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Supplementary Information: On track to achieve No Net Loss of forest at Madagascar's biggest mine

Katie Devenish[1#], Sébastien Desbureaux[2], Simon Willcock[1,3], Julia P G Jones[1]

[1] School of Natural Sciences, Bangor University, Bangor, Gwynedd, LL57 2DG, UK.

[2] Center for Environmental Economics – Montpellier (Univ. Montpellier, CNRS, INRAE, Montpellier SupAgro), Montpellier, France

[3] Rothamsted Research, Harpenden, Hertfordshire, AL5 2JQ, UK.

[#] Corresponding author: Katie Devenish, ktd19ycv@bangor.ac.uk

Table of contents

Supplementary Methods

Study site and context

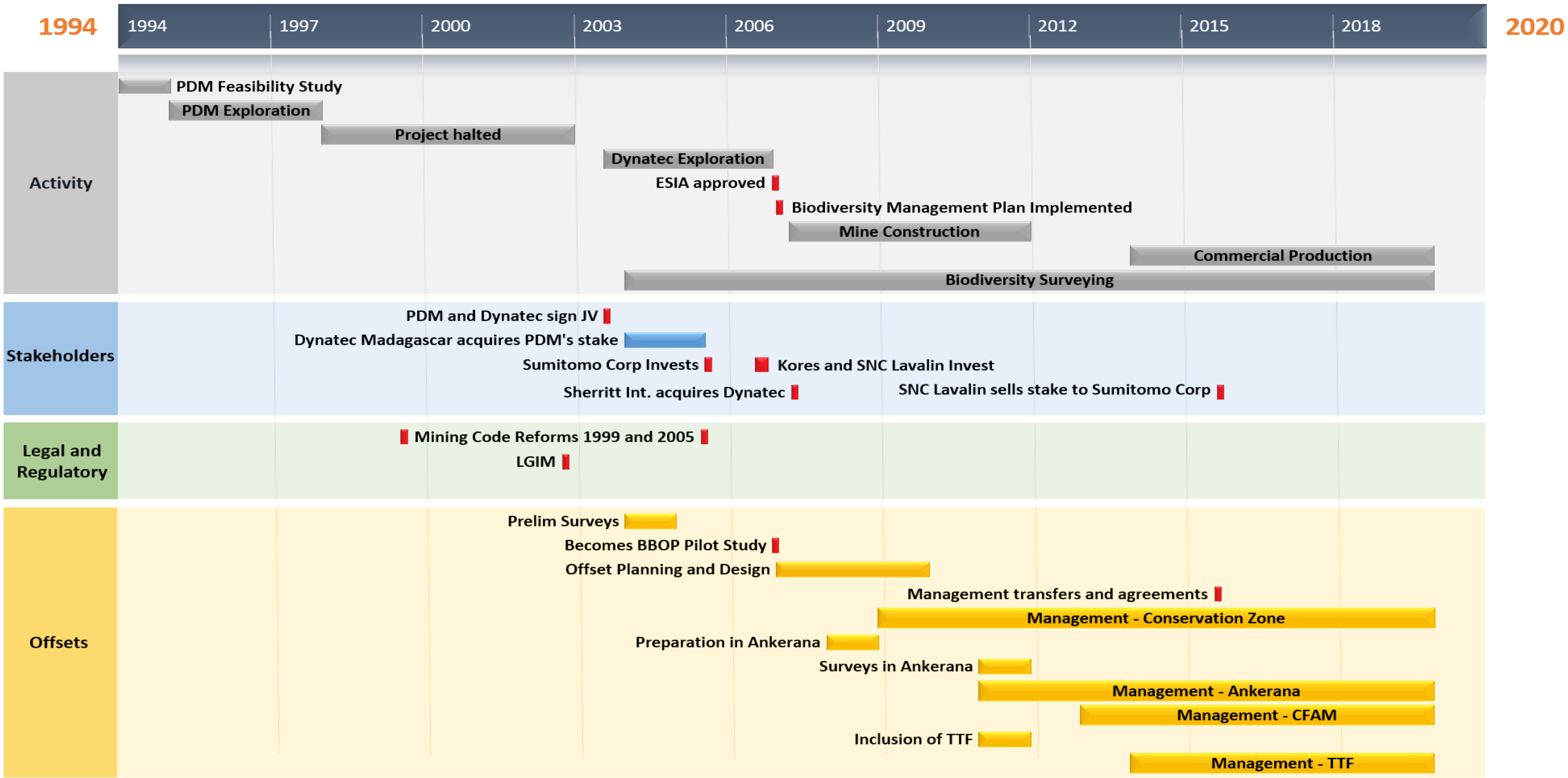
Measures taken to avoid, minimise and restore biodiversity loss at Ambatovy

The mitigation hierarchy states that damage to biodiversity resulting from development must first, and preferentially, be avoided, minimised and restored[1], with offsetting reserved for any remaining unavoidable impacts[2]. As part of its avoidance measures Ambatovy set aside several patches of rare azonal forest (totalling 306 ha) overlying the ore deposit for conservation, foregoing mineral extraction[3]. Additionally, the slurry pipeline was routed to avoid fragments of primary forests and sensitive habitats (eg. breeding habitat for the critically endangered Golden Mantella frog; *Mantella aurantiaca*)[3].

To minimise impacts on biodiversity, prior to the mine construction Ambatovy surveyed the area scheduled for clearance and the adjacent forests to ensure locally endemic species found within the footprint were also found elsewhere, ensuring the mine did not lead to species extinction[4]. During the construction phase, priority species with restricted mobility were salvaged from sites before clearance and relocated to conservation areas outside the mine footprint[4]. Floral species of concern were transplanted in an on-site nursery[4]. Forest clearance was paced, radiating from a central point to give mobile species time and space to disperse[3]. To aid future restoration efforts the removed top-soil was preserved[3].

Ambatovy has committed to restoring the mine site to a multi-functional forest[5]. Plant nurseries (including 5 community nurseries) and the forests within the Conservation Zone biodiversity offset will provide a source of seeds and propagules to aid forest restoration[5]. Whilst the mine is still in the early phase of operations the company has conducted trials of forest restoration to test and develop methods and in 2017, 6 ha of land was rehabilitated[5].

The BBOP case study where Ambatovy's NNL strategy is documented, and the Environmental Impact Assessment are available for download here: https://ambatovy.com/ang/media/reports/


1994
1994
1997
2000
2003
2006
2009
2012
2015
2018
2020
Activity
PDM Feasibility Study
PDM Exploration
Project halted
Dynatec Exploration
ESIA approved
Biodiversity Management Plan Implemented
Mine Construction
Commercial Production
Biodiversity Surveying
Stakeholders
PDM and Dynatec sign JV
Dynatec Madagascar acquires PDM's stake
Sumitomo Corp Invests
Kores and SNC Lavalin Invest
Sherritt Int. acquires Dynatec
SNC Lavalin sells stake to Sumitomo Corp
Legal and Regulatory
Mining Code Reforms 1999 and 2005
LGIM
Offsets
Prelim Surveys
Becomes BBOP Pilot Study
Offset Planning and Design
Management transfers and agreements
Management - Conservation Zone
Preparation in Ankerana
Surveys in Ankerana
Management - Ankerana
Management - CFAM
Inclusion of TTF
Management - TTF

Supplementary Figure 1: Timeline of key events in the development of Ambatovy. This includes exploration and mining activity, stakeholders, relevant legal and regulatory changes in Madagascar, and progress in the biodiversity offset programme. PDM = Phelps Dodge Madagascar (original concession-holder and predecessor of Ambatovy), ESIA = Environmental and Social Impact Assessment, JV = Joint Venture, LGIM = Law on Large Scale Investments in Mining - Law n°2001-031, BBOP = Business and Biodiversity Offset Partnership, CFAM = Corridor Forestier Analamay- Mantadia, TTF = Tototorofotsy.

Methods used by Ambatovy to quantify biodiversity losses and gains

Biodiversity losses and gains were calculated using a modified version of the habitat hectares approach which combines the area of habitat impacted with a composite measure of habitat quality (habitat hectares = area x quality)[6]. Prior to mine construction the forest was mapped and surveyed to calculate the impact area and measure the structural and compositional attributes that were selected as indicators of habitat quality[4]. The density of three species of critically endangered lemurs was also integrated into the habitat quality metric[4]. The company estimated that, in total, 2,064 ha of natural forest would be cleared or significantly degraded at the mine footprint and upper pipeline, translating to a loss of 1,467 habitat hectares[3].

Ambatovy aimed to compensate for these losses by reducing deforestation from shifting agriculture within 4 sites designated as biodiversity offsets[3]. To calculate the expected biodiversity gains from protecting these sites Ambatovy had to establish the baseline (how much biodiversity would be lost in the absence of protection) and estimate conservation effectiveness (how much of this loss could be prevented through protection).

The baseline was defined using historical background rates of deforestation in the district (Moramanga for the Conservation Zone, CFAM and Torotorofotsy, and Brickaville for Ankerana)[3]. Conservation effectiveness was based on the deforestation rate within the nearest protected areas (Mantadia National Park and Analamazoatra Special Reserve for the Conservation Zone, CFAM and Torotorofosty, and Mangerivola National Park for Ankerana), assuming that equivalent rates are achievable through protection of the offsets[3]. This was more realistic than other offset policies which assume 100% conservation effectiveness, or zero deforestation, within the offsets following protection[7].

To account for uncertainty and increase the likelihood of achieving NNL Ambatovy developed 4 possible scenarios of baseline deforestation and conservation effectiveness and ensured the required biodiversity gains could be achieved for all scenarios by 2040, before the company ceases operations[3]. These scenarios were based on the highest and lowest rates of deforestation in the associated district between 1990 and 2010 and the highest and lowest rates of deforestation within the nearest protected areas over the same period.

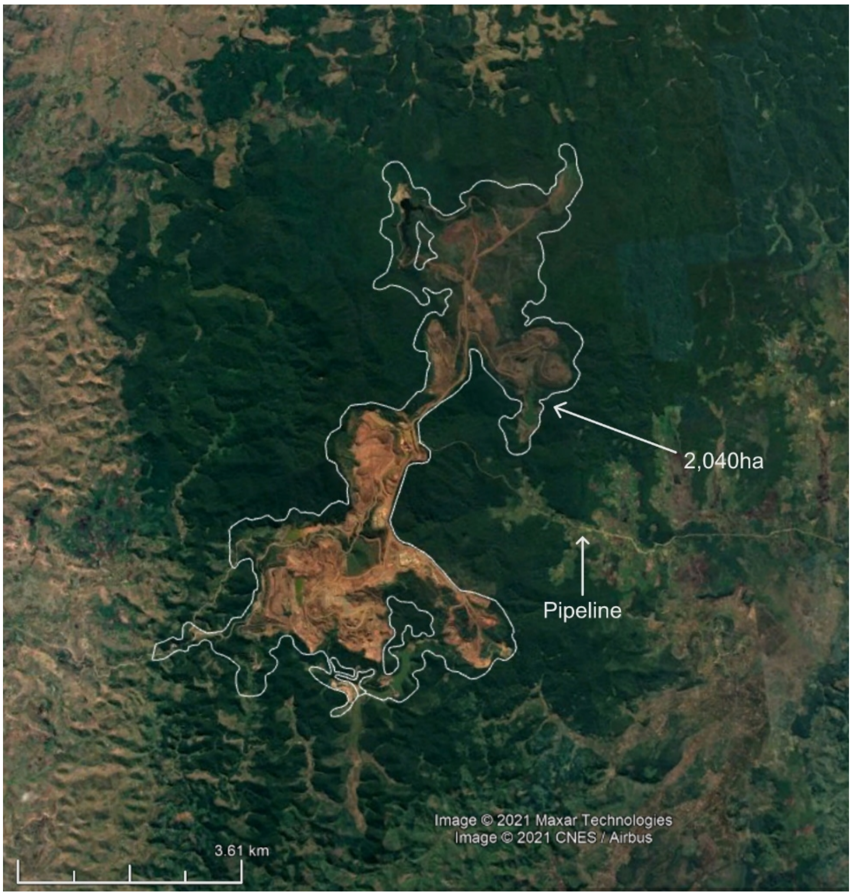
For each scenario the habitat hectares that could be gained through protection were estimated. First, the offset sites were surveyed to assess habitat quality. Then, gains in habitat area were estimated by subtracting the expected rate of deforestation within the offset following protection (i.e. the measure of conservation effectiveness) from the baseline deforestation rate. The most optimistic scenario, based on a high background rate of deforestation and high conservation effectiveness, predicted NNL of forest would be achieved during 2022[3].

Offset	Baseline annual deforestation rate used by Ambatovy (%)		Counterfactual annual deforestation rate (%) **after protection** estimated using matching and difference-in-differences regressions
	Highest	Lowest	
ANK	0.5	0.3	3.67
CZ	1.4	0.5	0.12
CFAM	1.4	0.5	N/A
TTF	1.4	0.5	3.1

Supplementary Table 1; Comparison of the baseline deforestation rates used by Ambatovy in their loss-gain calculations and the counterfactual deforestation rates estimated here using statistical matching and differences-in-differences regressions. We could not estimate the counterfactual deforestation rate for CFAM as it did not meet the requirements of parallel trends necessary for the matched controls to represent counterfactual outcomes.

Deforestation rates are highly spatially and temporally specific, influenced by a range of physical, social, economic and political factors operating at that point in time[8]. Therefore, attempts to extrapolate across space and time are highly uncertain. Our counterfactual deforestation rates were derived from observed outcomes in matched controls *over the same post-intervention period* (controlling for pre-intervention differences between treated and control samples). Therefore, we avoid extrapolating over time and mitigate the uncertainty of extrapolating over space through matching, as the matched samples have a similar probability of deforestation under baseline conditions (based on the measures of accessibility and agricultural suitability). Therefore, we consider our estimates of counterfactual deforestation a more reliable estimation of the deforestation which would have occurred within the offsets in the absence of protection than the historical rates employed by Ambatovy.

