# Supplementary Information for

## Learning lessons from over-crediting to ensure additionality in forest carbon credits

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**This document includes:**

**Supplementary note 1.** Contrasting methods to assess REDD+ impact.

In this section we summarise the overarching process of assessing REDD+ projects with certification and quasi-experimental methods. In both approaches, assessors possessed a degree of flexibility in decision-making that may have affected outcomes. Within certification methods, assessors had flexibility over the selection of the control area, the historic reference period, the remotely sensed forest classification and the *ex ante* model of future deforestation. For quasi-experimental methods, there was flexibility in the selection of pre-project characteristics, rules for determining the domain of untreated units, the remotely sensed forest classification, and the statistical model for selecting control units.

*Certification methods*

The methods used in the assessments of the first generation of REDD+ projects were taken from a set of available certification methods. While these methods differed in their detail, which is documented by Verra [1] and explained comprehensively in West et al. [2], they follow a broadly similar approach:

1. **Define the project area.** REDD+ projects may have inherited their boundaries from pre-existing protected areas but they must also have conformed to the applicability conditions of certification methods. This means projects must have possessed suitable forest cover for at least the preceding 10 years, as demonstrated using remotely sensed evidence. A project also specified a start date after which the intervention came into effect.
2. **Define the control area.** Control areas (also known as the reference area) were defined using a combination of geo-spatial layers. These control areas were selected so that they had similar characteristics to the project in terms of forest cover, and expected drivers of deforestation. Control areas were determined to be similar to projects if their characteristics fell within the range of values observed within the project (± percentage tolerance outside the range).
3. **Measure historic deforestation in the control area.** Historic deforestation figures were extracted from forest cover classification maps. These maps were typically produced from satellite remote sensing. Classification typically involved training a model to minimise errors when predicting a spatial dataset of forest and non-forest classes, produced from field or high-resolution aerial observations. It is well known that different results can be produced by changing the set of forest / non-forest observations, the satellite imagery or the underlying model. To estimate deforestation rates, measurements were made of the area of forest at the start of the project and at two or more historic time points. The period was often the same as the period used to check the applicability condition under (1), because it required the same assessment of forest cover. Thus, the availability of suitable cloud free satellite imagery determined the historic reference period during which deforestation rates were measured. The mean length of reference periods in our dataset was found to be 13.6 years.
4. **Predict *ex ante* counterfactual deforestation for the project.** REDD+ projects must have been forest for the preceding 10 years. Thus, projects should have no historic deforestation by definition. Therefore, control areas were effectively a space-for-time substitute for the project, assumed to be equivalent in terms of

probability of becoming a REDD+ project and exposure to the drivers of deforestation, but several years ahead in terms of the deforestation experienced. *Ex ante* counterfactual deforestation rates were estimated using one of a variety of possible methods. These spanned averaging historic rates, regressing linear and non-linear changes through time, and modelling spatial deforestation patterns using a risk modelling approach. Spatial risk models were developed over an area that included but was larger than the project (also known as the reference area for location). Deforestation was then allocated across the reference area for location in order of risk probability at the rate measured in (3). This meant that if the project was estimated to be at relatively high risk it would be allocated a larger proportion of the deforestation, and could experience a higher rate than the control area.

5. **Measure *ex post* deforestation in the project area.** A remote sensing classification is produced for the project at a point in time subsequent to the project commencing. The difference between the assessed forest cover at the time of monitoring and the start of the project provides the *ex post* measure of project deforestation.
6. **Calculate avoided deforestation by comparison of the project and counterfactual.** The *ex post* measurement of project deforestation is subtracted from the *ex ante* estimate for the counterfactual scenario for the same point in time to calculate avoided deforestation.
7. **Verify project assessment**. The report produced by the project proponent is submitted to a third-party auditor who verifies that the method hosted by the standard has been appropriately followed. Where methods have not been followed appropriately, assessments require revision.

Note that current jurisdictional methods follow a similar approach, but the project and control areas (for measuring historic deforestation and predicting risks) are both defined as the jurisdiction itself.

*Quasi-experimental methods*

Different quasi-experimental methods are available to assess the effect of REDD+ interventions on deforestation.These methods differ in their approaches and input data [3–9] are broadly similar in their structure and assumptions:

1. **Define the project area.** A spatial polygon and start date were accessed from an online repository.
2. **Define the control area.** A set of geospatial layers were compiled that encoded pre-project characteristics known to be associated with the selection of projects and deforestation (i.e. likely confounders). These pre-project characteristics could represent point specific features such as elevation or slope, or neighbourhood statistics covering a larger area such as surrounding forest cover. For each project, a sample was taken representing project exposure to these pre-project characteristics. Sampling required a specified unit size and technique: Unit sizes ranged from whole project areas to pixels at the highest geospatial resolution. For smaller units sizes, sampling typically occurred across a grid covering the project polygon. Pre-project samples were usually summarised as the mean and range of the various pre-project characteristics. Next the domain of possible untreated units was determined by filtering to locations that were identical to projects according to categorical

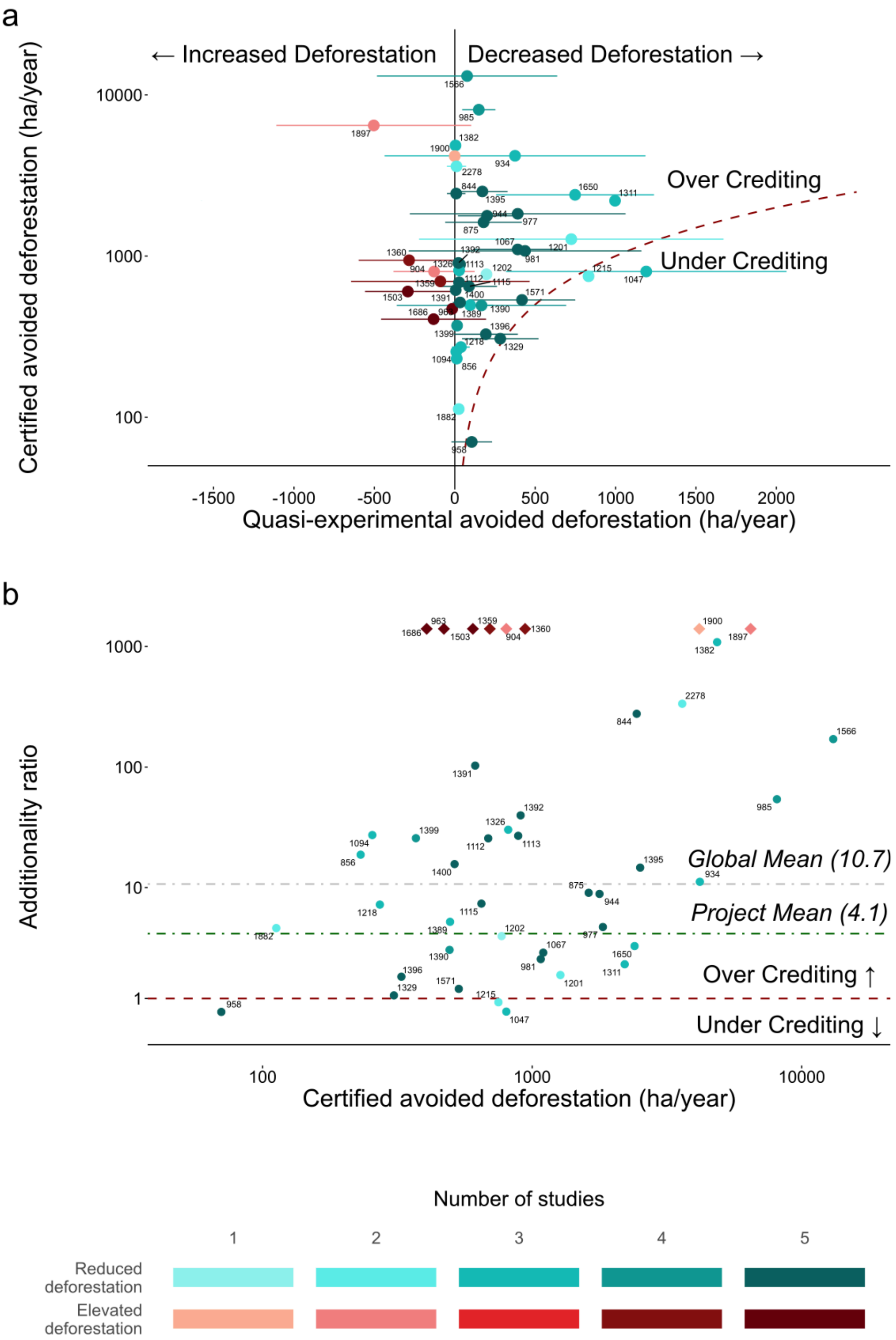
characteristics, for example within the same country and biome, not within another REDD+ project, and less than a specified maximum distance from the project. Across this domain and utilising the pre-project characteristics, a statistical method (Matching or Synthetic Control) was employed to select a set of untreated control units, which collectively form a control area equivalent to the project. Post-hoc tests were used to assess the validity of this control area.

3. **Measure *ex post* deforestation in the project and control areas.** A peer-reviewed forest cover classification was used to measure changes in forest cover in the project and control areas across the same time period. For both project and control areas, the difference between the forest cover at the time of monitoring and the start of the project provides an *ex post* measure of deforestation.
4. **Calculate avoided deforestation by comparison of the project and counterfactual.** The *ex post* measurement of project deforestation is subtracted from the *ex post* measurement of control area deforestation (which functions as an estimated counterfactual scenario) to calculate avoided deforestation. The requirement for REDD+ projects to be defined as 100% forested when they start makes it impossible to apply difference in difference methods as the pre-project deforestation rate should always be zero [8].
5. **Verify project assessment**. A quasi-experiment REDD+ assessment can be verified through third-party reproduction of results using the clearly stated method, publicly available datasets, and open-source code. In addition, peer-review ensures that up-to-date credible methods and data have been used.

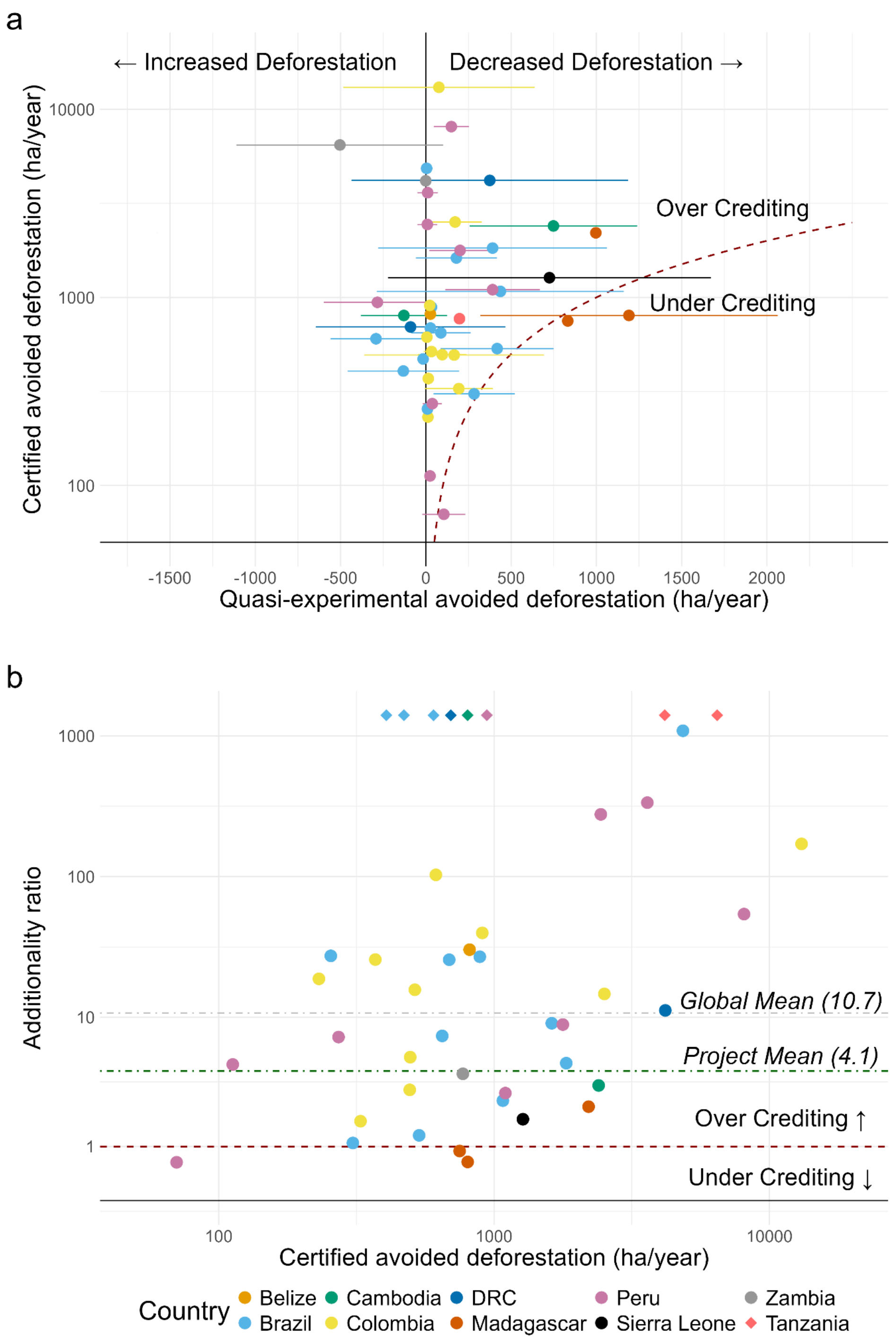
**Supplementary table 1.** Projects included in each analysis. Different subsets of projects were included in each analysis based on the information available. 46 projects analysed by the different statistical analyses that had certified amounts of avoided deforestation were included in Question 1. Question 2 required that project area deforestation rates were included in certified documents, this amounted to 36 projects. Question 3 required that reference areas could be acquired with reasonable accuracy from maps provided in the Project Design Documents; this applied to 17 projects. Question 4 covered the same 17 projects.

| Project | Country | Q1 (Fig. 2) | Q2 (Fig. 3) | Q3 (Fig. 4) | Q4 (Fig. 5) |
|---|---|---|---|---|---|
| 844 | Peru | x | x | | |
| 856 | Colombia | x | x | | |
| 875 | Brazil | x | x | | |
| 904 | Cambodia | x | | | |
| 934 | Congo | x | x | | |
| 944 | Peru | x | x | x | x |
| 958 | Peru | x | x | x | x |
| 963 | Brazil | x | x | | |
| 977 | Brazil | x | | | |
| 981 | Brazil | x | x | | |
| 985 | Peru | x | x | | |
| 1047 | Madagascar | x | x | x | x |
| 1067 | Peru | x | x | | |
| 1094 | Brazil | x | x | x | x |
| 1112 | Brazil | x | x | x | x |
| 1113 | Brazil | x | x | x | x |
| 1115 | Brazil | x | x | x | x |
| 1118 | Brazil | | x | | |
| 1201 | Sierra Leone | x | x | x | x |
| 1202 | Zambia | x | | | |
| 1215 | Madagascar | x | x | | |
| 1218 | Peru | x | | | |
| 1311 | Madagascar | x | x | | |
| 1326 | Belize | x | x | | |
| 1329 | Brazil | x | x | x | x |
| 1359 | D.R. Congo | x | | | |
| 1360 | Peru | x | x | | |
| 1382 | Brazil | x | x | | |
| 1389 | Colombia | x | x | | |
| 1390 | Colombia | x | x | x | x |
| 1391 | Colombia | x | x | | |
| 1392 | Colombia | x | x | x | x |
| 1395 | Colombia | x | x | | |
| 1396 | Colombia | x | x | | |
| 1399 | Colombia | x | x | x | x |
| 1400 | Colombia | x | x | x | x |
| 1503 | Brazil | x | x | | |
| 1566 | Colombia | x | x | x | x |
| 1571 | Brazil | x | x | x | x |
| 1650 | Cambodia | x | x | x | x |
| 1686 | Brazil | x | x | | |
| 1882 | Peru | x | x | | |
| 1897 | Tanzania | x | | | |

