

Action needed to make carbon offsets from tropical forest conservation work for climate change mitigation

Thales A. P. West^{1,2,*}, Sven Wunder^{3,4}, Erin O. Sills⁵, Jan Börner^{6,7}, Sami W. Rifai⁸, Alexandra N. Neidermeier¹, Gabriel Frey⁶, Andreas Kontoleon^{2,9}

¹ Environmental Geography Group, Institute for Environmental Studies (IVM), VU University Amsterdam, Amsterdam, The Netherlands

² Centre for Environment, Energy and Natural Resource Governance, University of Cambridge, Cambridge, United Kingdom

³ European Forest Institute (EFI), Barcelona, Spain

⁴ Center for International Forestry Research (CIFOR), Lima, Peru

⁵ Department of Forestry and Environmental Resources, North Carolina State University, Raleigh, USA

⁶ Center for Development Research (ZEF), University of Bonn, Bonn, Germany

⁷ Institute for Food and Resource Economics (ILR), University of Bonn, Bonn, Germany

⁸ ARC Centre of Excellence for Climate Extremes, University of New South Wales, Sydney, Australia

⁹ Department of Land Economy, University of Cambridge, Cambridge, UK

*Corresponding author: t.a.pupowest@vu.nl

Abstract

Carbon offsets from voluntary avoided deforestation projects are generated based on performance vis-à-vis *ex-ante* deforestation baselines. We examined the impacts of 26 such project sites in six countries on three continents using synthetic control methods for causal inference. We find that most projects have not significantly reduced deforestation. For projects that did, reductions were substantially lower than claimed. This reflects differences between the project *ex-ante* baselines and *ex-post* counterfactuals based on observed deforestation in control areas. Methodologies used to construct deforestation baselines for carbon offset interventions need urgent revisions in order to correctly attribute reduced deforestation to the projects, thus maintaining both incentives for forest conservation and the integrity of global carbon accounting.

Keywords: REDD+; Payments for environmental services; Deforestation; Synthetic control; Impact evaluation.

For nearly two decades, the performance-based payment mechanism for reduced carbon emissions from deforestation and forest degradation known as REDD+ has been under intense debate (1). While regulations and capacity for national REDD+ programs are still under development (2, 3), many stand-alone, voluntary REDD+ projects are operational worldwide (4). These projects intend to conserve forests through many activities, such as improved monitoring and enforcement, promotion of sustainable practices, and local stakeholder engagement, often funded by the commercialization of carbon offsets (each corresponding to 1 Mg CO₂ either removed from or not emitted into the atmosphere). In 2021, two-thirds of the 227.7 million offsets from the land use sector (excluding agriculture) traded in carbon markets, with a total value of USD 1.3 billion, originated from REDD+ projects (5).

Numerous policy discussions and initiatives focus on how to scale and integrate the carbon emission reductions claimed by voluntary carbon-offset projects, particularly from REDD+ activities, into climate policies and Nationally Determined Contributions (NDCs) reported to the UNFCCC (3, 6–8). However, there is little rigorous evidence on the contributions of these projects (9, 10), with some studies suggesting that many are associated with little or no actual emission reductions (11–17).

Carbon offsets from REDD+ projects are issued based on the comparison between the observed forest cover in the project areas and deforestation baseline scenarios expected to have been realized in the absence of REDD+, which are *de facto* unobservable (3, 17). Many project baselines are formed by extrapolation of historical deforestation averages or trends, often spatially projected over a reference region encompassing the project sites (17). These crediting baselines may become unrealistic counterfactuals with extensive changes in economic or political conditions known to affect deforestation rates (18), combined with questionable modeling decisions underlying the spatial projections (19, 20). Baselines could also be opportunistically inflated by profiteers seeking to maximize the volume of offsets issued by a project (21). As a result, carbon offsets may lack *additionality*, i.e., they may not reflect actual emission reductions (22).

This study provides a pan-tropical comparison between *ex-post* deforestation counterfactuals, informed by observable control areas, and the *ex-ante* baselines adopted by 27 voluntary REDD+ projects in six tropical countries: Peru, Colombia, Democratic Republic of Congo (DRC), Tanzania, Zambia, and Cambodia (Fig. 1, S1 & S2; Tables S1 & S2) certified under the Verified Carbon Standard (23). Because some projects are composed of multiple disconnected sites, we evaluate those individually, increasing our sample to 31 project sites. We present both project-specific and cross-project analyses based, respectively, on the standard and generalized versions of the synthetic control (SC) method for causal inference (24, 25), that estimate the reductions in deforestation in project sites attributable to the REDD+ interventions.

The SCs are constructed based on control areas (“donors”), selected from project-specific donor pools, which had similar levels of forest cover and other characteristics (Table S2), and were exposed to similar levels of deforestation pressure (as determined by comparing the average annual deforestation in the projects’ and donors’ 1-km and 10-km buffer zones prior to the project implementation). The SC method selects and constructs a weighted combination of control areas that has similar characteristics as the REDD+ site and follows a similar historical trajectory of deforestation (see SI for details). Before interpreting individual project results, we conducted project-specific “validation” tests to check whether the standard SC method (24) was able to construct SCs with similar deforestation rates as project areas during the immediate pre-project period (17). Conservatively, we focus the discussion of our results on projects with SCs that performed well in the validation test (Tables S3 & Fig. S5).

Average impacts were estimated with the generalized SC method (25) based on two independent sets of control areas. Furthermore, to address the concern that the selected control areas may not represent potential counterfactuals for REDD+ project sites, we also estimated average project impacts based on the comparison of operational project sites with “yet-to-become” project areas throughout the study period using the matching-based methods for time-series cross-sectional analyses (26). Because the evaluated projects span multiple countries and contexts, our analyses shed light on the robustness of the assumptions adopted for the construction of REDD+ baselines under a wide range of deforestation conditions (Fig. S2).

