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# Exemplifying Stratified Deforestation in Four Protected Areas in Madagascar

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**Abstract:** Protected areas (PAs) are a cornerstone for conservation biodiversity. Madagascar, as a hotspot for biodiversity, has a network of 114 terrestrial protected areas covering the main forest types occurring on the island. Deforestation continues unabated despite the network covering 11% of the island. Here we present a case study approach reporting on four PAs from the humid forests, dry western forests, and southwestern dry and spiny forests and thickets. To describe deforestation in and around the case sites, we have considered a time window of 30 years for analysis, focusing on six years with reliable data: 1990, 2000, 2010, 2015 (the year of latest PA network update), and 2017. We have considered forest versus other land covers within the PAs in "buffers" at a distance of 500 m, 2.5 km, 5 km, and 10 km from the border of the PA. These buffers were set from the border towards the center of the PA (inside the PAs) and from the border outside the PAs. The smallest PAs, Kasijy (IUCN IV), and Behara Tranomaro (no IUCN category), showed the least forest loss. Tsaratanana (IUCN I) had the highest deforestation rates within the last two years of analysis, with deforestation concentrated in the core area. Ranobe PK-32 (no IUCN category), originally with the largest forest extent, has lost most of its forest cover and showed the highest annual deforestation rate (3.5%) between 2015 and 2017. All four cases prove to be very challenging to manage. Future conservation activities require tailored interventions to account for site-specific current and potential future threats, as detailed in this contribution.

**Keywords:** forests; forest change; protected areas; buffers; conservation; IUCN category; biodiversity; deforestation over 30 years

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## 1. Introduction

Protected areas are a cornerstone for biodiversity conservation, ecosystem services, and human well-being [1–4]. The Convention on Biological Diversity (CBD) Aichi Target 11 aimed to protect a minimum of 17% of the global terrestrial areas that are of particular relevance for biodiversity and ecosystem services by 2020 [5]. This has led to rapid expansions of protected area systems in many countries. Assigning protected areas requires sophisticated conservation planning and decision-making [6–9]. It is critical for safeguarding biodiversity values for the future that protected area management is efficient and effective [10]. Studies have shown that only some 25% of the protected areas worldwide are based on sound management [11]; yet, "there remains a limited evidence base, and weak

understanding of the conditions under which protected areas succeed or fail to deliver conservation outcomes" [12]. Failure to achieve protection is most often assigned to the lack of financial, technical, and human resources, as well as other political challenges [8,13,14].

Madagascar, as a biodiversity hotspot, experienced a rapid expansion of its protected area network in 2015 [15,16]. The network of protected areas includes 114 terrestrial protected areas covering the main forest types of Madagascar, including humid, subhumid, western dry, southwestern dry spiny forests, and thickets [16,17]. Forty terrestrial protected areas (PAs)—and three marine PAs—are under the management regime of MNP (Madagascar National Parks), while another 60 terrestrial PAs and five marine PAs are under the management responsibility of an Environmental NGO. Two PAs are under the official management regime by either a University or a Mining Company [15].

With the CBD post-2020 framework being decided in 2021, there is still little evidence for Madagascar on the effectiveness of the protected area network for protecting its biodiversity heritage. While deforestation continues unabated (e.g., [15,18]), studies conducted by Eklund et al. [19] or Yesuf et al. [20] concluded that PAs in Madagascar could slow down deforestation. While Madagascar now has a network of protected areas across its main forests, only a few sites receive the bulk of attention from research, tourism, and NGOs [15,16,21]. The pressure on PAs is assumed to be the highest close to their borders; therefore, a national decree for the management of PAs defines a buffer zone 2.5 km outside the limits of the PAs—so-called "zone de protection"—which allows communities to access some natural resources in order to protect the PAs better. To estimate whether PAs provide the best protection against deforestation, as compared to land outside PAs, and to evaluate the role of the outside buffer zone in ensuring their protection, we analyze the evolution of forest cover according to the distance to the limits of PAs, inside and outside these PAs. Here we report on the patterns of deforestation in four so-far relatively under-researched sites that are subject to little management. The four case study sites have different gazettement histories and forest types to assess deforestation in detail over a period of some 30 years, from 1990 to 2017 [18].

## 2. Methods

### 2.1. Case Studies

We have selected four sites out of a pool of 100+ terrestrial protected areas with forest representing humid forest, dry western forest, and southwestern dry and spiny forests and thickets (Figure 1, Table 1) [21]. These have been gazetted between 1927 and 2015: Behara Tranomaro and Ranobe-PK32 protected since 2015, the Special Reserve of Kasijy since 1956, the Strict Nature Reserve of Tsaratanana, gazetted in 1927 and extended in 2015. The main selection criteria for this study were that little to no management must occur on a site.