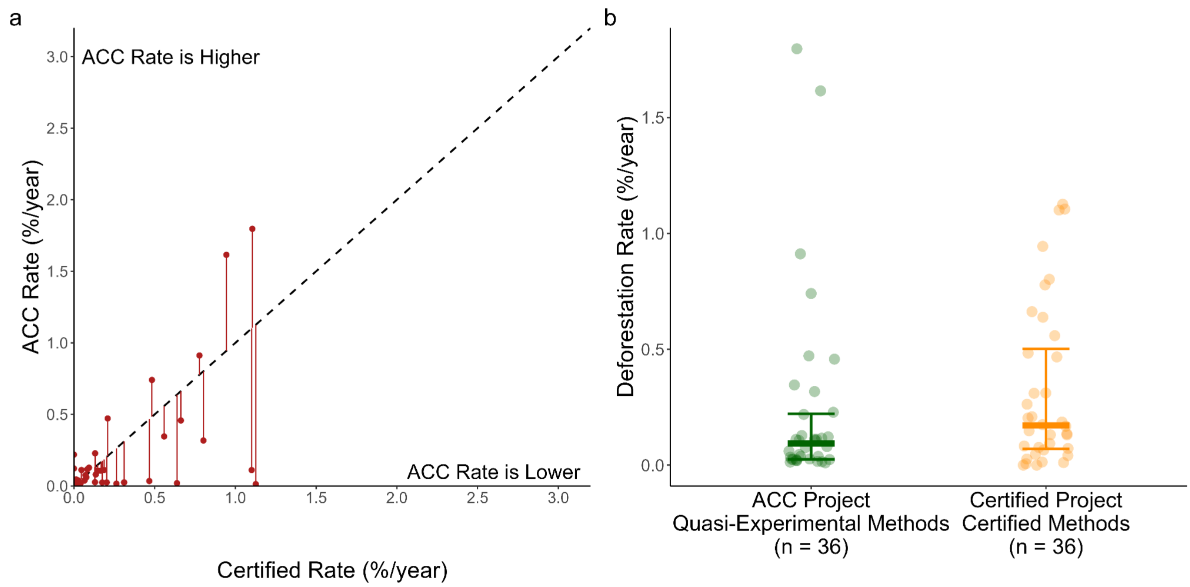
| | | | | | |
|---|---|---|---|---|---|
| 1900 | Tanzania | x | | | |
| 2278 | Peru | x | | | |
| **Total** | | **44** | **36** | **17** | **17** |



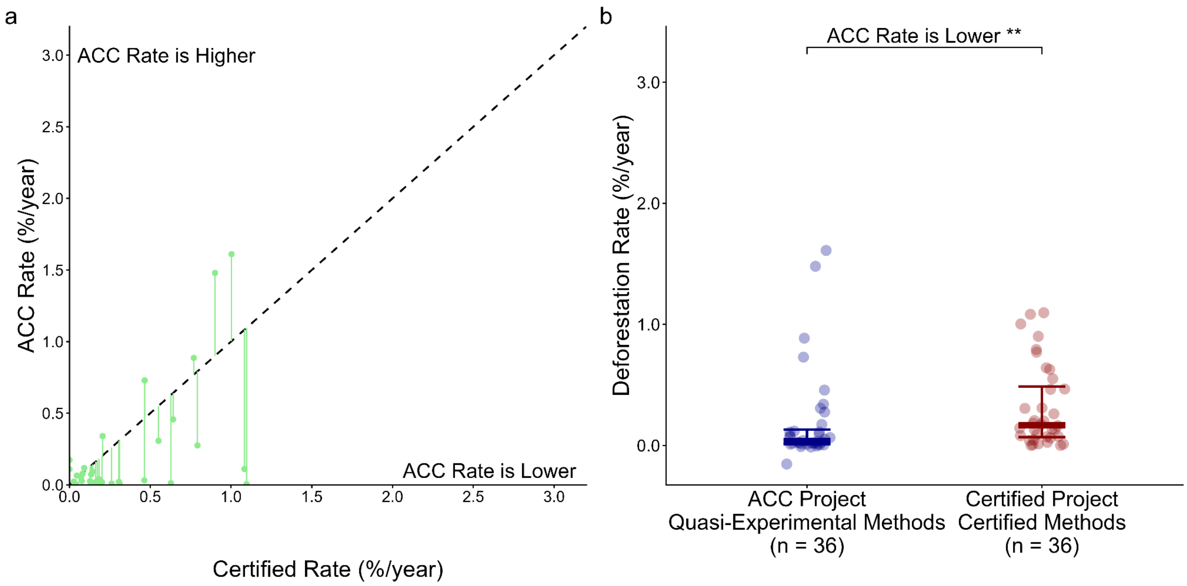

**Supplementary figure 1.** Comparison of quasi-experimental and certified estimates of project performance labelled by project. To enable interpretation of over-crediting ratios of individual projects, we have recreated figure 1 but with points labelled by the Verra project ID numbers. (a) 44 REDD+ projects' certified estimates of avoided deforestation against mean estimates from the five quasi-experimental methods, and (b) the over-crediting ratio (the mean quasi-experimental estimate divided by the certified estimate) against certified estimates of avoided deforestation. In both plots certified estimates of avoided deforestation are shown on logarithmic scales. Dashed black lines show where quasi-experimental and certified estimates are equal. In (b) the solid and dashed grey lines show the mean over-crediting ratio weighting projects equally and weighting them by the size of their certified estimates, respectively. Darker colours indicate projects that were assessed by a greater number of quasi-experimental approaches (to a maximum of five because there was no overlap in the projects assessed by the two West et al. studies). Hollow points show projects assessed to have negative additionality by certified assessments. Confidence intervals show 1.96 standard errors.



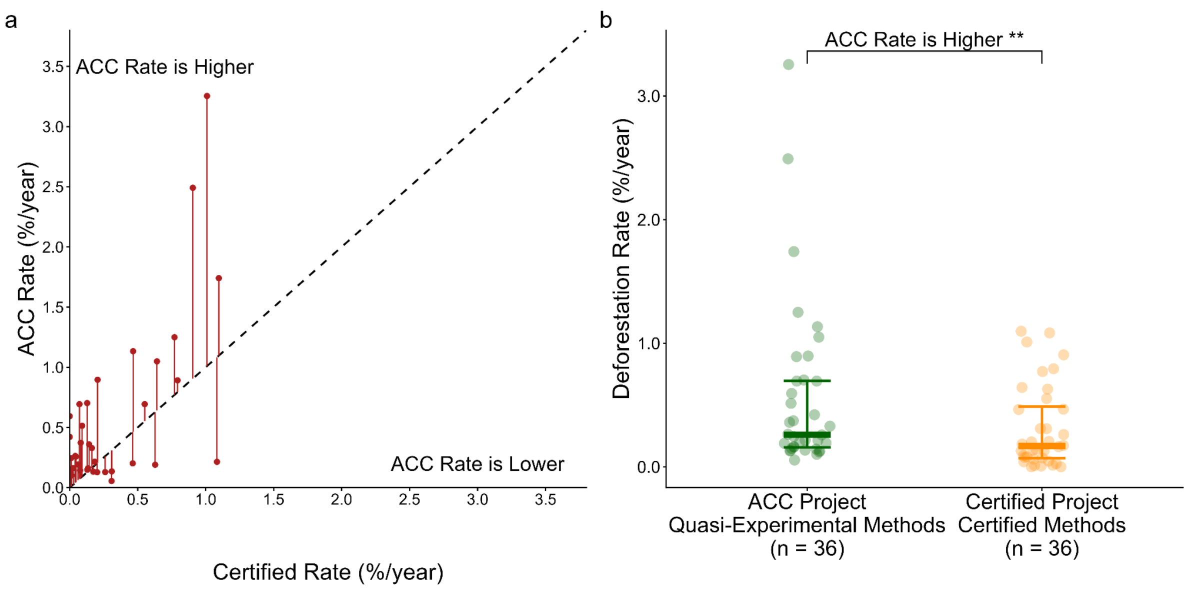

**Supplementary figure 2.** Comparison of quasi-experimental and certified estimates of project performance coloured by the country where the project was implemented**.** (a) Quasi-experimental evaluations show consistent evidence that REDD+ projects slowed deforestation, but certified estimates were higher, indicating widespread over-crediting. Points represent mean estimates from the six quasi-experimental studies, with error bars showing 95% confidence intervals. (b) The over-crediting ratio (the certified estimate divided by the mean quasi-experimental estimate) plotted against certified avoided deforestation estimates. The dashed grey line indicates the global mean over-crediting ratio and the dashed red lines mark parity between certified and quasi-experimental estimates. Points above and below the red line represent over- and under-crediting respectively. Colours denote the country where the project was implemented. The over-crediting ratio is undefined for the points that experienced more deforestation than predicted by their quasi-experimental controls (shown in red). Both panels use log-scaled y-axes.



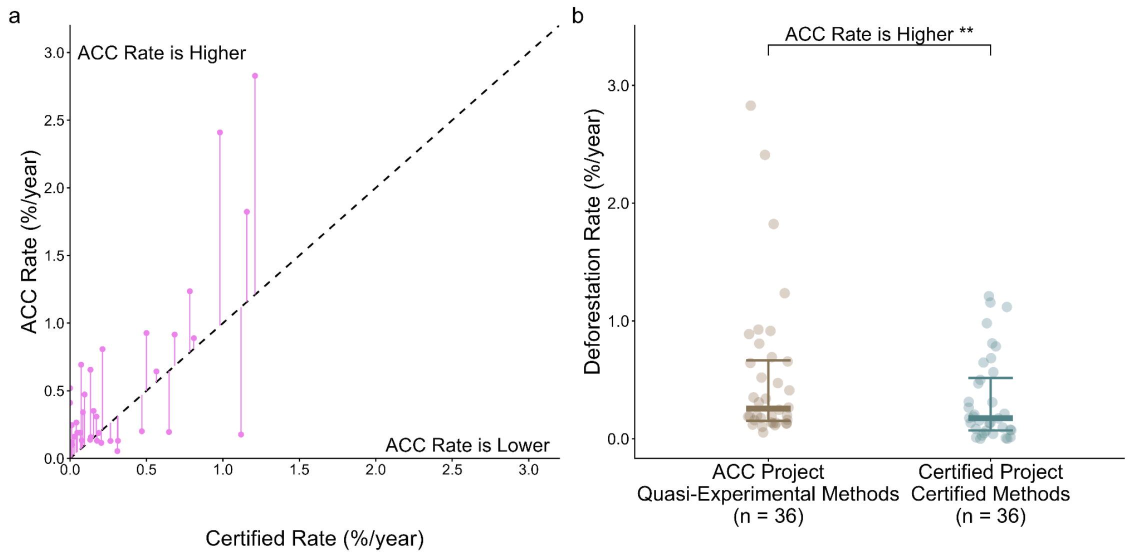

**Supplementary figure 3.** The remotely sensed deforestation rates in project areas when forest cover is defined as undisturbed or degraded. (a) *Ex post* annual deforestation rates in 36 project areas measured using the European Unions' Annual Change Collection (ACC) versus the bespoke forest cover layers used in certification. The identity line indicates where estimates are equal. (b) Changing the forest cover definition when using the ACC data to include the **undisturbed and degraded** forest classes reduced the *ex post* deforestation rates measured in project areas from 0.26%/year reported in figure 3 of the main text to 0.09%/year. The lower ACC deforestation rates result in there being no difference from the certified project deforestation rates (*Wilcoxon paired signed-ranks,* n = 36, V = 248, p = 0.1866). Error bars show the median and interquartile range. The reason for the reduction in ACC measured deforestation rates is that deforestation is judged to have occurred when disturbances last >2.5 years, even if regrowth subsequently occurs: short duration disturbances (<2.5 years) are not considered.



