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LETTER

Tree canopy density thresholds for improved forests cover estimation in protected areas of madagascar

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Abstract

The rich endemic biodiversity of Madagascar is concentrated in different types of natural forests primarily conserved within the network of protected areas (PAs). Since 1990, remote sensing has been utilized to monitor forest cover. The latest forest cover map generated using these techniques provides accurate estimates of natural forest cover within the PAs network. However, the standardized application of Tree Canopy Density (TCD), as used in global assessments of forest cover, yields erroneous estimates for different forest types in Madagascar because the standard TCD cannot be globally applied to all types of forests. Our study aims to utilize global remote sensing data at the scale of PAs to identify specific TCD thresholds for individual PAs. Starting from the year 2000 data, the application of these thresholds will allow us to estimate deforestation in subsequent years at reduced costs. We used the official PA boundaries, a reliable forest cover map at the national scale, and the TCDs published at a global scale to infer the values of TCD to be applied in each PA. The standard TCD threshold above 30% overestimates humid and dry forests and underestimates dry spiny forests in Madagascar. Our specific TCD thresholds inferred for each PA accurately estimate the forest cover in the vast majority of PAs. Using these specific TCD thresholds will allow for improved monitoring of forest cover within the network of PAs. The methodology detailed here can also be applied in other geographic regions, and future improvements in data on forest cover—both remotely sensed and field-collected—will enhance our ability to estimate forest cover and its changes over time.

1. Introduction

Madagascar is renowned worldwide for its forest biodiversity but is also grappling with high poverty levels and deforestation rates [1–4]. Over recent decades, Madagascar's land cover has undergone significant changes, with human activities being the main drivers of deforestation and forest fragmentation [5]. Agriculture, engaging three-quarters of the active population, is the leading cause of deforestation, while energy demand is another major driver across the island. Due to limited access to electricity, over 90% of rural inhabitants still rely on wood biomass, particularly charcoal and firewood, for their energy supply [6]. Despite these challenges, the Government of Madagascar has made significant strides in forest conservation in recent years to safeguard its natural resources and combat deforestation. Over the past two decades, the network of protected areas (PAs) in Madagascar has expanded to cover most of the remaining forests and previously underrepresented ecosystems, including the habitats of threatened endemic flora and fauna species [4, 6, 7]. Forest monitoring in PAs is crucial in Madagascar as it provides essential information for their management, particularly considering that the majority of the country's natural forests are located within these areas. Remote sensing tools, such as satellite imagery and aerial photography, play a vital role in enabling quick and cost-effective forest monitoring, allowing for extensive coverage. These tools facilitate mapping the extent of forests, monitoring changes in forest cover, and identifying areas of deforestation and degradation [8, 9]. This information is also crucial for identifying potential threats like fires, diseases, and illegal logging [10, 11]. By employing remote sensing tools for forest monitoring, managers of PAs in Madagascar can make well-informed decisions regarding the management and conservation of these valuable resources. The use of remotely sensed imagery to document forest change in Madagascar dates back more than four decades (see table S1). In 1990, Green and Sussman published the first maps based on satellite images of the eastern Madagascar rainforest, utilizing Landsat images from 1972–1973 and 1984–1985 [12]. Subsequently, estimates of all forest types in Madagascar as of 1990 were produced by [13, 14]. In 2007, Harper *et al* [15] created a digital forest cover map for Madagascar using Landsat images at a resolution of 28.5 m × 28.5 m (see table S1). To account for the various types of forest vegetation found in Madagascar, the authors applied two sets of forest definitions: (i) 'areas of primary vegetation dominated by tree cover at least seven meters in height, with neighboring tree crowns touching or overlapping when in full leaf,' and (ii) '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 meters in height in the extreme south.' However, the criteria used by [15] to determine the thresholds of tree heights are not described. Additionally, to differentiate between the two primary types of forests, they relied on a simplified bioclimate map created by [16] at a coarse scale. The authors generated forest cover maps with an estimated accuracy of 90% and provided information on national-level deforestation. However, approximately 11,244 km^2 of the remotely sensed area was obscured by clouds and could not be classified at that time [15].

