2020 (0,66 %), 2021 (0,62 %) et l'année suivante en 2022 (0,67 %) sur l'ensemble du réseau des 103 AP avec des forêts naturelles.

INTRODUCTION
Madagascar is globally recognized for its exceptional forest biodiversity, which faces ongoing threats due to escalating deforestation rates and high poverty levels (Ganzhorn et al. 2001, Rabesahala Horning 2012, Vieilledent et al. 2018, Jones et al. 2019, Estrada et al. 2022). The country's remarkable level of endemism and the proportion of threatened species has consistently placed it as a priority for conservation efforts (Ganzhorn et al. 2001, Waeber et al. 2016, Corson 2017, Rafanoharana et al. 2023a). Extensive research has shed light on the concerning levels of forest loss in Madagascar (Harper et al. 2007, Gorenflo et al. 2011, Allnutt et al. 2013, Mayaux et al. 2013, Zinner et al. 2014, Vieilledent et al. 2018). Despite challenges, the government has significantly expanded Protected Areas (PAs) to conserve remaining forests and protect endangered endemic flora and fauna (Gardner et al. 2018, Waeber et al. 2020, Ralimanana et al. 2022). Madagascar's forests are incredibly diverse, including dense humid forests, subhumid

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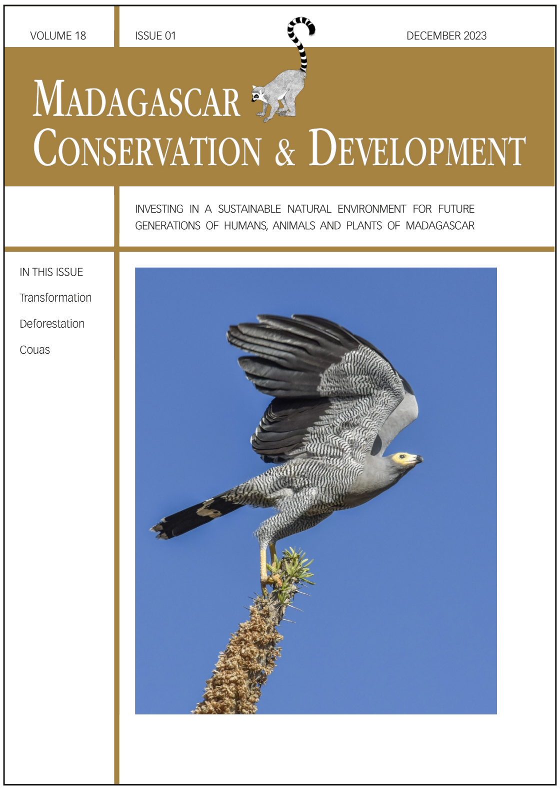

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forests, dry forests, dry spiny forests, and thickets. Distribution patterns are influenced by regional and local conditions (Moat and Smith 2007, Wilmé et al. 2006, 2012, Waeber et al. 2015, Hending et al. 2022).

Assessing the effectiveness of PAs in mitigating deforestation is crucial for Madagascar's conservation efforts. Eklund et al. (2016) analyzed data from two distinct time periods (1990–2000 and 2000–2010) and found evidence that PAs have played a role in reducing deforestation. The observed decrease in deforestation rates cannot be solely attributed to confounding factors related to protected land. The effectiveness of PAs varied between the two time periods, with lower deforestation rates in the later period alleviating pressures on PAs (Eklund et al. 2016). Nevertheless, Madagascar continues to experience a concerning trend of steadily increasing annual deforestation since 2005, with a significant loss of 99,000 hectares (ha) per year during 2010–2014, equivalent to a rate of 1.1% per year (Vieilledent et al. 2018). Of particular concern is the fact that approximately 46% of the remaining forest now lies within 100 meters of the forest edge, underscoring the immediate threat to the country's forest ecosystems (Vieilledent et al. 2018).

The assessment of forest cover using remote sensing relies on the algorithms employed for classifying various vegetation types, which include distinguishing between forested and non-forested areas. Rafanoharana et al. (2023b) developed an iterative approach adapted to accurately estimate forest cover within PAs. This methodology demonstrates a remarkable 89.4% accuracy in identifying specific thresholds of tree canopy density (TCD) compared to the standard TCD threshold of >30% with only 80.2% accuracy, represents a signuficant advancement in forest monitoring techniques. By applying this methodology, we seek to enhance our ability to effectively estimate annual deforestation to inform managers of Madagascar's PAs (Rafanoharana et al. 2023b).