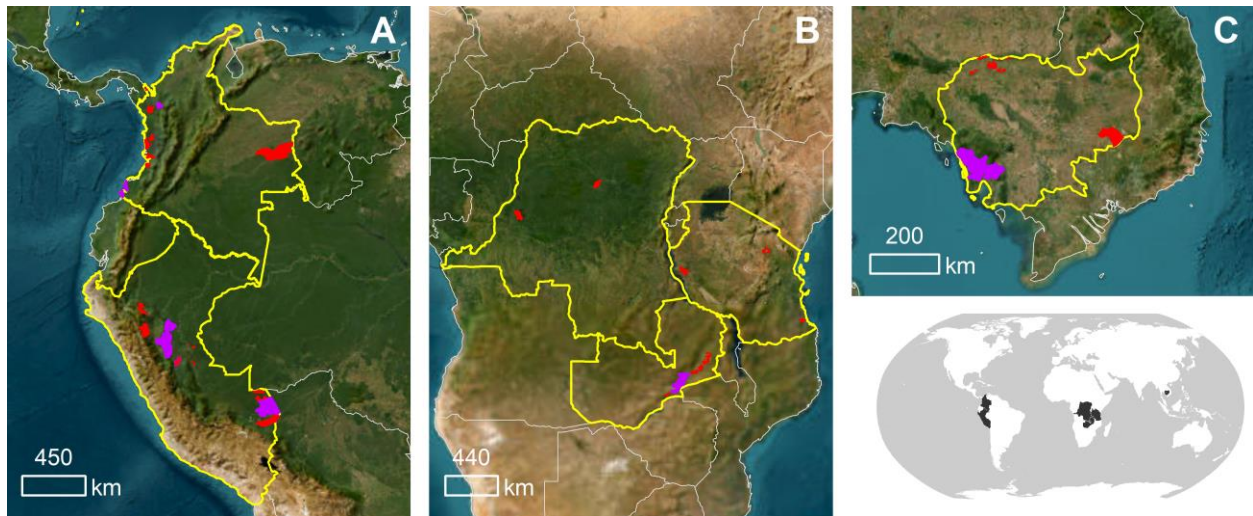


Fig. 1. Voluntary REDD+ project sites included in the study (red areas). Peru and Colombia (A), Democratic Republic of Congo, Tanzania, and Zambia (B), and Cambodia (C). Purple areas are the sites excluded from the analysis.

Individual REDD+ project impacts

The individual SC analyses show mixed impacts of the voluntary REDD+ projects on deforestation. Results from the validation tests suggest that the SC method could replicate pre-REDD+ deforestation trends in the “to-be” project sites (Tables S3 & Fig. S6). We discarded only one project (#1775-1) from the analyses due to the poor fit between the deforestation in the SC and the REDD+ site prior to project implementation in our validation test. Four other projects (#985, #1360-1, #1389, and #1748) were also discarded out of an abundance of caution because, despite the agreement in pre-project deforestation between the SCs and the REDD+ sites, their buffer deforestation rates suggested substantially different levels of deforestation pressure. Our final sample was thus reduced to 26 project sites.

Eight of the remaining 26 project sites showed some evidence of additional reductions in deforestation compared to their individual SCs (Fig. S7 & S8), although generally not to the extent claimed by the projects based on their *ex-ante* crediting baselines. Additionality was most likely in Peru, where half of the REDD+ sites had significantly less deforestation than the *ex-post* counterfactuals, with statistical significance judged by placebo tests. Three of the seven Colombian project sites, and one of two Cambodian sites, achieved significant deforestation reductions according to the SCs and placebo tests. No evidence of avoided deforestation was found for the REDD+ sites in the DRC, Tanzania, and Zambia vis-à-vis their counterfactuals.

Average REDD+ project impacts

Average project impacts on deforestation (i.e., average treatment effects on the treated; ATT) in Peru, Colombia, and Africa (DRC, Tanzania, and Zambia) were estimated with the generalized SC (GSC) method (Fig. 2, upper panels). Cambodian projects were excluded from this analysis due to the limited sample size. Unlike the individual project evaluations, the GSC analyses were based exclusively on annual deforestation rates and time-variant covariates. The GSC analyses were based on two independent sets of selected control areas for each region: in the first set, only the donors selected for the construction of the individual SCs were considered, whereas in the second

set, controls were selected based on cardinality matching (27), independent of the SC analyses. Our conclusions are robust to all of these methodological variations.

For the first set of controls, the average impact of the Peruvian projects on forest loss over ten years was -0.24% or avoided deforestation of 686 ha year^{-1} (Table S7). This effect was statistically significant in the first four years of project implementation (Fig. 2., lower panels). An ATT of -0.14% or 414 ha year^{-1} (Tables S8) was found for the African projects, whereas a smaller effect was associated with the Colombian projects (-0.03% or 49 ha year^{-1} ; Table S9). Neither the estimates for the Colombian nor the African groups of projects were statistically significant. Even assuming the estimated average reductions in deforestation to be significant in all three regions (a plausible assumption given our small sample sizes), they would still be substantially lower than avoided deforestation calculated based on the average *ex-ante* baseline deforestation rates adopted by the projects in Peru ($3661 \text{ ha year}^{-1}$), Colombia ($2550 \text{ ha year}^{-1}$), and Africa ($2700 \text{ ha year}^{-1}$) through 2020.

These results are robust to using control areas selected through cardinality matching. Based on our second control set, we estimate ATTs of the Peruvian, Colombian, and African REDD+ sites as -0.42% ($1266 \text{ ha year}^{-1}$), -0.01% (30 ha year^{-1}), and -0.21% (423 ha year^{-1}), respectively (Tables S10–S12 & Fig. S10, upper panel). Again, only the estimate for the Peruvian projects was statistically significant and only in the first four years of project implementation (Fig. S10, lower panels). While the estimated impacts in Peru were -0.18 percentage points larger compared to the first control set, the translated absolute average reduction still represents just one-third of the average reductions claimed by the Peruvian projects.

Finally, results from the analysis of already operational versus “to-become” project sites corroborate the findings from the GSC analyses. The average REDD+ impacts on deforestation ranged from $-0.01\% \text{ year}^{-1}$ to $0.12\% \text{ year}^{-1}$ (or $-113 \text{ ha year}^{-1}$ to 121 ha year^{-1}), across different model specifications, but the estimates were not significant in any of the regions (Fig. S14).