These results indicate that Ambatovy underestimated the amount of deforestation which would have occurred, absent protection, in Ankerana and Torotorofotsy and consequently the potential biodiversity gains (via avoided loss) which could be accrued through protection. However, Ambatovy's estimate was higher in the Conservation Zone.



Supplementary Figure 2; Independent estimate of the area of forest loss at the mine footprint through manual digitisation of a Google Earth image (Map data: Google, Maxar Technologies, CNES/Airbus, 2021). The image is dated 19/6/2021.

Ambatovy estimated that 2,064 ha of forest would be lost or significantly degraded at the mine footprint and upper pipeline and used this figure to calculate the residual biodiversity loss in habitat hectares. The company expected these losses to accrue between 2007 and 2022. Biodiversity loss associated with the pipeline was only calculated for the upper 2km which crosses the primary forests of the concession area as, for most of the route, the pipeline traverses a modified landscape of secondary vegetation of low biodiversity value[9]. Consequently, losses associated with the pipeline are small, amounting to 21.5 ha of forest or 4 habitat hectares (0.3% of the total estimated biodiversity loss resulting from the mine)[4]. Likewise, the processing plant and tailings facility at Toamasina were constructed on degraded secondary land and were therefore not included in the loss calculations[3]. Our independent estimate of the area of forest loss at the mine footprint (2,040 ha) supports Ambatovy's total estimate of forest loss at the footprint and upper pipeline (2,064 ha).

Offset	Ankerana	CFAM	Conservation Zone	Torotorofotsy	Total
Total Offset Area (ha)	6,904	9,423	3,787	8,626	28,740
Forest Area 2000 (ha)	6,459	5,916	3,035	2,653	18,062
% of total area forested in 2000	94	63	80	31	63
Forest area at year of protection (ha)	6,068	5,824	3,031	2,216	17,139
% of total area forested at year of protection	88	62	80	26	60
Forest area 2020 (ha)	5,985	5,529	3,017	1,437	15,968
% of total area forested by 2020	87	59	80	17	56
% Reduction in Forest Cover 2000-2019	7.3	6.5	0.6	46	12
Average annual deforestation rate **before** protection (%)	0.61	0.13	0.02	1.3	N/A
Average annual deforestation rate **after** protection (%)	0.15	0.72	0.04	5.9	N/A

Supplementary Table 2: Forest cover and loss statistics for each offset and the entire offset portfolio over the 19 year study period. These figures correspond to the total area of the offset.

To calculate forest area in 2000 we clipped the tree loss layer (the Global Forest Change dataset[10] masked to the forest cover 2000[11] layer) to the boundary of each offset polygon. The total number of pixels within this layer represents the area of forest in each offset in 2000. To convert to hectares we multiplied the count of pixels by 0.09. From this we subtracted the total number of pixels that were deforested between 2001 and the year of protection (converted to hectares) to give forest area at year of protection.

These results show that Ankerana is the most forested offset and since protection has experienced very little deforestation. The Conservation Zone is also highly forested and only lost 0.6% of its forest cover over the whole study period. The near-total lack of deforestation *before* protection in this offset underlines the impact the presence of the mine itself had on reducing forest loss.

Contrary to expectations, the average annual deforestation rate increased following protection in CFAM, the Conservation Zone (although it remained negligible) and Torotorofotsy. However, this does not necessarily mean the offsets had no effect as the increase in deforestation may have been higher without protection (as in the Conservation Zone, Supplementary Figure 4).

The situation in Torotorofotsy is particularly worrying. Between 2014, when the site became designated as a biodiversity offset, and January 2020 35% of its forests were cleared. Nearly 40% of which occurred in 2017 alone. An average deforestation rate of 5.9% per year between 2014 and 2020 is well above the national rate of 1.63% per year for the same period (calculated using the same data and methods as above). However, our results suggest there was no significant difference in deforestation between Torotorofotsy and the estimated counterfactual over this period, based on our representative sub-sample of pixels. In other words, this high rate of deforestation can be explained by the accessibility and suitability of the site for alternative uses (in this case rice production) as the matched control units which have similar characteristics also experienced high deforestation over this period.

Matching

Statistical matching is an approach used to construct a valid control sample in non-experimental studies where the intervention is not randomly assigned. It involves matching a set of units subject to an intervention (pixels or polygons) to control units not subject to the intervention, based on similarity in range of characteristics, termed covariates, hypothesised to influence the outcome of interest and selection to treatment[12,13]. As matched treated and control units have a similar probability of outcomes (e.g., deforestation) under baseline conditions, yet differ in exposure to the intervention, the matched control units represent the counterfactual scenario[14].

	Ankerana		CFAM		Conservation Zone		Torotorofotsy	
	Total	Sample (n = 2,862)	Total	Sample (n = 2,626)	Total	Sample (n = 1,340)	Total	Sample (n = 1,170)
Average annual deforestation rate % (2000-Year of Protection)	0.61	0.58	0.13	0.10	0.02	0.01	1.3	1.3
Average annual deforestation rate % (Year of Protection-2020)	0.15	0.12	0.72	0.64	0.04	0.04	5.9	6.1

Sampling treated and control units

Supplementary Table 3: Deforestation rates before and after protection in our sub-sample of pixels compared to the total rates for the whole offset. This indicates that our sample pixels, which comprise approximately 4% of pixels forested in 2000, were representative of deforestation outcomes within each offset. Sample sizes refer to the total number of pixels.

Data pre-cleaning

To obtain our pool of control units we used a grid-based sampling strategy to extract pixels from the province of Toamasina that were forested in the Year 2000 and outside the formal protected area network (excluding the CAZ) and the buffer zones of the biodiversity offsets. This produced 634,465 potential control pixels. To improve efficiency (which was particularly necessary when conducting the robustness checks) we defined a set of calipers based on the distribution of covariate values within the treated (offset) sample and removed control units with values outside this caliper which would never have been matched. This reduced the spread of values within the remaining control sample which brought the added benefit of producing closer matches by making the calipers in the matching algorithm (based on the standard deviation of the data) more restrictive.

First, we combined our sample of pixels from each offset with the full set of 634,465 potential control pixels. Then we filtered each dataset removing all observations with values greater than $\max(x) + \sigma(x)$ and smaller than $\min(x) - \sigma(x)$; where x refers to the covariate values in the offset sample and σ, the standard deviation. This was repeated for all 5 essential covariates in all four offset-control datasets. This resulted in the removal of up to 92% of the potential control pixels with covariate values way outside the range of the offset sample which would never have been matched.

Selection of covariates

In deforestation analyses selected covariates are primarily associated with accessibility and suitability of the site for alternative land uses, typically agriculture or the extraction of forest products[15–17].

The covariates selected for use in this study are presented in Supplementary Table 4. These are known drivers of deforestation, both in Madagascar and globally, and have been used in other impact-evaluation studies of deforestation (Supplementary Table 5). Following Eklund *et al*[18] annual precipitation, combined with slope and elevation is a proxy for agricultural suitability. Distance to forest edge and distance to recent deforestation reflect the frontier effect and the increased probability of deforestation occurring near previously cleared sites[19,20]. Distance to road, cart track and the nearest settlement, plus land surface characteristics such as elevation and slope are proxies for accessibility, demand, the ability to clear forest undetected and the ease of transporting harvested products to market[20,21].

The 5 additional covariates were so defined because of poorer data quality (population density and distance to settlement), correlation with essential variables (annual rainfall is highly correlated with elevation [0.7]) or because they are simply considered less influential drivers of deforestation in this context (distance to cart track, distance to river). Distance to settlement does not differentiate between the size of settlement, but demand for, and utilisation of, forest resources varies significantly between villages, towns, and cities. Whilst evidence for a significant relationship between population density and deforestation in Madagascar is mixed[21–24], possibly due to data limitations[20,23], population density is generally considered a key factor influencing deforestation globally and is a commonly used covariate in matching analyses (Supplementary Table 5). However, we chose not to include population density as an essential covariate as the available data at the appropriate spatial resolution is poorly measured in the study area. The data is based partly on night-light which, in a country where 73% of the population lacks access to electricity[25], is not the most reliable indicator. However, population density is indirectly controlled for in our matching analysis as it is collinear with our 5 essential covariates (Supplementary Table 6).

Covariate	Description	Resolution	Essential or Additional	Source
Distance to Road (m)	Euclidean Distance in metres to the nearest main road. Calculated in ArcMap 10.5 from the roads layer using the Euclidean Distance tool	30m	Essential	Roads - FTM (Foiben Taosarin-tanin 'I Madagasikara)
Distance to Forest Edge (m)	Distance in metres to the nearest forest edge in 2000.	30m	Essential	Vieilledent et al[11]
Distance to former deforestation 1990-2000 (m)	Euclidean Distance in metres to the nearest pixel deforested between 1990 and 2000. These were identified by extracting pixels classed as forest in 1990 but non-forest in 2000.	30m	Essential	Vieilledent et al[11]
Elevation (m)	Digital Elevation Model	30m	Essential	Shuttle Radar Topography Mission SRTM, 1 arc-second Digital Elevation Model. Downloaded from USGS Earth Explorer.
Slope (°)	Calculated from the DEM using the slope function in ArcMap 10.5	30m	Essential	
Annual Precipitation (mm)	Average annual precipitation 1970-2000.	490m	Additional	WorldClim v.2 Bioclimatic Variables. Fick and Hijmans[26]
Distance to River (m)	Euclidean distance in metres to the nearest river.	30m	Additional	Digital Chart of the World
Distance to Cart Track (m)	Euclidean Distance in metres to the nearest cart track.	30m	Additional	Cart Tracks – FTM

Distance to Settlement	Euclidean distance in metres to the nearest settlement	30m	Additional	NGA OCHA ROSA Madagascar Populated Places (2007)
Population Density	Estimated population density in Year 2000. Values represent people per pixel.	90m	Additional	WorldPop Version 2

Supplementary Table 4; List of covariates used in the statistical matching with their description, resolution and source. When Euclidean Distance was calculated the output cell size was set to 30m to match the resolution of the outcome variable (tree loss) layer. To align the data layers, covariates with 30m resolution were snapped to the tree loss layer, resulting in a maximum spatial error of 15m. All data was projected to WGS 1984 UTM Zone 38S. All data is publicly available online.

Previous Studies	Used Statistical Matching	Distance to road	Distance to settlement	Population Density	Population Pressure	Elevation	Slope	Aspect	Distance to forest edge	Distance to River	Distance to recent deforestation	Vegetation type/Ecoregion	Annual Rainfall	Population Growth	Distance to nearest agricultural cell	Distance to border of NP	Infrastructure	Conservation Activity	Awareness of deforestation	Amount of Hatsaky, charcoal production and cattle ranching.	Cropland	Agricultural Suitability	Irrigated rice suitability
Brinkmann et al, 2014 *		✓	✓	✓		✓										✓	✓	✓	✓	✓	✓		
Agrawal et al, 2005*		✓		✓		✓	✓																
Vagen, 2006 *		✓	✓			✓	✓							✓	✓								
Rasolofoson et al, 2015 *	✓	✓	✓	✓		✓	✓		✓		✓											✓	✓
Eklund et al, 2016 *	✓	✓	✓			✓	✓			✓	✓	✓	✓										
McConnell et al, 2004 *			✓	✓	✓	✓	✓		✓	✓					✓								
Green and Sussman, 1990 *				✓			✓																
Nagendra et al, 2003		✓	✓			✓																	
Honey-Roses et al, 2011	✓	✓				✓	✓	✓															
Cuenca et al, 2016	✓	✓	✓			✓	✓																
Jones and Lewis, 2015	✓	✓	✓			✓	✓		✓	✓													
Andam et al, 2008	✓	✓	✓	✓		✓	✓		✓	✓													
Bruggeman et al, 2015	✓	✓	✓			✓	✓					✓											
Buntaine et al, 2014	✓	✓		✓		✓	✓				✓												
Costedoat et al, 2015	✓	✓	✓	✓		✓	✓																
Sills et al, 2015	✓			✓		✓	✓																
Arriagada et al, 2012	✓						✓																
Simmons et al, 2018	✓						✓																
Assuncao et al, 2015																							

Supplementary Table 5: Covariates used in other matching and regression studies as predictors of deforestation. Studies marked with an asterix * are based in Madagascar. Covariates shown are red were selected for use in this study.

	Dependent variable = Population Density				
	(1)	(2)	(3)	(4)	(5)
	Overall	ANK + ctrl	CFAM + ctrl	CZ + ctrl	TTF + ctrl
Dist_road	-0.003***	-0.003***	-0.003***	-0.003***	-0.003***
	(0.00002)	(0.00002)	(0.00002)	(0.00002)	(0.00002)
Dist_edge	-0.008***	-0.009***	-0.008***	-0.008***	-0.008***
	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)
Dist_defor	0.002***	0.002***	0.002***	0.002***	0.002***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Slope	0.197***	0.144***	0.170***	0.158***	0.163***
	(0.026)	(0.026)	(0.027)	(0.027)	(0.027)
Elevation	-0.110***	-0.106***	-0.108***	-0.107***	-0.107***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Constant	286.550***	288.334***	288.376***	289.104***	288.836***
	(0.675)	(0.677)	(0.678)	(0.679)	(0.679)
Observations	641,437	636,301	636,065	634,779	634,609
R^2	0.107	0.109	0.108	0.109	0.109
Adjusted R^2	0.107	0.109	0.108	0.109	0.109

Note: *p< 0.1, **p<0.05, ***p<0.01

Supplementary Table 6: Correlation between population density and the 5 essential variables in our full pre-matching sample of pixels. Overall refers to the full sample of control and treated pixels (i.e. from all four offsets). Columns labelled 2,3,4 and 5 refer to the full control sample plus the sample of pixels from the named offset. ANK = Ankerana, CZ = Conservation Zone, CFAM = Corridor Forestier Analamay-Mantadia, TTF = Torotorofotsy. Results obtained from a linear regression with population density as the dependent variable and distance to road, distance to edge, distance to recent deforestation, slope and elevation as predictors.

This shows that population density is significantly correlated with the 5 essential covariates used in our main matching specification.