**Table 1.** Main features contextualizing the four protected areas.

| Features | Behara Tranomaro | Ranobe-PK32 | Kasijy | Tsaratanana |
|---|---|---|---|---|
| Area (hectares) according to the decree | 96,588 | 168,500 | 19,800 | 49,364 for 1927–2015<br>108,610 since 2015 |
| Borders (m) | 139,250 | 288,930 | 78,090 | 114,620 195,480 |
| Borders/area (m/ha) | 1.44 | 1.71 | 3.94 | 2.32 1.80 |
| Altitudinal range (m) | 30–1030 | 0–650 | 120–460 | 210–2876 (410–2876, 210–2876) |
| Slope (%; [18]) | 0–34 | 0–46 | 0–25 | 0–61 |
| Geological domain [22] | Metamorphic, plutonism, sedimentary in the south | Sedimentary | Sedimentary | Metamorphic, plutonism, some ancient volcanism |

**Table 1.** *Cont.*

| Features | Behara Tranomaro | Ranobe-PK32 | Kasijy | Tsaratanana |
|---|---|---|---|---|
| Forest types [17] | Southwestern dry spiny forest-thicket | Southwestern dry spiny forest-thicket | Western dry forest | Humid forest |
| Distance to main road | 1 km to RN13 | RN9 crosses the PA | 86 km to RN4 | 30 km to RN6 |
| Distance to main city | 50 km to Taolagnaro, 40 km to Ambovombe | 5 km to Toliara | 91 km to Maevatanana, 145 km to Mahajanga | 123 km to Antsohihy and 168 km to Antsiranana |
| Distance to main river | 500 m from Mandrare; drained by Kotrokotroka and Mananara | River Fiherenana borders the southern limit; River Manombo borders the northern boundary | The Mahavavy River borders the eastern boundary, its tributaries the Kiananga and the Tsimatahodiavolana border the southern boundary | The Sambirano River borders the southwestern boundary; its tributary, the Ramena River, drains the PA |
| Region | Anosy | Atsimo-Andrefana | Betsiboka | Diana, Sofia |
| District | Amboasary-Atsimo | Toliara II, Sakaraha | Kandreho | Ambanja, Ambilobe, Bealanana (Sofia) |
| Population of the districts in 2018 (and 1993). Numbers from [23,24] for the year 2018, and [25] for the year 1993 | 258,241 (120,248) | 371,156 (146,492); 150,366 (53,961) | 25,964 (9321) | 236,988 (100,465); 285,075 (112,917); 188,115 (79,302) |
| Date of creation and decree | N. 2015-808 du 5 Mai 2015 | N. 2015-808 du 5 Mai 2015 | Décret global du 10 Septembre 1956 for the Special Reserves | 31 December 1927 under N. 66-242 du 11 Juin 1966 (RN); N. 2015-782 du 28 Avril 2015 for the extended reserve in 2015 |
| IUCN categories | Not defined | Not defined | IV | I |
| Management responsibility | Under WWF as a potential site to be gazetted until 2006; currently Ministère de l'Environnement et du Développement Durable (Ministry of Environment and Sustainable Development) | Under WWF as a potential site to be gazetted until 2006, currently Ministry of Environment and Sustainable Development of Madagascar | Madagascar National Parks until 2015; currently Ministry of Environment and Sustainable Development of Madagascar | Madagascar National Parks |