In this study, we employ the methodology introduced by Rafanoharana et al. (2023b) to evaluate deforestation and annual deforestation rates in Madagascar's PAs spanning a 21-year duration. Our focus was on the period from 2013 to 2022, with a particular emphasis on the influence of the Covid-19 pandemic, characterized by a significant reduction in tourism and the temporary closure of PAs, on deforestation within these regions.

METHODOLOGY

In this study, we utilized the network of PAs as of 2015, which was detailed to noncontiguous parcels. We excluded any PAs or parcels that did not contain natural forests, resulting in a sample of 103 PAs comprising a total of 164 noncontiguous parcels (Rafanoharana et al. 2023b). To comprehend the general trend, we examined the deforestation over a span of 21 years, specifically analyzing the years with the highest and lowest rates of deforestation within the 103 PAs. Forest change was assessed by analyzing the evolution of tree canopy densities using specific thresholds as described by Rafanoharana et al. (2023b). Given that the areas of the 164 noncontiguous parcels ranged from 12 ha to 385,735 ha, we estimated not only the annual area of forest loss but also the annual deforestation rates of the remaining forest from the previous year. Our analysis primarily focused on the most recent 10-year period, starting in 2013, which coincided with the utilization of Landsat 8 and improved remote sensing data (Turubanova et al. 2023).

We employed the national shapefile obtained from Madagascar National Parks to encompass the entire network of PAs (Rafanoharana et al. 2023b). Additionally, we created a historical PA boundary by referencing the establishment decrees of each PA, thereby considering changes over time since 2000 (Figure 1, Table S1, Folder S1). To assess the changes in PA boundaries, we conducted a GIS analysis by overlaying the PA boundaries for the years 2000 and 2015. This process allowed us to determine the alterations in PA limits specifically in the years 2011, 2012, and 2015. The resulting PA boundaries were then combined with data on tree cover loss (TCL) and tree canopy density (TCD) obtained from sources such as Hansen et al. (2013) and Global Forest Watch (GFW 2022). The specific TCD (Rafanoharana et al. 2023b) was utilized to filter the deforestation in each noncontiguous parcel of every PA. We analyzed the deforestation in PAs regardless of the year in which they were gazetted.

To better understand and verify our interpretation of the identified deforestation patterns spanning the period from 2013 to 2022, we conducted consultations with some of the PA managers. Our primary objectives were twofold: first, to elucidate the drivers and causative factors contributing to deforestation, aimed at delineating the underlying reasons for deforestation in non-pandemic years. Secondly, we aimed to discern any notable alterations or plausible influences that may have occurred specifically during the Covid-19 pandemic years (2020 and 2021).

RESULTS

The network of PAs with natural forests has expanded significantly since 2000, comprising a total area of 6,351,500 ha of land across 103 PAs. This represents a 3.5-fold increase compared to the network of 43 PAs with natural forests in 2000 (Table 1, see also Table S1).

Deforestation within PAs is ongoing with annual deforestation representing at least 0.4% of the remaining forest every year since 2013. The rate consistently remains at or above 0.6% for the PAs gazetted in 2015 (Figure 2, Table 2). The total area of the network of the 103 PAs with forest was 2,407,830 ha in 2012 with an estimated forest cover of 1,694,460 ha (70.4%) based on Rafanoharana et al. (2023b), including Mikea National Park (NP) gazetted in 2011 (parcel 1 = 179,830 ha; parcel 2 = 4,805 ha) with an estimated area of dry spiny forest of 129,370 ha in parcel 1 in 2012 (80.9%), and Natural Park Makira gazetted in 2012 with an area of 373,340 ha including an estimated forest cover of 344,640 ha in 2012 (92.3%). IUCN conservation categories II and IV provide more effective forest protection in comparison to categories V and VI (Figure 3, Figure S2, Dudley 2008).

When considering the entire network of 103 PAs with natural forest from 2013 to 2022, the lowest annual deforestation rates have been estimated during the Covid-19 years in 2020 (0.66%), 2021 (0.62%) and the following year in 2022 (0.67%) (Figure 2, Table 2).

Table 1. Evolution of the network of protected areas with natural forests from 2000 to 2023 (marine parcels excluded).