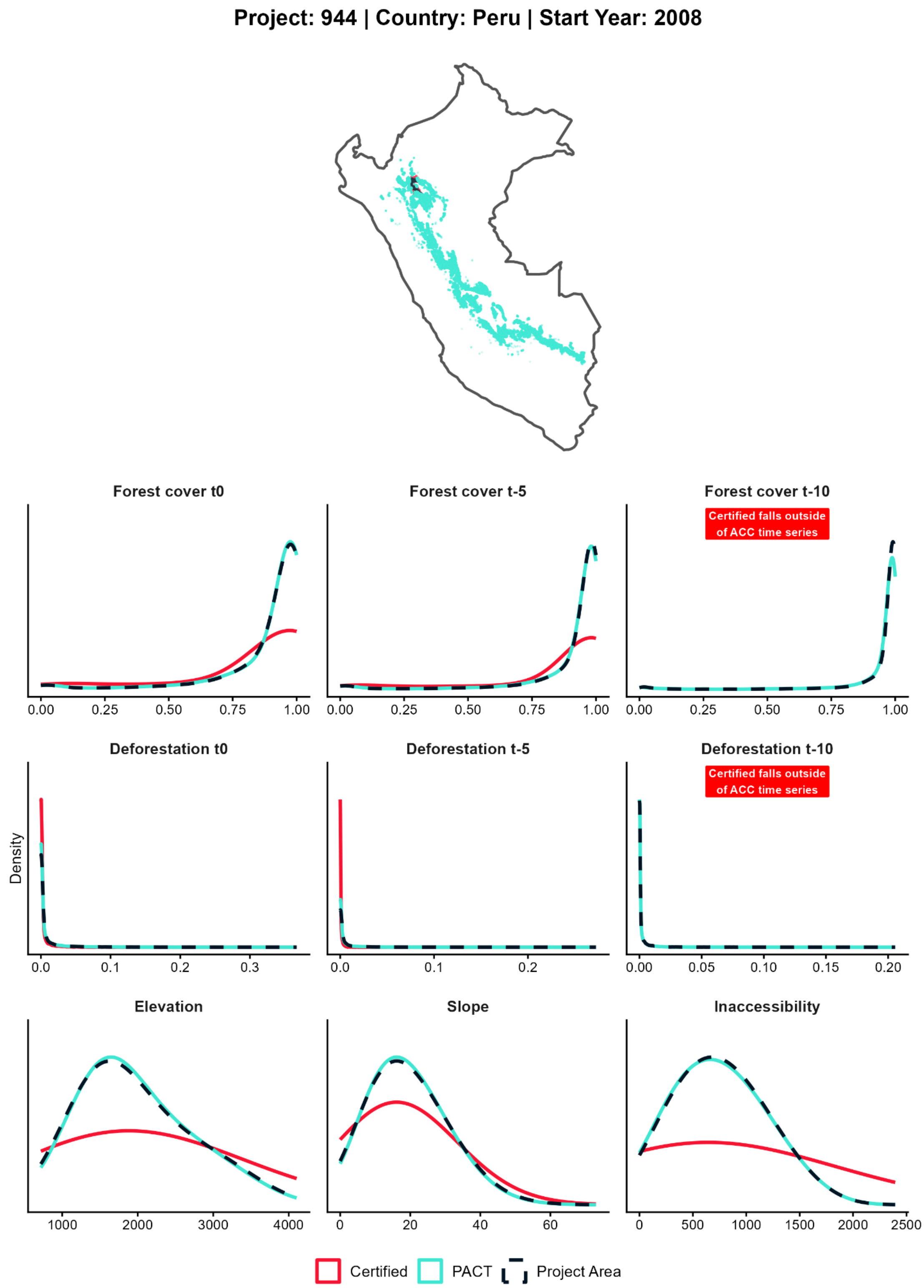

**Supplementary figure 4.** The remotely sensed deforestation rates in project areas when forest cover is defined as undisturbed, degraded or regrowth. *Ex post* annual deforestation rates in 36 project areas measured using the European Unions' Annual Change Collection (ACC) versus the bespoke forest cover layers used in certification. The identity line indicates where estimates are equal. (b) Changing the forest cover definition when using the ACC data to include the **undisturbed, degraded and regrowth** forest classes reduced the *ex post* deforestation rates measured in project areas from 0.26%/year reported in figure 3 of the main text to 0.04%/year. The ACC deforestation rates measured like this are significantly lower than the certified project deforestation rates (*Wilcoxon paired signed-ranks,* n=36 V = 173, p = 0.01098). Error bars show the median and interquartile range. The reduction in ACC measured deforestation rates are again lower because deforestation is judged to have occurred when disturbances last >2.5 years: short duration disturbances (<2.5 years) are not considered and even longer term disturbances are not considered if regrowth subsequently occurs.



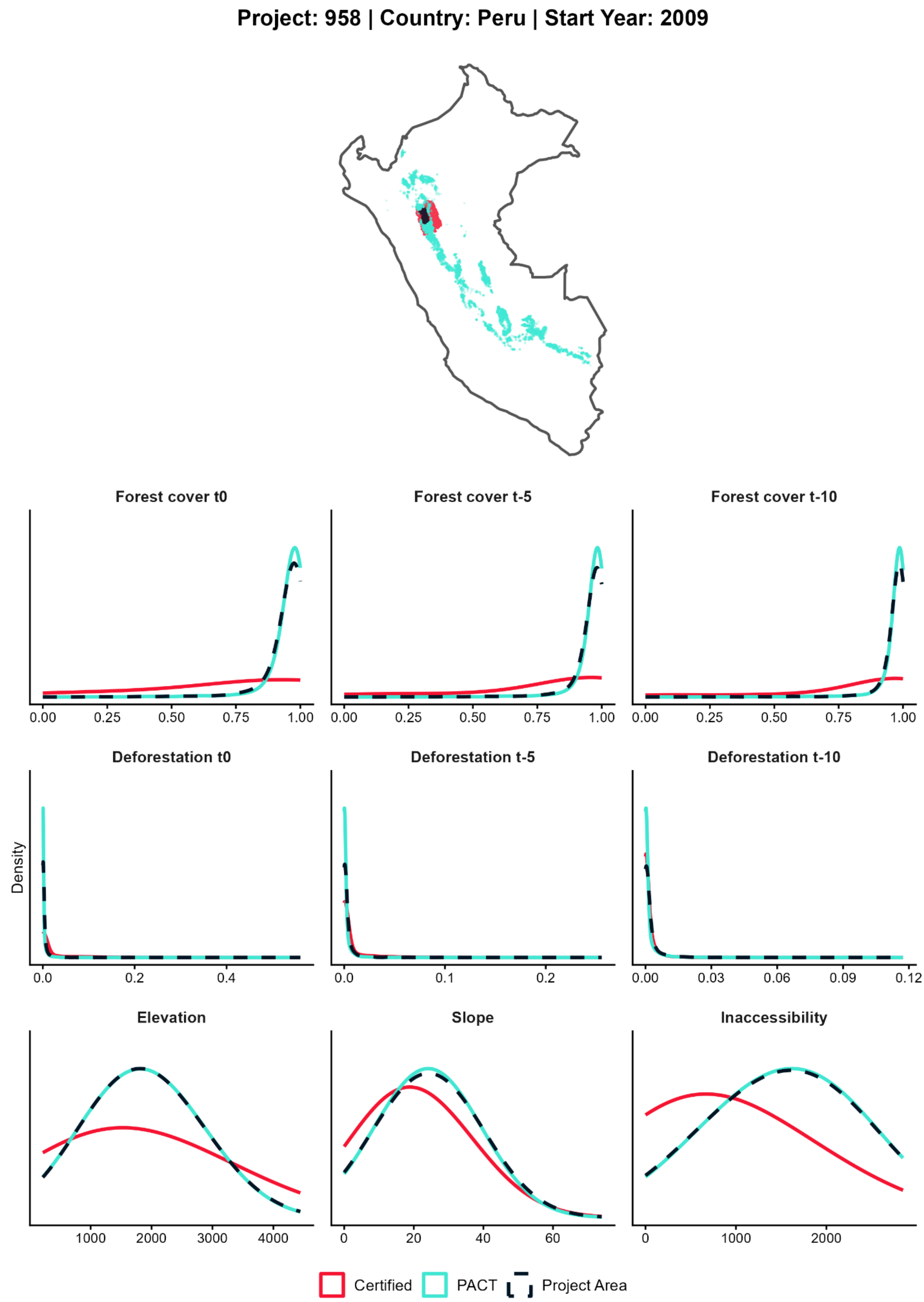
**Supplementary figure 5.** The remotely sensed deforestation rates in project areas when deforestation is defined as loss of undisturbed or degraded ACC classes. *Ex post* annual deforestation rates in 36 project areas measured using the European Unions' Annual Change Collection (ACC) versus the bespoke forest cover layers used in certification. The identity line indicates where estimates are equal. (b) Measuring deforestation as transitions: (1) from the undisturbed class to any other class, or (2) from the degraded class to the deforested class, did not change the *ex post* deforestation rates measured in project areas when compared just measuring the loss of undisturbed. The median ACC rate remained at 0.26% a year. Though the median project was relatively unaffected, some projects were more affected than others. For example, deforestation rates in project 1650 rose from 2.95% a year to 3.25% a year. Error bars show the median and interquartile range.



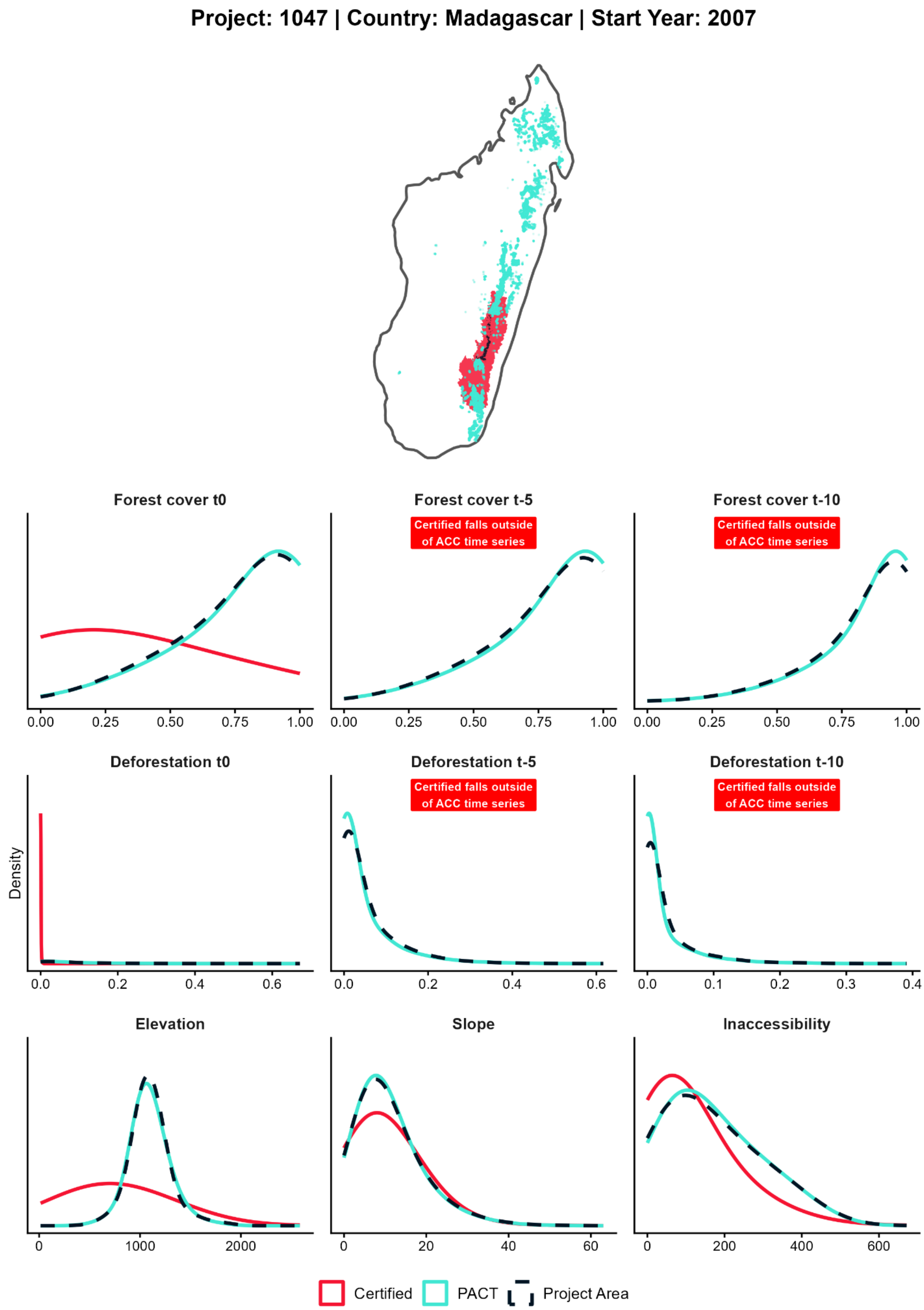

**Supplementary figure 6.** The remotely sensed deforestation rates in project areas when deforestation is defined as loss of undisturbed or regrowth ACC classes. *Ex post* annual deforestation rates in 36 project areas measured using the European Unions' Annual Change Collection (ACC) versus the bespoke forest cover layers used in certification. The identity line indicates where estimates are equal. (b) Measuring deforestation as transitions: (1) from the undisturbed class to any other class, or (2) from the regrowth class to the deforested class, did not change the median *ex post* deforestation rates measured in project areas when compared with measuring loss of undisturbed forest alone. The median ACC rate remained at 0.26% a year, as presented in figure 3. Error bars show the median and interquartile range.



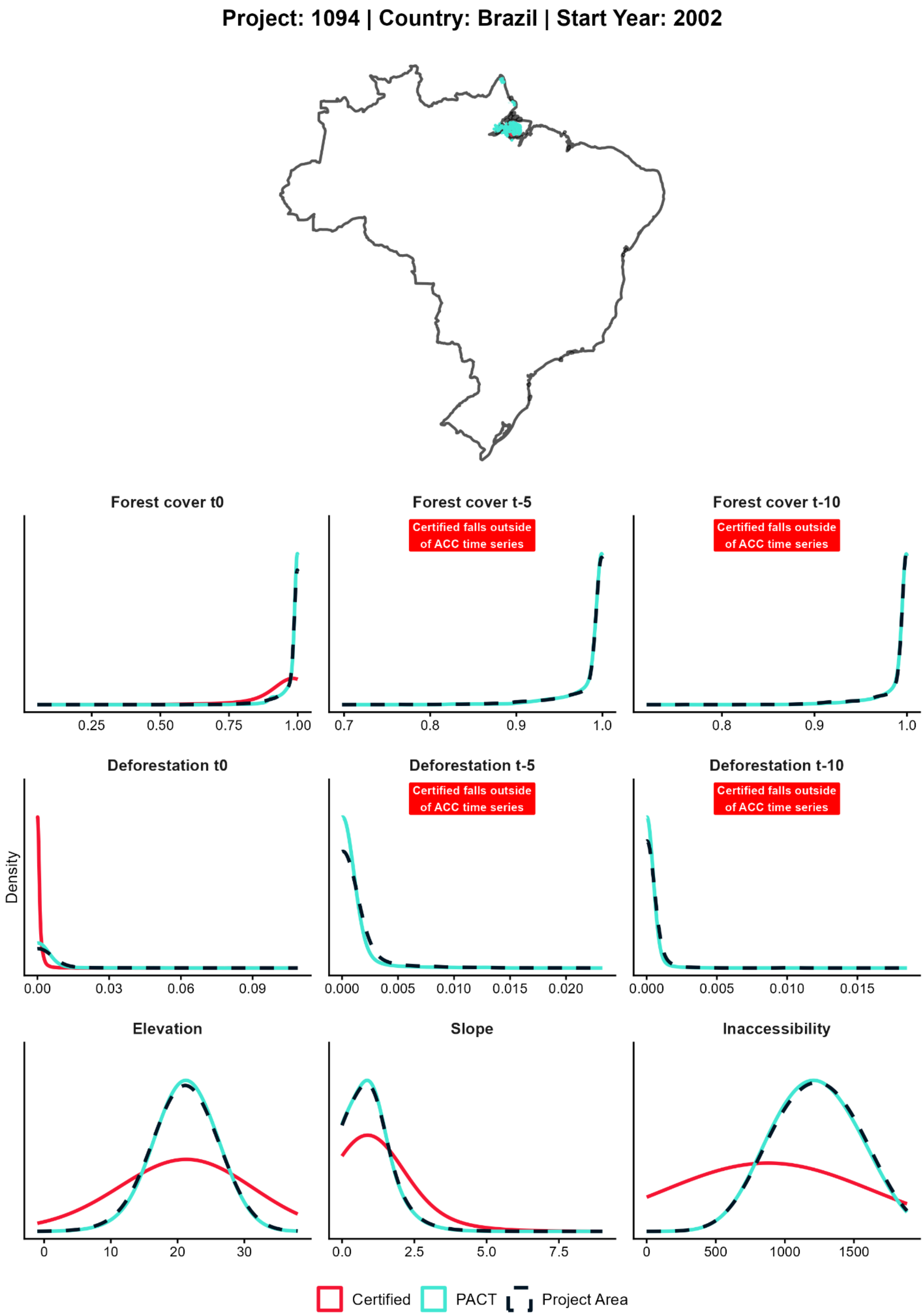

**Supplementary figure 7.** The location of the project, certified reference and PACT control areas, and differences in exposure to deforestation drivers for project 944**.** Univariate frequency distributions contrast exposure to observable confounders which may influence deforestation. The timing of measurements is expressed relative to the project start year ($t_0$) for quasi-experimental control areas, or the start of the reference period for reference areas.