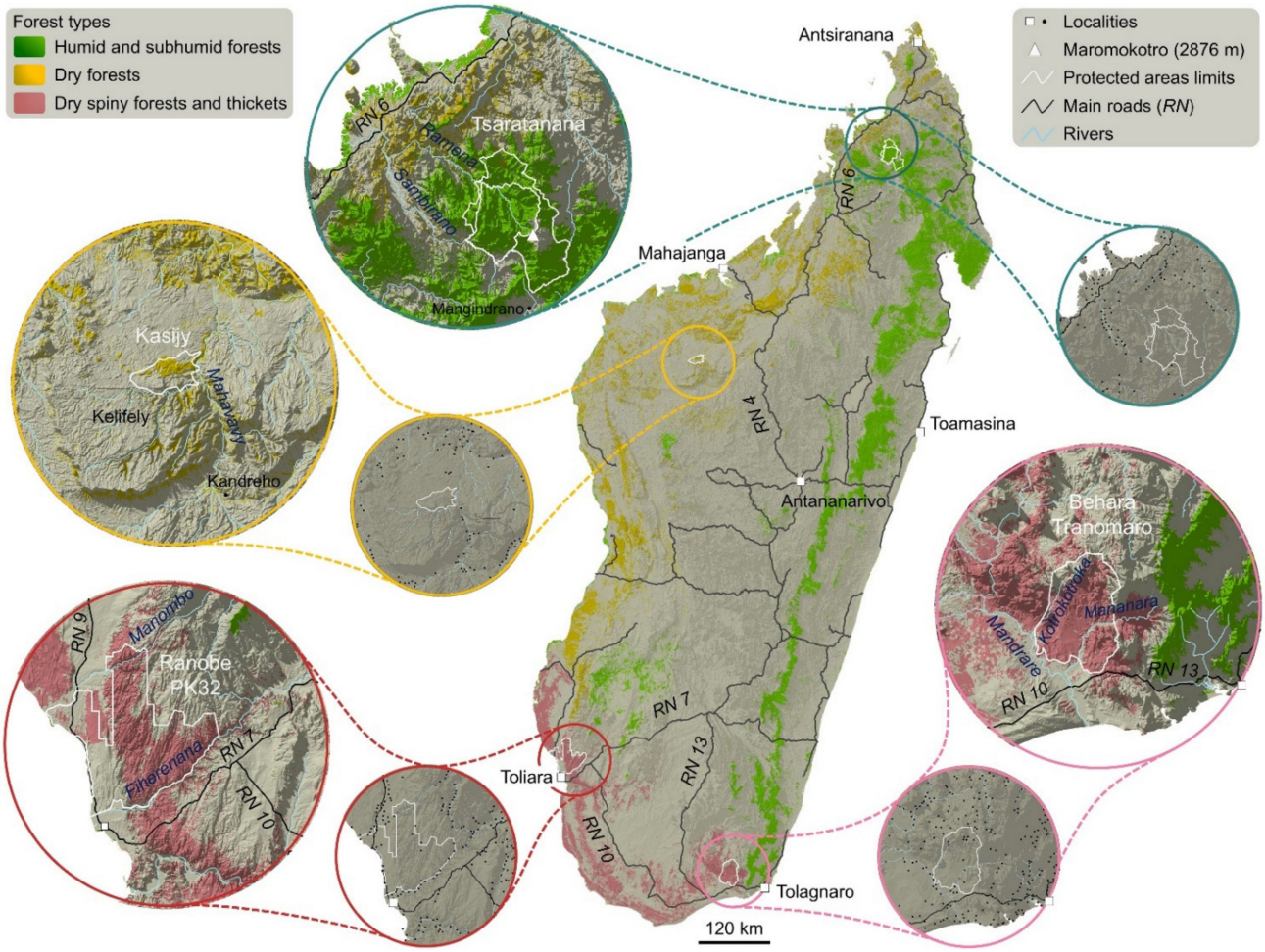



**Figure 1.** Case study sites. (Simplified forest types according to [17]; circles on the main map with a radius of 60 km, first inset showing the populated places according to the official FTM map BD500, 1:500,000; larger inset with details on geography).

### *2.2. Assessing Deforestation*

The raw shapefile data for the four sites were obtained from the protected area management system (SGAP) from the Ministry of Environment and Sustainable Development with their decree of creation.

Shapefiles: We started with preparing and cleaning the shapefiles of the protected areas by checking and repairing the geometry of each of the features for any possible errors. After the geometric correction, we reprojected all data sets into the same coordinate system, which is the national Laborde projection [26]. We analyzed the history of each of the protected areas with the legal acts and other relevant documents obtained from the Madagascar National Parks database to obtain the exact boundary and its evolution through time (Table 1).

Selecting the buffers: Four buffers were chosen from 500 m, 2.5 km, 5 km, and 10 km for the inside of a protected site, and the core area beyond the 10 km buffer for the largest PAs; the same four buffers were applied reciprocally for the outside (Figure 2). The buffer of 2.5 km is based on Article 18 of the national decree N. 2005-013 on protected areas signed 11 January 2005. This states that agricultural and pastoral activities, fishing, and other types of activities are allowed within a buffer zone of 2.5 km around the protected areas if they do not have negative impacts on the protected areas. The 5 km and 10 km buffers were chosen to obtain more information as one moves further from the protected area borders by doubling the 2.5 km distance of the initial buffer. The 500 m buffer was chosen to consider changes closer to the park boundary, both inside and outside a PA.

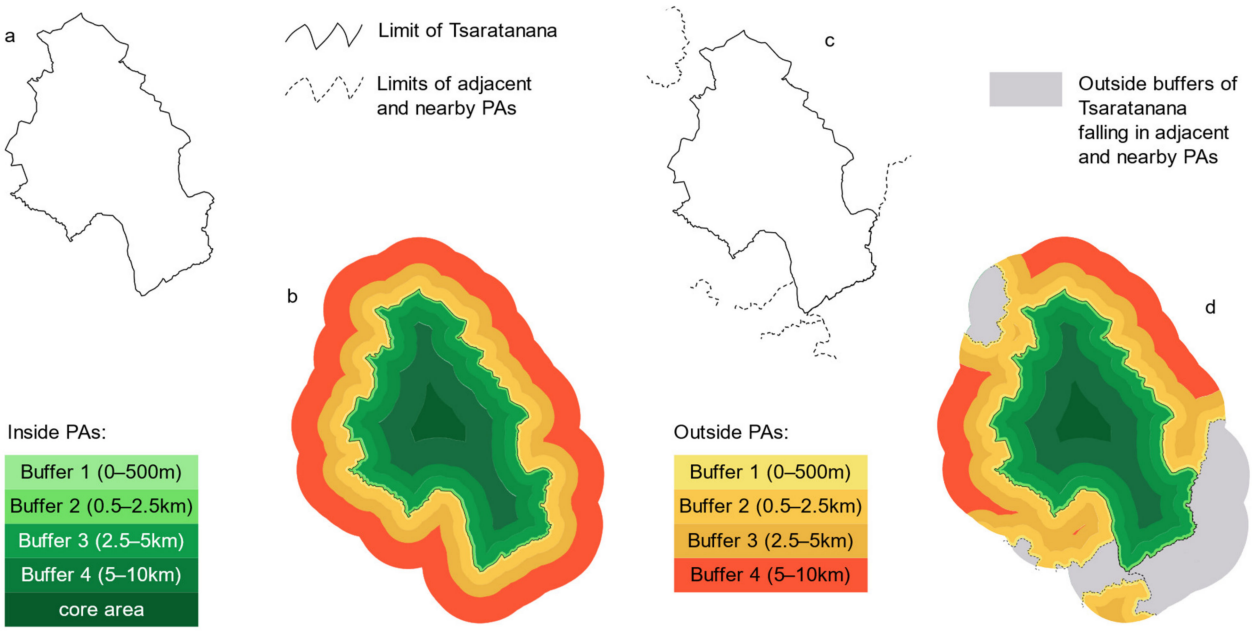



**Figure 2.** Four buffers and the core area inside the Tsaratanana PA, and the four reciprocal buffers outside. (**a**) limits of the PA in 2015; (**b**) buffers (inside/outside) according to distance to the limit; (**c**) limit of the Tsaratanana PA and limits of adjacent and nearby PAs in 2015; (**d**) final buffers when the PA is considered in the entire network of PAs, given that some outside buffers partly fall within other close PAs (grey), or in buffers closer to other PAs).