On a global scale, [17] have generated a tree cover map based on Tree Canopy Density (TCD) ranging from 0 (no tree cover) to 100 (dense closed canopy forests) at a spatial resolution of 30 m × 30 m. According to this TCD classification, tree cover loss is defined as the complete removal of TCD, transitioning from any value to 0, at the Landsat pixel scale of approximately 30 m × 30 m. Vieilledent *et al* [5, 18] updated the forest cover maps for Madagascar using data from [15] and the TCD published by [17] for the years 2000, 2005, 2010, 2015, and 2017 with a resolution of 30 m × 30 m, while addressing some data gaps. Vieilledent *et al* [5] followed the approach of [19] to determine that a TCD greater than 75% accurately represents the humid forests in the northeast, where the forest definition by [15] was hindered by cloud cover. This TCD threshold is consistent with the 80% tree cover specified in [15]'s initial forest definition, which applies to the humid regions. Every year, a dataset is produced through collaboration between the University of Maryland, Google, the US Geological Survey (USGS), and NASA (National Aeronautics and Space Administration) to measure tree cover loss across all global land at an approximate spatial resolution of 30 m × 30 m (GFW 2022) [20]. In 2021, the same group made improvements to the 'tree canopy cover' data for the year 2000, specifically the TCD in the new version 1.9 (GFW 2022, University of Maryland 2023) [20, 21].

Despite significant advancements in the application of remote sensing tools, using a single TCD threshold is unlikely to adequately represent the diverse range of forests in a country like Madagascar. This is because Madagascar exhibits a wide variety of forest types, ranging from dense humid forests with more than 2000 mm of rain per year in the east to dry spiny thickets with less than 400 mm of rain per year in the southwest [22]. The forest types also vary with latitude, longitude, and elevation across the island [22–24]. Although Madagascar is smaller in size compared to the Congo Basin in Central Africa, it has a higher number of plant species, with 14,000 plant species in Madagascar compared to 10,000 species in the Congo Basin [14]. Moreover, Madagascar has a significantly higher endemism rate for its plant species at 80%, while the Congo Basin has a rate of 30% [14]. Studies examining plant diversity within one-hectare parcels, such as the littoral forests along the east coast, have revealed a high turnover of plant species even within a single forest type [25]. Since different floral compositions may also represent different forest structures, a single value cannot accurately capture the complexity and diversity of these forest types. While assessments of humid forests may be relatively well-resolved, evaluating the extent of drier forest types poses greater challenges. Dry forest canopies can be discontinuous due to small crown diameters or even the absence of crowns, as seen in stands of *Alluaudia* spp. (Didiereaceae) in Madagascar's unique spiny forests. To achieve a similar level of accuracy obtained in local-scale forest cover estimates across the network of PAs using globally derived TCD values, we propose a methodology that identifies specific TCD tresholds on local forest maps. This approach will help us achieve comparable quality of estimates.

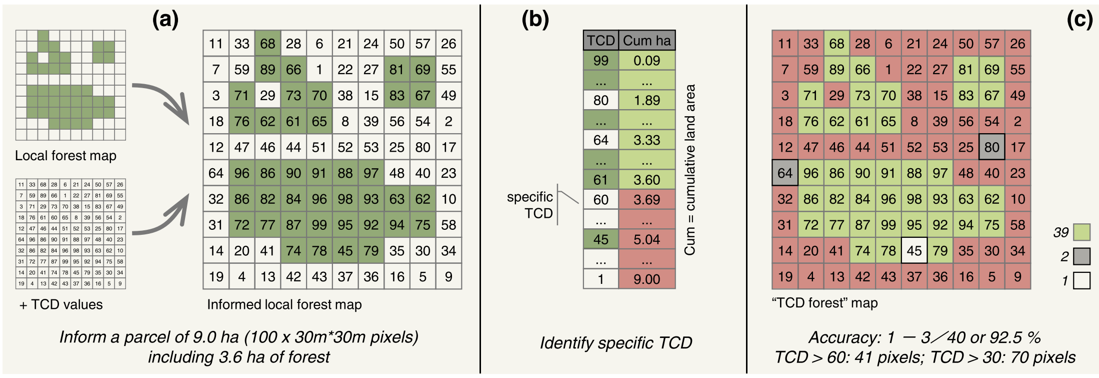

Figure 1. Protocole to identify the specific Tree Canopy Density (TCD) value for each parcel in the network of terrestrial protected areas. (a. we consider a parcel of 10 × 10 pixels of 30 m × 30 m, of which 40 are considered as forest according to a forest map at the local level; b. we sort the information according to decreasing TCD values and calculate the cumulative area; c. we extract the pixels not matching the forest cover map, i.e., 0.18 ha (TCD 64 and 80) overestimating the forest, and 0.09 ha underestimating the forest cover (TCD 45); despite geographical discrepencies, we estimate that the specific TCD have been able to identify a total area of 41 pixels or 3.69 ha, i.e., any pixel with a TCD > 60. For this parcel of 9 ha, applying the standard TCD > 30, would have resulted in an estimated forest cover of 70 pixels or 6.3 ha).