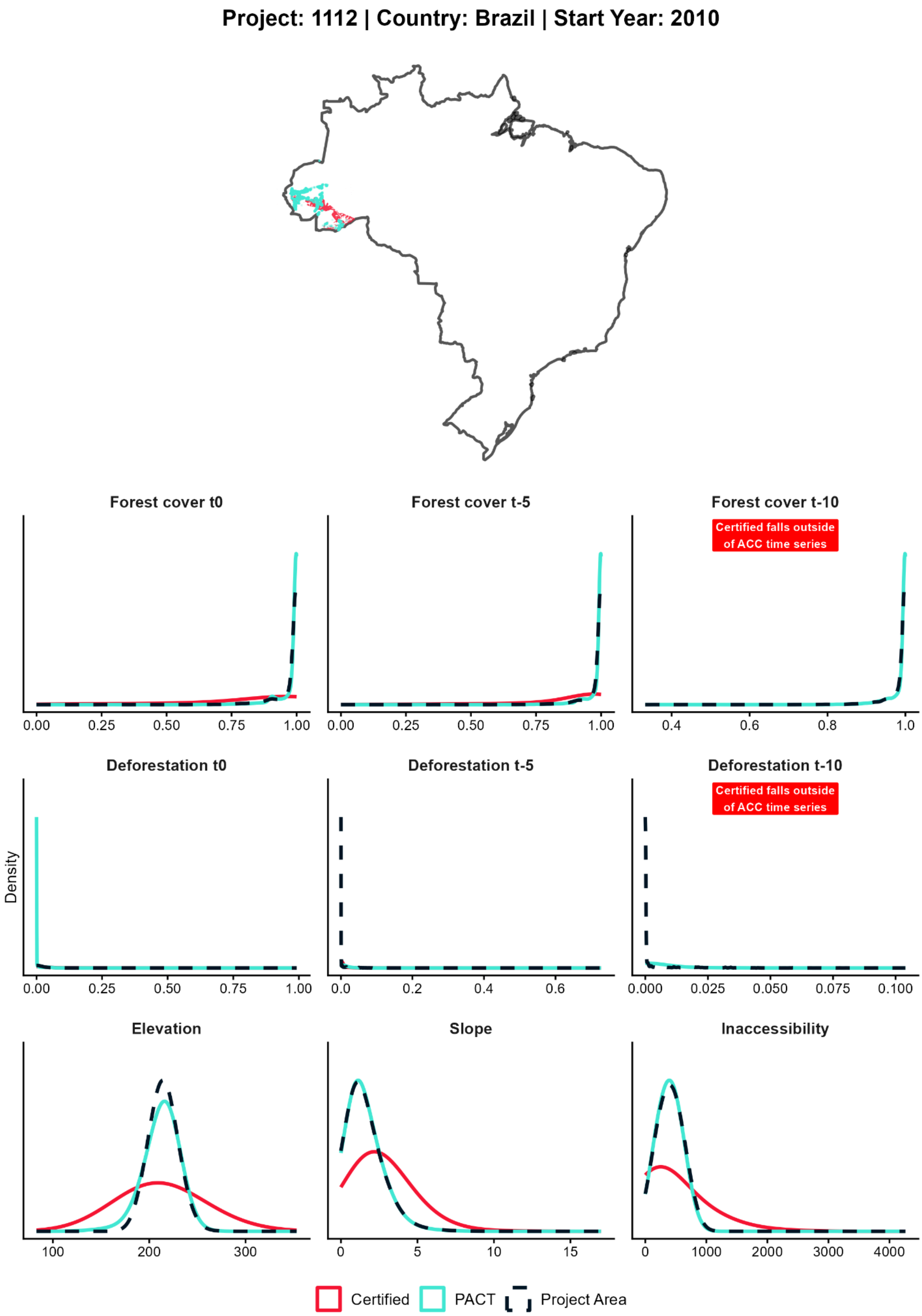

**Supplementary figure 8.** The location of the project, certified reference and PACT control areas, and differences in exposure to deforestation drivers for project 958**.** Univariate frequency distributions contrast exposure to observable confounders which may influence deforestation. The timing of measurements is expressed relative to the project start year ($t_0$) for quasi-experimental control areas, or the start of the reference period for reference areas.



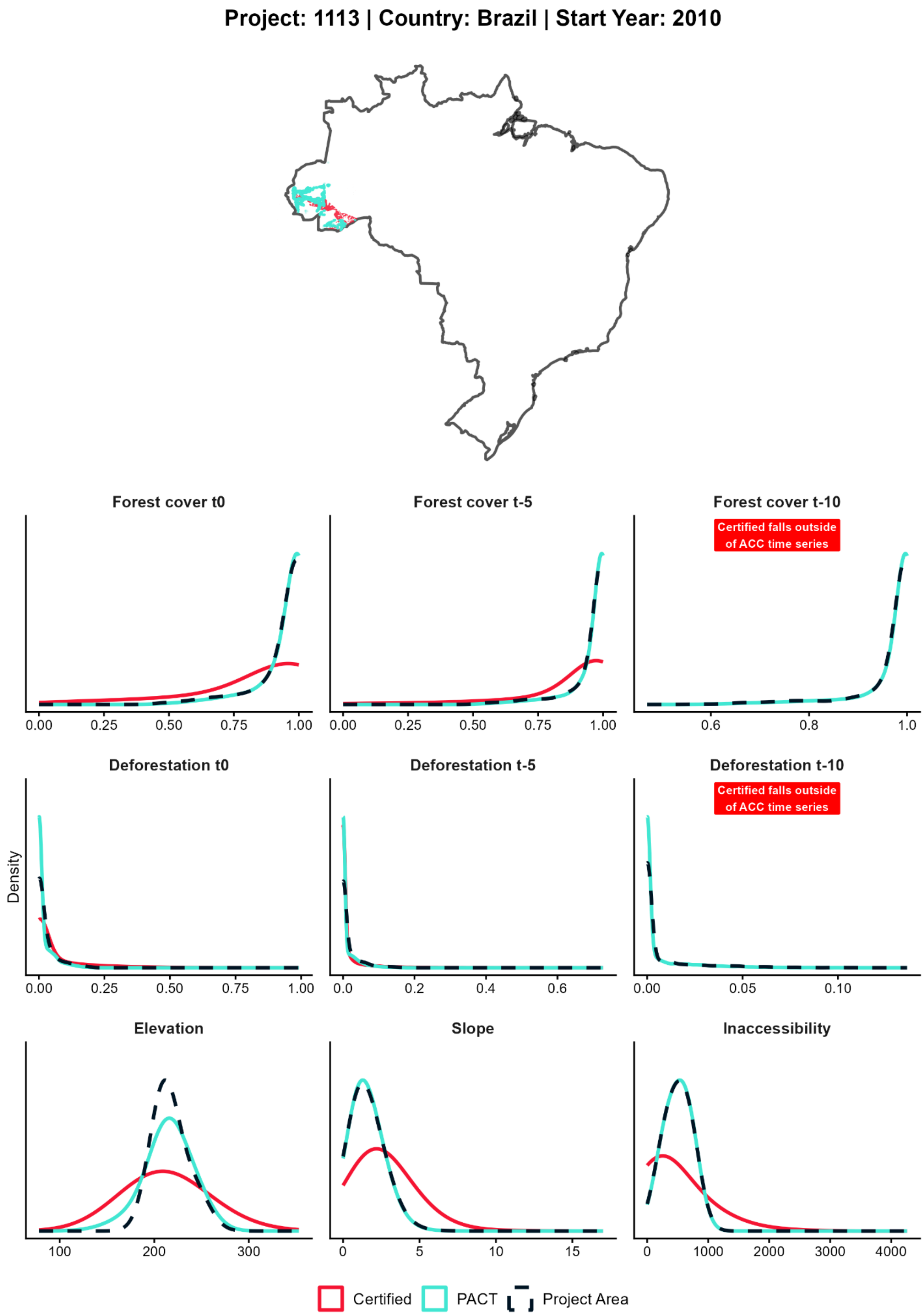

**Supplementary figure 9.** The location of the project, certified reference and PACT control areas, and differences in exposure to deforestation drivers for project 1047**.** Univariate frequency distributions contrast exposure to observable confounders which may influence deforestation. The timing of measurements is expressed relative to the project start year ($t_0$) for quasi-experimental control areas, or the start of the reference period for reference areas.



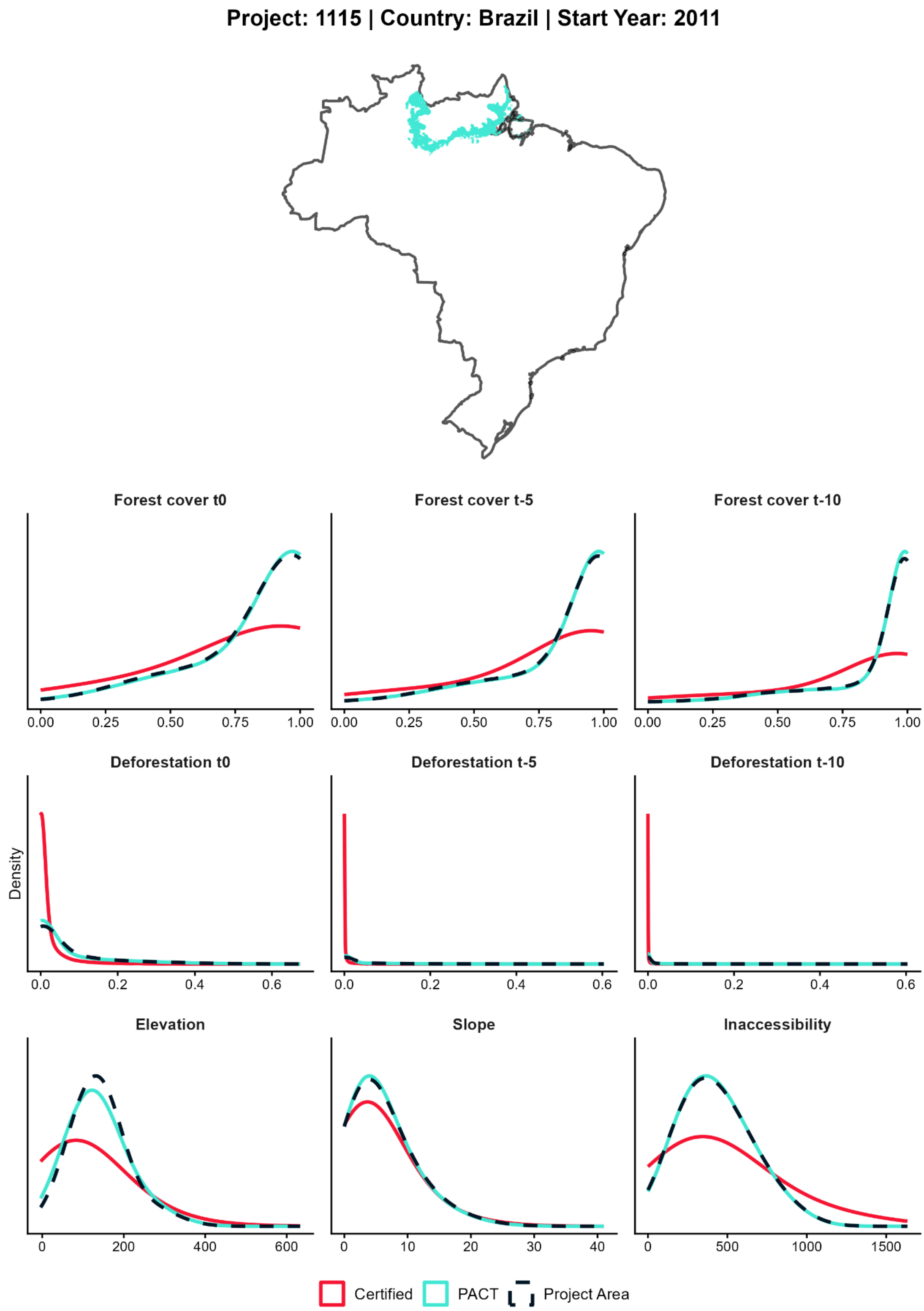

**Supplementary figure 10.** The location of the project, certified reference and PACT control areas, and differences in exposure to deforestation drivers for project 1094**.** Univariate frequency distributions contrast exposure to observable confounders which may influence deforestation. The timing of measurements is expressed relative to the project start year ($t_0$) for quasi-experimental control areas, or the start of the reference period for reference areas.



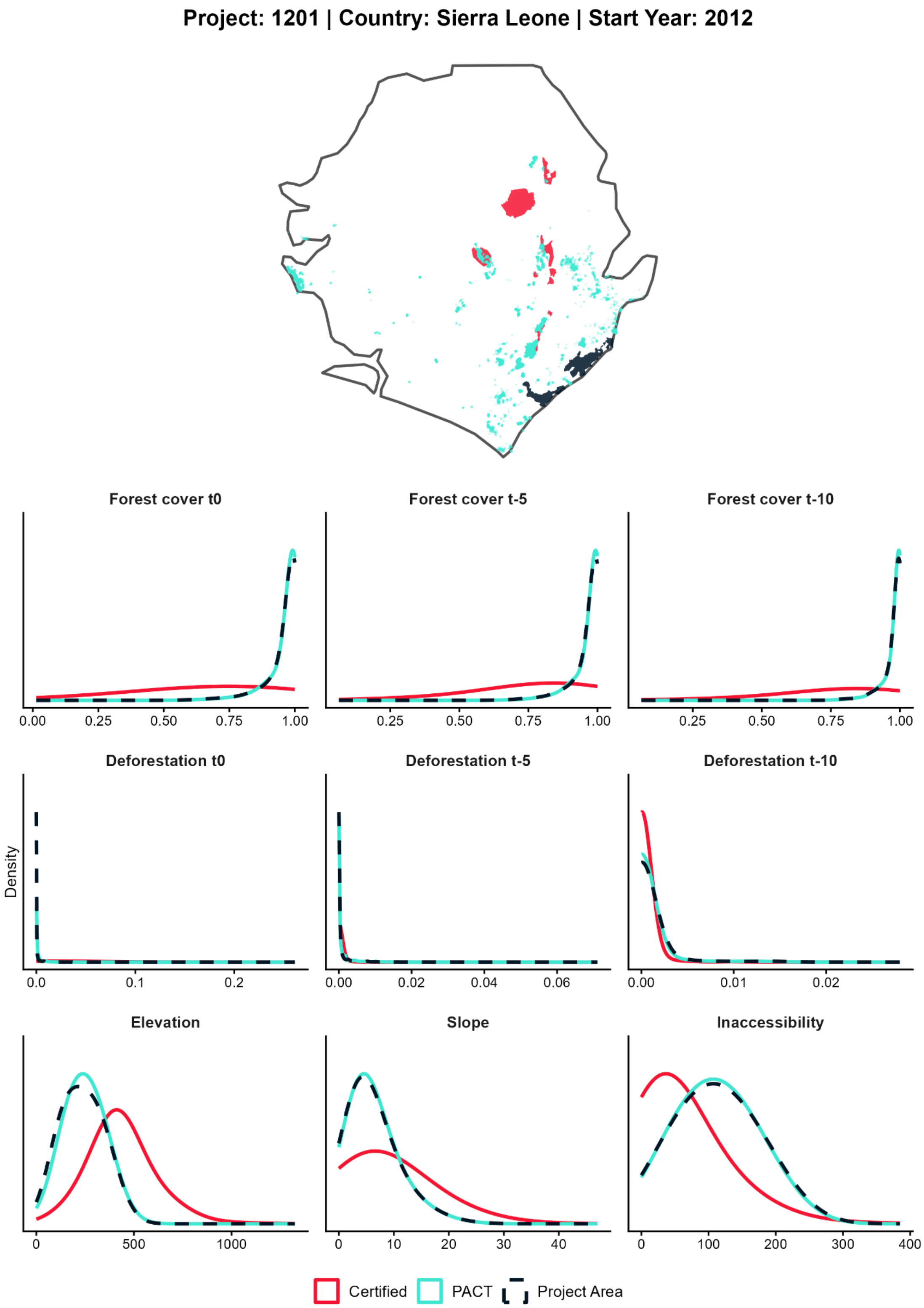

**Supplementary figure 11.** The location of the project, certified reference and PACT control areas, and differences in exposure to deforestation drivers for project 1112**.** Univariate frequency distributions contrast exposure to observable confounders which may influence deforestation. The timing of measurements is expressed relative to the project start year ($t_0$) for quasi-experimental control areas, or the start of the reference period for reference areas.