Analyzing change within buffers: Once the buffer zones were defined and their data were ready to use, we developed a python script to automate the analysis to process the buffer. Each of the buffers was processed separately. We used time-series forest cover data for the years 1990, 2000, 2005, 2010, 2015, and 2017. The 1990 and 2000 data were taken from the original data of Harper et al. [27] and resampled by Vieilledent et al. [18] at a resolution of 30 m using a nearest-neighbor interpolation from which they labeled the unclassified data due to cloud cover of 2000 from the 2000 tree cover of Hansen et al. [28]. To obtain the forest cover map for the years 2005, 2010, 2015, and 2017, we used the data from Vieilledent et al. [18], which was the result of a combination of the forest cover map of the year 2000 with the annual tree cover loss maps at 30 m spatial resolution [28,29]. For each year, we have given specific names to each of the resulting features to reflect the time of change. Since we only used previously processed information from Vieilledent et al. [18], we did not provide an accuracy assessment in our case study paper.

For comparison and analysis reasons, we kept the size of a site constant over the period of 30 years. For instance, for the year 1990, we considered the area of Behara Tranomaro and Ranobe-PK32 and the forest cover of these areas in 1990 even if these sites were only formally protected in 2015. We considered the RNI of Tsaratanana with its area of 1927 but also its extension, which was not classified until 2015.

We used the administrative boundary of Madagascar at the national level from the Global Administrative Areas (GADM) version 3.6 data sets [30]. These data were preprocessed to separate the mainland from the small satellite islands. Each small island was numbered to facilitate the identification of each portion. We merged this administrative boundary with the results from the merged buffered forest cover inside and outside the protected areas. The area values were then calculated from the results of the merged data sets, which were exported into a spreadsheet. The geography of some protected areas did not match the area mentioned in the decree of classification. These PAs need some readjustment to be implemented at the legal level by the managing entity in the future. This is the case for Kasijy, for which the decree mentions a vague description including the total area of approximately 19,800 hectares, while the shapefile established on the description of the PA results in a total area of 22,956 hectares.

Forest data used here have some biases linked to the poor capacity of the algorithms to adapt to the type of forests. The remote sensing tools tend to underestimate the forest cover in the dry forests and overestimate it in the humid [16,31]. The numbers for the dry forests used here should be regarded as a minimum. Forest cover changes are likely higher.

## 3. Results

Considering forest cover in the four case studies, Kasijy has the lowest proportion of forest cover (25%). The other three study sites held at least 80% of forests in 1990 (Table 2). In contrast, Ranobe-PK32, with the largest forest cover of some 138,000 hectares in 1990, lost almost 60,000 hectares between 1990 and 2017 (Table 2). Behara Tranomaro maintained its forest extent over the period 1990 to 2017, experiencing relatively small changes only, from 80% to 76%. Tsaratanana is a particular case since its formally protected area was doubled in 2015. During the preceding period, forest cover changes were the same for both formally protected (91% to 88%) vs. not protected areas (87% to 84%) (Table 2). The last two years, 2015 and 2017, allowed us to compare the four sites at equal footing: all are under formal protection (though with different IUCN statuses). Ranobe-PK32 experienced the biggest forest cover loss amounting to almost 12,000 hectares (or 7%) in two years. Tsaratanana lost some 3000 hectares (2%) in the same period. Kasijy and Behara Tranomaro remained stable (Table 2). Ranobe-PK32 showed the highest deforestation rates throughout the study period, while Kasijy showed the lowest. Deforestation rates picked up momentum for three out of the four case studies between 2005 and 2010 (Figure 3).

**Table 2.** Forest cover for the six years of analysis of the four case study sites. (Numbers are in hectares as used in our shapefiles.

| | | **Behara Tranomaro** | **Ranobe-PK32** | **Kasijy** | **Tsaratanana** | |
|---|---|---|---|---|---|---|
| Years | Total area | 96,590 | 168,200 | 22,960 | 49,364 | 59,252 |
| 1990 | Forest | 77,180 (80%) | 138,375 (82%) | 5783 (25%) | 45,020 (91%) | 51,601 (87%) |
| 2000 | Forest | 76,290 (79%) | 132,656 (79%) | 5700 (25%) | 44,173 (91%) | 51,146 (86%) |
| 2005 | Forest | 75,890 (79%) | 129,100 (77%) | 5690 (25%) | 44,478 (90%) | 50,622 (85%) |
| 2010 | Forest | 74,550 (77%) | 110,250 (66%) | 5686 (25%) | 43,577 (88%) | 49,478 (84%) |
| 2015 | Forest | 73,890 (76%) | 90,260 (54%) | 5680 (25%) | 89,106 (82%) | |
| 2017 | Forest | 73,240 (76%) | 78,340 (47%) | 5650 (25%) | 86,800 (80%) | |