2. Methodology

We have developed a hypothesis that suggests the highest values of TCDs correspond to the forest cover in PAs. In order to test this hypothesis, we have developed a rigorous protocol that outlines the steps required to assess forest cover across different forest types in Madagascar (figure 1, appendix S1). By implementing this protocol, we aim to obtain empirical evidence that either supports or refutes our initial hypothesis. This will help to ensure that our findings are robust and reliable and will provide valuable insights into the effectiveness of current conservation efforts in Madagascar.

To analyse forest cover in PAs, two raster files with 30 m resolution (forest cover and TCD) and one shapefile (PAs) were utilized. To align with the PA boundaries, both raster files were clipped and converted into shapefiles. These three datasets were then reprojected to the same coordinate system using the Madagascar Laborde projection, which is the official projection in Madagascar [26]. The three shapefiles (datasets) were processed in ArcGIS 10.7 (figure 1(a)). The resulting information is summarized for every PA and parcel for each unique TCD value (tables S2, S3). We ranked information with decreasing TCD and calculated cumulative areas of the forest according to [5, 18] and the PA to identify when cumulative PA area matches best the forest cover to identify the corresponding TCD value (figure 1(b), see also appendix S1, table S4), to produce a 'TCD forest map' which we compare to the local forest map (figure 1(c)).

We also compared the results obtained with our specific TCDs with the standard TCD (=TCD > 30%, indicating that all pixels with more than 30% canopy cover are considered to represent forest) used at the global level to estimate tree cover [20] and calculated the discrepancies between forest according to [5, 18] and forest estimates with the specific TCD and the standard TCD.

3. Results

3.1. Comparing standard TCD (> 30%) and specific TCD

The specific TCDs for the 103 PAs with 164 parcels ranged from > 0% to > 97% (see also table S3). The highest specific TCD values applied to humid forests, with values ranging from 97 to 61%. The lowest values applied to the driest forests and thickets in the south, with values ranging from 12 to 0%. Values ranging from 59 to 15 applied to all other types of forests (figure 2).

Applying the standard TCD > 30% to the network of PAs (as of 2015) resulted in an estimated tree cover area of 4,076,083 ha in 2000, which is only marginally different (1.4%) from the forest cover of 4,021,536 ha estimated by [5, 18]. When applying the standard TCD > 30% to estimate the tree cover in the 164 parcels the calculated forest cover was overestimated by at least 10% in 101 parcels and underestimated in 31 parcels. In contrast, when applying the specific TCDs, forest cover was overestimated by 10% or more in only 7 parcels and underestimated in 6 parcels. These numbers decreased to 0 and 3 parcels, respectively, for over and underestimations by at least 50%.

The application of the standard TCD > 30% mostly overestimated the humid forests, to a lesser degree the dry forests in the northwest and underestimated the dry spiny forests in the south based on simplified forest