Implementation of matching

Mahalanobis matching has been shown to produce better balance across individual covariates than propensity score matching and is appropriate and effective when there are small number of covariates upon which close matches are desired[12,39].

Following the recommendations of Schleicher et al[14] we tested several matching specifications and compared the resulting match quality before the deciding upon the main matching specification. All specifications used nearest-neighbour matching with Mahalanobis distance on the 5 essential covariates but the size of caliper (0.25, 0.5 and 1 standard deviation), matching with/without replacement and the ratio of treated to control units (1:1 and 1:5) were varied. Match quality was assessed through the post-matching standardised difference in mean covariate values between treated and control samples (Supplementary Table 6). Values less than 0.25 are generally considered to represent an acceptable match but the closer to zero the better[12].

In selecting the most appropriate matching specification there is a trade-off between the quality of matches and the number of treated units for which a match can be found[14]. Setting a caliper of 0.25 standard deviations resulted in a very close matches but left hundreds of treated units un-matched. Rejecting treated units could bias the results if the un-matched units are non-random, i.e. if they share a common characteristic, such as location. Therefore, we chose the specification which matched all treated units in all offsets yet still produced a very good covariate balance (maximum standardised difference in means < 0.05). This was 1:1 nearest neighbour matching without replacement using Mahalanobis distance and a caliper of 1sd. Neither matching with replacement nor with ratio a of 1:5 yielded a consistent improvement in balance in comparison.

Covariates	1sd caliper	0.5sd caliper	0.25sd caliper	0.5sd caliper + matching with replacement	1sd caliper + ratio of control to treated units of 1:5
Ankerana (N =2862 pixels)					
Slope	-0.0003	-0.0007	0.0011	0.0008	0.0091
Elevation	0.0035	0.0079	0.0073	-0.0091	-0.022
Distance to road	-0.017	-0.012	0.0003	-0.04	-0.033
Distance to edge	0.04	0.04	0.022	0.019	0.06
Distance to deforestation	0.033	0.029	0.013	0.019	0.031
Number of un-matched treated units	0	57	426	5	0
CFAM (N = 2626)					
Slope	-0.012	-0.0091	-0.0035	-0.0058	-0.0061
Elevation	-0.055	-0.047	-0.016	-0.014	-0.2
Distance to road	-0.0041	-0.0043	-0.0014	0.013	0.027
Distance to edge	0.013	0.0062	0.0099	0.016	-0.044
Distance to deforestation	0.039	0.031	0.013	0.019	0.09
Number of un-matched treated units	0	95	649	15	0
Conservation Zone (N= 1340)					
Slope	0.002	0.0036	-0.0011	0.0043	0.03
Elevation	0.039	0.04	0.028	0.026	0.077
Distance to road	-0.0083	-0.0065	0.0036	-0.012	-0.053
Distance to edge	0.013	0.011	0.011	0.013	-0.016
Distance to deforestation	0.034	0.037	0.015	0.021	0.074
Number of un-matched treated units	0	10	343	2	0
Torotorofotsy (N= 1170)					
Slope	-0.0072	-0.0074	-0.009	-0.011	-0.0009
Elevation	0.0042	0.0062	0.0022	-0.0032	-0.021

Distance to road	0.019	0.021	0.015	0.0011	0.04
Distance to edge	0.0065	0.0067	0.0028	0.0099	-0.045
Distance to deforestation	0.017	0.019	0.016	0.016	0.032
Number of un-matched treated units	0	2	158	2	0

Supplementary Table 7; Post-matching standardised difference in mean covariate values between offset and the matched control samples for each of the matching specifications tested. All specifications used nearest-neighbour matching with Mahalanobis distance on the 5 essential covariates. Unless otherwise specified in the column heading matching was conducted without replacement and with a ratio of 1:1. Only the parameter specified in the column heading was varied.

Calculating counterfactual and avoided deforestation

To estimate the amount of deforestation which would have occurred each year in the offsets in the absence of protection we use the estimated treatment effect to convert observed deforestation to counterfactual levels.

For example, results from our site-based difference-in-differences regression showed that protection reduced average annual deforestation by an estimated 96% in Ankerana. In other words, observed deforestation was 4% of the estimated counterfactual. To convert the area of observed deforestation each year to the counterfactual levels we used the following formula:

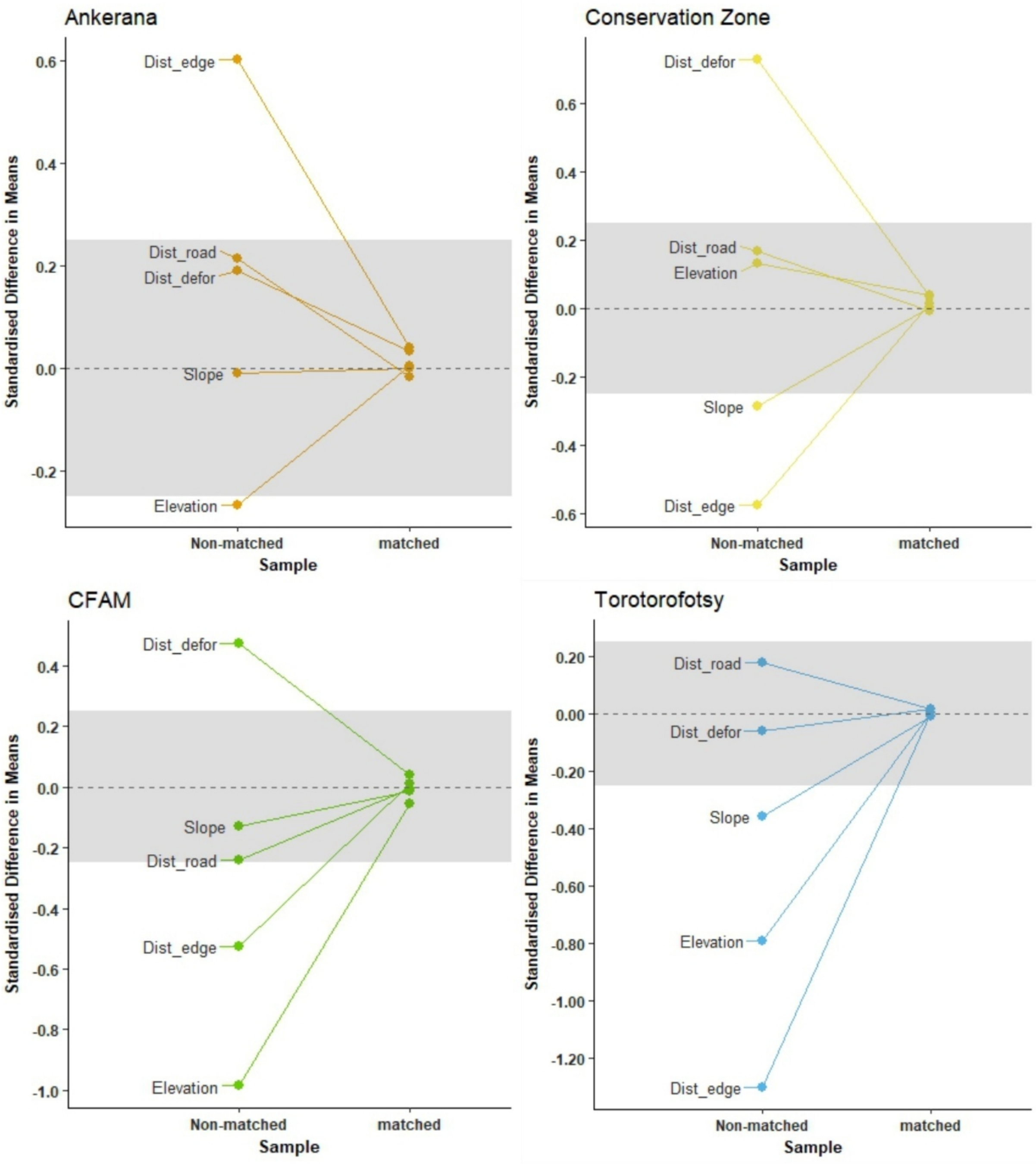
$$\text{Counterfactual deforestation} = \text{observed deforestation} \times \frac{100}{(100 - \text{Treatment Effect})}$$

Avoided deforestation is subsequently defined as the difference between the observed and estimated counterfactual deforestation.

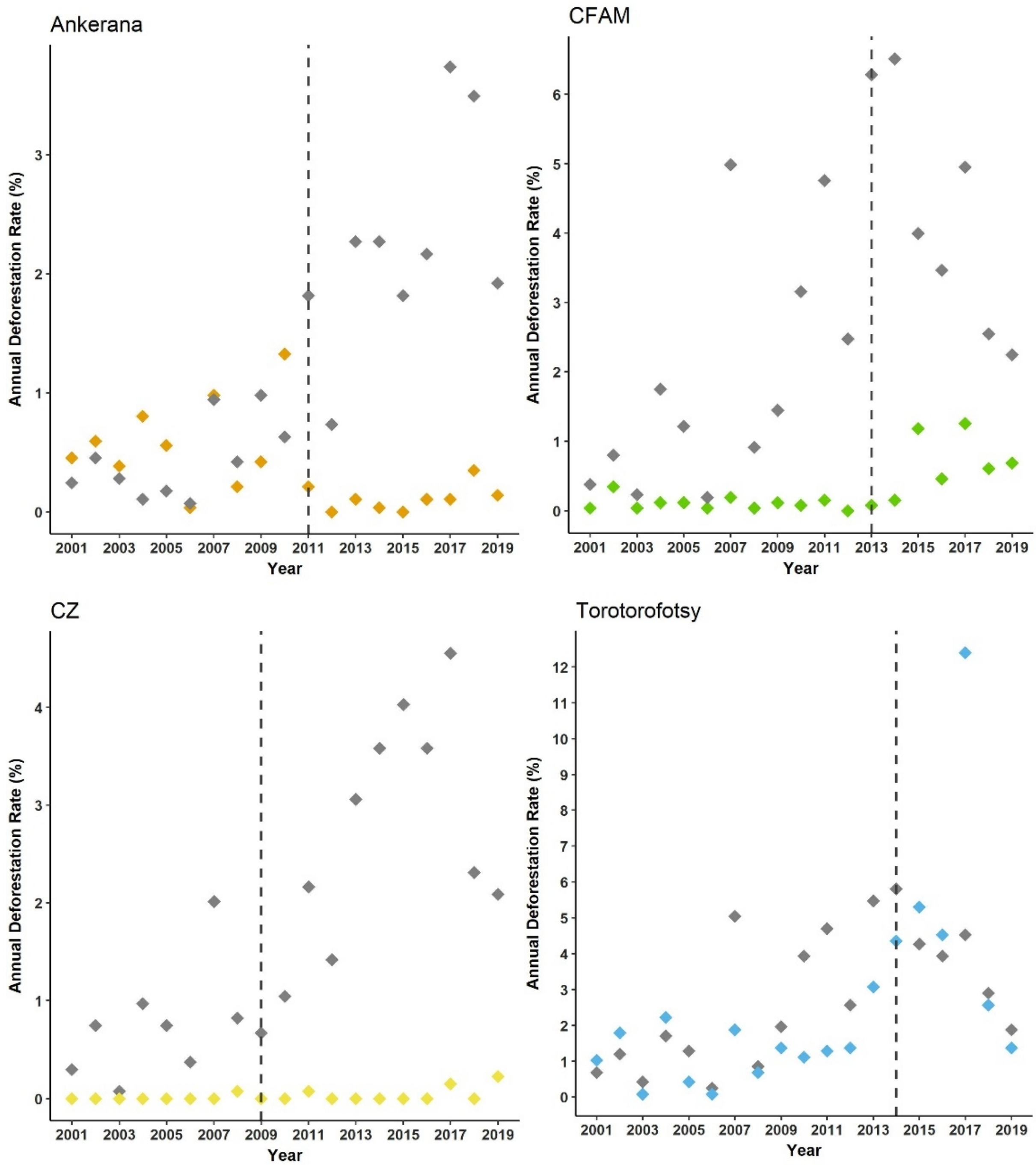
We calculated the upper and lower confidence intervals around our estimates of counterfactual, and consequently avoided deforestation, using the upper and lower confidence intervals of the estimated treatment effect.

Supplementary Results

Matching



Supplementary Figure 3; Evaluation of the quality of matches produced using the main matching specification. This is assessed through the standardised difference in mean covariate values between offset and matched control samples. The shaded grey area indicates the ± 0.25 interval widely considered an acceptable match. The maximum standardised difference in mean covariate values was 0.05, well below the acceptable threshold.