Years	Number of PAs with natural forests	Total area of PAs with natural forests
2000–2006	43	1,839,570 ha
2007–2010	44	1,850,860 ha
2011	45	2,035,490 ha
2012–2014	46	2,407,830 ha
2015–2023	103	6,351,460 ha

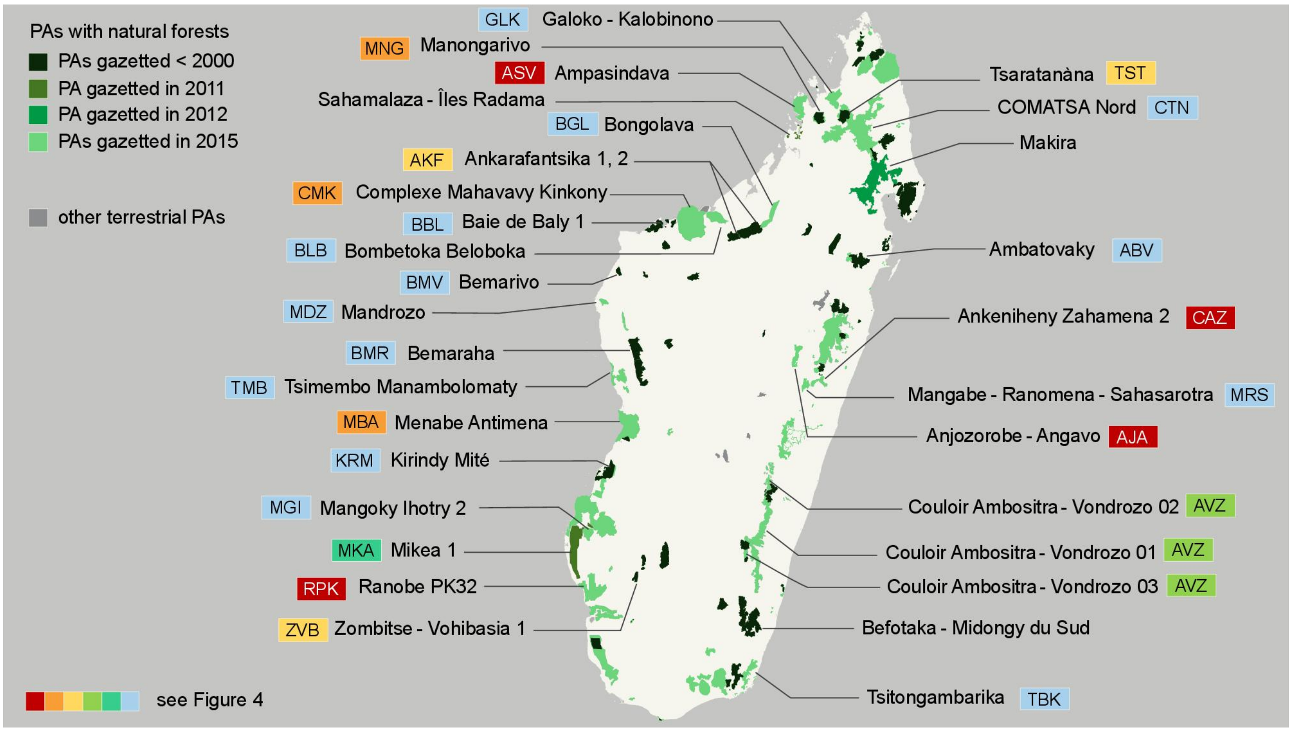

Figure 1. Evolution of the network of protected areas (PAs) of Madagascar since 2000. (Abbreviations in color refer to Figure 4)

The analysis reveal significant deforestation in the PA network over the last decade, particularly in 2014, 2017, 2018, and 2019. In 2014 and 2017, deforestation encompassed nearly 60,000 ha, whereas it dropped to just under 50,000 ha in 2018 and 2019 when we consider the entire network of PAs (Table 3). Over these four years, the total forest loss exceeded 200,000 ha, which is equivalent to more than 5% of the remaining forest area in 2012 within the 103 PAs containing natural forests. Notably, more than 50% of the annual deforestation over this four-year period took place within eight specific PAs (Table 3).

Within te network of 103 PAs with natural forests we selected the 75 larger parcels with total area above 10,000 ha to identify the top 10 parcels with highest annual deforestation rates. In 2022, 6 PAs out of 10 were amongst the oldest, i.e., gazetted before 2000 and 4 PAs were gazetted in 2015 (Figure 4).