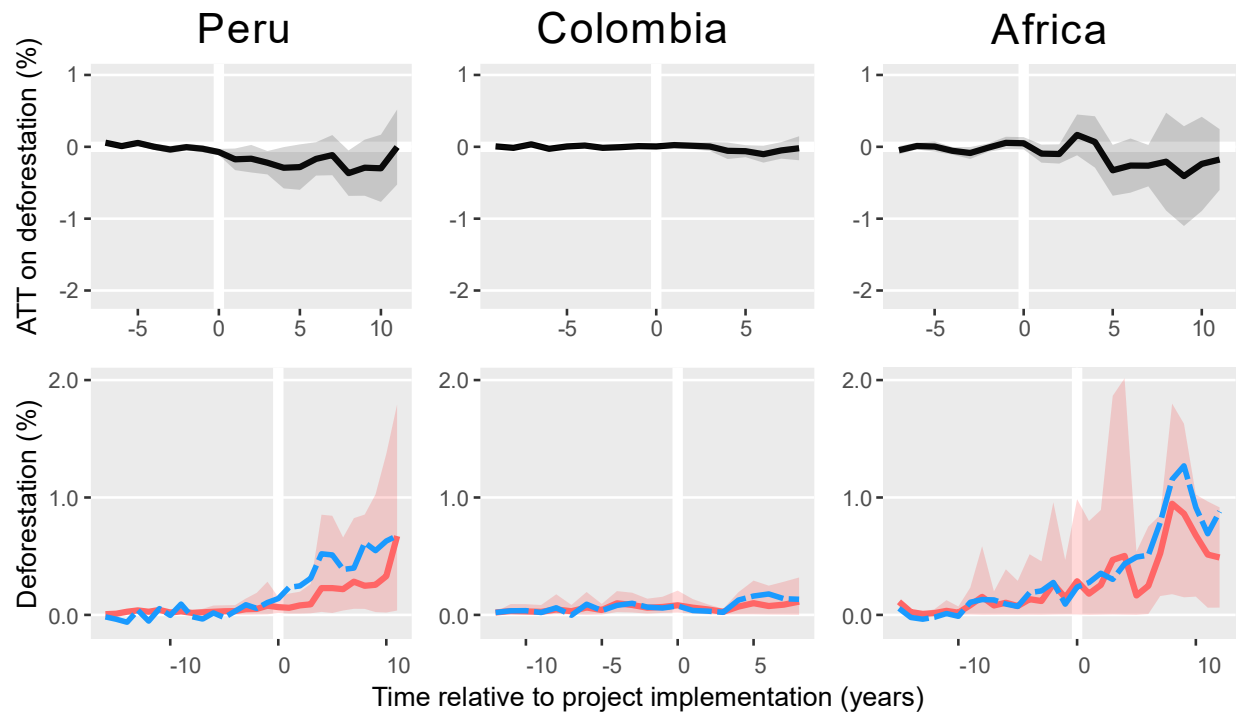


Fig. 2. Estimated average impacts of REDD+ projects in Peru, Colombia, and Africa on annual deforestation. Based on the generalized synthetic control (GSC) method and the donor pool of control areas selected for the individual project's synthetic controls. Upper panels display the average treatment effect on the treated (ATT) project sites. Lower panels display projects' (solid red line) and counterfactuals' (dashed blue line) deforestation averages. Shaded red areas represent bootstrapped 95% confidence intervals around the projects' deforestation average.

Carbon offset implications

We investigated the implications of our findings for the environmental integrity of the credits issued by the REDD+ projects. These implications are based on the 18 out of 26 projects with sufficient publicly available information about baseline deforestation rates (Fig. 3; Tables S5 & S6). Only one project baseline was lower than its SC (Project #958), and only one project baseline was similar to its SC (Project #1325). All other *ex-ante* baselines posited more deforestation than estimated *ex-post* based on SCs. According to the projects' *ex-ante* estimates, up to 89 million carbon offsets could potentially have been generated by these 18 REDD+ projects through 2020. Yet, 60.2 million of these offsets (68%) would have originated from projects that have not significantly reduced deforestation (and emissions) compared to their SCs. The remaining 28.8 million offsets (32%) would have originated from projects likely associated with some avoided deforestation, but not to the extent expected by the project developers. If we replace the *ex-ante* baselines adopted by the projects with the deforestation observed in the SCs, our estimates suggest that only 5.4 million (6.1%) of the 89 million expected offsets from the REDD+ projects would likely be associated with additional carbon emission reductions.

As of November 2021, those 18 REDD+ projects had issued 62 million carbon-offset credits (Table S4). Out of those, at least 14.6 million (24%) have already been used by individuals or organizations around the world to offset their greenhouse gas emissions. Thus, according to our SC-based estimates, these projects have already been used to offset almost three times more carbon

emissions than their actual contributions to climate change mitigation—with another 47.4 million carbon offsets being readily available in the market.

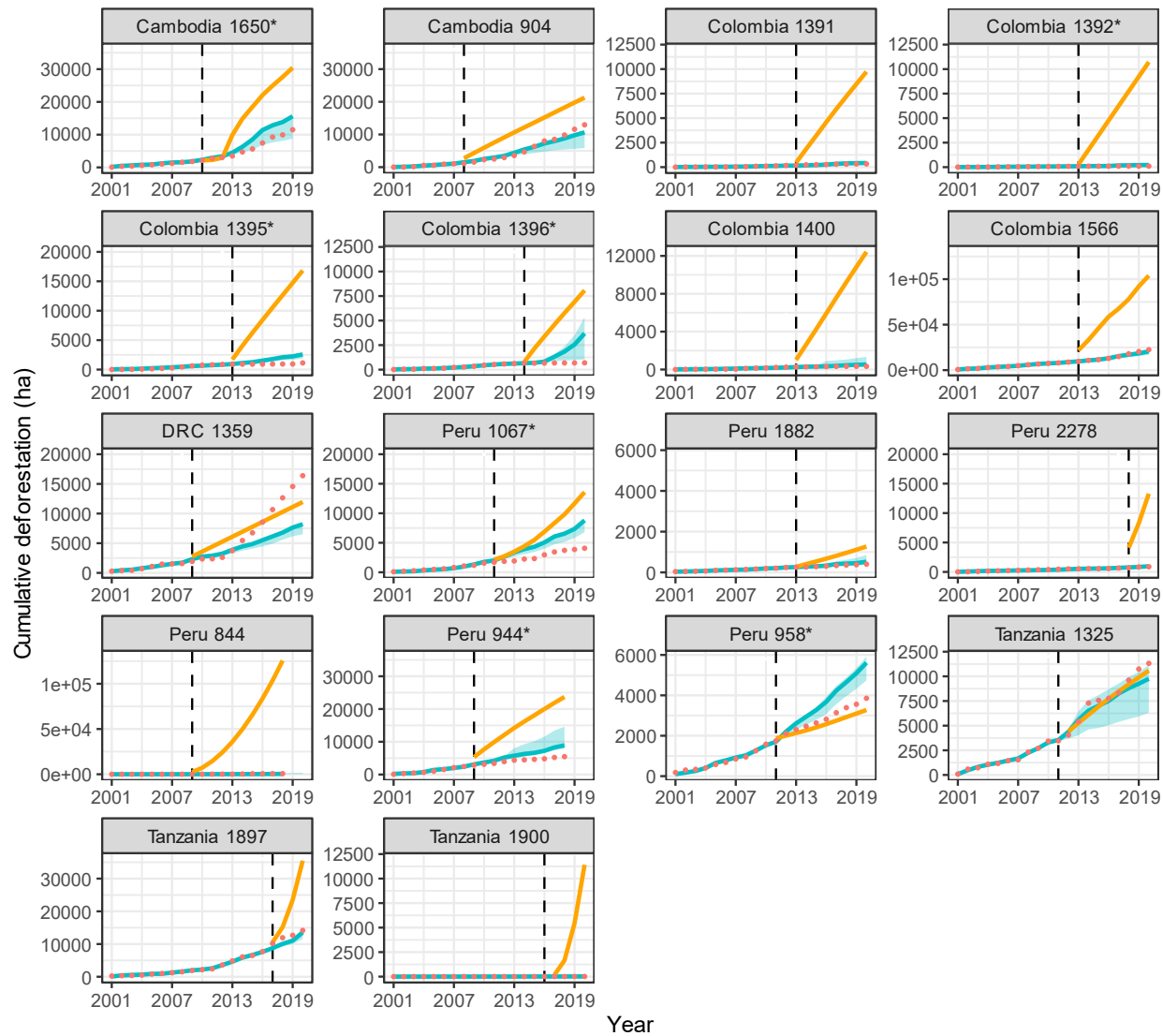


Fig. 3. Cumulative deforestation from the baseline scenarios adopted by the REDD+ projects (orange) versus observed cumulative deforestation in the synthetic controls (blue). Dotted red lines are the observed cumulative deforestation in the project sites. Dashed black lines indicate the project implementation year. Asterisks indicate a significant reduction in deforestation in the REDD+ site compared to the SC based on placebo tests (note: scales differ).