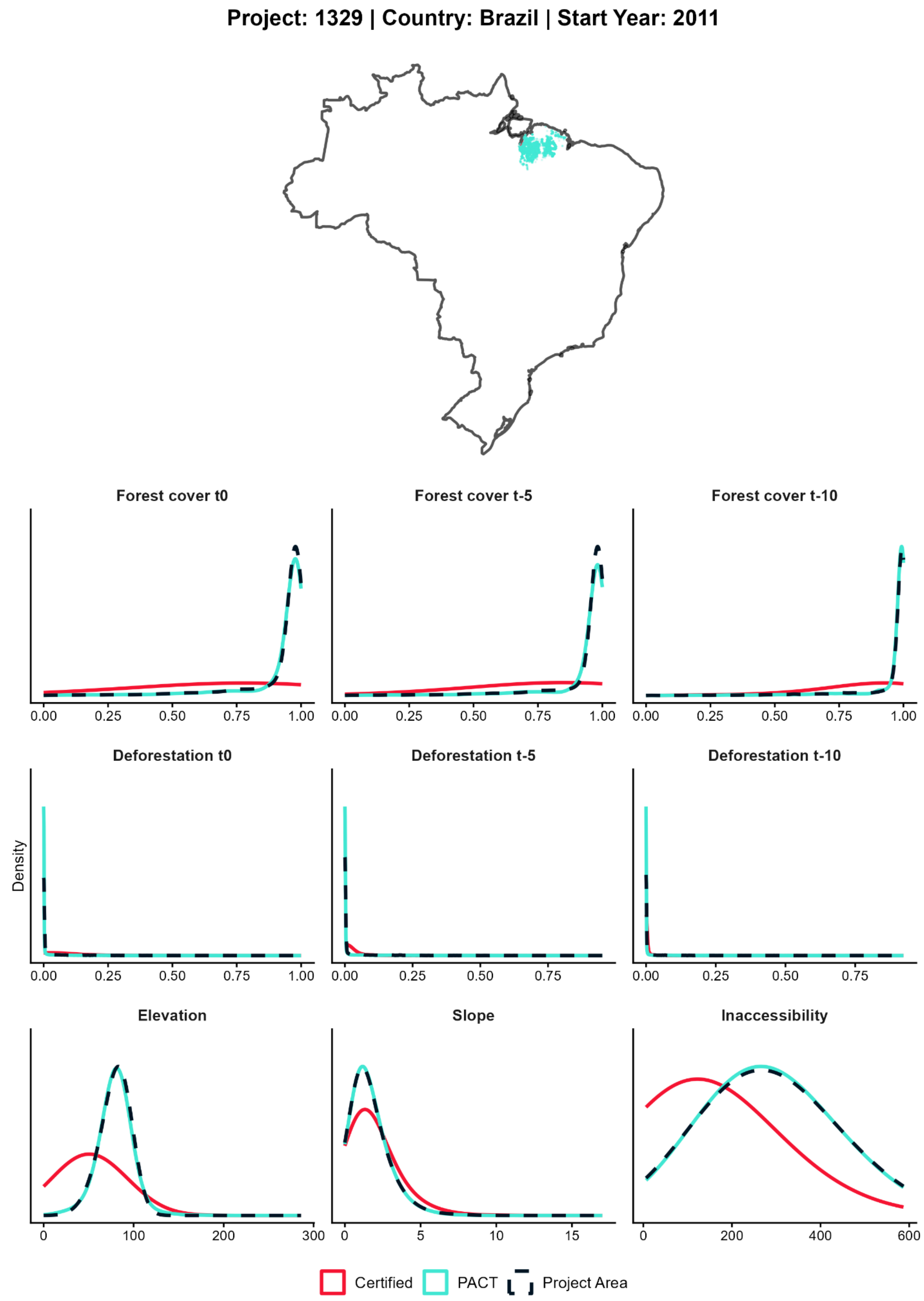

**Supplementary figure 12.** The location of the project, certified reference and PACT control areas, and differences in exposure to deforestation drivers for project 1113**.** Univariate frequency distributions contrast exposure to observable confounders which may influence deforestation. The timing of measurements is expressed relative to the project start year ($t_0$) for quasi-experimental control areas, or the start of the reference period for reference areas.



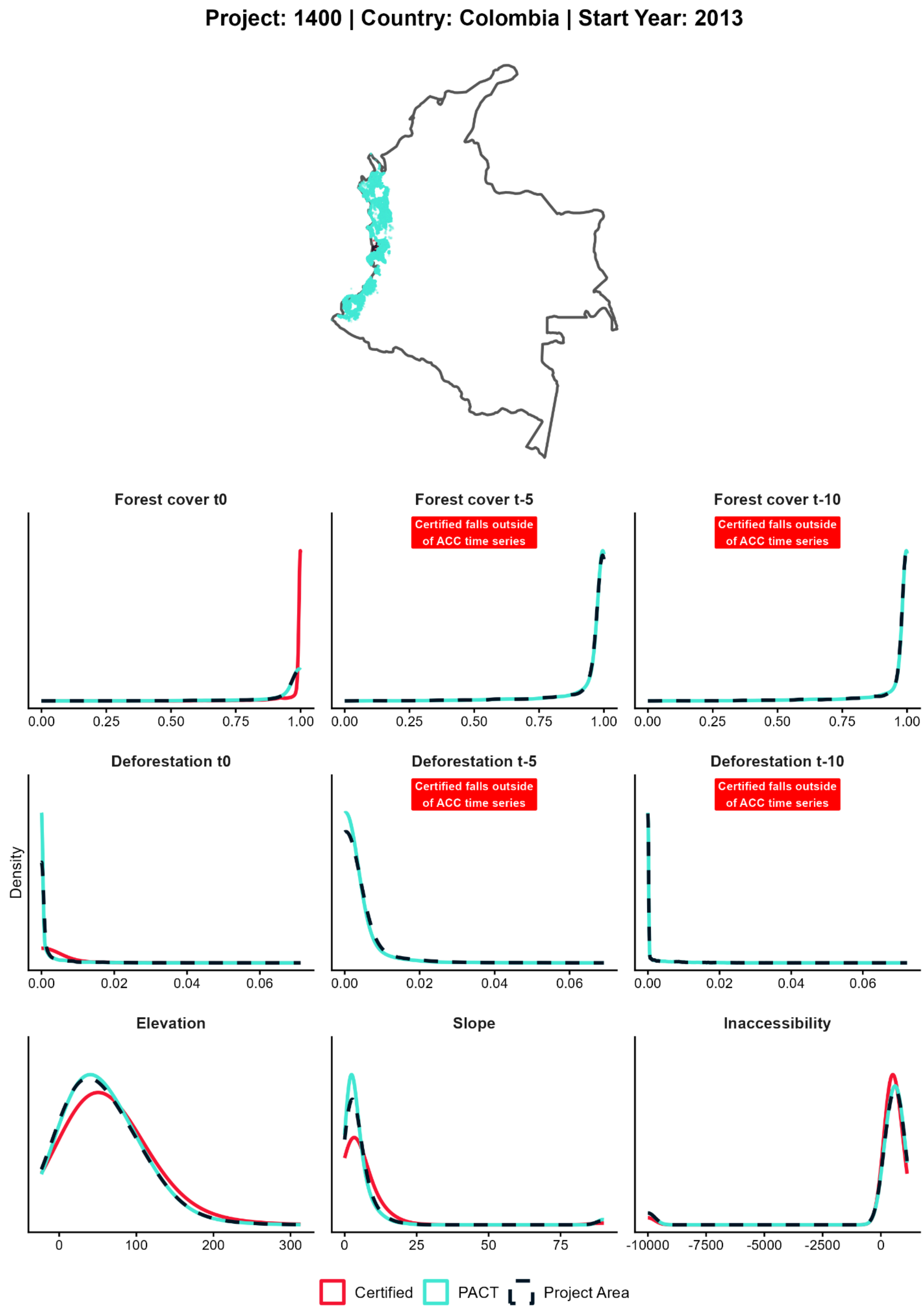

**Supplementary figure 13.** The location of the project, certified reference and PACT control areas, and differences in exposure to deforestation drivers for project 1115**.** Univariate frequency distributions contrast exposure to observable confounders which may influence deforestation. The timing of measurements is expressed relative to the project start year ($t_0$) for quasi-experimental control areas, or the start of the reference period for reference areas.



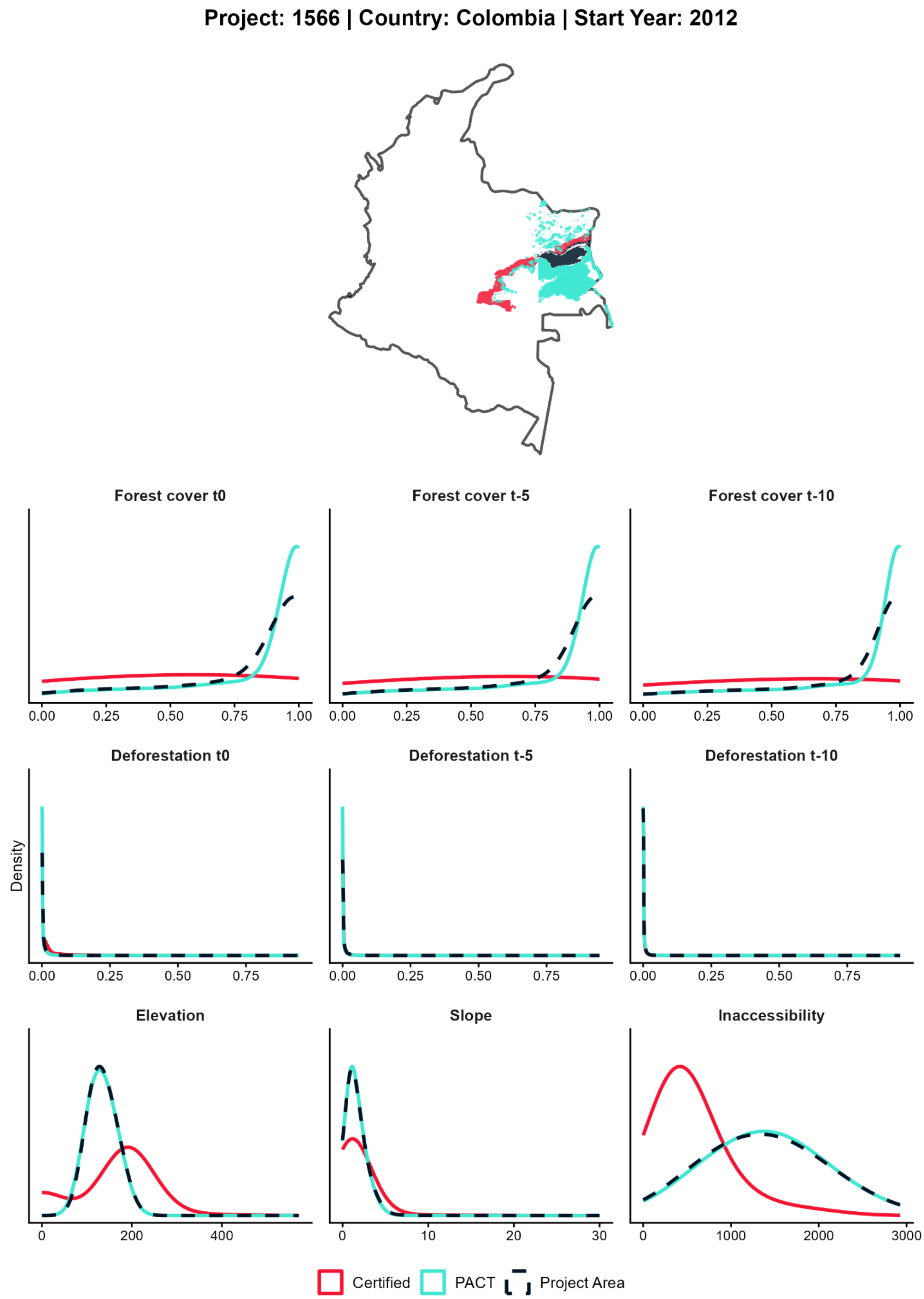

**Supplementary figure 14.** The location of the project, certified reference and PACT control areas, and differences in exposure to deforestation drivers for project 1201**.** Univariate frequency distributions contrast exposure to observable confounders which may influence deforestation. The timing of measurements is expressed relative to the project start year ($t_0$) for quasi-experimental control areas, or the start of the reference period for reference areas.