DISCUSSION

PRE COVID-19 YEARS. The expansion of PA areas, as outlined in the Durban vision announced in 2003, was almost complete by late 2008 (Gardner et al. 2013). However, the process was delayed for several years due to a coup d'état in January 2009 (Randrianja 2012). Consequently, the new PAs and extensions of existing PAs, which were supposed to be enacted, were considered as new PAs from 2009 to 2015. Only two PAs were officially established during this period.

For Mikea NP, the peak deforestation rate was projected for 2014, but in reality, this surge took place in 2013, a mere two years after the official gazettement of the NP. The annual data provided by Global Forest Watch covers the period from January to December and is confirmed by the University of Maryland (UMD). Tree cover losses are only validated by UMD when multiple satellite images confirm the change. However, for the forests in Mikea NP, deforestation was only confirmed in early 2014.

On 22 February 2013, Mikea NP was severely impacted by tropical cyclone Haruna, with estimated wind gusts of 210 km/h. The dry spiny forest experienced extensive damage, characterized by fallen and stripped trees. By September 2013, fires ignited by local people leveraged the abundance of large volumes of dead wood, leading to significant propagation across vast areas of the park (P. G. Manantsoa, pers. comm.).

It has been suggested that deforestation is significant in the year preceding the gazettement of a PA. This was observed in the Complexe Zones Humides Mahavavy Kinkony category V PA, with the highest deforestation rate occurring in 2014 before its gazettement in 2015 (T. H. Razafindralambo, pers. comm.). To counteract this effect, exceptional budgets are allocated by FAPBM (the Madagascar protected areas and biodiversity fund) during the process of PA creation (Andrianambinina et al. 2023, Folder S1).

The increase in deforestation in 2014, one year before the expansion of the PA network in 2015, was observed in PAs gazetted before 2000, in 2011, 2012, and in 2015. Apart from Mikea NP, the remaining three PAs responsible for over 50% of the annual deforestation in 2014 were gazetted in 2015 under IUCN category V. These include Ranobe PK32, Menabe Antimena, and Mangoky Ihotry. Ranobe PK32 and Menabe Antimena have experienced heavy deforestation over the past few decades and consistently rank among the top 10 PAs with the highest annual deforestation rates, particularly during the years 2014 and 2017–2019.

Slash-and-burn agriculture has been devastating the dry forests of Menabe Antimena since the early 1970s, intensified in 1992 for corn production intended for the brewing industry and export outside of Madagascar (Zinner et al. 2014, Vieilledent et al. 2016, Hudson et al. 2018). Similarly, the unique dry spiny forests of Ranobe PK32 in southwestern Madagascar have been severely depleted during a similar timeframe. This specific dry spiny forest on sandy soil has been devastated due to a combination of local population's discontent with a mining project aimed at exploiting ilmenite and the excessive demand for wood charcoal from the neighboring city of Toliara (Gardner et al. 2016, Llopis et al. 2019, Rafanoharana et al. 2021).

Table 2. Forest area (ha) in the network of protected areas according to year they have been gazetted, and annual rate of deforestation in brackets.

Years	PAs gazetted < 2000	PAs as in 2015	PAs gazetted < 2012	PAs gazetted < 2013
2013	1,208,120 (0.37%)	3,779,377 (0.68%)	1,344,134 (0.38%)	1,688,168 (0.35%)
2014	1,199,119 (0.71%)	3,721,372 (1.56%)	1,318,131 (1.99%)	1,661,166 (1.68%)
2015	1,194,119 (0.42%)	3,692,369 (0.79%)	1,312,131 (0.45%)	1,654,165 (0.42%)
2016	1,186,118 (0.68%)	3,661,366 (0.83%)	1,303,130 (0.66%)	1,644,164 (0.59%)
2017	1,174,117 (0.99%)	3,601,360 (1.60%)	1,291,129 (0.93%)	1,630,163 (0.83%)
2018	1,162,116 (0.96%)	3,553,355 (1.33%)	1,279,127 (0.92%)	1,616,161 (0.86%)
2019	1,154,115 (0.70%)	3,514,351 (1.05%)	1,268,126 (0.83%)	1,604,160 (0.74%)
2020	1,149,114 (0.42%)	3,489,348 (0.66%)	1,263,126 (0.39%)	1,598,159 (0.38%)
2021	1,143,114 (0.51%)	3,465,346 (0.62%)	1,256,125 (0.47%)	1,591,159 (0.41%)
2022	1,135,113 (0.65%)	3,440,344 (0.67%)	1,248,124 (0.60%)	1,582,158 (0.52%)
Average deforestation rate	0.64%	0.98%	0.76%	0.68%