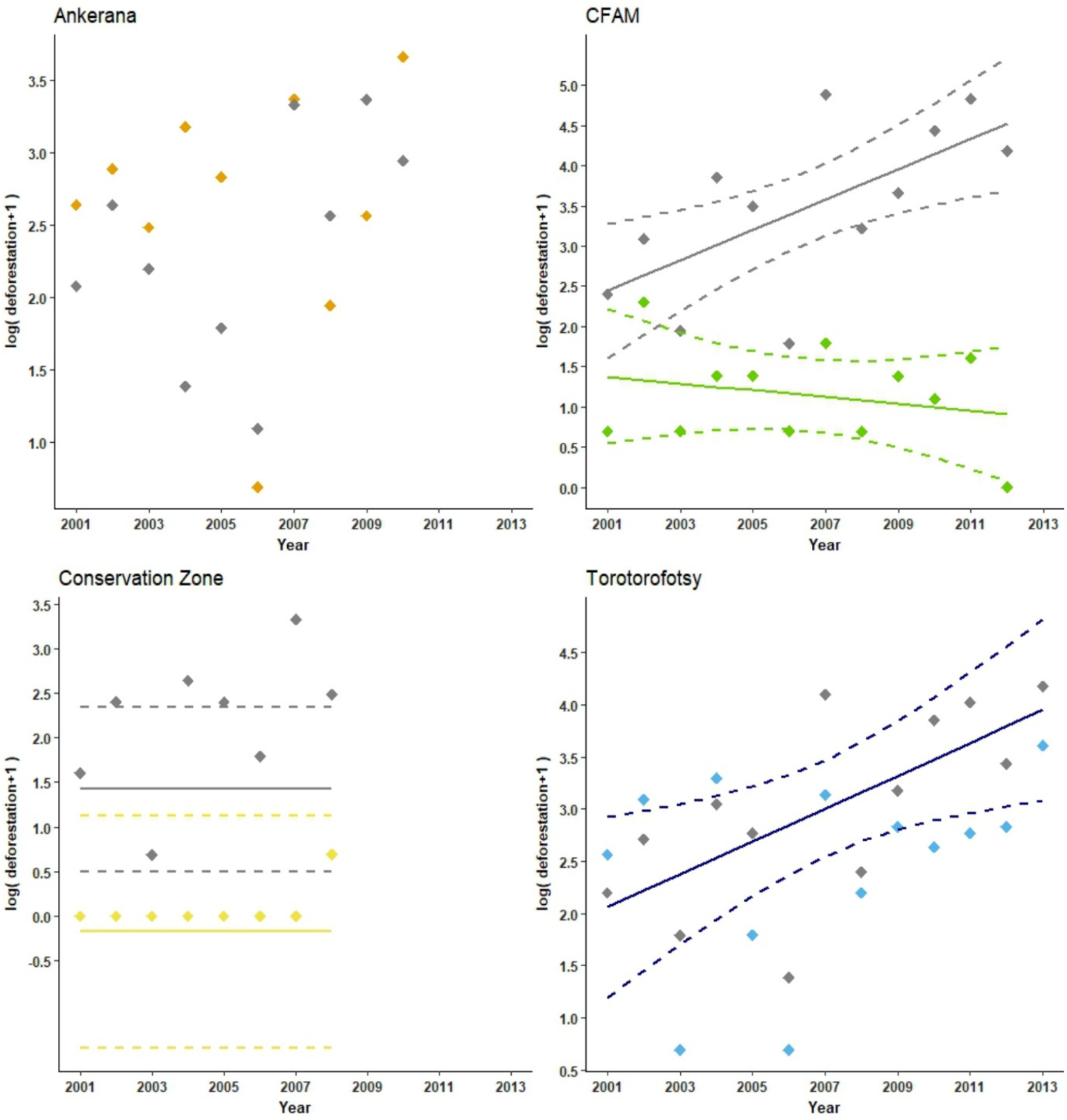


Supplementary Figure 4; **Comparison of the annual deforestation rate within the sample of pixels from each offset and the matched controls over the whole study period.** The offset sample is shown in colour whilst the matched control sample is shown in grey. The dashed line indicates the year of protection. The offset and matched control samples contain an equal number of pixels (2862 for Ankerana, 2626 for CFAM, 1340 for the Conservation Zone and 1170 for Torotorofotsy) as the ratio of treated to control units in the matching was set to 1:1. For each offset, N = 38.

Before Ankerana was protected it experienced similar rates of deforestation to the matched control sample, but this diverged considerably following protection. For CFAM, deforestation became increasingly higher within the matched control sample relative to the offset sample in the years before protection of the offset. However, contrary to expectations, after protection deforestation increased within the offset but declined within the matched control sample. Forest loss within the Conservation Zone was extremely low throughout the study period with zero deforestation occurring in the sample for 15 out of the 19 years. By contrast, deforestation within the matched control was much higher and increased rapidly after 2009. Torotorofotsy experienced a similar magnitude and pattern of deforestation to the matched control both before and after protection. Excluding 2017, which was a record year for deforestation within Torotorofotsy (12.4% of all sample pixels were deforested in that year), forest loss within both the offset and matched control sample has declined since 2014 when the offset was protected.

Outcome Regressions

Testing the assumptions



Supplementary Figure 5; **Test for parallel trends in deforestation between each offset and its matched control sample in the pre-intervention period**. Points show the log(y+1) transformed count of deforested pixels within each offset (shown in colour) and its matched control sample (grey). Lines plot the significant coefficients from the linear regression model

$$\log(\text{count of deforestation} + 1)_{i,t} = \beta_0 + \beta_1 Year_t + \beta_2 CI_i + \beta_3 Year * CI_{it} + \in,$$

where *i* denotes the sample, *t* denotes the year and CI is a binary variable indicating whether the observation is from the offset (1) or control (0) sample (see Supplementary Table 7). Diagonal lines indicate significant temporal trends in the data (Year is a significant predictor) whilst paired horizontal lines indicate a significant difference in deforestation, on average, between the two samples. Dashed lines represent the 95% confidence intervals around the significant coefficients. Lines are coloured according to whether the coefficient corresponds to the offset or the matched control sample except for Tototorofotsy where the line applies to both. This is because the slope of the relationship between year and the log-transformed count of deforestation does not differ significantly between the two samples. N= 20 for Ankerana, 24 for CFAM, 16 for the CZ and 26 for Torotorofotsy.

In Ankerana neither year nor treated status were significant predictors of the annual deforestation rate (shown by the lack of lines in the Figure above). This indicates that there were no temporal trends in deforestation in either the offset or the matched control sample in the pre-intervention period. In CFAM, there was a significant declining trend in deforestation prior to protection whilst the matched control sample showed a significant increasing trend (Supplementary Figure 4 suggests these trends may have reversed post-intervention). This violates the assumption of parallel trends meaning CFAM cannot be used in the difference-in-differences analysis. There were no significant trends in deforestation over time in the Conservation Zone nor its matched control sample, however, on average, deforestation was significantly lower within the offset than the matched control sample (shown by the two horizonal lines in Supplementary Figure 5). Torotorofotsy did experience a trend in deforestation over time which was not significantly different to the trend in the matched control sample, hence the single trend line. Furthermore, there was no significant difference in deforestation, on average, between the two samples. Therefore, Ankerana, the Conservation Zone and Torotorofotsy show parallel trends in deforestation to their matched control sample in the pre-intervention period and can therefore be used in the difference-in-differences analysis. However, there is an important caveat to this in that the small sample size in these regressions (N = 16 for the Conservation Zone) produces large uncertainty, reducing the likelihood of finding a significant difference in trend even if the true trends are not parallel.

Raw results from parallel trends test

Offset		Intercept	Year	CI	Year:CI
Ankerana	estimate	1.6779	0.1204	0.8589	-0.1042
	std.error	0.5516	0.0889	0.7801	0.1257
	statistic	3.0418	1.3543	1.1010	-0.8287
	p.value	0.0078	0.1945	0.2872	0.4195
CFAM	estimate	2.2526	0.1893	-0.8352	-0.2313
	std.error	0.4540	0.0617	0.6421	0.0872
	statistic	4.9616	3.0685	-1.3009	-2.6510
	p.value	0.0001	0.0061	0.2081	0.0153
CZ	estimate	1.4261	0.1649	-1.5994	-0.1072
	std.error	0.4238	0.0839	0.5993	0.1187
	statistic	3.3650	1.9653	-2.6685	-0.9030
	p.value	0.0056	0.0730	0.0205	0.3843
TTF	estimate	1.9016	0.1575	-0.0023	-0.0755
	std.error	0.4709	0.0593	0.6660	0.0839
	statistic	4.0379	2.6546	-0.0035	-0.9001
	p.value	0.0005	0.0145	0.9972	0.3778

Note: N= 20 for Ankerana, 24 for CFAM, 16 for the CZ and 26 for Torotorofotsy

Supplementary Table 8; Raw results from the test for parallel trends in deforestation between each offset and its matched control sample in the pre-intervention period. CI is a binary variable indicating treatment status; whether the observation is from an offset (1) or matched control sample (0). The interaction between Year and CI is the coefficient of interest which indicates whether the relationship between the Year and the log(y+1) transformed count of deforestation differs significantly between treated and control samples. This coefficient is only significant (p = 0.0153) for CFAM.

Site-based difference-in-differences regression

Offset		Intercept	BA	CI	BA:CI
Ankerana	estimate	2.3401	0.2859	1.7573	-3.1827
	std.error	0.2347	0.3319	0.3410	0.4823
	statistic	9.9704	0.8614	5.1530	-6.5994
	p.value	0.0000	0.3951	0.0000	0.0000
CZ	estimate	2.1683	-2.0816	1.2768	-1.0746
	std.error	0.1997	0.2824	0.2625	0.3712
	statistic	10.8572	-7.3704	4.8647	-2.8949
	p.value	0.0000	0.0000	0.0000	0.0066
TTF	estimate	3.0042	-0.5310	0.7785	0.6374
	std.error	0.2290	0.3238	0.4075	0.5763
	statistic	13.1195	-1.6397	1.9104	1.1060
	p.value	0.0000	0.1103	0.0645	0.2765

Note: N= 38

Supplementary Table 9; **Results from the site-based difference-in-differences regression for each offset-control sample that met the condition of parallel trends**. Results are from the regression $\log(\text{count of deforestation} + 1)_{i,t} = \beta_0 + \beta_1 BA_t + \beta_2 CI_i + \beta_3 BA * CI_{i,t} + \in$, where BA and CI are a binary variables indicating whether the observation is from the period before (0) or after (1) protection (BA), from the offset (1) or matched control (0) sample (CI). BA:CI is the coefficient of interest which represents the effect of being in an offset after protection on the log-transformed count of deforestation. Back-transforming this estimate $((\exp(\text{estimate}) - 1) \times 100)$, gives the treatment effect, expressed as the percentage difference in average annual deforestation between the offset and the estimated counterfactual, following protection. Counterfactual deforestation is estimated by adjusting the average annual deforestation within the matched control sample after the intervention, to account for the pre-intervention difference in deforestation between the two samples.

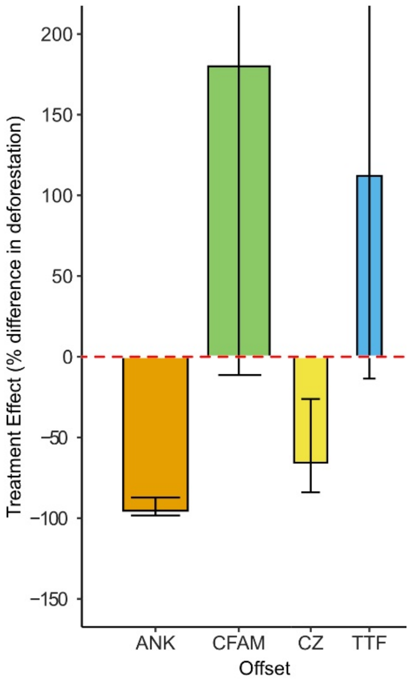
These results show highly significant reductions in deforestation of 96% (95% CI: 89 to 98%) in Ankerana and 66% (27 to 84%) in the Conservation Zone. In Torotorofotsy, average annual deforestation was higher in the offset than the estimated counterfactual after protection, but this difference was not significant.

Site-based difference-in-differences regression with alternative temporal specification

As an additional robustness check we repeated our site-based difference-in-differences regressions using an equal number of years before and after treatment and corresponding alternative baseline year for each offset.

Sample	BA:CI estimate	Standard error	Parallel trends	N years before and after	Treatment effect	Upper_CI	Lower_CI	df
ANK	-3.0789	0.5206	TRUE	8	-95.3992	-86.0437	-98.4833	15
CFAM	1.0297	0.5211	TRUE	6	180.0124	781.5570	-11.0586	11
CZ	-1.0693	0.3910	TRUE	8	-65.6742	-21.0103	-85.0834	15
TTF	0.7520	0.4157	TRUE	5	112.1211	443.2284	-17.1705	9

Supplementary Table 10: Results from the site-based difference-in-differences regression with alternative temporal specification. The estimate of BA:CI represents the effect of being in an offset after protection on the log-transformed count of deforestation. These values were back-transformed as detailed above to give the treatment effect, expressed as the percentage difference in average annual deforestation between the offset and the estimated counterfactual**.**