Discussion

Overall, the weight of evidence suggests that the voluntary REDD+ projects in our sample across six tropical countries achieved much less avoided deforestation than forecast by project developers. Only a minority of projects achieved statistically significant reductions in comparison to *ex-post* counterfactuals. Our findings corroborate prior studies questioning the additionality, and

thus environmental integrity, of carbon-offset interventions (11–17). *Ex-ante* baselines that exaggerate the deforestation that would occur without REDD+, likely facilitated by methodological flexibility in their construction and exacerbated by adverse site selection (14), are a major reason for the gap between offsets projected *ex-ante* and actual offsets estimated *ex-post*. Poor performance by the REDD+ projects (i.e., failure to *de facto* reduce deforestation) may also be a factor (21, 28).

In an evaluation of voluntary REDD+ projects in the Brazilian Amazon, West et al. (17) pointed to the potential confounding effect created by Brazil's post-2004 policy interventions to control deforestation, triggering a wide-spread reduction in forest loss between 2004 and 2012 (29). As a result, the high regional deforestation rates observed prior to 2004, used to inform the Brazilian project *ex-ante* baselines, likely led to an overestimation of the projects' performance. Yet, unlike Brazil, the six countries in this study did not experience a similar nationwide reduction in deforestation after the REDD+ projects were implemented (Fig. S3). Hence, the unrealistic *ex-ante* baselines adopted by many projects likely resulted from the use of methodologies that systematically fail to produce credible counterfactuals for the REDD+ interventions, compromising the evaluation of the projects' effect on mitigating deforestation and thus carbon emissions. This may be due to potentially four complementary reasons: poor foresight, adverse site selection, limited room for adjustments over time, and "gaming." First, projects may have (unintentionally) overestimated future deforestation pressures by following baseline methodologies heavily relying on the continuation of historical trends that no longer represent current conditions, often combined with problematic spatial deforestation projections (19, 30). Second, projects may have been preferentially sited where conditions are conducive to reducing deforestation and therefore where deforestation may have been lower than suggested by *ex-ante* baselines constructed from deforestation trends in the surrounding region (14). Third, rules adopted by certification standards require baselines to be fixed for a period of usually 10 years, restricting adjustments to reflect changes in deforestation drivers over time (23). Finally, flexibility in baseline methodologies may have been opportunistically exploited to maximize revenues from offset sales.

In contrast, both standard and generalized SC methods use pre-REDD+ information to identify control areas, but employ contemporaneous *ex-post* information on deforestation in the project and control areas to measure additionality. Following well-accepted guidelines for rigorous impact evaluation (31), if properly selected, such *ex-post* counterfactuals can capture the effects of contemporaneous changes in deforestation drivers, and thus are less likely to generate effect estimates confounded by external factors (10, 17). If REDD+ projects were to adopt a similar dynamic approach, it would likely reduce the additionality problems with project *ex-ante* baselines and offsets identified in this study.

Despite the clear advantages (from a causal inference perspective) of using *ex-post* methods such as SCs to construct deforestation baselines for REDD+ interventions, some implementation and monitoring challenges would likely arise from their adoption. First, given the biophysical heterogeneity of tropical regions, and limited data, ideal control areas for the project sites may not always exist or be possible to identify (Tables A1–A26). Second, those control areas could be manipulated (e.g., intentionally degraded or conserved) to misleadingly improve or reduce estimated project performance. Third, dynamic baselines may still fail to account for all relevant determinants of deforestation due to data constraints. Finally, long-lasting voluntary REDD+ projects may eventually outlive their SCs, as new interventions or other regime shifts occur in control sites.

One alternative would be to require projects to adopt transparent *ex-ante* jurisdictional baselines that are pre-established by government agencies. While these baselines might still fall short at demonstrating causal links and thus additionality, they could be both more transparent and updated more frequently than individual project baselines to reflect emerging deforestation pressures and spatial patterns. Reductions in deforestation relative to jurisdictional baselines would still have to be correctly attributed to either government efforts to control forest loss, or to private REDD+ interventions (10), in addition to changes in external deforestation drivers (e.g., agricultural commodity prices). Transferring the responsibility of baseline construction from project developers to jurisdictions could reduce the room for “baseline gaming,” although the risk of adverse site selection would remain (14). On balance, nesting voluntary projects into subnational jurisdictions appears to be a promising future pathway for REDD+, a practice that is gaining traction globally (6). However, the specifics of implementation are crucial and require careful consideration.

Another possible explanation for limited additionality is poor performance by the projects. This would be likely if projects were failing to control deforestation in project areas. We observe generally low deforestation rates in project areas, but we cannot compare that to the projects’ targeted deforestation rates in those areas because those are not always reported in the publicly available information on projects. However, it is clear that some projects have struggled with on-the-ground implementation and execution of envisioned conservation activities; others may have promoted ineffective actions, whether due to funding uncertainties, slow commercialization of carbon credits, lack of experience, or poor management (21, 28, 32). Notably, many projects claimed to have started much earlier than the year they were certified. While this allows projects to issue and sell retroactive offsets immediately after certification (33), it also implies that they did not have had access to carbon funding during their initial years, potentially compromising the execution of planned conservation actions.

A recent evaluation on the effectiveness of the same type of REDD+ interventions reported significant reductions in average deforestation rates (34). The study, based on satellite pixel matching, estimated an average deforestation rate of 0.2% year⁻¹ in the REDD+ sites versus 0.4% year⁻¹ for their matched control areas. The size of these estimates is similar to some of our estimates from GSC analyses; but in our case, they were statistically insignificant, potentially due to our smaller sample sizes compared to the pixel-based samples from the previous study. More importantly from the offsetting perspective, the average reductions—significant or not—are substantially lower than the additional reductions in deforestation projected and claimed by the projects.

Our study provides further evidence on the effectiveness of voluntary REDD+ projects and questions their *de facto* additionality (35). Only a minority of the projects significantly reduced deforestation in the project areas compared to the *ex-post* counterfactuals, and even those did not reduce deforestation to the extent claimed. While REDD+ payments are typically conditioned on performance in project areas, only the offsets associated with additional reductions in deforestation relative to a counterfactual genuinely offset emissions of potential buyers in the voluntary carbon markets (7, 21). Certification schemes are allegedly in place to safeguard the additionality of offsets, but our results indicate that currently approved methodologies do not guarantee additionality. It is critical to develop new and rigorous methods for the construction of credible deforestation baselines for voluntary REDD+ interventions, and to properly and regularly assess their contribution to climate change mitigation.

Finally, the evidence from this and other studies indicates that some voluntary projects have effectively reduced deforestation (34), particularly in Peru. For REDD+ to be scaled and achieve its ambitious goals worldwide, it is paramount that we better understand the factors that drive both mitigation performance and impacts on local communities. Building on this knowledge, practitioners and policy makers must form effective partnerships to help REDD+ fulfill its original promise.