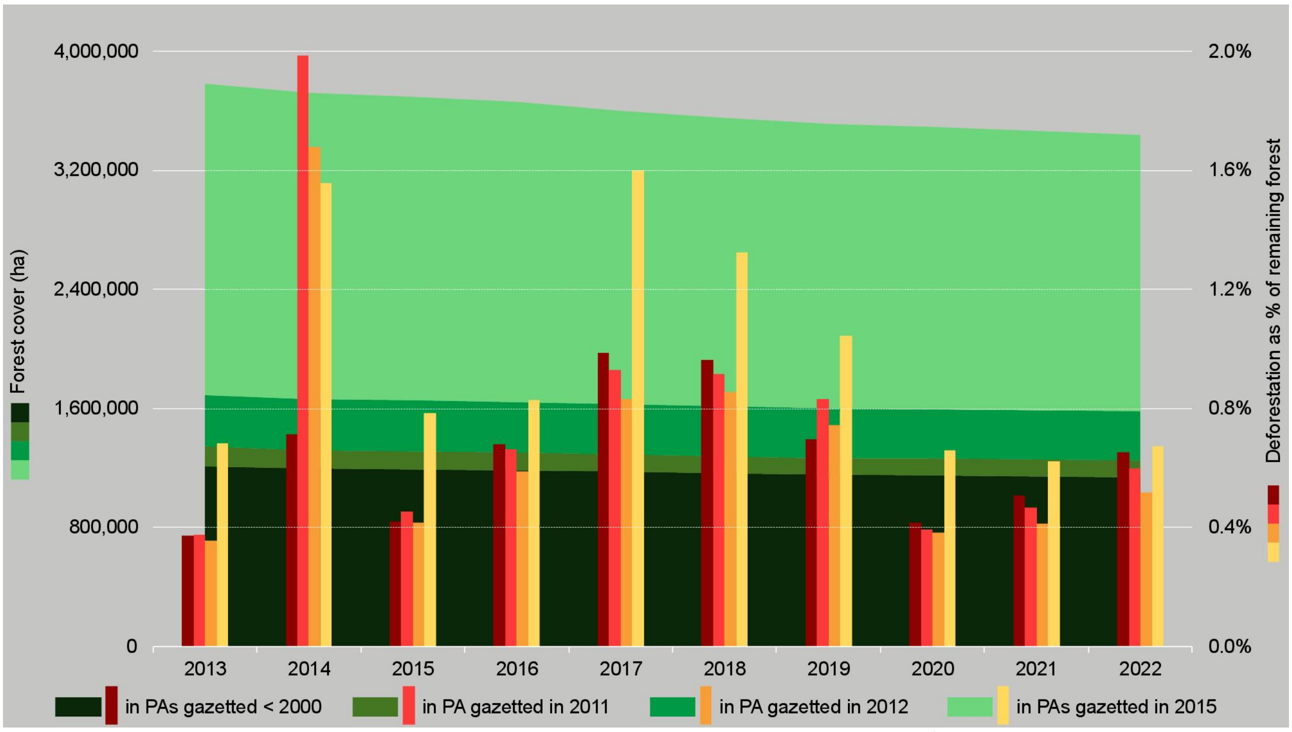

Figure 2. Changes in forest cover and deforestation in protected areas (PAs) from 2013 to 2022. (National Park Sahamalaza-Îles Radama with a total area of 11,280 ha gazetted in 2007, is included in PAs gazetted in 2011)