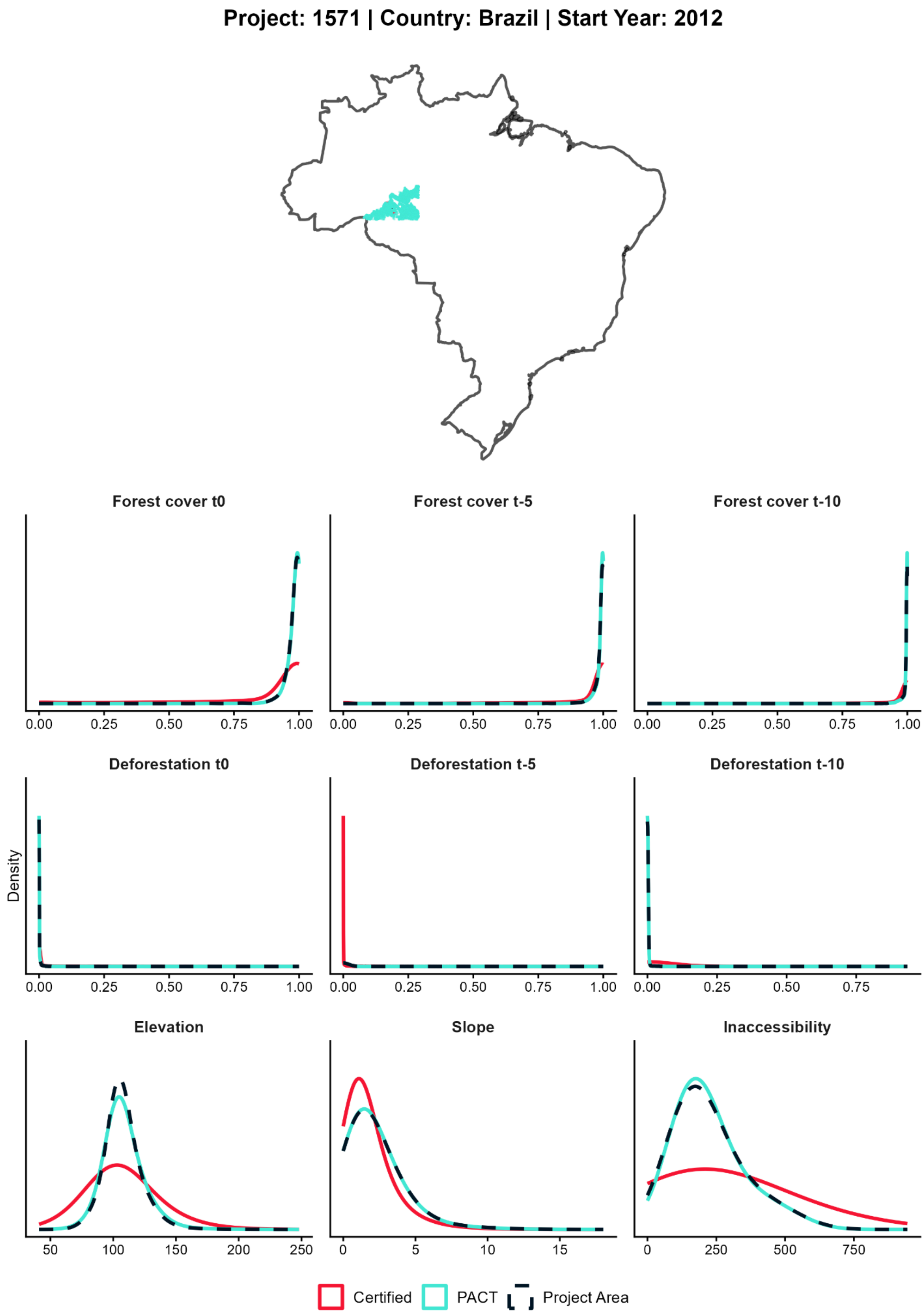

**Supplementary figure 15.** The location of the project, certified reference and PACT control areas, and differences in exposure to deforestation drivers for project 1329**.** Univariate frequency distributions contrast exposure to observable confounders which may influence deforestation. The timing of measurements is expressed relative to the project start year ($t_0$) for quasi-experimental control areas, or the start of the reference period for reference areas.



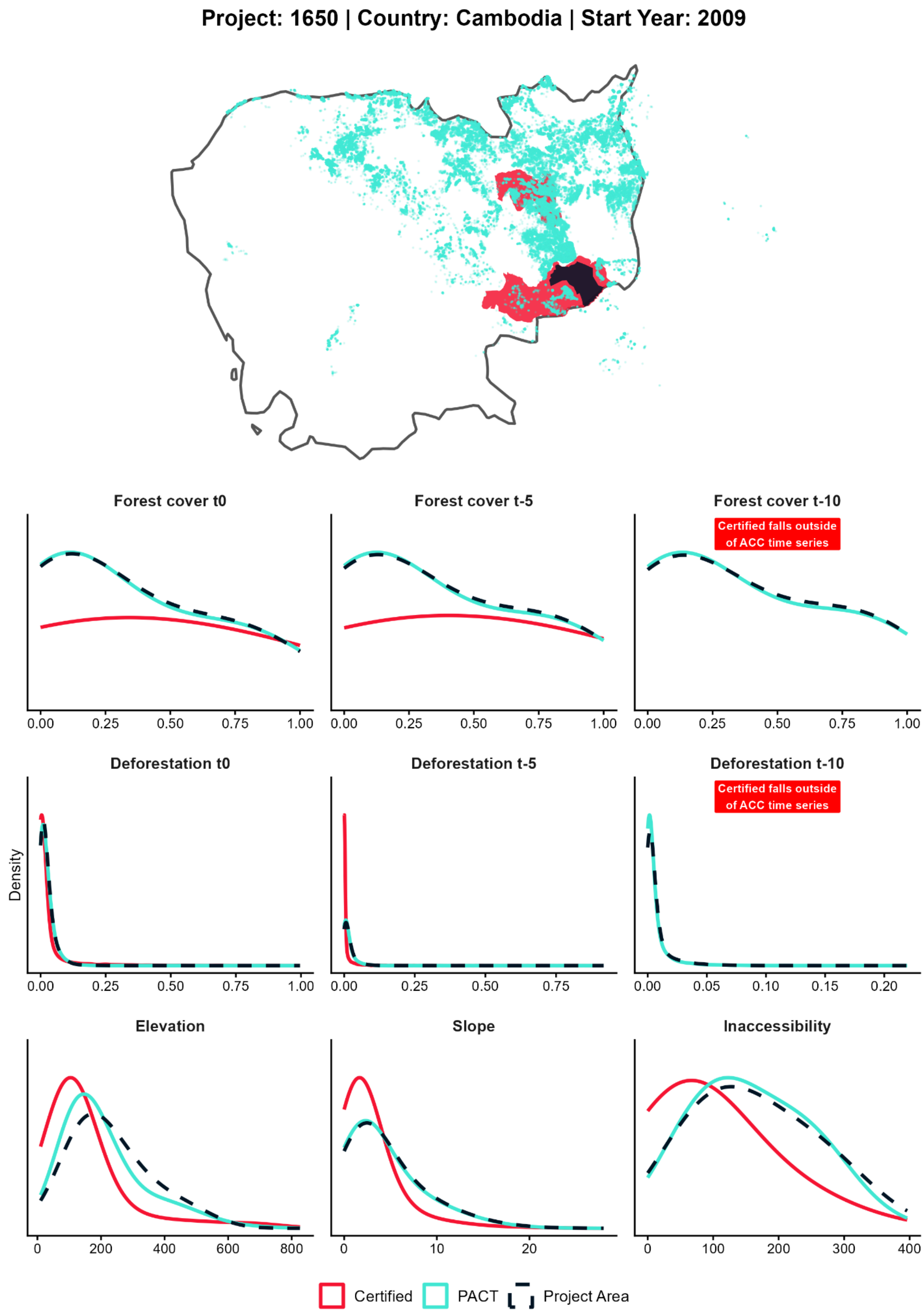

**Supplementary figure 16.** The location of the project, certified reference and PACT control areas, and differences in exposure to deforestation drivers for project 1400**.** Univariate frequency distributions contrast exposure to observable confounders which may influence deforestation. The timing of measurements is expressed relative to the project start year ($t_0$) for quasi-experimental control areas, or the start of the reference period for reference areas.



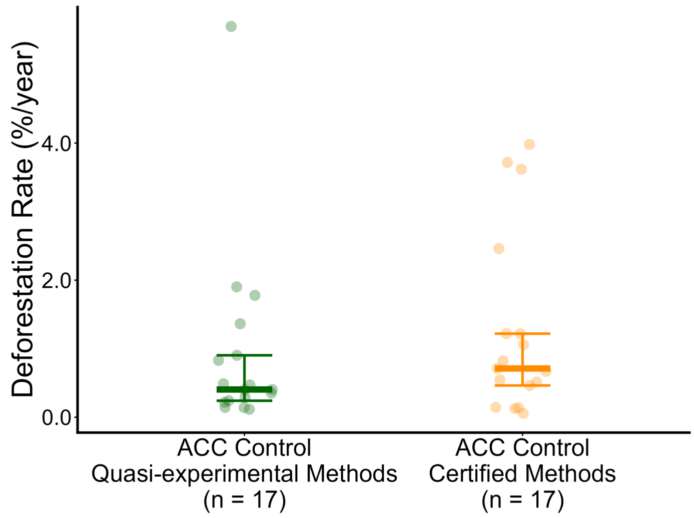

**Supplementary figure 17.** The location of the project, certified reference and PACT control areas, and differences in exposure to deforestation drivers for project 1566**.** Univariate frequency distributions contrast exposure to observable confounders which may influence deforestation. The timing of measurements is expressed relative to the project start year ($t_0$) for quasi-experimental control areas, or the start of the reference period for reference areas.



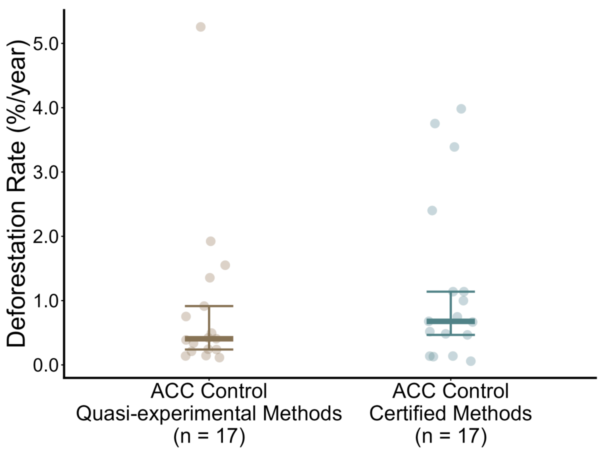

**Supplementary figure 18.** The location of the project, certified reference and PACT control areas, and differences in exposure to deforestation drivers for project 1571**.** Univariate frequency distributions contrast exposure to observable confounders which may influence deforestation. The timing of measurements is expressed relative to the project start year ($t_0$) for quasi-experimental control areas, or the start of the reference period for reference areas.



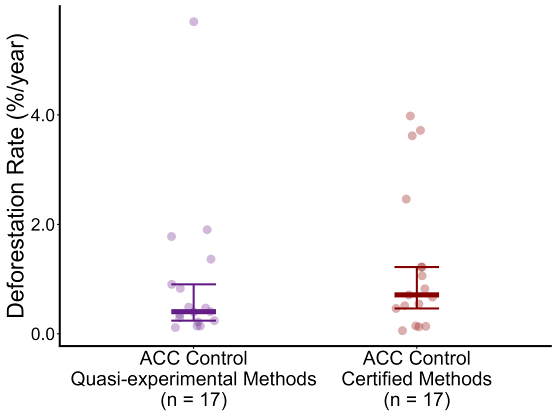

**Supplementary figure 19.** The location of the project, certified reference and PACT control areas, and differences in exposure to deforestation drivers for project 1650**.** Univariate frequency distributions contrast exposure to observable confounders which may influence deforestation. The timing of measurements is expressed relative to the project start year ($t_0$) for quasi-experimental control areas, or the start of the reference period for reference areas.



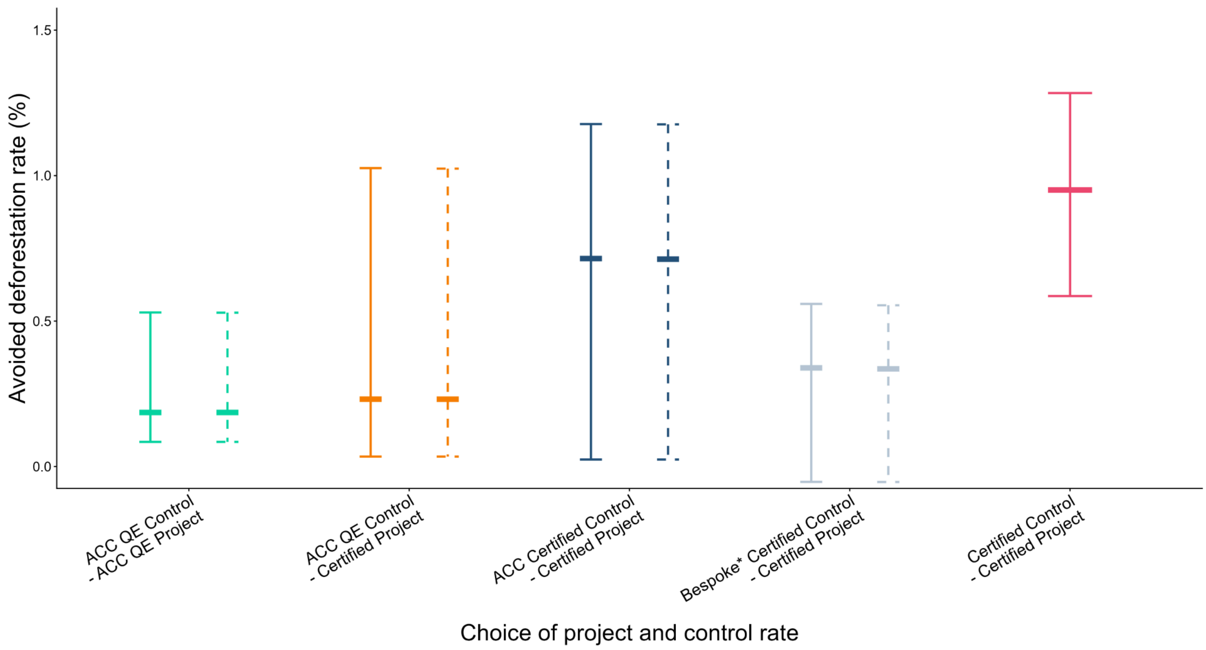

**Supplementary figure 20.** The remotely sensed deforestation rates in control areas when deforestation is defined as loss of undisturbed or degraded. Measuring deforestation as transitions: (1) from the undisturbed class to any other class, or (2) from the degraded class to the deforested class, had no effect on the median deforestation rate measured in quasi-experimental control areas, which remained at 0.41%/year, as presented in figure 4. In certified control areas deforestation rates increased from 0.69%/year in figure 4 to 0.71%/year. Error bars show the median and interquartile range.




**Supplementary figure 21.** The remotely sensed deforestation rates in control areas when deforestation is defined as loss of undisturbed or regrowth. Measuring deforestation as transitions: (1) from undisturbed forest to any other class, or (2) from the regrowth class to the deforested class, had no effect on the median deforestation rate measured in quasi-experimental control areas, which remained at 0.41%/year, as presented in figure 4. In certified control areas deforestation rates decreased from 0.69%/year in figure 4 to 0.68%/year. Error bars show the median and interquartile range.




**Supplementary figure 22.** The remotely sensed deforestation rates in control areas when deforestation is defined as loss of undisturbed, degraded or regrowth. Measuring deforestation as transitions: (1) from the undisturbed class to any other class, (2) from the degraded class to the deforested class, or (3) from the regrowth class to the deforested class, had no effect on the median deforestation rate measured in quasi-experimental control areas, which remained at 0.41%/year, as presented in figure 4. In certified control areas deforestation rates increased from 0.69%/year in figure 4 to 0.71%/year. Error bars show the median and interquartile range.