It is assumed that protection increases towards the center of protected areas. This assumption held true for the Tsaratanana reserve only during the first 15 years, where higher deforestation rates can be observed closer to the protected area border. Yet, the situation was reversed during 2005–2010, when the highest change rates occurred closer to the center of the protected area. This pattern was accentuated in the years after 2010 (Figure 4). A second assumption is that deforestation rates should be higher outside a protected area compared to the area inside formal protection. This was the case for the first 15 years in Tsaratanana; then, forest cover change rates inside the PA became considerably higher compared to its outer buffers (Figure 4). The case of Ranobe-PK32 revealed a similar pattern (cf. also Figure 5); though this site was formally protected only in 2015, and thus the assumptions of the distance to border effect as well as outside versus inside deforestation do not hold. The annual deforestation rates in Behara Tranomaro and Kasijy are extremely low as compared to the latter two cases (Figure 6).

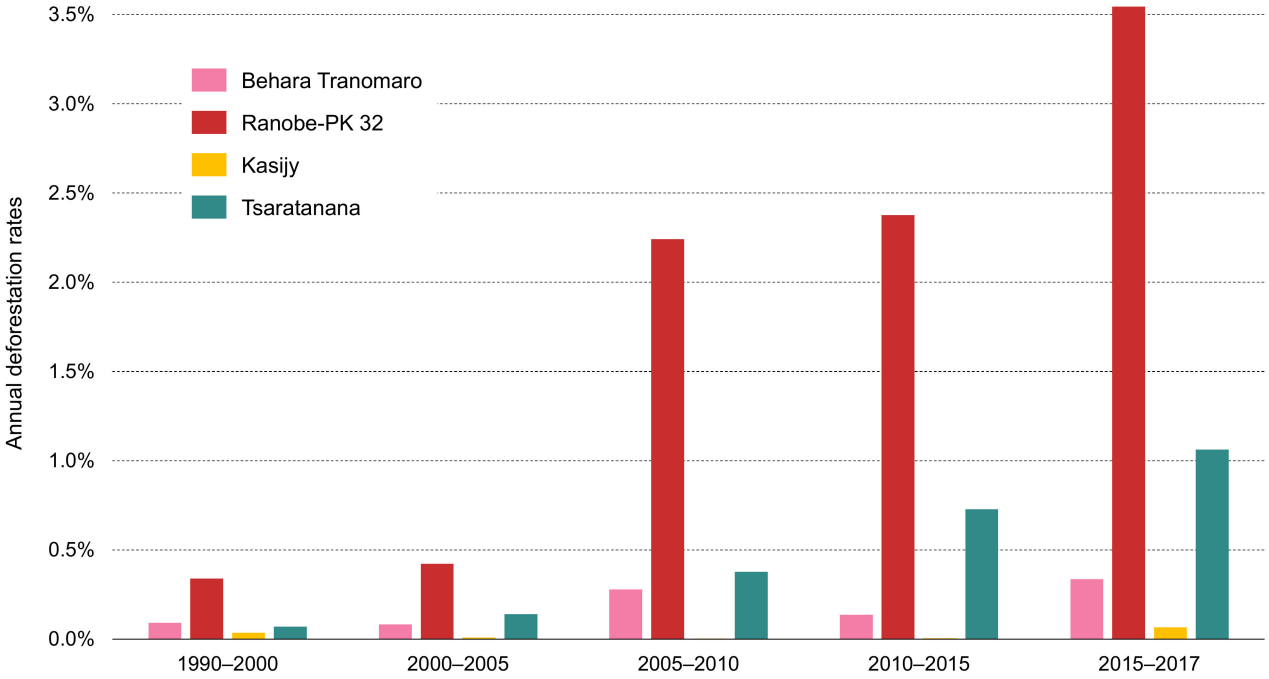



**Figure 3.** Annual deforestation rates in the four case study sites. (Behara Tranomaro and Ranobe-PK 32 had been gazetted in 2015; the deforestation rates have been calculated in previous years for the area gazetted in 2015; Tsaratanana total area under protection was doubled in 2015).