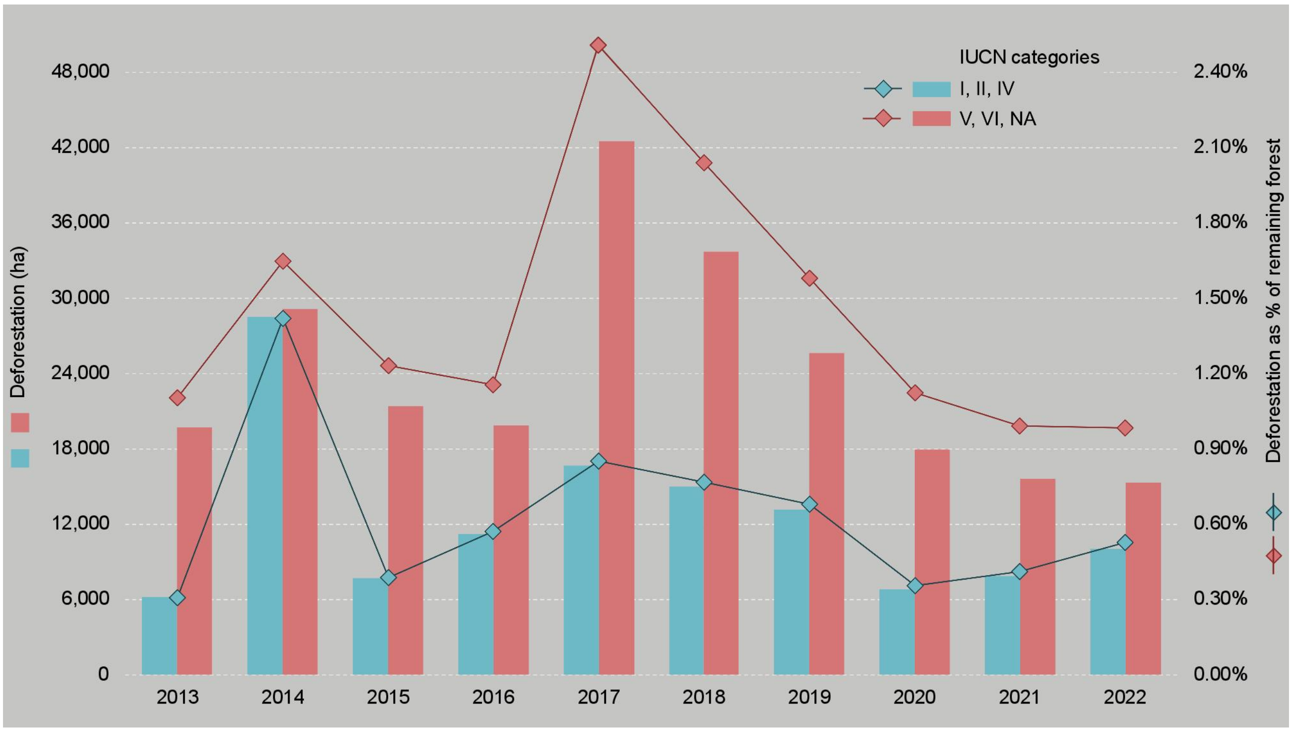

Figure 3. Deforestation and IUCN conservation categories. Comparing deforestation in IUCN categories I, II, and IV protected areas (PAs) to categories V and VI. (NA indicates PAs without category assignment but which are typically managed as category V)