**Supplementary figure 23.** The avoided deforestation rates for the 17 projects in the main analysis (solid lines in Fig. 5) are compared with avoided deforestation rates that also include transitions from the regrowth class to the deforested class (dashed lines). Almost no differences were observed due to the very low proportion of regrowth pixels within projects. There is no bar for deforestation rates including regrowth for certified control - certified project, as this does not make use of the ACC layers. Error bars represent medians and interquartile ranges.

**Supplementary note 2.** Differences in avoided deforestation estimates produced by alternative certified modelling approaches.

For the first generation of REDD+ projects, there were several different certification methods available for estimating counterfactual deforestation. West, Bomfim, and Haya [2] applied the four most common Verra methods (Table 1 in the main text) to four projects to assess the sensitivity of avoided deforestation estimates in control areas to the choice of the four most common certification methods. Within these 4 methods, the impact of different modelling configurations was also explored: for VM0006 the forest scarcity factor was applied at two separate levels, and for VM0007 and VM0015 two different algorithms were used to develop spatial deforestation risk maps. This resulted in two estimates for each of these three methods. Thus, there were a total of eight separate estimates across the four methods, including the projects' certified estimate. Taking West, Bomfim, and Haya's estimates, we contrasted the outcomes of various certification methods against the distribution of different quasi-experimental results using t-tests.

$$p_{\mathrm{m}} = 1 - F_t\left(|t_{\mathrm{m}}|, df_{\mathrm{q}}\right) \qquad \text{Eq. 1}$$

$$t_{\mathrm{m}} = \frac{x_{\mathrm{m}} - \mu_{\mathrm{q}}}{\mathrm{SE}_{\mathrm{q}}} \qquad \text{Eq. 2}$$

We extracted the mean ($\mu_{\mathrm{q}}$) and standard error ($\mathrm{SE}_{\mathrm{q}}$) of quasi-experimental estimates of the avoided deforestation achieved by each of the four projects. Using these we calculated the one tailed t-scores ($t_{\mathrm{m}}$) of each certification method estimate ($x_{\mathrm{m}}$) against the quasi-experimental distribution. With these t-scores and the degrees of freedom allotted by the number of quasi-experimental findings for each project ($df_{\mathrm{q}}$) we calculated p-values for the estimates produced by each certified method ($p_{\mathrm{m}}$) across the respective cumulative probability function of the t-distribution ($F_t$). These p-scores represent the probability that an estimate produced by a certification method was significantly higher than the distribution of quasi-experimental findings (in other words a result that could be considered an example of over-crediting).

Modelling approaches produced a range of avoided deforestation estimates. Comparing these with the quasi-experimental estimates revealed that projects each could have produced a deforestation estimate within, or more conservative than, the distribution of quasi-experimental estimates. However, for 3 of 4 projects, modelling approaches generated estimates significantly higher than these distributions. For these projects, the method used for certification produced one of these higher estimates. As an example, 5 of the 8 possible estimates for Project 944 were similar to the distribution of quasi-experimental results (Table 2). Yet, the modelling approach chosen produced a significantly higher-than-probable ($t$ = 18.25, d.f. = 3, $p$ = 0.0002) estimate of 1777.7 ha/year of avoided deforestations (against the quasi-experimental mean of 139.1 ha/year). In the case of Project 1396, the only example where the certified estimate was not significantly different from quasi-experimental results, all possible alternatives fell within the quasi-experimental distribution.

**Supplementary table 2.** Modelling approaches, available under different certification methods, typically produced higher estimates of avoided deforestation than quasi-experimental methods, and projects used methods which produced improbably high estimates. Estimates of avoided deforestation (ha/year) for four projects, based on four quasi-experimental methods (QEM) applied by independent researchers, against the certified estimates used to produce credits, and alternative estimates from different possible certification methods by West, Bomfim and Haya[10]. The methods used are summarised in table 1. Significant differences between certified estimates and the mean and distribution of quasi-experimental results were assessed using t-tests, with *t*-scores reported. Estimates above the 95% confidence intervals for quasi-experimental method (QEM) results are shaded in grey, with significance indicated by * p<0.05, ** p<0.01, and *** p<0.001. No adjustment was made for multiple testing.

| **Method** | ***Project 934*** | ***Project 944*** | ***Project 1112*** | ***Project 1396*** |
|---|---|---|---|---|
| QEM n | 3 | 4 | 4 | 4 |
| QEM Mean | 180.8 | 139.1 | 78.4 | 378.6 |
| QEM 95% CI | -853.0 to 1214.6 | -13.3 to 291.5 | -13.1 to 170.0 | 1.1 to 756.1 |
| *Certified* Estimate | 4815.8 ** (T = 7.20, p = 0.0094) | 1750.4 *** (T = 17.68, p < 0.001) | 674.8 *** (T = 11.18, p < 0.001) | 1210.2 * (T = 3.74, p = 0.0167) |
| *VM0006-FSF-1* | -1589.2 (T = -3.06, p = 0.9539) | -48.1 (T = -2.11, p = 0.9370) | 2.1 (T = -1.53, p = 0.8882) | 54.6 (T = -1.46, p = 0.8794) |
| *VM0006-FSF-2* | -1691.6 (T = -3.23, p = 0.9579) | -107.9 (T = -2.76, p = 0.9650) | -6.5 (T = -1.69, p = 0.9054) | 39.6 (T = -1.52, p = 0.8876) |
| *VM0007-MLP* | 3185.3 * (T = 4.59, p = 0.0222) | -262.5 (T = -4.46, p = 0.9895) | 5415.8 *** (T = 100.74, p < 0.001) | 404.0 (T = 0.11, p = 0.4582) |
| *VM0007-SW* | 4123.2 * (T = 6.09, p = 0.0129) | 3062.2 *** (T = 32.10, p < 0.001) | 24.9 (T = -1.10, p = 0.8237) | 190.8 (T = -0.84, p = 0.7698) |
| *VM0009* | 519.3 (T = 0.32, p = 0.3903) | 7530.3 *** (T = 81.25, p < 0.001) | 77.1 (T = -0.11, p = 0.5414) | 179.7 (T = -0.89, p = 0.7815) |
| *VM0015-MLP* | 3140.8 * (T = 4.52, p = 0.0228) | -232.8 (T = -4.14, p = 0.9872) | 5153.6 *** (T = 95.78, p < 0.001) | 402.4 (T = 0.11, p = 0.4609) |
| *VM0015-SW* | 4077.8 * (T = 6.02, p = 0.0132) | 2779.3 *** (T = 28.99, p < 0.001) | 22.3 (T = -1.15, p = 0.8328) | 189.9 (T = -0.85, p = 0.7708) |

**Supplementary table 3.** Details of the calculation of avoided deforestation using the numbers extracted from the most recent VERRA monitoring reports for each project included in our assessment. Certified numbers were taken from the most recent monitoring reports or project design documents which are publicly available on the VCS search registry. Mean annual deforestation was calculated by summing the total deforestation across the years considered and dividing by the length of the monitoring period, calculated as the difference between the start and end year.

| Project ID | Start year | End year | Total certified counterfactual deforestation (ha) | Total certified project deforestation (ha) | Total certified avoided deforestation (ha) | Mean Annual Avoided Deforestation (ha/ yr) |
|---|---|---|---|---|---|---|
| 844 | 2009 | 2018 | 21,982.83 | 0.00 | 21982.83 | 2442.536 |
| 856 | 2010 | 2017 | 1,618 | 0.00 | 1618 | 231.1429 |
| 875 | 2009 | 2019 | 18391.23 | 2185.6 | 16205.63 | 1620.563 |
| 904 | 2008 | 2011 | 5,444.00 | 3,039.00 | 2405 | 801.6667 |
| 934 | 2011 | 2021 | NA | NA | 41889.19 | 4188.919 |
| 944 | 2009 | 2020 | 22,358.00 | 3,268.00 | 19555* | 1777.727 |
| 958 | 2010 | 2020 | 1,525.00 | 822.00 | 703 | 70.3 |
| 963 | 2011 | 2020 | 6,037.00 | 1,801.50 | 4235.5 | 470.6111 |
| 977 | 2009 | 2011 | 3,698.40 | 39.70 | 3658.7 | 1829.35 |
| 981 | 2009 | 2017 | 9681 | 1069 | 8612 | 1076.5 |
| 985 | 2009 | 2021 | 98134.45 | 1040.22 | 97094.23 | 8091.186 |
| 1047 | 2007 | 2012 | 7,090.00 | 3,080.00 | 4010 | 802 |
| 1067 | 2010 | 2020 | 11893 | 955.15 | 10993.02** | 1099.302 |
| 1094 | 2003 | 2017 | 5,469.02 | 1,895.02 | 3574 | 255.2857 |
| 1112 | 2012 | 2017 | 3,654.00 | 217.90 | 3436.1 | 687.22 |
| 1113 | 2012 | 2017 | 4788.6 | 349.6 | 4439 | 887.8 |
| 1115 | 2011 | 2019 | 5957 | 771 | 5186 | 648.25 |
| 1122 | 2009 | 2012 | NA | NA | 1908.542 | 636.1808 |
| 1201 | 2012 | 2019 | 9,105.00 | 194.00 | 8911 | 1273 |
| 1202 | 2009 | 2021 | 9327.44 | 80.60 | 9246.84 | 770.57 |
| 1215 | 2005 | 2013 | 10641 | 4643 | 5998 | 749.75 |
| 1218 | 2011 | 2020 | 2,658.68 | 207.30 | 2451.38 | 272.3756 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 1311 | 2008 | 2011 | 16,299.00 | 9,684.00 | 6615 | 2205 |
| 1326 | 2011 | 2020 | 8240 | 904.9258 | 7335.074 | 815.0082 |
| 1329 | 2012 | 2019 | 2175 | 25.25 | 2149.75 | 307.1071 |
| 1359 | 2009 | 2013 | NA | NA | 2786 | 696.5 |
| 1360 | 2010 | 2019 | 18260.6 | 9786.4 | 8474.2 | 941.5778 |
| 1382 | 2013 | 2021 | NA | NA | 38836.2 | 4854.525 |
| 1389 | 2013 | 2018 | 5354 | 2874 | 2480 | 496 |
| 1390 | 2014 | 2017 | 1954 | 472 | 1482 | 494 |
| 1391 | 2013 | 2017 | 3579 | 1120 | 2459 | 614.75 |
| 1392 | 2013 | 2017 | 4514.8917 | 890 | 3624.892 | 906.2229 |
| 1395 | 2013 | 2017 | 11,016.16 | 951.00 | 10065.16 | 2516.291 |
| 1396 | 2014 | 2017 | 2600 | 1618 | 982 | 327.3333 |
| 1399 | 2013 | 2017 | 1,954.00 | 472 | 1482 | 370.5 |
| 1400 | 2013 | 2017 | 2,878 | 816 | 2062.19 | 515.5476 |
| 1503 | 2013 | 2020 | 10103 | 5884 | 4219 | 602.7143 |
| 1566 | 2013 | 2019 | 82,444.00 | 3,904.10 | 78539.9 | 13089.98 |
| 1571 | 2013 | 2020 | 3968 | 227 | 3741 | 534.4286 |
| 1650 | 2010 | 2019 | 28304 | 6716 | 21588 | 2398.667 |
| 1686 | 2014 | 2021 | 3,847.16 | 1,004.04 | 2843.118 | 406.1597 |
| 1882 | 2013 | 2020 | 1,017.00 | 230.00 | 787 | 112.4286 |
| 1897 | 2017 | 2021 | 33,856.90 | 8,009.30 | 25847.6 | 6461.9 |
| 1900 | 2017 | 2022 | 24,641.30 | 1,111.40 | 20842 | 4168.4 |
| 2278 | 2018 | 2020 | NA | NA | 7207.22 | 3603.61 |

* Reported avoided deforestation is 465 ha larger than the difference between baseline and project deforestation. This is due to differences in the treatment of clouds in satellite imagery during different monitoring periods.

** Reported avoided deforestation is 55 ha larger than the difference between baseline and project deforestation. The reason for this is unclear.

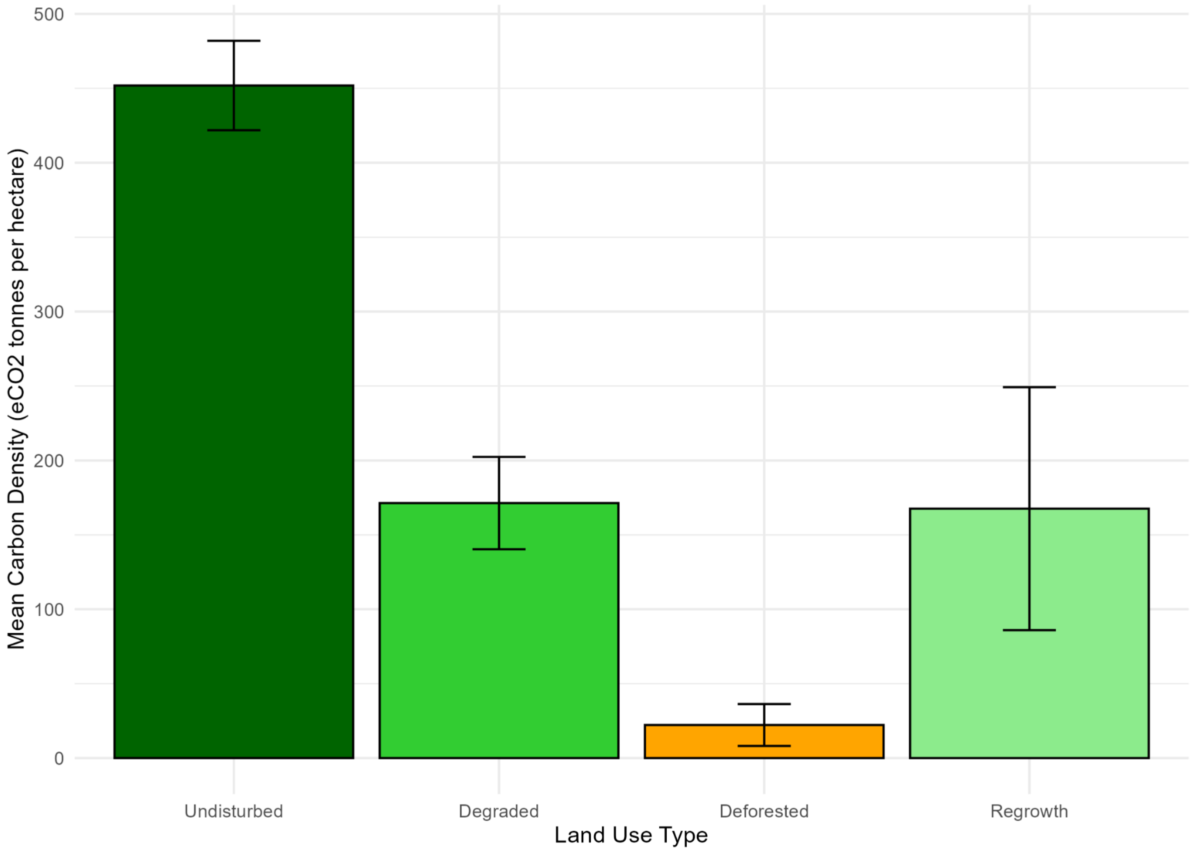
**Supplementary table 4.** Details of the calculation of avoided deforestation using the numbers produced by PACT for each project included in our assessment. Mean annual deforestation was calculated by summing the total deforestation across the years considered and dividing by the length of the monitoring period, calculated as the difference between the start and end year.