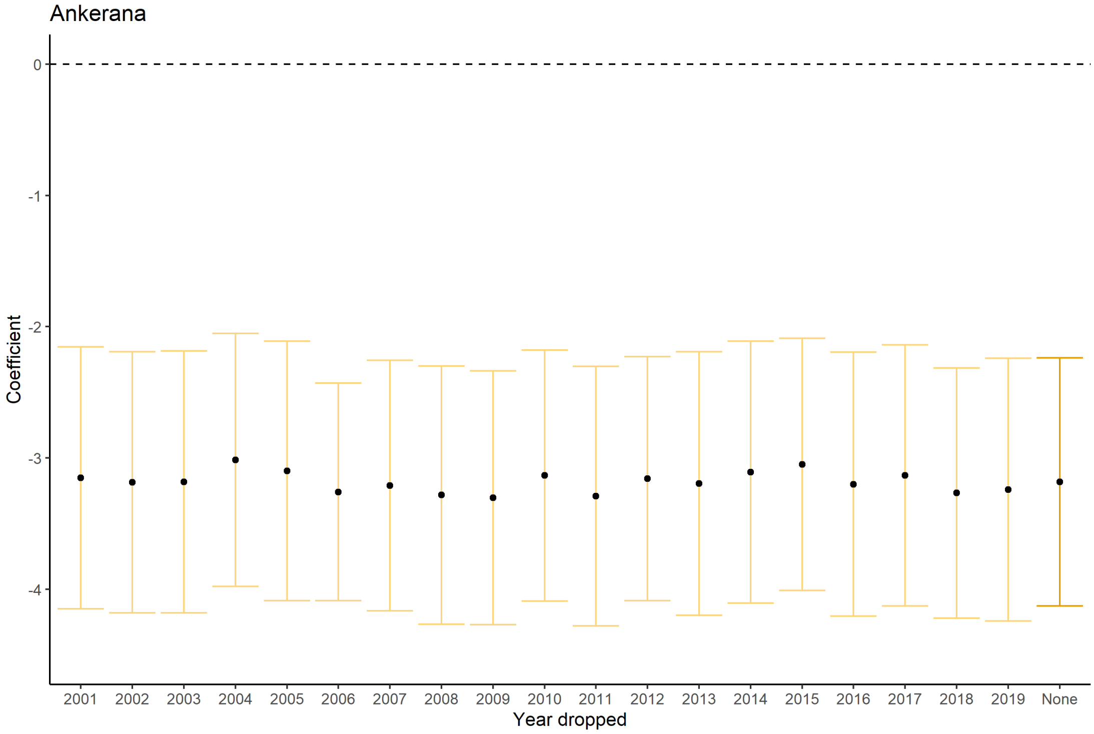


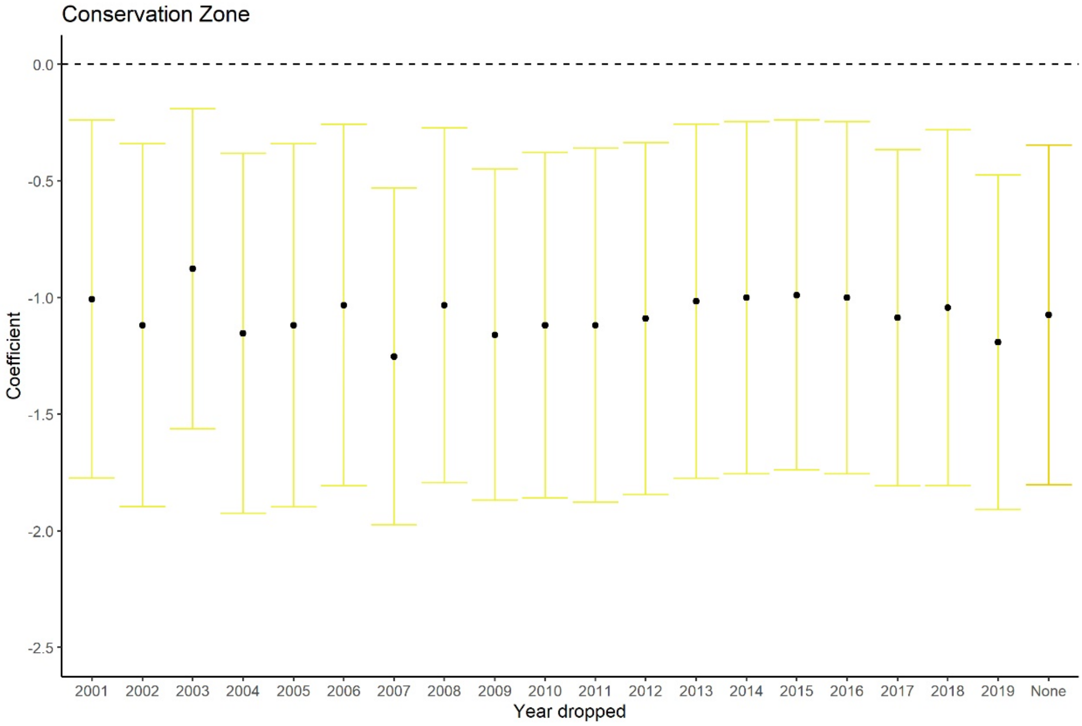
Supplementary Figure 6: The estimated percentage reduction in deforestation within each offset from the site-based difference-in-differences regression with alternative temporal specification. Error bars represent 95% confidence intervals (the upper bound extends to +443% for TTF and +782% for CFAM). The width of the bar is proportional to the area of forest within each offset at the year of protection (Supplementary Table 2). ANK = Ankerana, CFAM = Corridor Forestier Analamay-Mantadia, TTF = Torotorofotsy. N = 16 for Ankerana, 12 for CFAM, 16 for the Conservation Zone and 10 for Tototorofotsy.

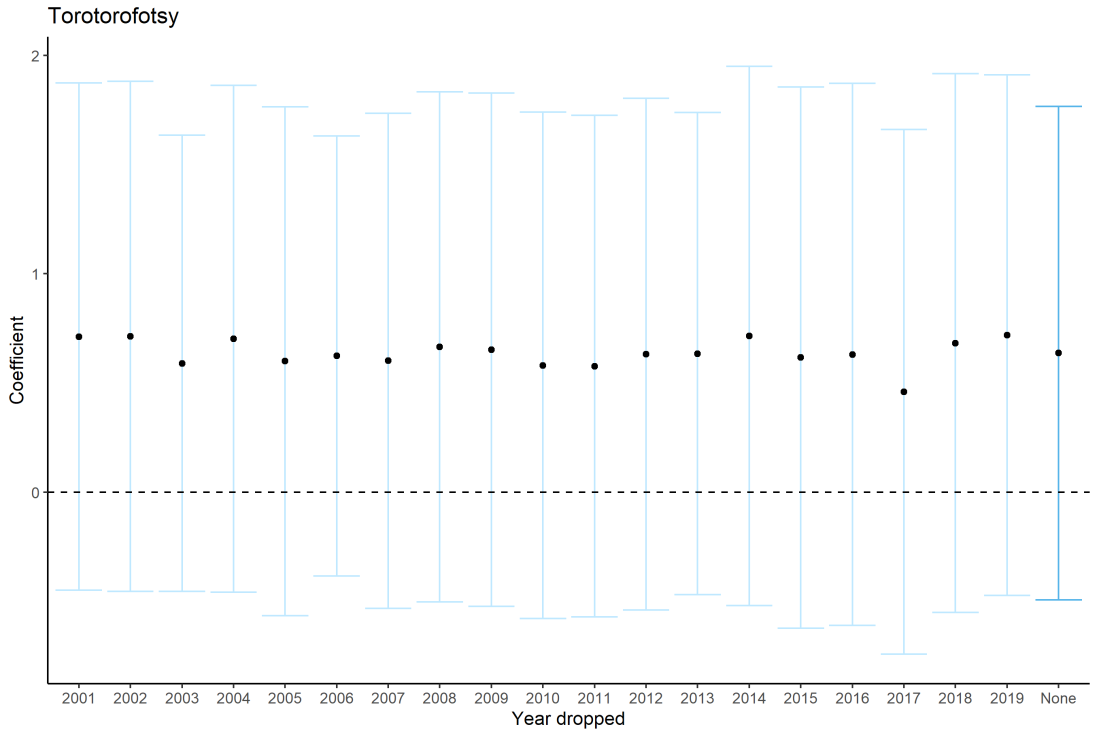
These results are consistent with those obtained from our main modelling specification. They show a significant reduction in deforestation of 95.4% in Ankerana and 65.7% in the Conservation Zone. This is extremely close to the estimates from the main specification of 96% and 66% respectively. Whilst the estimated increase in deforestation within Torotorofotsy relative to the counterfactual was higher than the main specification (+112% compared to +89%), the effect remained insignificant. In contrast to the main specification, CFAM met the condition of parallel trends meaning it could be assessed in the difference-in-differences analysis. This showed higher deforestation within CFAM than the estimated counterfactual but this difference was not statistically significant. However, the small sample size (eg. N = 10 for Torotorofotsy) produces very large uncertainty, decreasing the likelihood of showing a significant effect, either positive or negative. Given this caveat, our finding of a significant negative effect in Ankerana and the Conservation Zone indicates the strength of the signal of reduced deforestation within these offsets. Overall, this analysis shows that our results are robust to an alternative temporal specification.

Site-based difference-in-differences regression dropping individual years

Given the relatively small sample size (N = 38) of our difference-in-differences regressions we tested whether our results were influenced by a single data value by repeating the each regression 19 times, each time dropping an observation for one year.







Supplementary Figure 7: Results from the site-based difference-in-differences regression dropping an individual year from the analysis. Points represent the estimated raw treatment effect; the coefficient of BA*CI from the difference-in-differences regression. Year dropped refers to the year of the observation which was removed from the analysis. Bars show the 95% confidence intervals around the estimated treatment effect. Results from the main specification including all years (Supplementary Table 9) are shown in the darker shade. N = 36 for all estimates except where Year dropped is None where N = 38. Results are only included for the three offsets which passed the parallel trends test.

This shows that our results are robust to removal of individual years from the analysis and are therefore not likely to be influenced by a single data point.

Site-based difference-in-differences regression including a time trend

	Ankerana		Conservation Zone		Torotorofotsy	
	Main	With Year	Main	With Year	Main	With Year
CI (Treated Status)	0.286	0.286	-2.082^{***}	-2.082^{***}	-0.531	-0.531^{*}
	(0.332)	(0.319)	(0.282)	(0.244)	(0.324)	(0.303)
BA (Before-After)	1.757^{***}	0.973^{*}	1.277^{***}	0.336	0.778^{*}	-0.102
	(0.341)	(0.518)	(0.262)	(0.350)	(0.407)	(0.530)
BA*CI	-3.183^{***}	-3.183^{***}	-1.075^{***}	-1.075^{***}	0.637	0.637
	(0.482)	(0.463)	(0.371)	(0.321)	(0.576)	(0.540)
Year		0.083^{*}		0.099^{***}		0.093^{**}
		(0.042)		(0.028)		(0.039)
Constant	2.340^{***}	1.886^{***}	2.168^{***}	1.723^{***}	3.004^{***}	2.355^{***}
	(0.235)	(0.324)	(0.200)	(0.214)	(0.229)	(0.346)
Observations	38	38	38	38	38	38
Adjusted R^2	0.643	0.671	0.866	0.900	0.278	0.366

$^{*}p< 0.1$, $^{**}p< 0.05$, $^{***}p<0.01$

Supplementary Table 11: Comparison of results from our site-based difference-in-differences regression with and without a time trend. The difference-in-differences regression with a time trend takes the form; $\log(\text{count of deforestation} + 1)_{i,t} = \beta_0 + \beta_1 BA_t + \beta_2 CI_i + \beta_3 BA * CI_{i,t} + Year_t + \in_{i,t}$. BA*CI is the coefficient of interest. The column 'With Year' shows the results of the difference-in-differences regression including Year as a predictor. The standard error is shown in brackets below the estimate.

This shows that the addition of time trends to our canonical difference-in-differences model does not change our estimated treatment effect. In fact, it decreases the standard error of the coefficient of interest (BA*CI), increasing the significance of our results.

Fixed Effects Panel Regression

A key limitation of the difference-in-differences approach is that it assumes the difference in outcomes between the treated and control sample is completely attributable to the intervention, that there are no unobserved factors correlated with treated status that may have biased outcomes[40]. Pre-processing the data through statistical matching strengthens this assumption but may not be sufficient if there is omitted variable bias[41].

To test this assumption, we conducted a secondary analysis using a fixed effects panel regression to obtain an overall estimate of treatment effect across all 4 biodiversity offsets, controlling for time-invariant unobserved heterogeneity. Fixed effects panel regressions exploit cross-sectional and temporal variability in time-series panel data to control for time-invariant, between group unobserved bias[32,42]. This provides a more accurate estimate of treatment effect when unobserved bias is present than other methods[32]. Ferraro and Miranda[43] found that matching plus fixed effects panel regression was able to approximate the results of treatment effect obtained from an experimental study.

Results from our fixed effects panel regression on the pooled data show that protection reduced deforestation across all four biodiversity offsets by an average of 58% (37 -73%) per year (Column 1, Supplementary Table 12).

To test whether inclusion of the fixed effects was necessary we ran an F-test for individual and time effects, comparing the fixed effects model to a pooled OLS regression of the following form:

$$\log(\text{count of deforestation} + 1)_{i,t} = \beta_0 + \beta_1 Tr_{i,t} + \in_{i,t}$$

This revealed significant ($p < 0.05$) heterogeneity between sites and over time, supporting the inclusion these variables as fixed effects in the modelling process.

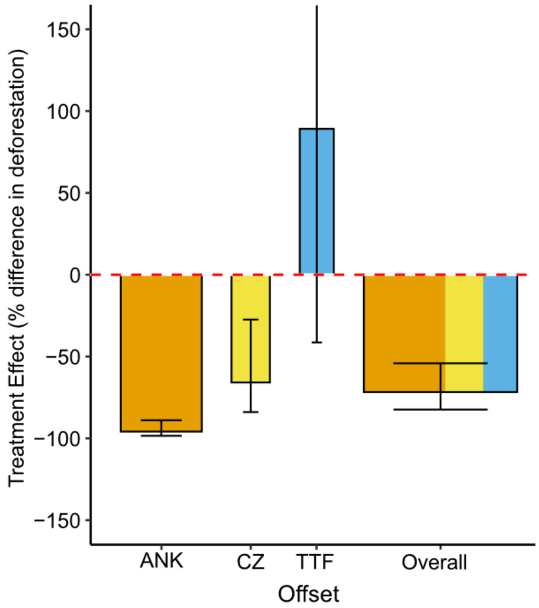
Although fixed effects panel regressions are not based on an identifying assumption of parallel trends between groups in the pre-treatment period[44], we tested the effect of excluding CFAM and its matched control sample (which show diverging pre-treatment trends in deforestation) from the regression (Column 2, Supplementary Table 12). We found that this increased the precision and magnitude of the estimated treatment effect. Excluding CFAM increased the estimated average reduction in deforestation from 58% to 72% per year (95% CI: 54 to 83%) following protection of the remaining 3 offsets. This translates to 2,221 ha (1039 to 4132 ha) of avoided deforestation between the year of protection of each offset and January 2020, exceeding the 2,064 ha of forest loss at the mine site which was required to be offset. Therefore, according to this estimate, Ambatovy has already achieved No Net Loss of forest. However, in the main text, we prefer to highlight the more conservative estimate, which incorporates the effect of all four offsets.