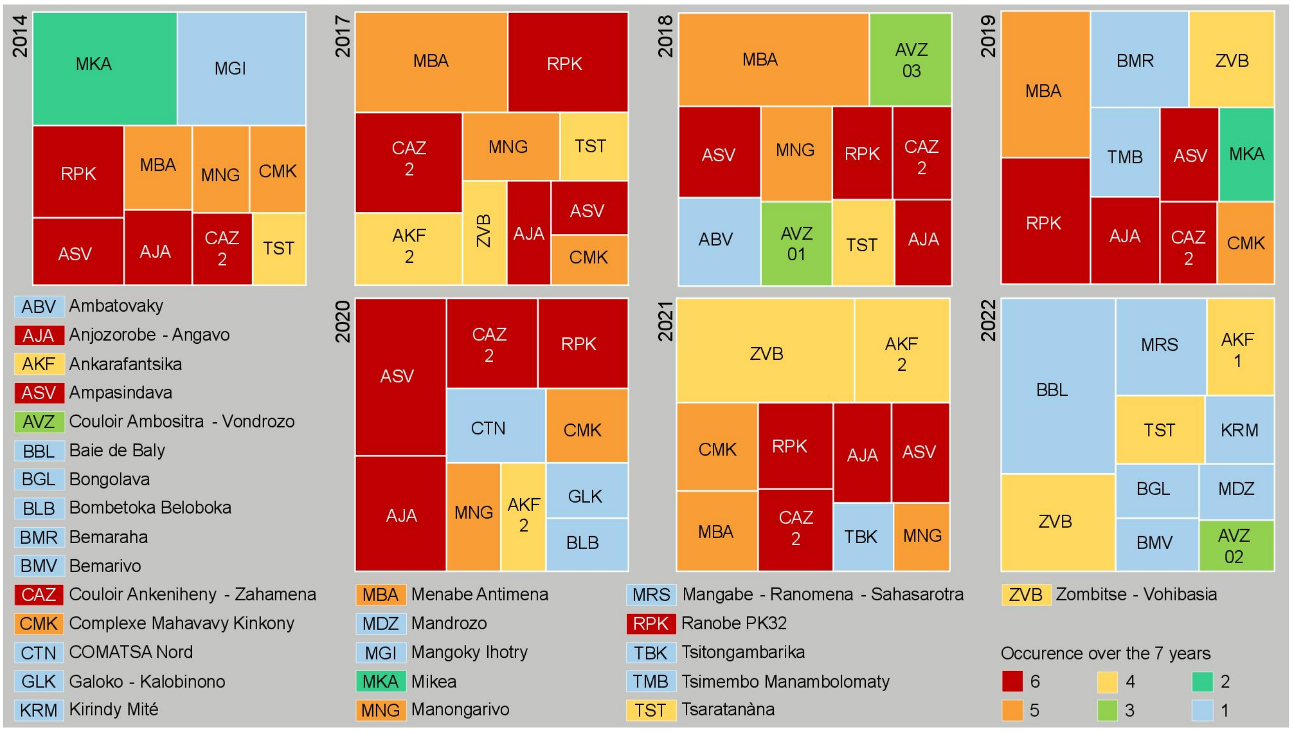

Figure 4. High-deforestation protected areas: 2014, 2017–2019, 2020–2022. Top 10 of the protected areas (PAs) or parcels of PAs with total area > 10,000 ha and highest annual deforestation rates in years 2014 and 2017–2019, and 2020–2022. (PAs or parcels of PAs in light blue are only mentioned once over these 7 years; one unique color for other PAs, see also Figure 1)

Table 3. Protected areas (PAs) explaining >50% of the total deforestation for the years 2014 and 2017–2019. (percentage given for the deforestation in the specific PA or parcel of PA per total deforestation for the year)

PA	Year gazetted	PA area (ha)	Estimated forest cover in 2012 (ha)	2014	2017	2018	2019
Menabe Antimena	2015	201,927	91,895	3,688 (6.3%)	8,791 (14.7%)	7,214 (14.6%)	4,503 (11.6%)
Ranobe PK32	2015	168,500	98,023	7,149 (12.3%)	9,372 (15.6%)	3,040 (6.2%)	4,880 (12.5%)
Mikea 1	2011	179,834	129,371	17,489 (30.0%)			2,595 (6.7%)
Ankeniheny-Zahamena 1	2015	328,141	297,760		4,494 (7.5%)	4,586 (9.3%)	1,877 (4.8%)
Ambositra-Vondrozo 1	2015	255,554	183,188		2,801 (4.7%)	5,129 (10.4%)	1,886 (4.8%)
Mangoky Ihotry 1	2015	385,735	138,374	3,245 (5.6%)	2,889 (4.8%)		1,848 (4.7%)
COMATSA Nord	2015	238,176	186,038			2,847 (5.8%)	2,526 (6.5%)
Befotaka / Midongy	< 2000	205,985	146,086		2,766 (4.6%)	2,751 (5.6%)	
Subtotal deforestation				31,570 (54.2%)	31,113 (53.3%)	25,568 (51.8%)	20,114 (51,6%)
Deforestation in the 103 PAs				57,709	59,355	48,824	38,792

COVID-19 YEARS. In the years 2020 and 2021, when the Covid-19 pandemic had a significant impact, there was a notable reduction in forest cover loss and annual deforestation rates as compared to the years 2014 and 2017–2019. Andrianambinina et al. (2023) reported that the pandemic led to a near standstill in tourism due to travel restrictions, including a ban on travel within the country. In response to these circumstances, Madagascar National Parks intensified patrolling efforts in the western region of Madagascar. The aim was to provide an alternative source of income for local communities involved in monitoring the PAs to prevent potential encroachments into PAs during the travel ban (Andrianambinina et al. 2022).

While there is no direct causal link explaining the reduced deforestation, it's essential to understand the context and consider potential factors. One hypothesis that merits further investigation is the disruption of supply chains due to travel bans, which may have impacted the export of resources taken from within the PAs by people living near or around PAs, possibly contributing to the reduction in deforestation.