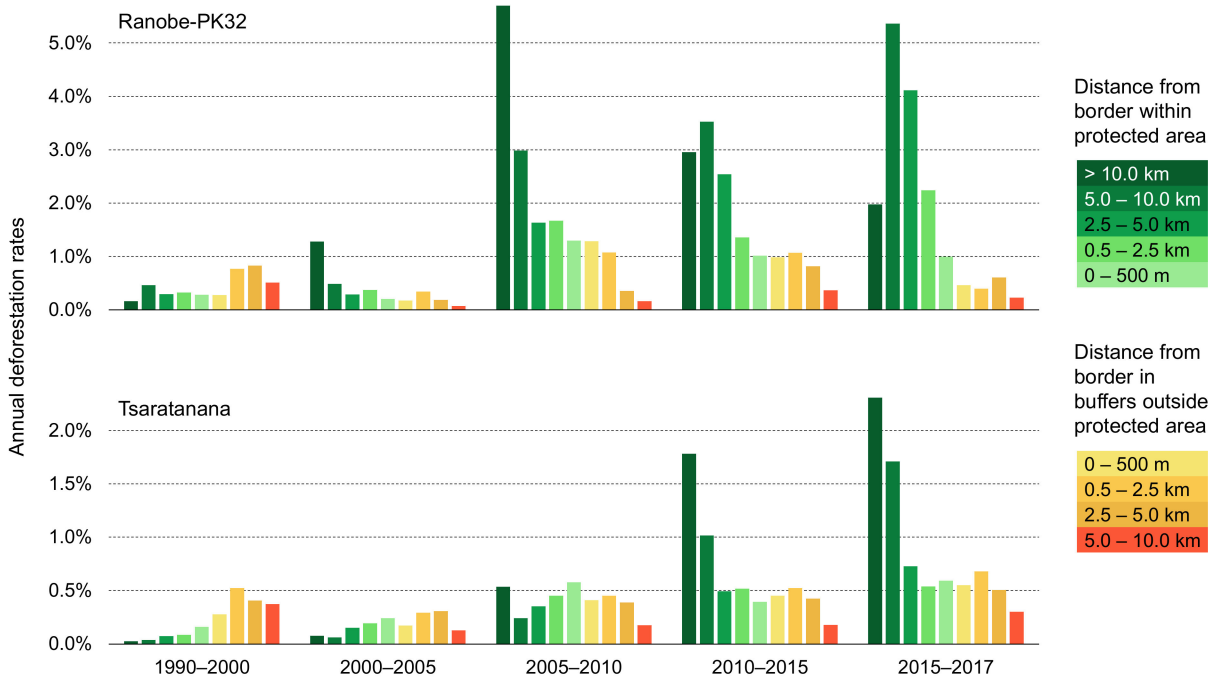



**Figure 4.** Annual deforestation rates in the two larger case study sites and their buffers according to their distance to PA borders. (Pattern as in Figure 1).

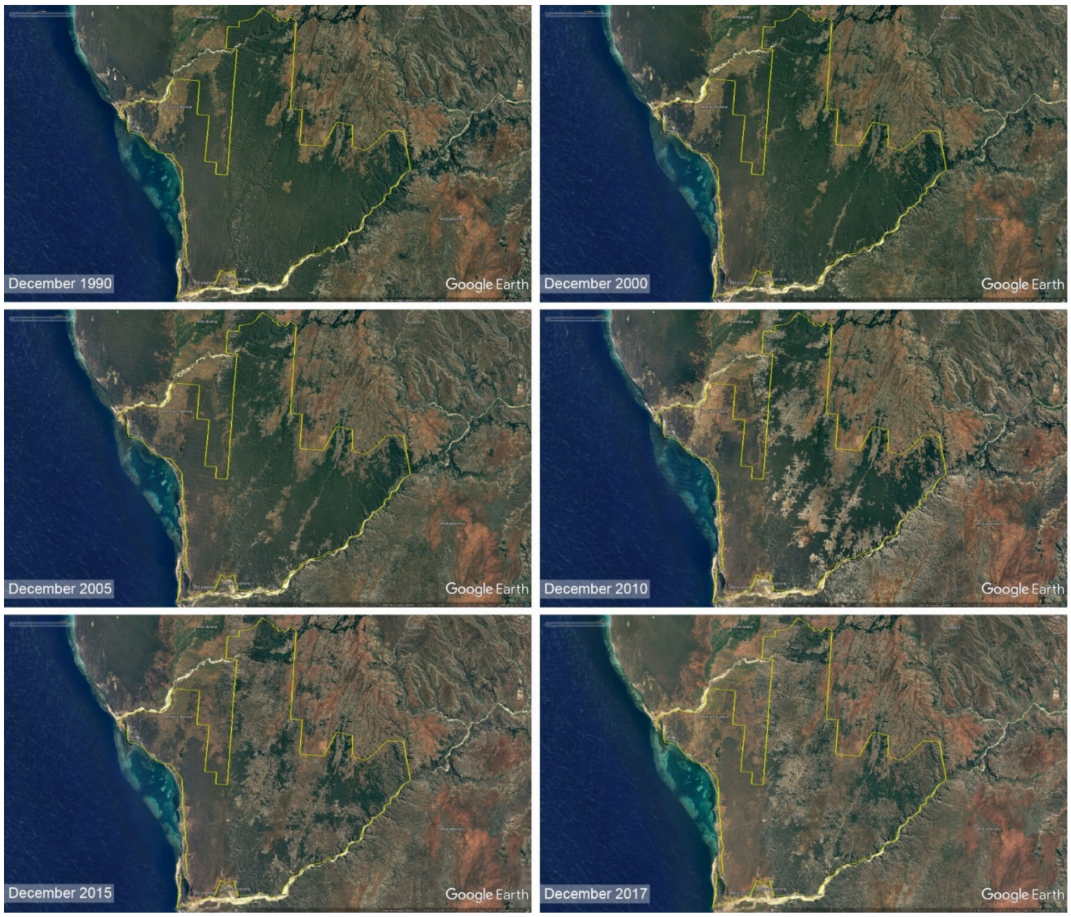



**Figure 5.** Deforestation for the six years of study at Ranobe PK-32. (Google Earth images, see online for a complete year-by-year time series) with the following link https://earthengine.google.com/timelapse/#v=-23.12537,43.27126,7.217,latLng&t=0&ps=50&bt=19840101&et=20201231&startDwell=0&endDwell=0.