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Supplementary Materials for

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Thales A. P. West, Sven Wunder, Erin O. Sills, Jan Börner, Sami W. Rifai, Alexandra N.
Neidermeier, Gabriel Frey, Andreas Kontoleon

correspondence to: t.a.pupowest@vu.nl

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Materials and Methods

Project sample

As of July 2021, there were 27 voluntary REDD+ projects seeking to avoid unplanned (illegal) deforestation in Peru, Colombia, DRC, Tanzania, Zambia, and Cambodia that were certified under Verra's Verified Carbon Standard (VCS; Verra, 2019) (Table S1; Fig. 1, S1 & S2). We chose these six countries for two main reasons: (i) with the exception of Brazil and Indonesia, they had the largest numbers of projects with the necessary publicly available information for us to conduct impact evaluations and (ii) they provide coverage of all tropical continents. Brazil and Indonesia were excluded because most of the Brazilian REDD+ projects were already evaluated in a previous study (1), whereas all Indonesian projects claim credits based on avoided planned (legal) deforestation.

We adopted VCS' unique IDs to identify the projects in our study. Because Project 1360 from Peru is composed of three disconnected sites, each of these sites was evaluated independently (identified with IDs 1360-1, 1360-2, and 1360-3). We adopted the same approach for Project 1775 from Tanzania. Project sites were defined by the geospatial polygons (KML files) provided by the project developers and available from the VCS project database (<https://registry.verra.org/>). While we intended to examine all VCS-certified projects in our focal countries, we removed projects lacking geospatial data or with corrupted KML files on their boundaries (i.e., Projects #868 from Peru and #1399 and #1695 from Colombia). Overall, officially reported project areas matched the areas of the KML files reasonably well, except for Project #1566 from Colombia and #1325 from Tanzania (Table S1).

Deforestation baselines adopted by these projects followed VCS-approved methodologies for REDD+ interventions (Table S1). While there are differences among these methodologies, they generally require baselines to be established *ex-ante* based on historical regional deforestation averages or trends (typically from reference regions that encompass the project sites), observed over 10-year intervals prior to project implementation. Baseline deforestation trends can be forecasted with linear or non-linear regression models (e.g., logistic regressions). In addition, while some methodologies proportionally apply the estimated baseline deforestation rate to the project areas, others rely on a spatial allocation procedure where the regional baseline rates are annually allocated across the project's reference region; the project's baseline is then set as the amount of deforestation that was allocated within project boundaries. Both the spatial allocation and the historically-informed forecasting of baseline rates (particularly from logistic regression models) can substantially influence, and potentially overestimate, the project's baseline scenario.

Individual synthetic control analyses

Impact evaluations that define causality based on potential outcomes rely on the establishment of credible counterfactuals quantifying what would have happened in the absence of an intervention. These counterfactuals are inherently unobservable. The most common strategy for establishing robust counterfactuals is to observe outcomes in control areas, which are not exposed to the treatment under evaluation, but which are otherwise very similar to those areas (2). Following West et al. (1), we employed the synthetic control (SC) method to construct project-specific weighted combinations of control areas to serve as counterfactuals for the REDD+ project sites (3–5). We adopted this method due to our

small sample size and likely heterogeneous effects of voluntary REDD+ projects (5). SCs were constructed as a weighted average of control areas through a nested optimization procedure that minimizes the differences in pre-REDD+ characteristics of the project sites and their respective SCs. The characteristics of the control areas (i.e., model covariates; Table S2) are weighted such that the resulting weighted average outcome of the selected areas most closely matches the cumulative pre-REDD+ deforestation rates in the project sites since 2001. The individual SC analyses were conducted with the *Synth* package (3), v.1.1-5, available for R software (v.4.1.0). Results from the nested optimizations were refined based on the augmented method proposed by Becker and Klößner (6).

One of the key challenges with counterfactual-based impact evaluation is defining and characterizing potential controls, in our case, areas that could have been but are not REDD+ projects. West et al. (1) defined potential controls as property polygons obtained from Brazil's national Rural Environmental Registry (CAR; Portuguese acronym), a spatially explicit database created to determine forest restoration requirements. However, similar cadastral databases are not available for the countries considered in this study. We addressed this limitation by creating a pool of 1000 circular spatial polygons for each project, representing potential control areas (or "donors"). These areas are randomly distributed across the focal countries and have the same size as the project site (Fig. S3).

Prior to the construction of the SCs, we subset the donor pools to donors with levels of deforestation in their 10-km buffer zones similar to the deforestation observed in the project sites' 10-km buffer zones. These levels of deforestation were calculated as the average annual deforestation in the 10-km buffer zones observed from 2001 to the project start year and are used as a measure of deforestation pressure. We first attempted to include donors with $\pm 10\%$ buffer deforestation as the project sites. We increased this range by an additional $\pm 10\%$ each time the SC optimization failed to identify a feasible solution (6) or whenever the SC failed to replicate the historical deforestation pattern in the project site (and achieve reasonable covariate balance between the SC and project site). This approach was of critical importance because, unlike in West et al. (1), many of the projects' KML files from our sample were restricted to the forested areas within the project site at the start of project. Hence, without explicitly controlling for deforestation pressure surrounding the KML boundaries, the SCs could potentially be based on control areas exposed to much lower risk of deforestation, rendering them poor counterfactuals for the REDD+ sites (7). Overall, most SCs experienced similar levels of buffer deforestation as the REDD+ sites (see Annex A for the covariate balance between projects and SCs).

To construct the SCs, we used covariates (listed in Table S2) related to deforestation (8). We also included pre-REDD+ annual and post-2000 cumulative deforestation rates for the construction of the SCs. Annual deforestation data for the focal countries, from 2001 to 2020, were processed in Google Earth Engine based on the Global Forest Change (GFC) product (9). Many remote sensing studies highlight the differences in deforestation rates detected by GFC and officially recognized by governments (10–12). Such differences emerge from different mapping methodologies and definitions of deforestation and forest degradation. We use the GFC data for consistency across countries. Since the GFC data is used to map deforestation rates both inside the project sites and in the control areas, both before and after project implementation, it is reasonable to use this database to estimate REDD+ impacts in all study countries. Moreover, we inspected each donor area selected for the construction of the SCs. We found that deforestation in four of them (out of 86)

seemed to “flatten out” after 2011, potentially as a result of recent improvements in the GFC mapping methodology.¹ These donors were removed and new SCs were constructed for those project sites. Deforestation trends in the donor areas ultimately used for the construction of the SCs (Figure S4) are displayed in Figure S5.

Given the volatility of deforestation time series, we conducted an additional analysis to check the sensitivity of the individual SCs to changes in the donor pool. This was performed by randomly sampling 80% of each project’s donor pool and using those sampled pool to construct an alternative SC 100 times for each project site. We discarded alternative SCs with mean squared prediction error (MSPE) more than 50% higher than of the MSPE of the project’s “main” SC (i.e., the SC based on 100% of the project’s donor pool). We then computed “possibility intervals” based on the minimum and maximum deforestation ranges across all of the remaining SCs for each project site (Fig. 3 & S7).