Finally, we tested the robustness of our results from the fixed effects panel regression to the alternative specification of site and year as random effects (Column 3, Supplementary Table

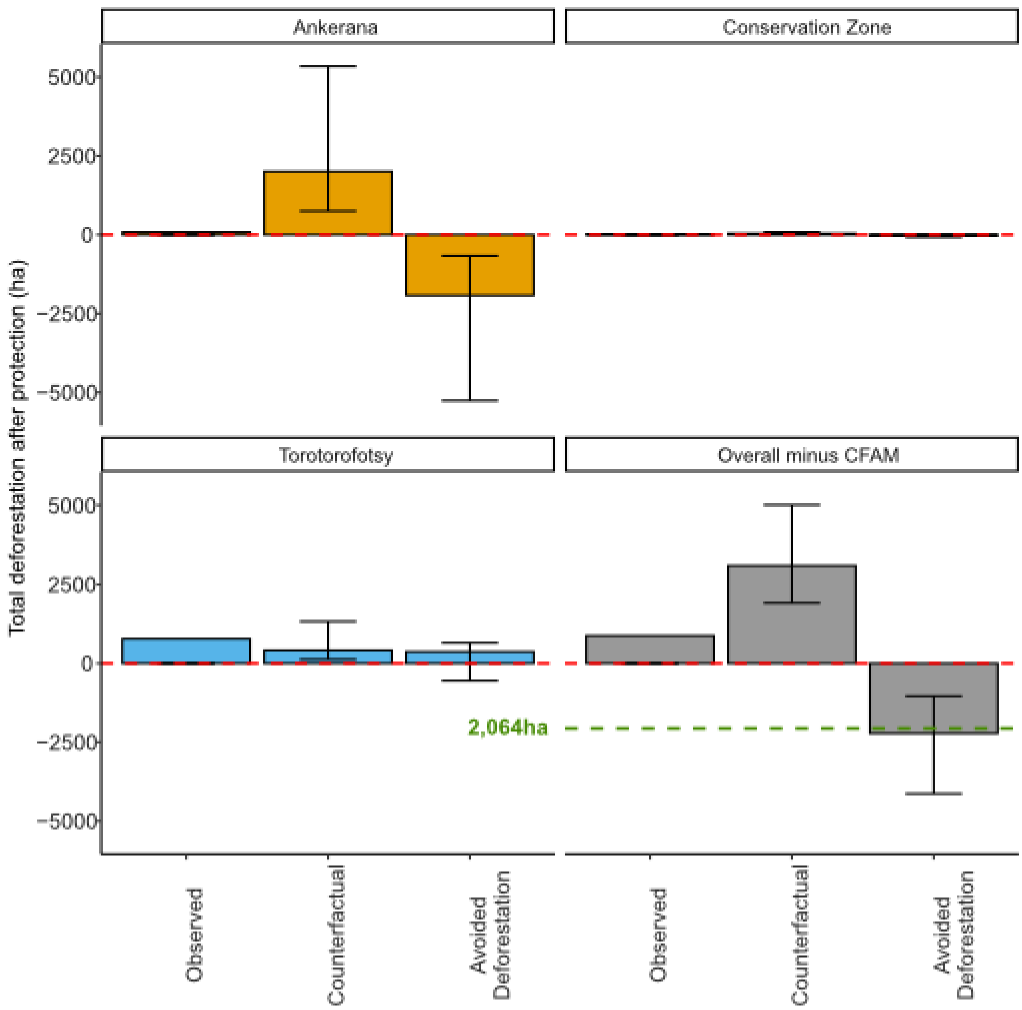
12). This gives a significant overall reduction in deforestation of 53% (27% to 69%) per year, following protection of the 4 biodiversity offsets. This estimate is within the confidence intervals, and extremely close, to the estimate derived from the fixed effects panel regression.

Term	Treatment effect (Tr)		
Model	All 4 offsets (1)	Excluding CFAM and its matched control sample (2)	With Site and Year as random effects (3)
estimate	-0.8774	-1.2631	-0.7476
std.error	0.2154	0.2453	0.207
statistic	-4.0732	-5.1489	-3.612
p.value	0.0001	0.000002	0.0004
N	152	114	152
df	125	89	125

Supplementary Table 12; Results from the fixed effects panel regression on the pooled data. The fixed effects regression takes the form $\log(\text{count of deforestation} + 1)_{i,t} = \beta_0 + \beta_1 Tr_{i,t} + \propto_i + \gamma_t + \epsilon_{it}$, where Tr is a binary measure indicating the treated status of observation *i* in year *t* (Tr = 1 for observations from offset sites in the years following protection and 0 for all other observations), $\propto_i$ and γ_t represent site and year fixed effects respectively (modelled as random effects in model 3), and ϵ_{it} represents the composite error. Tr is the coefficient of interest which represents the effect of being in an offset after protection on the log(y+1) transformed count of deforestation. The estimate is back-transformed as described above to express the treatment effect as the percentage difference in average annual deforestation following protection. The table shows the results from the main fixed effects model specification (Column 1) and two alternative specifications to test the robustness of results to the exclusion of CFAM (Column 2) and the designation of site and year as random effects (Column 3). Models 1 and 3 were run on the full pooled data comprising an observation for each site (i=8, 4 offset and 4 control) for each year (t =19). Model 2 only included observations for Ankerana, the Conservation Zone and Torotorofotsy (i = 6, t= 19).



Supplementary Figure 8: The estimated percentage reduction in annual deforestation within each offset (from the site-based difference-in-differences regressions) and overall, across the 3 offsets which met the condition of parallel trends (from the fixed effects panel regression excluding CFAM). The treatment effect is expressed as the average percentage difference in annual deforestation between the three offset(s) and the estimated counterfactual following protection. Error bars represent 95% confidence intervals (the upper bound for TTF extends to +510%). The width of the bar is proportional to the area of forest within each offset at the year of protection (Supplementary Table 2). ANK: Ankerana (orange), CZ: the Conservation Zone (yellow), TTF: Torotorofotsy (blue). N = 38 for Ankerana, the Conservation Zone and Torotorofotsy and N = 114 for the Overall result.



Supplementary Figure 9: The total observed, counterfactual and the resulting estimate of avoided deforestation within each offset (estimated using site-based difference-in-differences regressions) and overall, for the 3 offsets which met the condition of parallel trends (using the fixed effects panel regression excluding CFAM), between the year of protection and January 2020. The counterfactual is an estimate of the deforestation which would have occurred in the absence of protection and was calculated using the estimated treatment effect (N = 38; Supplementary methods). Avoided deforestation is the difference between the observed and counterfactual deforestation; negative values indicate the offset resulted in a reduction in deforestation. The error bars show the 95% confidence interval of the estimates of counterfactual deforestation (derived from the upper and lower confidence intervals of the treatment effect) and the resulting estimates of avoided deforestation. The green dashed line indicates the 2,064 ha of forest loss caused by the mine itself. The number of years following protection is 9 for Ankerana, 11 for the Conservation Zone, 6 for Torotorofotsy and 11 Overall (deforestation within later protected offsets is only counted from the year of protection).

Comparison of our estimated effect size to those of other interventions aimed at slowing deforestation

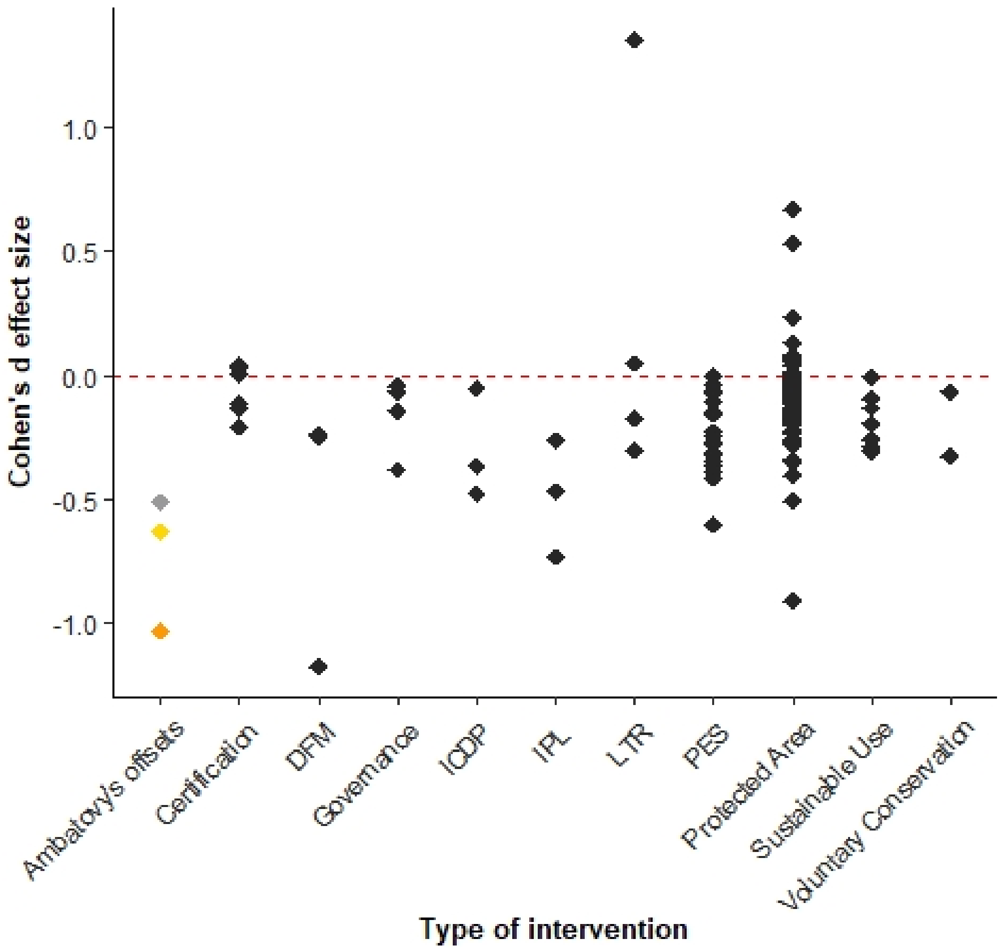
In a recent review Borner et al[45] compiled and summarised the results of 99 studies using counterfactual methods to evaluate the effectiveness of various forest conservation interventions at reducing deforestation. From these studies the authors obtained estimates of effect size for 136 conservation interventions, which were converted to a normalised Cohen's d effect size for comparison. The interventions were grouped by type (eg. protected areas, Payments for Ecosystem Services, land titling reform) to assess whether certain forms of intervention were more successful than others.

To enable comparison of our results to those compiled by Borner et al we converted our estimate of avoided deforestation to a Cohen's d effect size using the following formula[46]:

$$\text{Cohen's d effect size} = \frac{\text{(mean treated - mean counterfactual)}}{\text{standard deviation(counterfactual)}}$$

where the numerator refers to the difference in average annual deforestation between the offset(s) and the estimated counterfactual (calculated as described above) following protection, and the denominator is the standard deviation of the counterfactual annual deforestation in the post-intervention period. Whilst Cohen's d is usually calculated using standard deviation of the pooled samples, we follow Borner et al[45] in using the standard deviation of the control sample.

The Cohen's d statistic is -1.03 for Ankerana classed as a 'large effect'[46], -0.63 for the Conservation Zone and – 0.51 overall (across the entire offset portfolio), both classed as 'medium effects'.



Supplementary Figure 10: Comparison of normalised Cohen's d effect sizes for Ambatovy's biodiversity offsets and 136 other conservation interventions compiled by Borner et al. Coloured points show the statistically significant results from this study converted to a normalised Cohen's d effect size. Orange = Ankerana, yellow = the Conservation Zone and grey = the Overall effect of Ambatovy's four biodiversity offsets (from the fixed effects panel regression). Black points represent the normalised effect sizes of 136 conservation interventions grouped by type from Borner et al. DFM = Decentralised Forest Management, ICDP = Integrated Conservation and Development Programmes, LTR = Land Titling and Reform, PES = Payments for Ecosystem Services. Negative values indicate the intervention led to a reduction in forest loss.

This comparison shows that overall Ambatovy's biodiversity offsets were more effective at reducing deforestation than 97% of the other interventions and all bar one of the protected area interventions. Ankerana was the second most effective intervention overall and the most effective protected area intervention. These results are particularly striking and reinforce the need for future work to evaluate the reasons behind Ambatovy's apparent success at conserving its biodiversity offsets as this could help to inform and improve offsetting and conservation practices more broadly.

Robustness checks

We evaluated the extent to which our primary results, derived from the main matching specification, are affected by arbitrary modelling choices following the procedure proposed in Desbureaux 2021[47]. In this study, arbitrary modelling choices concerned the selection of covariates (5 essential covariates included), matching distance measure (Mahalanobis), value of the calipers (1 SD), matching without replacement, and the number of nearest neighbours to match on (1 nearest neighbour).

We tested the robustness of our results to the inclusion of 5 additional covariates (Supplementary Table 4), alternative matching distance measures (standard PSM and Random Forest PSM), caliper values (0.25 and 0.5 SD), matching with replacement, and different numbers of nearest neighbours (5 and 10 nearest neighbours), in three stages.