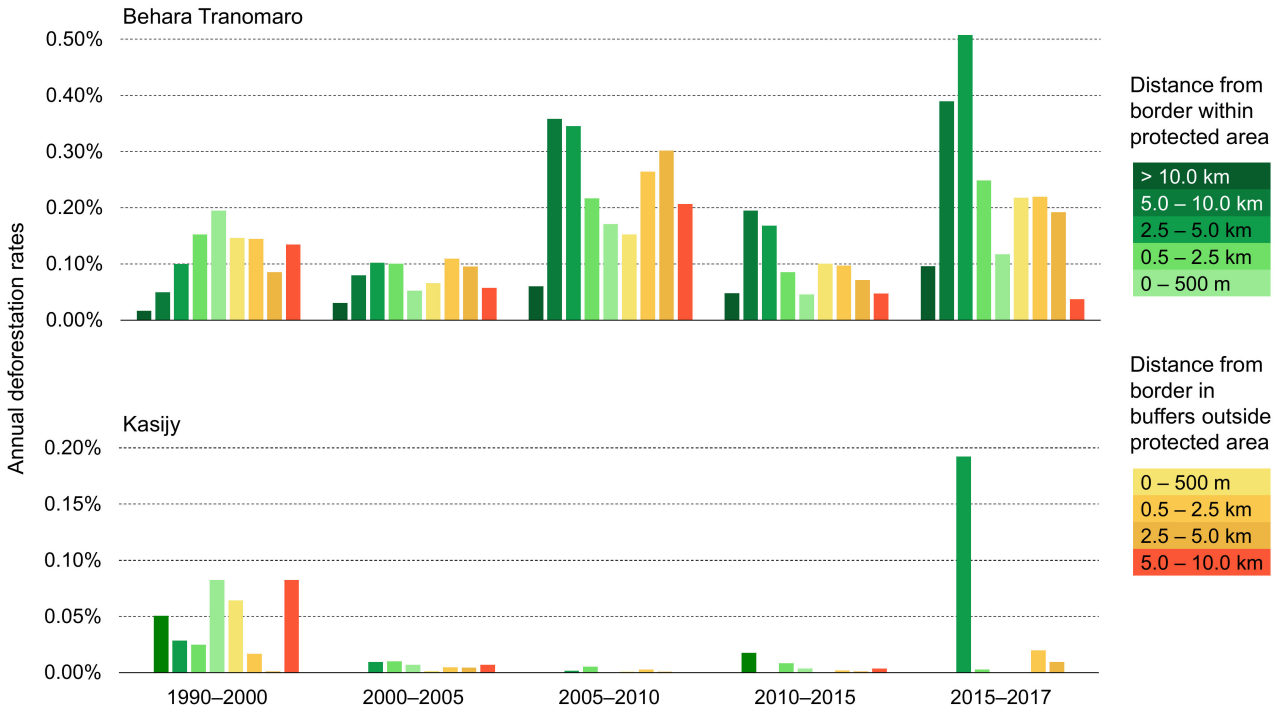



**Figure 6.** Annual deforestation rates in the two smaller case study sites and their buffers according to their distance to PA borders. (pattern as in Figure 1; note that the y axe has scale/10 as compared to scales in Figure 4).

## 4. Discussion

This study exemplifies the variation in deforestation patterns using four protected areas in Madagascar. For the time being, the sample size is too small, and the four cases cannot be used to derive general patterns or causes for deforestation. Rather, the examples should be considered as an indication of caution against broad generalizations. The smallest protected area, Kasijy, a reserve since 1956, has the most stable forest cover amongst the four case studies. Usually, we would expect smaller protected areas to be more vulnerable to human impacts and less resilient to changes in forest cover [32]. In contrast, the biggest site (Ranobe-PK32 with a total area of 168,000 hectares), a newly protected area with formal protection since 2015, experienced the highest forest cover changes and rates of all four case studies. The area was considered as an intact forest landscape (sensu Heino et al. [33]) in the 1990s, justifying its inclusion in the system of protected areas in 2015, but the forest loss in this area accelerated since 2005, especially during the last two years of analysis when all the four cases were under formal protection. The Behara Tranomaro, similar in size to Tsaratanana, was also considered to be an intact forest landscape prior to its gazettement in 2015 due to its big forest extents. The forest cover remained almost unchanged between 1990 and 2017, and less than 700 hectares have been lost between 2015 and 2017 (Figure 6). The accelerated deforestation rates observed in 3 out of the 4 case studies coincides with the coup d'état in 2009, which paralyzed law enforcement at the time [34,35]. The years of the transitional government (2009–2014) were characterized by decreasing rule-of-law, transparency, and government effectiveness [36]. In this period, illicit rosewood sourcing and trafficking spiked and made international headlines [37–40]. It was also at this time that increased deforestation was registered at the national scale [18].