Synthetic control method: “proof of concept”

We “validated” the use of SC method following West et al. (1), by constructing a SC for each project site based on data only from the first half of the pre-REDD+ period (i.e., training interval) and validating against the second half of the period (i.e., testing interval). In theory, the validity of the method would be empirically proven if the future REDD+ sites and their respective SCs shared a similar deforestation trend in the testing interval. This validation approach focuses on each REDD+ site individually. We considered the SC method validated for the sites in which the gaps between the project and SC deforestation at the end of the validation interval were lower than 0.5% of the project area (Tables S3 & Fig. S6). This “proof of concept” differs from standard model validation practices because the donors selected to compose the SCs based on the first half of the pre-REDD+ periods are not necessarily the same donors selected when the full pre-REDD+ period is used to evaluate the project impacts. Still, passing this test, along with the computation of the “possibility intervals,” arguably increases the credibility of the SC analysis for these sites.

Placebo tests

We assessed the statistical significance of our findings for individual projects with a series of placebo tests, in which we create SCs for all areas in the project-specific donor pool subsets and compute the difference in cumulative deforestation between each placebo and its SC in the years after that REDD+ project was implemented. Because placebo areas are not exposed to REDD+, any differences in forest loss between placebos and their SCs are considered statistical “noise.” Following the previous literature (1, 3), we discarded placebo tests with MSPE five times higher than the MSPE of its respective REDD+ project. We then used the gaps in deforestation between the remaining placebos and their respective SCs to create 95% confidence intervals around the mean placebo effect, which was generally close to zero as expected (Fig. S8). Estimated impacts that fall outside this 95% confidence interval are considered statistically significant.

Additionality of the carbon offsets

We estimated the volume of (additional) carbon offsets from the voluntary REDD+ projects by comparing observed deforestation in the project polygons to observed deforestation in the SCs. To calculate avoided carbon emissions due to reduced

¹ <https://storage.googleapis.com/earthenginepartners-hansen/GFC-2021-v1.9/download.html>

deforestation and compare those to carbon offsets issued by the project, we used information from official project documents. Credits from these projects are generally issued after third-party audits. These credits are based on the estimated carbon emission reductions from the avoided deforestation due to project activities, calculated as the net difference between the carbon emissions under the crediting baseline and the carbon emissions from observed deforestation in the project area (1). Under this crediting system, the *ex-post* volume of carbon offsets generated by the REDD+ projects is determined by *ex-post* deforestation in the REDD+ project as compared to the *ex-ante* crediting baseline. Due to project data constraints, we employed a simplified approach to estimate such volumes by assuming a linear, per-hectare relationship between the baseline deforestation adopted by projects and their reported *ex-ante* volume of credits to be generated through 2020. Projects with insufficient public information about *ex-ante* annual baseline deforestation rates were excluded from this additionality assessment (Tables S4 & S5; Fig. 3).

First, we identified projects that had a statistically significant impact at reducing deforestation based on the placebo tests. Projects that failed to achieve significant reductions in deforestation were assumed not to have reduced net carbon emissions. Then, we estimated the net reduction in deforestation achieved by each project that significantly reduced deforestation based on the difference in observed deforestation (ha) between the SC and the project areas. Finally, we estimate the volume of (additional) offsets generated by each project by multiplying the net deforestation reduction (ha) in each project by the per-hectare number of *ex-ante* offsets associated with the avoided deforestation of one hectare in each project area. The per-hectare number of *ex-ante* offsets was calculated based on the total number of *ex-ante* offsets reported by the project proponents divided by the reported *ex-ante* baseline deforestation through 2020 (Tables S4 & S5; Fig. 3).

Generalized synthetic control analyses

Standard applications of the SC method consider individual interventions (4, 5), which limits the generalization of results. The method developed by Xu (13) is a generalization of the SC method, unified with a special case of the difference-in-differences estimator for causal inference in time-series cross-sectional data that relaxes the parallel trends assumption. This method is known as the generalized synthetic control (GSC). First, an interactive fixed-effects model is estimated based solely on the control group data, and a fixed number of latent factors (i.e., time-varying intercepts) is selected. Then, factor loadings (i.e., unit-specific intercepts) are estimated for each REDD+ project based on the linear projection of pre-REDD+ deforestation rates. This formulation allows for the estimation of the average treatment effect on the treated unit (ATT), which in our case, corresponds to the average relative REDD+ impact on deforestation (% year⁻¹) across the project sites within a country or region. Last, the estimated latent factors and loadings are used to create GSCs, which in our case are the projects' average deforestation counterfactuals.

We adopted the GSC method as a way to generalize and estimate the average effect of REDD+ projects in countries (Peru and Colombia) and regions (Africa) with relatively large numbers of projects implemented. In addition, because the GSCs are independent of the individual SCs—and based on annual, rather than cumulative, deforestation rates—they also serve as robustness checks of the individual SC results. Following Xu (13), we

adopted Equation 1 as the underlying interactive two-way fixed-effects model of our GSC analyses:

$$D_{it} = \delta_{it}T_{it} + X_{it}\beta + \lambda_i f_t + \varepsilon_{it} \quad (1)$$

where, D_{it} is the annual deforestation in project site i in year t ; T_{it} is a dummy variable indicating project implementation (from 1 to time T); δ_{it} captures the heterogeneous REDD+ effect on unit i at year t ; X_{it} is a matrix of observed time-variant covariates, i.e., precipitation and deforestation in 1-km and 10-km buffer zones (results from augmented Dickey-Fuller tests suggest stationarity of the deforestation time series at the unit level); β is a vector of unknown parameters; λ_i is a vector of unknown factor loadings; f_t is a vector of unobserved common latent factors; and ε_{it} represents unobserved idiosyncratic shocks with zero mean [see Xu (13) for details on the GSC framework and the ATT calculation].

The GSC analyses were implemented with the *gsynth* package (v.1.2.1) available for R software. The package allows for several different specifications. Estimates were produced with the Expectation Maximization algorithm (14), which benefits from the project area information in the pre-REDD+ period. Due to the relatively low number of observations in our data, we adopted the *gsynth*'s matrix completion method as the GSC estimator (15). A cross-validation procedure was implemented to select the optimal number of factors in the matrix completion algorithm, ranging from zero to five. Last, uncertainty estimates were produced based on 1000-bootstrap runs [see Xu (13) for details].

Equation 1 implies that time-invariant covariates are dropped from the model by demeaning. To improve the robustness of the GSC analyses by indirectly considering time-invariant covariates, the GSCs were constructed based on pre-selected controls from two independent sets of controls: (1) the first set is exclusively based on the control sites selected for the construction of the individual SCs (i.e., all control sites with non-zero weights in any SC), while the other (2) is based exclusively on control areas selected with cardinality matching (16), independent of the SC analyses. The cardinality matching was performed with the *MatchIt* package (v.4.10-8) available for R software. Cardinality matching identifies the largest matched set that satisfies the covariate balance constraints among treatment groups (in our case, set to <10% of absolute standardized mean differences), with the additional constraint of the ratio of the number of matched treated to matched control units (1:10, in our case, respectively). We included a subset of the variables described in Table S2 in the matching analyses (see Fig. S9 for the included variables). As a result, three out of 10 Peruvian project sites, two out of 10 Colombian sites, and one out of 9 African sites were dropped from the cardinality-matching GSC analyses. This procedure was necessary to ensure the presence of common support among treated and control units (17), which could not be properly achieved with other matching methods we tested (Fig. S9).