Interestingly, Menabe Antimena did not rank among the top 10 PAs with a high annual deforestation rate, unlike Ranobe PK32. Even during the Covid-19 pandemic, when there were travel restrictions and PAs were closed, the demand for wood charcoal remained active, especially in Toliara, just south of Ranobe PK32. It's noteworthy that the production of wood charcoal is a significant factor contributing to deforestation, like in parcel 2 of the Corridor Ankaniheny-Zahamena. Notably, during the Covid-19 years, this area experienced a decrease in annual deforestation rates, which might suggest the possibility of wood charcoal being exported beyond the immediate production region (M. Ratsimbason, pers. comm.). In parcels 1 and 3 of the Corridor Forestier Ambositra-Vondrozo PA, the annual rates of deforestation decreased during the Covid-19 years, indicating that the products from slash and burn agriculture and illegal mining were likely intended for exportation beyond the region. However, in parcel 2, the annual deforestation rates remained high during the Covid-19 years. In Ampasindava, slash and burn agriculture posed the main threat to the forests, and the deforestation rates remained high during the Covid-19 years (P. Ranirison, pers. comm.). Similar threats were observed in parcel 2 of Corridor Ankeniheny-Zahamena and Complexe Anjozorobe-Angavo IUCN category V PAs. Ankarafantsika NP and parcel 1 of Zombitse-Vohibasia NP are located along major national roads. When any of these PAs are set on fire by the local population, it receives national media attention as a means for the local communities to draw the attention of the central government. In 2021, these PAs ranked second and first, respectively, for the highest deforestation rates. The decrease in annual deforestation rates can also be attributed to the exportation of resources exploited in some PAs, such as illegal gem mining in Corridor Ankeniheny-Zahamena PA, maize cultivation in Menabe Antimena PA for national brewery or exportation to Mauritius and other countries, and the cultivation of khat (*Catha edulis*) and marijuana (*Cannabis* sp.) in Tsaratanàna Strict Nature Reserve (IUCN category Ia, SNR) for the national market (Rafanoharana et al. 2021).

YEAR 2022. Despite the conclusion of the Covid-19 pandemic, deforestation rates in 2022 did not reach the high levels observed in 2014 and 2017–2019. Many of the PAs that ranked in the top 10 for deforestation rates in 2014 and 2017–2019 were not included in the top 10 in 2022. For example, Ankeniheny-Zahamena, Ambositra-Vondrozo, and Menabe Antimena were not among the PAs with the highest deforestation rates in 2022, while Tsaratanàna SNR was listed again. Comparatively, deforestation in 2022 remained lower than in 2014 and 2017–2019.

The highest deforestation rates in 2022 were observed in the "usual suspects," namely Ankarafantsika NP, Zombitse-Vohibasia NP, and Tsaratanàna SNR. However, six PAs that were not mentioned in the top 10 in previous years joined the top 10 list in 2022. In Corridor Ambositra-Vondrozo PA, the high deforestation rates observed in 2018 were attributed to illegal mining of gold and crystals within the PA. Although this activity was partially halted during the Covid-19 years, it resumed to some extent in 2022 (M. R. A. Ranosy, pers. Comm.). Forests in Ankarafantsika and Zombitse-Vohibasia NPs experienced fires in 2022, albeit to a lesser extent than Baie de Baly NP, which garnered significant media coverage despite its remote location.

The introduction of a new approach in the estimation of forest losses (Rafanoharana et al. 2023b), provides valuable data for analyzing the local and regional factors driving deforestation in and around Madagascar's PAs. This advancement opens the door to a fresh perspective on understanding the drivers of deforestation in the region. It also serves as a valuable model for conservation science, exemplified by Rafanoharana et al. (2023a), who assessed lemur populations based on forest area analysis and deforestation rates across Madagascar's PAs from 2015 to 2017, projecting their development until 2050.

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SUPPLEMENTARY MATERIAL

Table S1. Evolution of the network of protected areas (PAs), its forest cover from 2000 to 2022.

Figure S1. Changes in forest cover and deforestation rates in protected areas (PAs) from 2001 to 2022. (National Park Sahamalaza-Îles Radama with a total area of 11,280 ha gazetted in 2007, is included in PAs gazetted in 2011)

Figure S2. Deforestation and IUCN conservation categories. Comparing deforestation in IUCN categories I and II, versus IV, versus V and VI. (NA indicates PAs without category assignment but which are typically managed as category V)

Folder S1. Shapefile of Protected Areas as of 2015 (Laborde Madagascar projection)