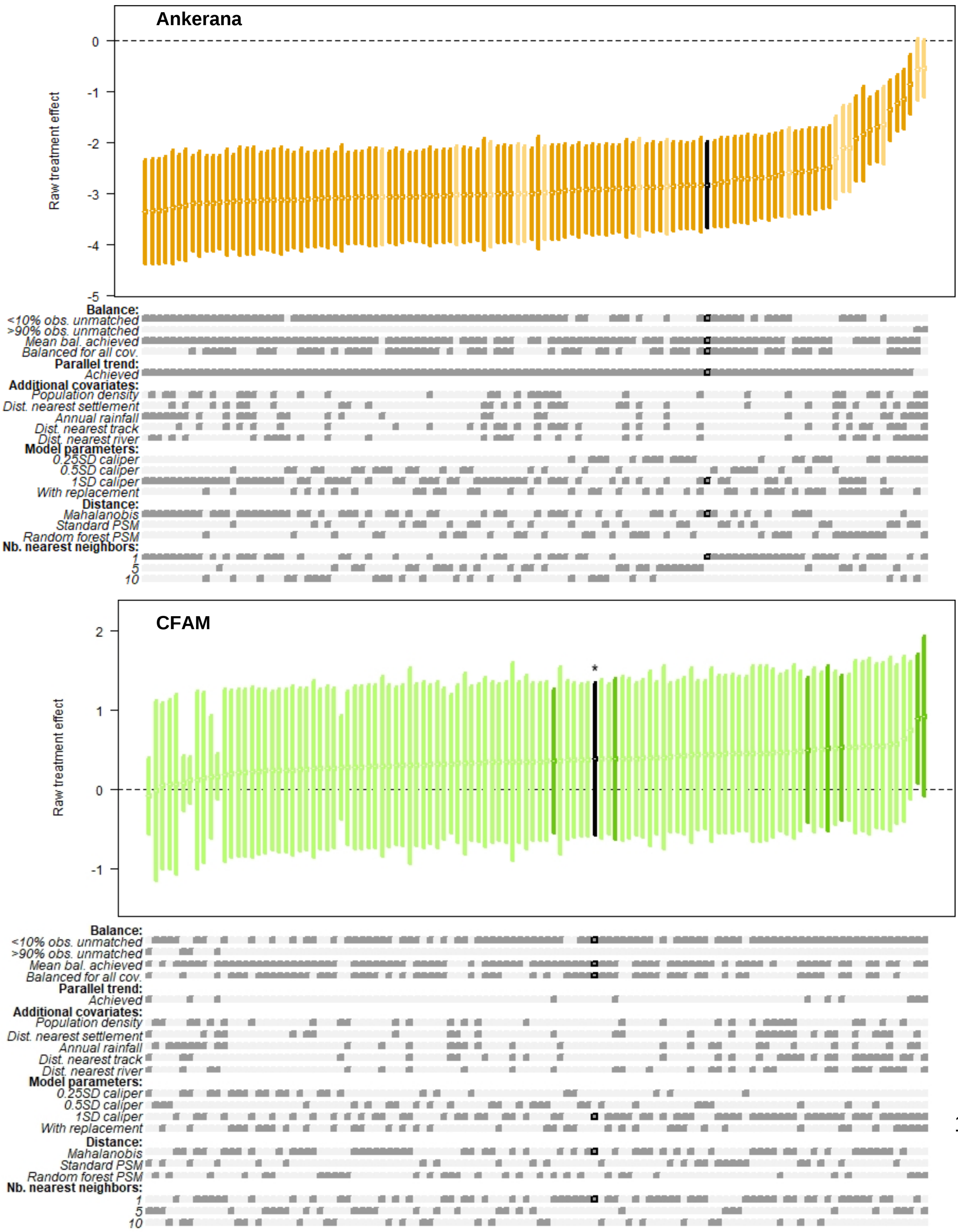
First, holding the choice of covariates constant (using only the essential covariates) we tested the robustness of results to alternative matching distance measures and model parameters (calipers, number of nearest neighbours, matching with/without replacement). This led to the estimation of 54 different models (e.g, Mahalanobis distance x 0.5 SD caliper x 1 nearest neighbour x with replacement, Mahalanobis distance x 0.5 SD caliper x 5 nearest neighbours x without replacement, Mahalanobis distance x 0.5 SD caliper x 5 nearest neighbours x with replacement, … Random PSM distance x 0.25 SD caliper x 10 nearest neighbours x with replacement).

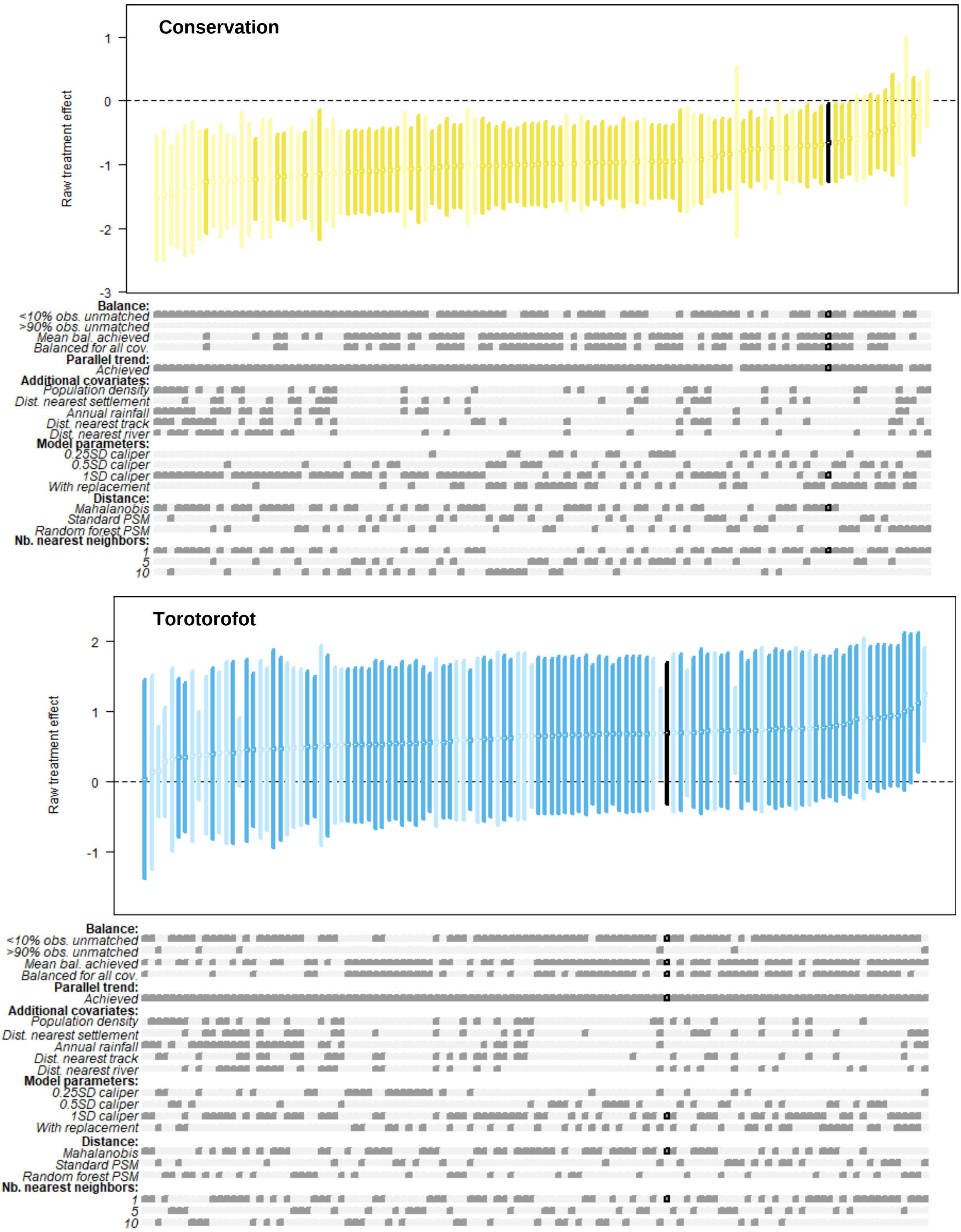
Second, we tested the robustness of results to the inclusion of the 5 additional covariates. Holding the choice of distance measure and model parameters constant, we constructed 31 models based on all possible combinations of additional covariates with the core set of essential covariates.

Finally, we explore the robustness of results for 31 randomly selected combinations of distance measure, model parameters and additional covariates.

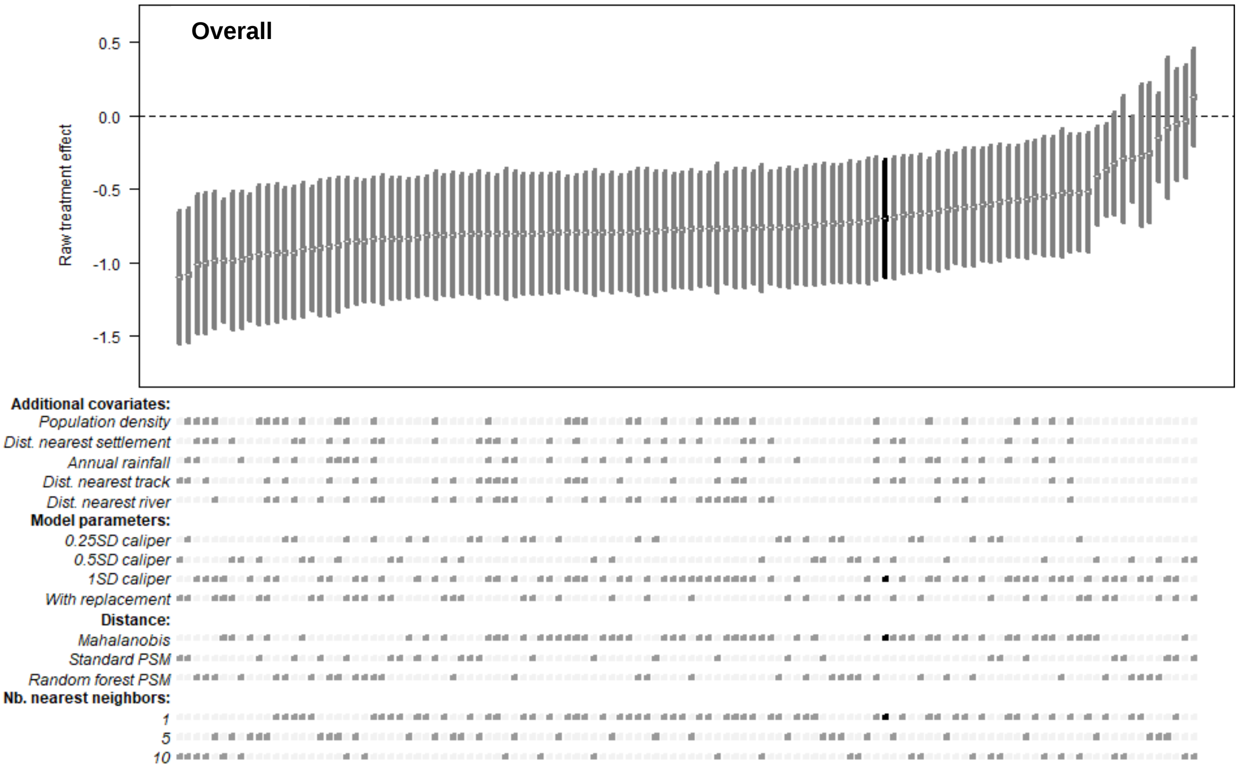
All models are *a priori* valid, as they follow the best practice guidelines defined by Schleicher et al[14]. However, they are considered *a posteriori* invalid if they meet any of the following three conditions: 1) no adequate matches are found for over 90% of treated observations; 2) the post-matching average covariate balance (defined as the standardised difference in means) is above the accepted threshold of 0.25; and 3) the resulting matched data violate the assumption of parallel trends in outcomes between treated and control samples in the pre-intervention period. Failure to match a large number of treated observations leads to their rejection from the sample which could bias results if the remaining observations are no longer representative of the original sample. Failure to achieve an acceptable post-matching covariate balance means the matched control sample cannot be considered an appropriate counterfactual for the treated sample.

To aid interpretation of how alternative modelling choices affect the direction, significance, and magnitude of our results we expand upon Figure 4 presented in the main text to show which model specifications are associated with each result. We then test which modelling choices exert the greatest influence on our estimated impacts.





corresponding 95% confidence intervals (bars) derived from 116 alternative matching model specifications for each of the 4 biodiversity offsets. The dark grey squares in the panel below each plot indicate the model specifications (additional covariates, model parameters and matching distance measure) associated with each estimate and the outcome of the post-matching validity checks (the percentage of treated observations unmatched, whether an acceptable mean covariate balance and parallel trends have been achieved). In each plot models which do not pass these validity checks, and are consequently considered *a posteriori* invalid, are shown in lighter shades. Our primary result, derived from the main matching specification, is shown in black. An asterix indicates that the main model was not *a posteriori* valid. Values are reported un-transformed and represent the effect of treatment on the log(y + 1) transformed count of annual deforestation.



Supplementary Figure 12: Raw estimates of treatment effect (points) and corresponding 95% confidence intervals (bars) derived from 116 alternative matching model specifications for the pooled data. The dark grey squares in the panel below the plot indicate the model specifications (additional covariates, model parameters and matching distance measure) associated with each estimate. Our primary result, derived from the main matching specification, is shown in black. Values are reported un-transformed and represent the effect of treatment on the log(y + 1) transformed count of annual deforestation.

The effect of arbitrary modelling choices on our results

Arbitrary modelling choices can exert a significant influence on the estimated impact of conservation interventions[47]. We explore which modelling choices have the greatest influence on our estimated treatment effect by regressing the 456 coefficients estimated in our robustness checks on a series of dummy variables representing the associated modelling choices. Results are summarised in Supplementary Table 13.

Overall, the results suggest that the choice of matching algorithm (Mahalanobis matching, standard propensity score matching or Random Forest propensity score matching) and model parameters (caliper value, matching with/without replacement and the number of nearest neighbours) have the most consistent effect on the estimated impact of the offsets. The effect of including additional covariates in the matching process is less clear with some covariates having a significant effect in some offsets but not others, except for annual rainfall which has a mostly significant, yet ambiguous effect. These results are pretty much aligned with the conclusions of Desbureaux[47].