Only two out of the 70 control areas in Peru (2.8%) selected with cardinality matching were also used to construct the individual Peruvian SCs. Out of the 80 control areas in Colombia selected with cardinality matching, six (0.7%) were also used for the construction of the individual Colombian SCs. None of the 80 cardinality-matching selected controls across DRC, Tanzania, and Zambia were included in the African SCs. The lack of significant overlap between the two independent sets of controls increases the robustness of the GSC results.

Time-series cross-sectional matching methods

An additional robustness test was performed where operational REDD+ sites were matched with “to-be” REDD+ sites using the matching-based methods for cross-sectional panel data analysis developed by Imai et al. (18) and implemented with the *PanelMatch* package (v.1.0.0) available for R software. Specifically, each operational REDD+ site was matched to up to five not-yet-operational REDD+ sites (or a weighted combination of those) that share a similar covariate history over a 3-year interval prior to project implementation and that remained not-operational over a five year evaluation period (Fig. S12 & S13). This analysis included only projects for which we observe at least 5 years of deforestation data post-REDD+. Matching was performed based on three methods: propensity score matching, Mahalanobis distance, and propensity score weighting. ATTs were annually estimated for evaluation periods ranging 1–5 years following project implementation (Fig. S14).

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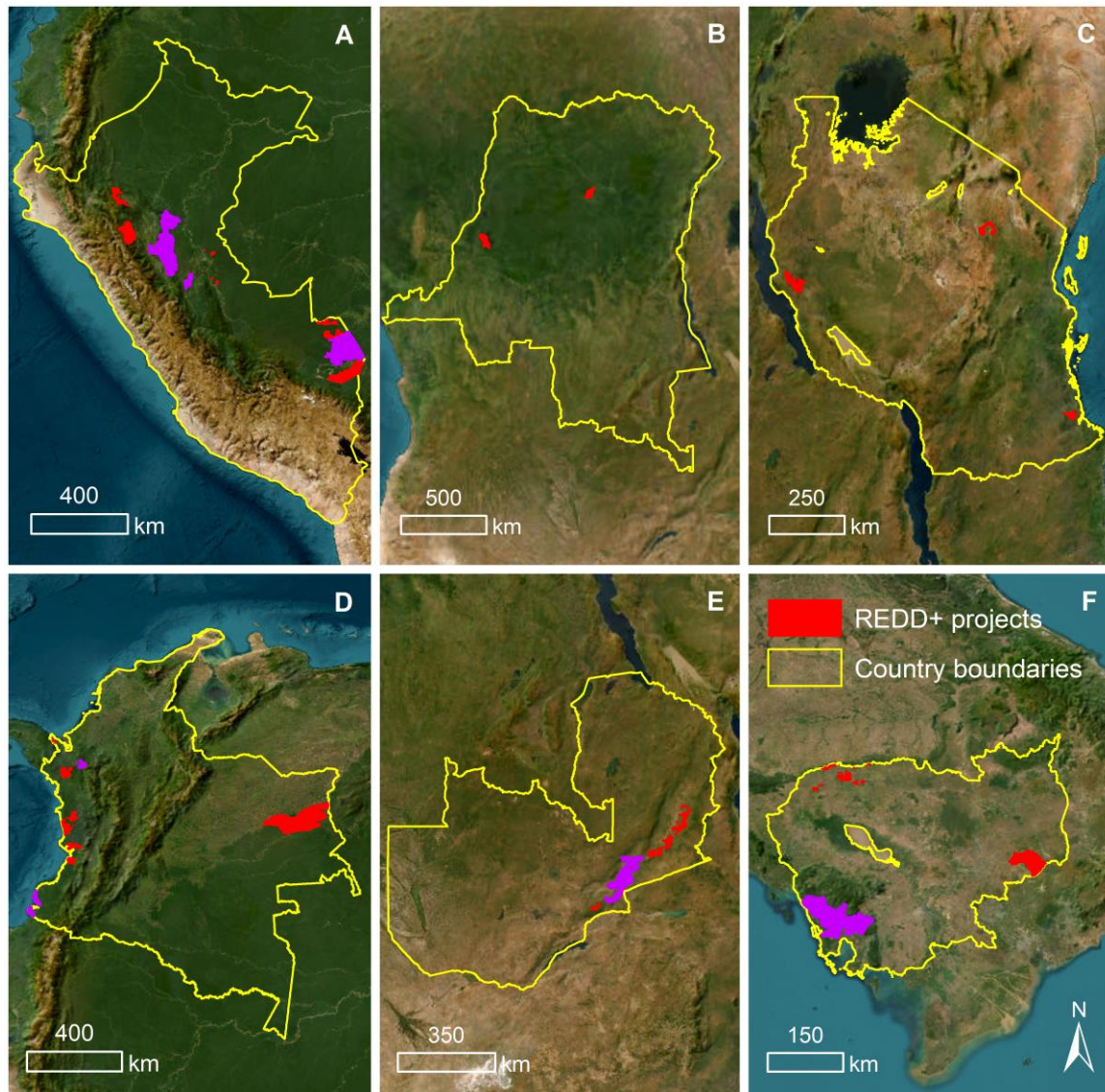
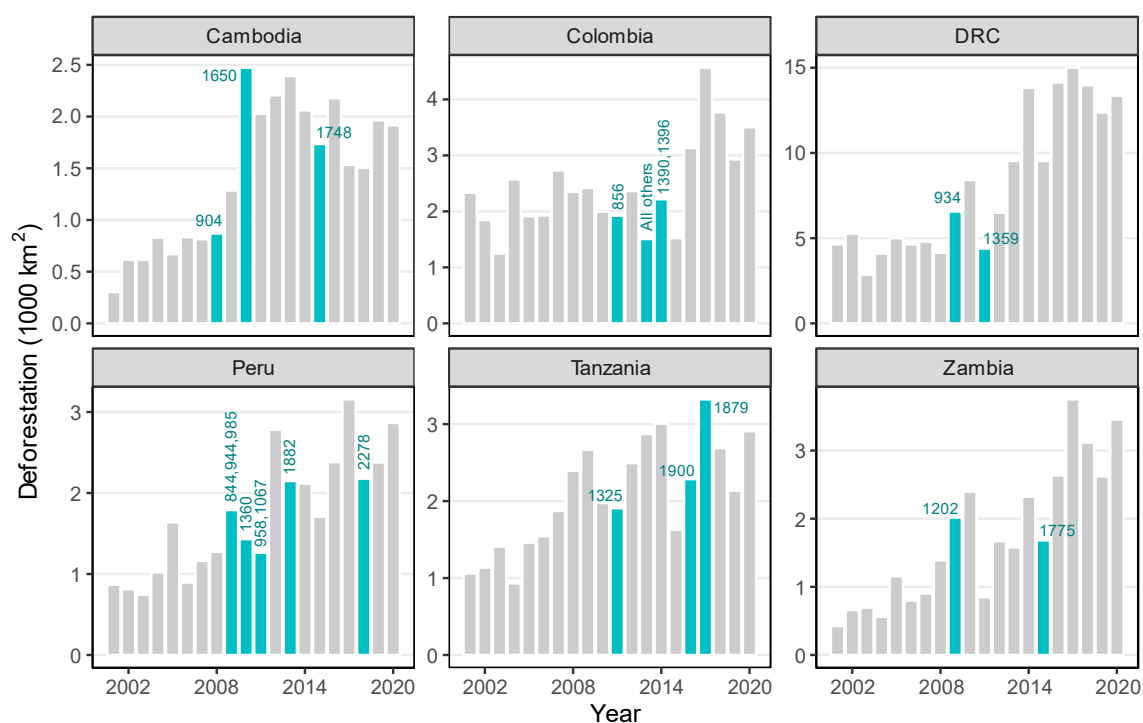


Fig. S1. VCS-certified REDD+ project sites based on avoided unplanned deforestation implemented during 2009–2020 in Peru (A), Democratic Republic of Congo (B), Tanzania (C), Colombia (D), Zambia (E), and Cambodia (F). Purple areas are the sites excluded from the analysis due to either data issues or the inability to construct high-quality synthetic controls.