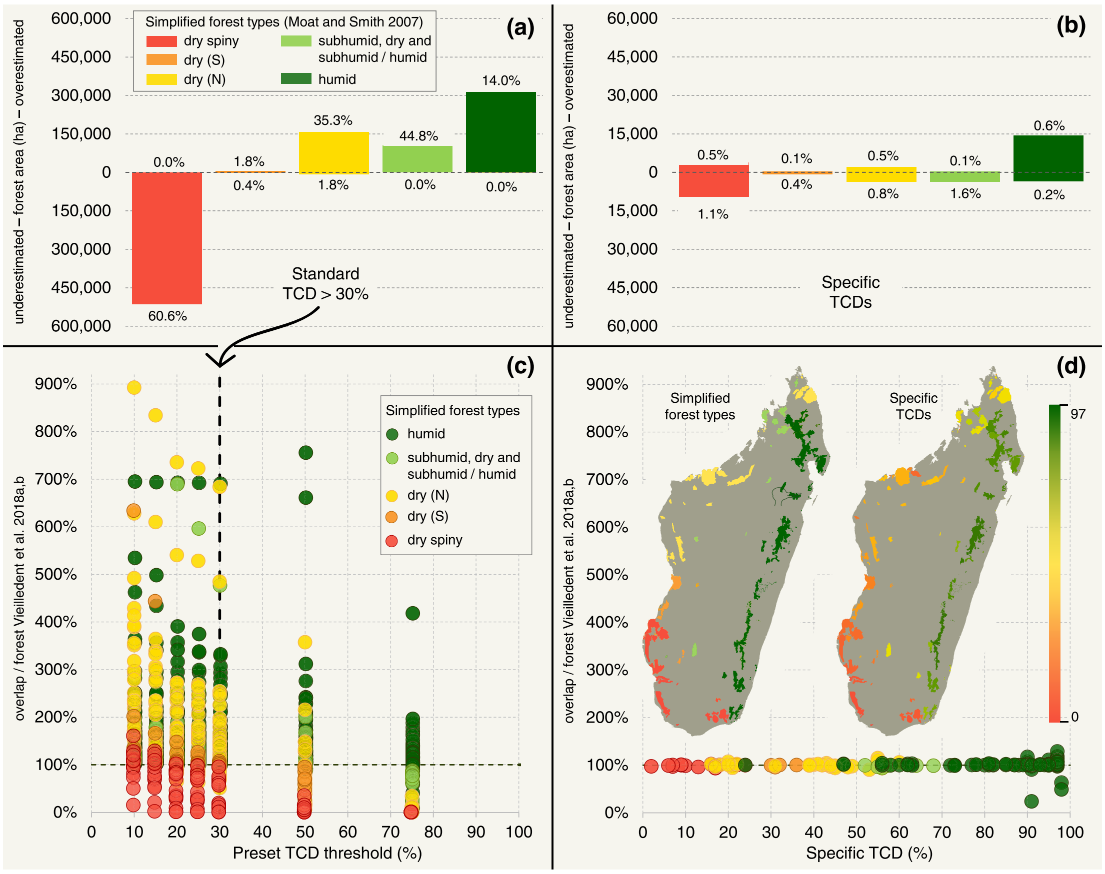

Figure 2. Estimations of forest cover when applying specific Tree Canopy Density (TCD) values to the protected areas (PAs) and the standard TCD > 30% and other preset TCD thresholds as compared to forest estimated by [5, 18] in 2000. (TCD according to [17]; main types of forests simplified following [22]; (a) overestimation or underestimation of the tree cover when the standard TCD > 30% is applied on the PAs according to the main types of forest—over estimation above the '0' line, underestimation below the '0' line; (b) overestimation and underestimation of the tree cover when specific TCDs are applied; (c) overestimation and underestimations of forest cover in PAs when the preset TCD thresholds are applied to PAs according to main types of forests, as compared to the forest estimations by [5, 18]; and (d) range of the specific TCDs to apply to estimate forest area in PAs according to simplified types of forests, and the overlaps of the estimates as compared to forest estimated by [5, 18] in 2000, map left showing the network of terrestrial PAs with forests according to simplified types of forest, map right showing the same network with a pattern according to the TCD values—suggesting latitudinal, longitudinal and altitudinal influences).

types according to [22] (figure 2). Applying specific TCDs resulted in a total underestimated area of 21,673 ha and a total underestimated area of 20,828 ha. The sum of absolute discrepancies was 42,501 ha (1.1%) when using specific TCDs. In contrast, applying the standard TCD > 30% resulted in an overestimation of the forested area of 526,282 ha and an underestimated area of 580,830 ha. This adds up to a discrepancy of 1,107,112 ha (27.5%) when using the standard TCD > 30% (figure 2, see also table S3). Preset TCDs tend to underestimate forest cover in parcels with dry spiny forests, including TCD > 10%, and overestimate forest cover in PAs with humid forests, including TCD > 75% (figure 2(c)).

When comparing our final sample of 164 parcels, our methodology can estimate the forest cover with an accuracy of > 80% for 128 parcels (78.0% of the 164 parcels). Applying the standard TCD > 30% would have resulted in estimates with the same accuracy for 72 parcels (43.9% of all parcels). With the specific TCD, a total area of 5,678,479 ha matches the local forest cover map (89.4%) while the area is only 4,699,332 ha when applying a TCD > 30% (74.0%).

3.2. Parcel size

The study comprised of 164 parcels ranging in size from 12 ha to 385,735 ha, with a median parcel size of 6199 ha. The level of accuracy for identifying the specific TCD to estimate the forest cover in PAs varies with the size of the parcels. Errors are larger in smaller parcels and become accurate at parcels larger than 3,200 ha (table 1).

Table 1. Accuracy to estimate the forest cover with the specific TCDs as compared to forest cover estimated by [5, 18] according to the area of PAs or constituting parcels.