	All	<10% unmatched	Mean diff <.25	Max diff <.25	Parallel Trend	ANK	CFAM	CZ	TTF
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Pop Density	-0.037	-0.059**	-0.068	0.124	-0.059	0.009	-0.081***	0.023	-0.114***
	(0.036)	(0.025)	(0.055)	(0.093)	(0.040)	(0.089)	(0.030)	(0.050)	(0.036)
Dist Sett.	0.124***	0.078***	0.099**	0.047	0.091**	0.258***	0.009	0.120**	0.065*
	(0.036)	(0.025)	(0.046)	(0.058)	(0.040)	(0.089)	(0.030)	(0.050)	(0.036)
Annual Rain	-0.059	-0.135***	-0.045	0.472***	-0.096**	0.119	-0.081***	-0.184***	-0.148***
	(0.036)	(0.026)	(0.051)	(0.097)	(0.041)	(0.090)	(0.030)	(0.051)	(0.036)
Dist Track	0.078**	0.068***	0.084*	0.024	0.082**	0.203**	0.120***	-0.019	-0.004
	(0.036)	(0.025)	(0.045)	(0.057)	(0.040)	(0.089)	(0.030)	(0.050)	(0.036)
Dist_River	0.103***	0.004	0.141***	0.111*	0.067*	0.304***	0.057*	-0.031	0.026
	(0.036)	(0.026)	(0.046)	(0.062)	(0.040)	(0.090)	(0.031)	(0.051)	(0.036)
Caliper 0.25	0.191***		0.184***	0.139***	0.203***	0.756***	-0.169***	0.173***	-0.112***
	(0.039)		(0.042)	(0.044)	(0.044)	(0.095)	(0.033)	(0.058)	(0.038)
Caliper 0.5	0.089**	-0.002	0.096**	0.116**	0.103**	0.214**	-0.065**	0.157***	0.018
	(0.038)	(0.027)	(0.042)	(0.045)	(0.043)	(0.096)	(0.032)	(0.052)	(0.039)
With repl.	0.144***	0.166***	0.103***	0.098**	0.144***	0.259***	0.062**	0.154***	0.076**
	(0.033)	(0.025)	(0.035)	(0.038)	(0.037)	(0.082)	(0.028)	(0.045)	(0.033)
Mahalanobis	-0.182***	-0.193***	-0.163***	-0.079	-0.211***	-0.366***	-0.056*	-0.257***	-0.050
	(0.035)	(0.027)	(0.043)	(0.053)	(0.039)	(0.087)	(0.030)	(0.047)	(0.035)
PSM GLM	-0.026	-0.068**	-0.001	0.067	-0.062	-0.060	-0.001	-0.148***	0.070*
	(0.040)	(0.031)	(0.044)	(0.053)	(0.044)	(0.099)	(0.034)	(0.056)	(0.040)
1 nearest neigh.	0.167***	0.203***	0.149***	0.123***	0.222***	0.202**	0.059*	0.306***	0.137***
	(0.039)	(0.031)	(0.044)	(0.046)	(0.044)	(0.097)	(0.033)	(0.054)	(0.039)
5 nearest neigh.	0.012	0.057*	0.004	0.004	0.054	0.010	-0.017	0.080	0.009
	(0.041)	(0.031)	(0.045)	(0.047)	(0.046)	(0.102)	(0.034)	(0.056)	(0.041)
CFAM	3.150***	3.338***	3.175***	3.170***	3.127***				
	(0.040)	(0.029)	(0.043)	(0.051)	(0.096)				
CZ	1.846***	1.951***	1.906***	1.939***	1.872***				
	(0.040)	(0.029)	(0.048)	(0.052)	(0.039)				
TTF	3.418***	3.607***	3.472***	3.510***	3.453***				
	(0.039)	(0.029)	(0.044)	(0.050)	(0.038)				
Constant	-2.951***	-3.001***	-2.980***	-3.031***	-2.975***	-3.257***	0.382***	-1.076***	0.611***
	(0.054)	(0.038)	(0.063)	(0.076)	(0.058)	(0.119)	(0.040)	(0.065)	(0.048)
Observations	456	349	342	251	349	116	114	110	116
Adjusted R^2	0.954	0.983	0.961	0.963	0.960	0.530	0.344	0.483	0.347

Note: $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

Supplementary Table 13: The effect of arbitrary modelling choices on the estimated impact of Ambatovy's biodiversity offsets. The coefficients of treatment effect obtained in the robustness checks (shown in Supplementary Figures 9 and 10) were regressed on a series of dummy variables representing the modelling choices associated with each result (1 if the choice was made and 0 if not). Columns 1-5 refer to the pooled data (coefficients from all four offsets) and the regressions include dummy variables for each offset to allow the effect of the offset itself to be distinguished from the effect of the modelling choices. Column 1 includes all

456 estimated coefficients, regardless of whether the models are *a posteriori* valid or not. Columns 2, 3, 4 and 5, only include estimates from matching models where less than 10% of the treated pixels are unmatched (column 2), where acceptable covariate balance was achieved on average (column 3) and for all covariates (column 4), and where parallel trends were achieved (column 5). In columns 6 to 9, we estimate the impact of modelling choices on the estimated treatment effects for each individual offset. Standard error is shown in brackets beneath the estimated coefficient.

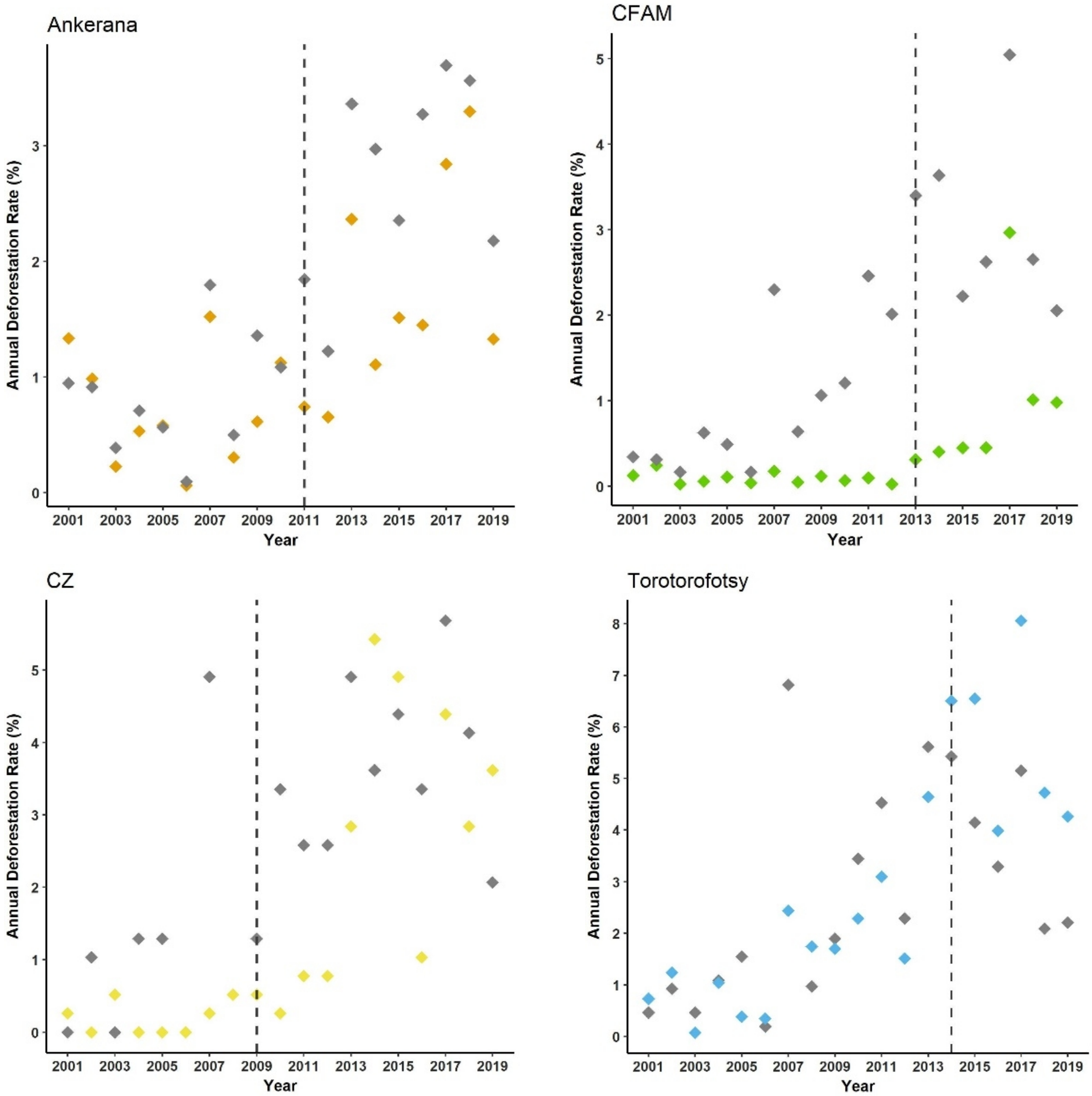
Evaluation of deforestation leakage

To determine whether protection of the biodiversity offsets displaced the anthropogenic drivers of deforestation into the surrounding landscape, we repeated the analysis using pixels sampled from the 10km buffer zone around each offset as the treated sample. The date of the intervention remains the year the adjacent offset was protected. If deforestation within these buffer zones was significantly higher than the estimated counterfactual, it would suggest deforestation has been displaced from the offsets into the surrounding area, undermining the true biodiversity ‘gains’ achieved through offset protection.

Matching

Acceptable matches (within 1 standard deviation of the Mahalanobis distance) were found for all buffer units associated with Ankerana, the Conservation Zone and Torotorofotsy. Only 28 out of 10,203 units from the buffer zone of CFAM could not be matched.

The standardised difference in mean covariate values between buffer and matched control samples was within the acceptable threshold of 0.25 for all covariates and all four buffer zones. The maximum post-matching standardised difference in mean covariates values was -0.15, indicating that, on average, buffer and control samples were well-matched.



Supplementary Figure 13; Comparison of deforestation outcomes between the sample of pixels from the buffer zone of each offset (shown in colour) and the matched controls (grey) over the whole study period. The dashed line indicates the adjacent was offset was protected. The buffer zone and the matched control samples have an equal sample size (12,344 for Ankerana, 10,203 for CFAM, 387 for the Conservation Zone and 2581 for Torotorofotsy) as the ratio of treated to control units in the matching was set to 1:1.

Testing the assumptions

Buffer Zone		Intercept	Year	Treated	Year:Treated
Ankerana	Estimate	4.2207	0.0381	0.0739	-0.0521
	std.error	0.6272	0.1011	0.8870	0.1429
	Statistic	6.7296	0.3766	0.0833	-0.3644
	p.value	0.0000	0.7114	0.9346	0.7204
CFAM	Estimate	2.9556	0.1989	-0.4228	-0.2490
	std.error	0.3797	0.0516	0.5370	0.0730
	Statistic	7.7832	3.8549	-0.7872	-3.4120
	p.value	0.0000	0.0010	0.4404	0.0028
Conservation Zone	Estimate	0.3776	0.1741	-0.0908	-0.1383
	std.error	0.6693	0.1325	0.9465	0.1874
	Statistic	0.5642	1.3133	-0.0959	-0.7376
	p.value	0.5830	0.2136	0.9251	0.4749
Torotorofotsy	Estimate	2.4177	0.1812	-0.2174	-0.0077
	std.error	0.4561	0.0575	0.6450	0.0813
	Statistic	5.3007	3.1528	-0.3370	-0.0945
	p.value	0.0000	0.0046	0.7393	0.9256

Note: N= 20 for Ankerana, 24 for CFAM, 16 for the CZ and 26 for Torotorofotsy

Supplementary Table 14; Test for parallel trends in deforestation between each buffer zone and its matched control sample in the pre-intervention period. Parallel trends in deforestation between the buffer zone and matched control samples were present for the buffer zones of Ankerana, the Conservation Zone and Torotorofotsy ($p > 0.05$). However, within the buffer zone of CFAM deforestation was declining prior to the intervention ($p = 0.0028$), whilst it was increasing in the matched control sample ($p = 0.001$). Consequently, the buffer zone of CFAM did not meet the assumption of parallel trends and could not be used in the subsequent difference-in-differences analysis. Interestingly, this replicates the findings of the main analysis.

Site-based difference-in-differences regressions

Buffer Zone		Intercept	Treated	Time	Treated:Time
Ankerana	estimate	4.4300	-0.2126	1.3354	-0.3354
	std.error	0.2248	0.3179	0.3267	0.4620
	statistic	19.7049	-0.6686	4.0882	-0.7261
	p.value	0.0000	0.5082	0.0003	0.4727
Conservation Zone	estimate	1.1609	-0.7130	1.4414	0.1860
	std.error	0.2642	0.3736	0.3472	0.4910
	statistic	4.3943	-1.9083	4.1515	0.3787
	p.value	0.0001	0.0648	0.0002	0.7072
Torotorofotsy	estimate	3.6859	-0.2711	0.8226	0.7250
	std.error	0.2420	0.3423	0.4307	0.6091
	statistic	15.2282	-0.7921	1.9099	1.1903
	p.value	0.0000	0.4338	0.0646	0.2422

Note: N = 38.

Supplementary Table 15; Results from the site-based differences-in-differences regression for each buffer zone. The buffer zone of CFAM could not be included due to the lack of parallel trends. Treated and Time are a binary variables indicating whether the observation is from the buffer zone (1) or matched control (0) sample, from before (0) or after (1) the intervention. The coefficient of interest is Treated:Time which represents the effect of being within 10km of a protected biodiversity offset on the log(y+1) transformed count of deforestation.

Results show no significant difference in average annual deforestation between the buffer zone and the estimated counterfactual for Ankerana, the Conservation Zone and Torotorofotsy following protection of the offsets. Therefore, there is no evidence of deforestation leakage from the protected offsets into the surrounding forested landscape.

Fixed effects panel regression

As in the main analysis the data for all four buffer zones and their matched control samples were pooled to form one dataset with 152 observations comprising an observation for each site (i=8, 4 buffer zone and 4 control) for each year (t =19).

term	Tr
estimate	0.2271
std.error	0.1564
statistic	1.4520
p.value	0.1490

Note: N = 152, df = 125

Supplementary Table 16; Results from the fixed effects panel regression on the pooled buffer zone data. The fixed effects regression takes the form $\log(\text{count of deforestation} + 1)_{i,t} = \beta_0 + \beta_1 Tr_{i,t} + \propto_i + \gamma_t + \epsilon_{it}$, where Tr is a binary measure indicating the treated status of observation *i* in year *t* (Tr = 1 for observations from a buffer zone in the years following protection of the adjacent offset, and 0 for all other observations), $\propto_i$ and γ_t represent site and year fixed effects respectively and ϵ_{it} represents the composite error. The sample size is 152. The coefficient of Tr indicates the treatment effect – the effect of being within 10km of a protected biodiversity offset on the log-transformed count of deforestation.

Results show that overall, protection of the biodiversity offsets had no significant effect on deforestation within a 10km radius, relative to the matched controls and the pre-intervention period. This verifies the findings of the site-based difference-in-differences regressions (and captures the effect of CFAM) that there is no evidence of deforestation leakage from Ambatovy's four biodiversity offsets into the surrounding forested landscape.

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