Tsaratanana, as the oldest protected area gazetted in 1927, has experienced high deforestation in recent years. This is one of the most inaccessible protected areas in Madagascar with rugged terrain. It was well protected for years since 1927 but suffered increased deforestation in recent years following the cultivation of khat and cannabis [41]. For decades, the consumption of khat (*Catha edulis* (Vahl) Forsskal ex Endl. Celastraceae) was localized in the surrounding of Antsiranana, the northern regional capital city where khat is consumed openly and is considered "quasilegal" as in many countries in Africa [42,43]. Its illegal cultivation has been reported as a problem in the southern, less accessible part of Montagne d'Ambre National Park [44]. Since the 2000s, the consumption of khat has extended to the SAVA region in the northeast, and is more widely consumed in northern Madagascar. Cannabis (*Cannabis sativa* L. Cannabaceae) is considered an illegal drug in Madagascar, and any activity related to it can be severely condemned in court [41]. The cultivation of khat and later cannabis in the reserve started near the borders, which are more accessible. Mixed teams of park rangers and military personnel patrol the park to prevent these illegal cultivations. These patrols are expensive, ca. USD 90,000 per year and only take place during the dry season when access is facilitated. The interventions have turned out to be ineffective since khat and cannabis farmers moved to more remote areas in the core of the reserve, which explains the highest deforestation rates in the PAs' core area. In the current system of protected areas and the principles driving conservation in Madagascar [16,45–47], the management of Tsaratanana is almost impossible and beyond the capacities of most park managers. The use of violence and implication of the army in the context of PA management risks undermining the conservation targets and further fueling the escalation of violence in the region.

Kasijy lies in the least populated district, Kandreho, with a density of 4.3 inhabitants per square kilometer [24]. Most settlements are located in the Mahavavy river valley to the east of the reserve. The so-called Kelifely, i.e., the cuesta to the west of Kasijy, is almost devoid of inhabitants. The largest urban center is Kandreho, located some 40 km to the SE of the reserve (Figure 1). This situation certainly explains the low rate of deforestation in the reserve between 1990 and 2017. The reserve was managed by Madagascar National Parks (MNP) until 2015. However, MNP has not been able to implement the needed management unit in this remote region; it is now under the sole responsibility of the

Ministry of Environment and Sustainable Development. Future extractive industries may change the relatively stable situation for this site. Kasijy coincides with the Bekodoka 2104 concession to the north of the well-known Bemolanga 3102 and Tsimiroro 3104 concessions which are in advanced stages of exploitation [48]. In 2015, the Bekodoka concession was reported as being contracted to Madagascar Petroleum Energy [49]. In 2017, it was reported as being contracted to the company MPE (Madagascar Petroleum Energy) and in the "phase of Evaluation of EIA [Environmental Impact Assessment] for 2D seismic acquisition; seismic acquisition program" [48] (pp. 63). Interestingly, an official 2019 map [50] presents the Bekodoka 2104 concession as a "free bloc", i.e., no ongoing exploration efforts are documented by OMNIS, the government organization operating under the auspices of the Ministry of Energy.

Ranobe-PK32 lies mainly in the district of Toliary II, with its northern part in the district of Sakaraha. Toliara II had a density of 38.6 inhabitants per square kilometer in 2018 (among the highest in Madagascar); Sakaraha had a density of 17.7 in 2018. The wood charcoal for the regional capital city of Toliara is the main cause of deforestation in this case study site. The demand tripled during 2000–2007 when most of the charcoal production came from the western border of the site [51]. Starting in 2005, deforestation shifted towards the core area at distances above 5 km from the borders to exploit new forests. In the dry west, charcoal production does not rely on plantations as is common elsewhere in more humid areas of the country [52]. Forest regeneration is extremely slow due to harsh environmental and climatic conditions [49,53,54]. Thus, more charcoal production requires new forests to be opened. Ranobe-PK32 is the protected area with the highest conservation value index [55]. The site is surrounded by mining concessions, including the large area encroaching the northern part of the reserve. An exploitation permit for a sand mining project, e.g., ilmenite, zircon, was issued by the transitional government to Toliara Sands in 2014 and signed in 2016 despite heavy environmental and social impacts. The expected start in 2019 has been blocked by civil rights protests. Some question the validity of such a contract signed by a government that originated from the 2009 coup d'état [56].

Behara Tranomaro is in the district of Amboasary Atsimo and had a density of 26.1 inhabitants per square kilometer in 2018. The Anosy region, and the nearby Androy region, have been experiencing extended drought for decades. Associated food insecurity and famines, leading to migration waves of people towards the west [57–62] and further towards the north, is resulting in high deforestation rates in the Menabe [35]. Since 2013, southern Madagascar has suffered an extreme drought period intensified by the impacts of the Indian Ocean Dipole associated with the 2015 El Niño [63,64].

## 5. Conclusions

The four case studies show different histories of conservation and pattern of deforestation, but all share the same commonality: challenging management. The combination of threats and challenges requires increased financial and technical resources in the long run; none of the parks considered here are safe from future deforestation. The areas selected for the present study can be considered "paper parks" as they belong to the group of protected areas that receive little management and funding [15]. Yet, contrary to expectation, deforestation is not excessively high in all four areas. The current threats described here will likely remain in the future, and new ones like climate change or extractive industries are looming. The current study does highlight site-specific features of failures and successes. It shows that local context matters, and management and conservation interventions require tailored solutions.

A Madagascar scale analysis is needed to inform the effectiveness of the national system of protected areas to protect forested landscapes and biodiversity. What are the features of protected areas for the conservation of biodiversity and the sustainable management of natural resources? Future studies should consider, amongst others, the size and shape of sites, the relief and other geomorphological features, the conservation value indices, and current and future threats.

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