Area [ha]	Number of parcels	Total area (ha)	Accuracy
[11–800]	35	14,306	82.6%
[800–1600]	17	20,213	79.4%
[1600–3200]	12	25,673	78.9%
[3200–6400]	20	88,983	85.5%
[6400–12,800]	12	120,452	89.0%
[12,800–25,600]	16	302,191	88.1%
[25,600–51,200]	17	638,167	87.6%
[51,200–102,400]	18	1,298,391	87.9%
[102,400–204,800]	8	1,248,887	88.8%
[204,800–385,735]	9	2,594,202	91.4%
Total	164	6,351,463	89.4%

4. Discussion

Our methodology has shown promising results in identifying specific TCD thresholds to estimate forest cover with an accuracy of 89.4%, compared to 74.0% when the standard TCD > 30% threshold is applied. However, our approach has limitations in PAs where different forest types coexist, such as parcel 1 of Montagne d'Ambre, where humid forests at higher altitudes transition into dry forests towards the northern part of the national park. To address this issue, it is necessary to split the area according to forest types to better reflect this unique characteristic. Ankarana Special Reserve presents a similar challenge, with subhumid forests found in canyons, while dry to spiny forests occur elsewhere. An updated land cover map is essential, considering that previous studies did not apply appropriate methodologies to differentiate between humid and dry forests. In particular, [15] did not verify the 7 m tree height in humid forests using remote sensing technology. Additionally, the simplified bioclimates used in their study, based on the work of [16], were a simplification of Cornet's map published in 1972 at a scale of 1:900,000. Since Cornet's map is outdated and at a coarse scale, it requires improvement as suggested by the author at the time [27]. Harper *et al* [15] used Humbert and Cours Darne's map (1965) [28] for forest delineation, which is based on floral composition, in contrast to Moat and Smith's map (2007) [22], which is based on vegetation structure (physiognomy). The vegetation map proposed by [22] should be updated with higher spatial resolution for the western dry forests to allow for better distinction between natural forests, disturbed forests, and tree plantations.

The characterization of understory structure in closed canopy forests can be challenging due to its obscured nature beneath the overstory canopy. This challenge is particularly pronounced in the western forests of Madagascar, where understanding the structure of dry forests remains a complex task e.g., [22], leaving ample room for further investigation. One crucial aspect that has yet to be explored is the synchronous or asynchronous desiccation patterns between the canopy and lower strata e.g., [29]. Therefore, additional research is necessary to elucidate the phenological variations between the overstory and understory in different forest types. Undertaking this endeavour poses significant challenges, particularly in tropical forests, including evergreen humid forests, as well as some western dry forests of Madagascar, where trees and bushes retain foliage throughout the dry season. Previous studies on fire disturbance in the Menabe region of the western dry forests have indicated a substantial impact on the middle strata, while the lower and upper strata appear to be less affected [30]. Additionally, a recent investigation that combined fieldwork and remote sensing techniques in a dry forest in northern Madagascar, exhibiting varying degrees of disturbance, revealed different vegetation information obtained through these methodologies [31]. Incorporating altitude information in the largest PAs can potentially enhance the accuracy of specific TCD thresholds used in different geographies, particularly in the east where altitudinal gradients are more pronounced compared to the west. While measuring tree height would be desirable to better account for forest types, it necessitates additional remote sensing tools such as LiDAR, which could make routine application of the method complex and costly [32–34]. Remote sensing technologies like RADAR, Sentinel, and Landsat can be utilized to identify and differentiate various forest types [35]. However, to achieve accurate forest maps, it is crucial to continually assess and account for the accuracy of the data. The need for an updated and accurate vegetation map of Madagascar, specifically an updated forest cover map that incorporates forest gains for humid forests, is imperative for effective forest management and conservation efforts.

5. Conclusion

We have identified an opportunity to utilize globally estimated TCDs for accurate estimation of forest cover on local forest maps. Unlike forest maps, which are not consistently produced at national or sub-national scales, TCDs are regularly published on an annual basis. Our approach connects TCDs with forest maps, allowing us to track changes in forests as new TCDs become available and refine specific TCDs with more accurate forest maps. By utilizing specific TCD values to estimate forest cover in PAs, our methodology can contribute to addressing deforestation in PAs since 2001 and provide annual updates on tree cover losses. However, to gain a comprehensive understanding of the pressures on forests, it is crucial to also consider tree cover outside PAs, especially in the outer buffers of PAs. While tree cover gain has been observed in the most humid forests over a 20-year period, it may take longer for dry spiny forests and thickets to recover from deforestation. Therefore, ongoing monitoring and assessment of these forest types are essential for a more complete picture of forest dynamics.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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