| Project ID | Start year | End year | Project Area (ha) | End Year ACC Undisturbed in Project (ha) | End Year ACC Undisturbed in Control Units (ha) | Total Avoided Deforestation (ha) | Mean Annual Avoided Deforestation (ha / yr) |
|---|---|---|---|---|---|---|---|
| 844 | 2008 | 2018 | 101764 | 91300.75 | 91027.61 | 273.1445 | 27.31445 |
| 875 | 2008 | 2019 | 73514.71 | 71043.43 | 63877.29 | 7166.136 | 651.4669 |
| 934 | 2010 | 2021 | 283332.7 | 225911.9 | 226927.3 | -1015.36 | -92.3051 |
| 944 | 2008 | 2020 | 179314.7 | 154773.8 | 152528.5 | 2245.265 | 187.1054 |
| 958 | 2009 | 2020 | 300000.2 | 283137.8 | 282709.7 | 428.0313 | 38.91194 |
| 963 | 2010 | 2020 | 36710.17 | 32268.74 | 32738.92 | -470.181 | -47.0181 |
| 977 | 2009 | 2011 | 194925.7 | 190851.7 | 190757.9 | 93.80071 | 46.90035 |
| 981 | 2008 | 2017 | 149416.6 | 136603.4 | 135564.4 | 1039.011 | 115.4457 |
| 985 | 2009 | 2021 | 1376941 | 1328742 | 1325342 | 3399.99 | 283.3325 |
| 1047 | 2007 | 2012 | 166280.3 | 135792.6 | 130019.1 | 5773.454 | 1154.691 |
| 1067 | 2010 | 2020 | 592500.1 | 559263.9 | 551662.4 | 7601.468 | 760.1468 |
| 1094 | 2002 | 2017 | 98533.15 | 94430.82 | 94592.23 | -161.406 | -10.7604 |
| 1112 | 2010 | 2017 | 43388.84 | 41956.75 | 41635.03 | 321.715 | 45.95929 |
| 1113 | 2010 | 2017 | 29574.87 | 27484.07 | 26903.51 | 580.56 | 82.93714 |
| 1115 | 2011 | 2019 | 77722.75 | 62981.33 | 62163.85 | 817.4765 | 102.1846 |
| 1118 | 2009 | 2017 | 257056 | 171882.2 | 183066.9 | -11184.7 | -1398.09 |
| 1122 | 2009 | 2012 | 653764.5 | 633607.2 | 633036.3 | 570.8616 | 190.2872 |
| 1201 | 2012 | 2019 | 71151.99 | 69093.47 | 67402.18 | 1691.295 | 241.6135 |
| 1215 | 2004 | 2013 | 399999.6 | 353864.1 | 346472.5 | 7391.635 | 821.2927 |
| 1311 | 2007 | 2011 | 433047.6 | 379874.6 | 371883.8 | 7990.79 | 1997.698 |
| 1325 | 2011 | 2013 | 68098.36 | 11.10584 | 10.21737 | 0.888467 | 0.444234 |
| 1326 | 2010 | 2020 | 9530.362 | 7340.2 | 6791.516 | 548.6845 | 54.86845 |
| 1329 | 2011 | 2019 | 30138.1 | 27624.99 | 23230.32 | 4394.667 | 549.3333 |
| 1359 | 2009 | 2013 | 187231 | 179930.6 | 178387.1 | 1543.475 | 385.8688 |
| 1360 | 2010 | 2019 | 131818.4 | 117101.6 | 120251.1 | -3149.42 | -349.935 |
| 1382 | 2013 | 2021 | 37698.2 | 36695.86 | 36834.6 | -138.733 | -17.3416 |
| 1390 | 2013 | 2017 | 142399.7 | 125050.2 | 121222.3 | 3827.924 | 956.9809 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1391 | 2013 | 2017 | 60142.42 | 56851.88 | 56796.01 | 55.86808 | 13.96702 |
| 1392 | 2013 | 2017 | 74893.16 | 69142.72 | 68850.33 | 292.3878 | 73.09694 |
| 1395 | 2013 | 2017 | 129318.8 | 123321.4 | 121508.2 | 1813.248 | 453.312 |
| 1396 | 2014 | 2017 | 85291.4 | 81134.43 | 80010.77 | 1123.659 | 374.5532 |
| 1399 | 2013 | 2017 | 9956.79 | 9540.3 | 9443.274 | 97.02574 | 24.25644 |
| 1400 | 2013 | 2017 | 73303.66 | 69221.32 | 68729.69 | 491.628 | 122.907 |
| 1503 | 2012 | 2020 | 103427.7 | 89579.41 | 91936.25 | -2356.84 | -294.605 |
| 1566 | 2012 | 2019 | 1359662 | 1171476 | 1164965 | 6511.406 | 930.2009 |
| 1571 | 2012 | 2020 | 74905.16 | 71789.92 | 64239.32 | 7550.601 | 943.8252 |
| 1650 | 2009 | 2019 | 180410.3 | 44613.79 | 32238.9 | 12374.89 | 1237.489 |
| 1686 | 2014 | 2021 | 190549.5 | 178282.1 | 183503 | -5221 | -745.856 |

**Supplementary table 5.** The $CO_2e$ (t) of each ACC land cover class as measured by GEDI in each project. To analyse the effect of different land use transitions within the ACC on carbon and above-ground biomass, we examined several different project areas (n =  using the densities pipeline of the PACT v2.1 Method. This entailed taking a 30 km buffer around the project area and sampling for the overlap with the GEDI AGB (tonnes/ha) readings taken in this buffered zone in the year 2020. Filtering for the high-quality readings, we then further reduced our sample to those shots that fell within 3×3 patches tiles of the same land-use class in the ACC raster layer for 2020. With these, we then took the median value for each land use class for each project. We then converted these AGB values to stored $CO_2$ equivalents ($CO_2e$) by first multiplying by 1.31 to account for belowground biomass (20%) and leaf litter (11%), then multiplying 0.47 to produce the mean carbon density, and finallying multiplying by 44/12 to produce the mean $CO_2e$, assuming all stored carbon would be oxidised to $CO_2$. It is worth noting that some projects were included in this analysis that were absent from the key queries of this study, primarily due to a lack of certified results for them. Project level GEDI derived $CO_2e$ densities are shown in the table below.

| Project ID | Undisturbed | Degraded | Deforested | Regrowth |
|---|---|---|---|---|
| 1047 | 389.28 | 235.26 | 65.28 | 101.87 |
| 1094 | 287.16 | 45.99 | 0 | 52.01 |
| 1112 | 402.51 | 246.96 | 0.02 | 200.93 |
| 1113 | 421.44 | 298.57 | 0.07 | 204.44 |
| 1115 | 597.41 | 137.8 | 43.88 | 21.49 |
| 1118 | 467.74 | 279.53 | 0.31 | 136.86 |
| 1122 | 623.17 | 188.73 | 17.04 | 136.09 |
| 1133 | 463.15 | 339.21 | 7.75 | 244.47 |
| 1201 | 479.62 | 89.88 | 45.77 | 65.75 |
| 1215 | 413 | 164.42 | 70.73 | 178.23 |
| 1311 | 377.77 | 148.93 | 52.02 | 85.42 |
| 1326 | 249.12 | 93.35 | 2.4 | 13.61 |
| 1329 | 262.07 | 120.99 | 0 | 8.96 |
| 1359 | 432.08 | 78.23 | 32.93 | 31.79 |
| 1360 | 403.27 | 219.63 | 1.33 | 103.33 |
| 1382 | 521.41 | 127.1 | 0 | 367.49 |
| 1390 | 341.19 | 4.43 | 0 | 1544.12 |
| 1395 | 344.94 | 44.91 | 7.17 | 96.5 |
| 1396 | 415.36 | 183.37 | 6.01 | 0 |
| 1399 | 512.95 | 290.86 | 0 | 309.9 |
| 1503 | 471.65 | 116.41 | 1.37 | 101.26 |
| 1566 | 308.2 | 189.42 | 0.13 | 98.07 |
| 1571 | 517.06 | 95.65 | 2.31 | 181.92 |
| 1650 | 493.03 | 316.46 | 49.72 | 178.28 |
| 1686 | 542.6 | 286.51 | 5.69 | 378.88 |
| 2502 | 519.54 | 178.62 | 1.15 | 235.27 |
| 2558 | 463.4 | 136.54 | 0.18 | 2.62 |
| 3141 | 478.08 | 250.89 | 0 | 238.6 |
| 3347 | 614.4 | 429.28 | 115.98 | 323.81 |
| 674 | 374.66 | 50.78 | 101.17 | 27 |
| 832 | 438.88 | 196.42 | 0.1 | 77.18 |
| 844 | 507.24 | 177.48 | 1.12 | 213.48 |
| 856 | 599.91 | 1.22 | 216.97 | 84.1 |
| 875 | 453.51 | 198.33 | 3.28 | 42.83 |
| 944 | 383.7 | 131.2 | 2.4 | 33.12 |
| 958 | 498.5 | 231.18 | 12.15 | 29.8 |




**Supplementary figure 24.** The mean carbon densities of each ACC forest and cover class as from GEDI across 39 projects. Error bars represent 95% confidence intervals. Both degraded and regrowth classes have a mean $CO_2e$ density < 50% that of the undisturbed class, which was a primary reason to focus on the loss of undisturbed forest in the main analysis.

**Supplementary table 6.** Details of the calculation of certified compound annual deforestation rates. The amounts of deforestation in ha were taken from figures published in project monitoring documents. The initial forest cover against which rates were derived was determined using the ACC for the start year of the project.

| Project ID | Exact Evaluation Period (years) | Project size (ha) | Percent Undisturbed at t0 (%) | Undisturbed Forest in Project at t0 | Certified Counterfactual Deforestation Rate (%/year) | Certified Project Deforestation Rate (%/year) |
|---|---|---|---|---|---|---|
| 875 | 10.003 | 71958.563 | 99.495 | 71594.899 | 2.925 | 0.309 |
| 944 | 12.005 | 178294.550 | 94.645 | 168746.092 | 1.177 | 0.163 |
| 958 | 10.805 | 296675.526 | 99.187 | 294263.524 | 0.048 | 0.026 |
| 963 | 9.616 | 35972.004 | 96.659 | 34770.064 | 1.964 | 0.552 |
| 985 | 12.405 | 1357783.248 | 99.395 | 1349574.226 | 0.607 | 0.006 |
| 1094 | 15.008 | 98929.399 | 99.372 | 98308.162 | 0.381 | 0.130 |
| 1112 | 6.797 | 42695.224 | 98.662 | 42123.877 | 1.326 | 0.076 |
| 1113 | 6.792 | 29110.718 | 96.864 | 28197.914 | 2.703 | 0.184 |
| 1115 | 8.671 | 78060.622 | 89.082 | 69537.589 | 1.028 | 0.128 |
| 1201 | 7.419 | 70222.601 | 99.668 | 69989.146 | 1.861 | 0.202 |
| 1392 | 4.132 | 74955.985 | 93.674 | 70214.202 | 1.596 | 0.308 |
| 1395 | 4.351 | 129259.792 | 97.986 | 126656.771 | 2.070 | 0.173 |
| 1399 | 4.518 | 9843.988 | 99.872 | 9831.405 | 4.786 | 1.083 |
| 1400 | 4.458 | 73137.379 | 96.313 | 70440.687 | 0.931 | 0.261 |
| 1566 | 7.000 | 1358183.321 | 89.551 | 1216270.549 | 0.998 | 0.046 |
| 1650 | 10.003 | 172871.023 | 40.240 | 69562.522 | 5.088 | 1.010 |
| 1047 | 5.003 | 144097.414 | 92.472 | 133249.242 | 1.087 | 0.466 |
| 1329 | 8.005 | 30175.894 | 96.006 | 28970.780 | 0.970 | 0.011 |
| 1390 | 3.926 | 140883.072 | 93.558 | 131807.032 | 0.380 | 0.091 |
| 1396 | 3.085 | 84963.637 | 98.877 | 84009.427 | 1.014 | 0.628 |
| 1571 | 7.603 | 73438.020 | 99.742 | 73248.888 | 0.730 | 0.041 |

**Supplementary table 7.** Comparison of compound annual deforestation rates in PACT counterfactuals, projects and certified reference areas measured using the ACC. Only 17 projects had certified reference area polygons from which to derive deforestation rates.

| Project ID | Compound PACT counterfactual deforestation (%/year) | Compound project ACC deforestation (%/year) | Compound certified reference area ACC deforestation (%/year) |
|---|---|---|---|
| 844 | 0.647 | 0.558 | NA |
| 856 | 0.332 | 0.465 | NA |
| 875 | 1.072 | 0.146 | NA |
| 904 | 5.883 | 2.384 | NA |
| 934 | 0.843 | 0.885 | NA |
| 944 | 0.438 | 0.310 | 0.740 |
| 958 | 0.158 | 0.156 | 0.843 |
| 963 | 0.559 | 0.712 | NA |
| 981 | 0.466 | 0.388 | NA |
| 985 | 0.141 | 0.121 | NA |
| 1047 | 2.005 | 1.174 | 3.959 |
| 1067 | 0.243 | 0.104 | NA |
| 1094 | 0.148 | 0.146 | 0.156 |
| 1112 | 0.252 | 0.140 | 1.252 |
| 1113 | 0.478 | 0.202 | 1.252 |
| 1115 | 0.784 | 0.637 | 0.537 |
| 1122 | 0.074 | 0.048 | NA |
| 1201 | 0.466 | 0.113 | 4.436 |
| 1215 | 0.633 | 0.381 | NA |
| 1311 | 1.426 | 1.037 | NA |
| 1326 | 2.291 | 1.677 | NA |
| 1329 | 1.900 | 0.236 | 2.643 |
| 1359 | 0.612 | 0.471 | NA |
| 1360 | 0.685 | 1.018 | NA |
| 1382 | 0.129 | 0.170 | NA |

| | | | |
|---|---|---|---|
| 1390 | 1.058 | 0.566 | 0.574 |
| 1391 | 0.242 | 0.183 | NA |
| 1392 | 0.147 | 0.060 | 0.141 |
| 1395 | 0.444 | 0.148 | NA |
| 1396 | 0.613 | 0.245 | 0.144 |
| 1399 | 0.408 | 0.209 | 0.507 |
| 1400 | 0.294 | 0.130 | 0.063 |
| 1503 | 1.175 | 1.280 | NA |
| 1566 | 0.266 | 0.187 | 0.762 |
| 1571 | 1.845 | 0.284 | 1.110 |
| 1650 | 5.709 | 2.949 | 3.691 |
| 1686 | 0.335 | 0.706 | NA |
| 1882 | 0.405 | 0.224 | NA |

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