328



329

330 **Fig. S2.** Annual deforestation rates (1000 km²) in the study countries based on the Global
 331 Forest Change dataset (bars). Blue bars indicate the implementation year of the VCS-
 332 certified REDD+ projects. Project IDs displayed in blue.
 333

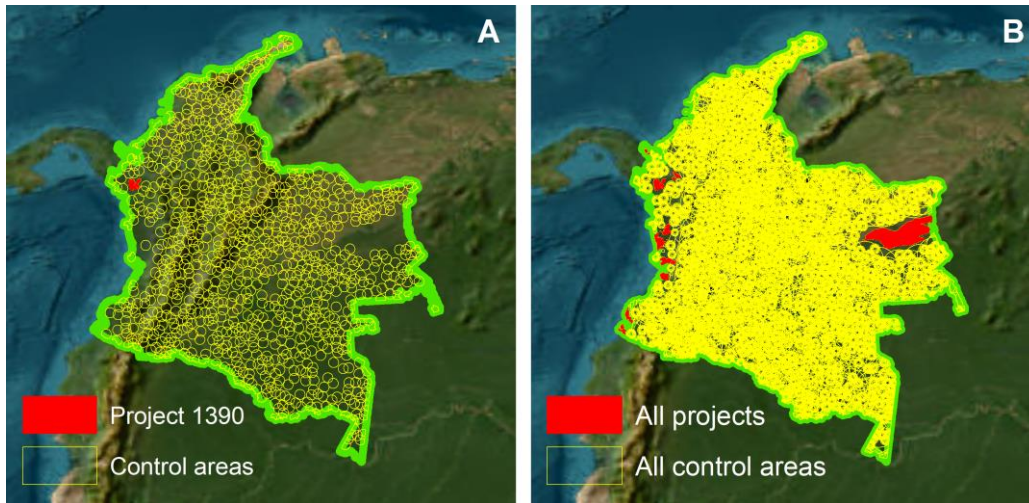


Fig. S3. Example of the 1000 circular spatial polygons created randomly as potential control areas for Project #1390 in Colombia (A) and all combined polygons for the Colombian projects (B). Circular spatial polygons are later intersected with all covariate maps described in Table S8.

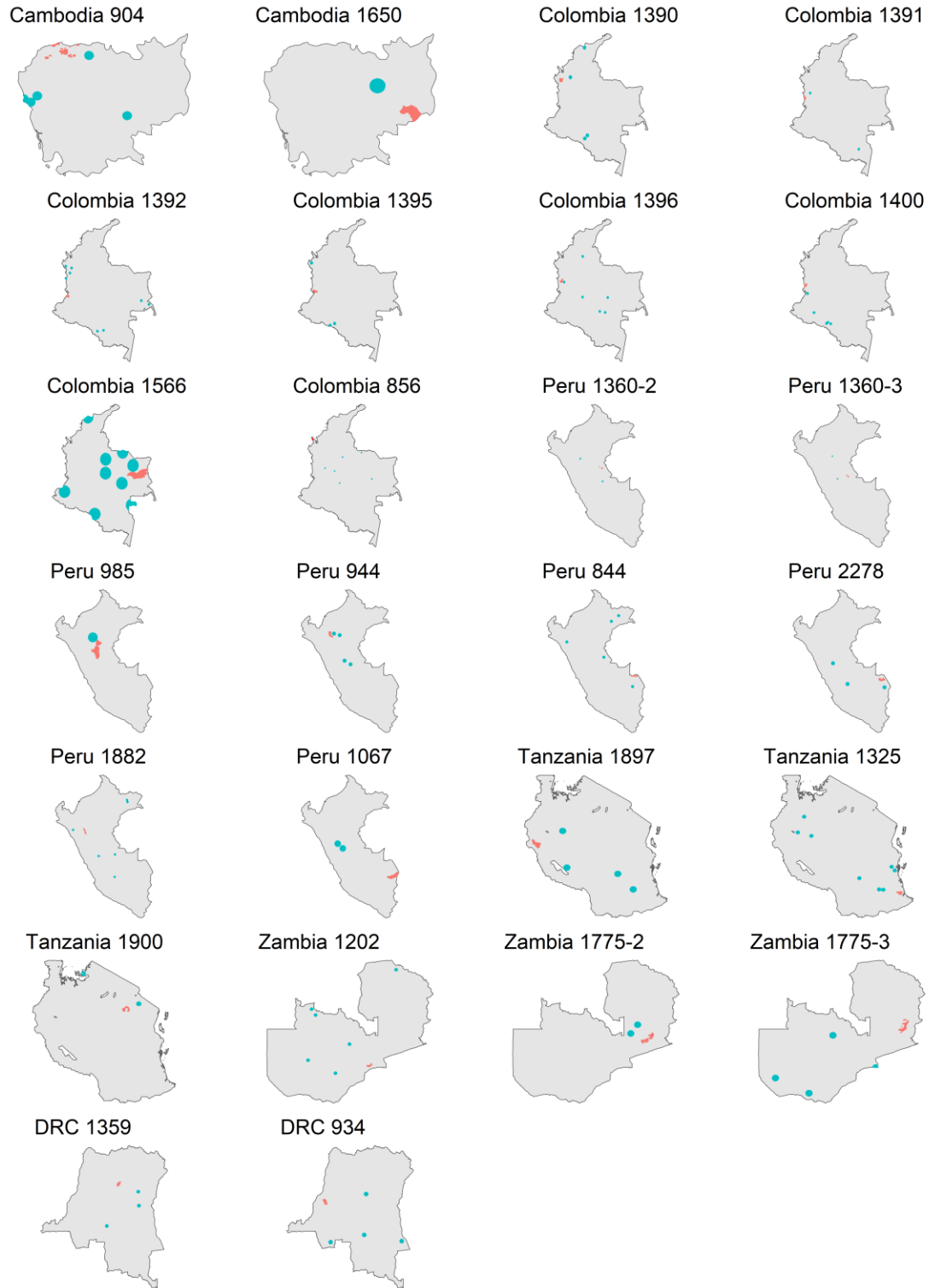
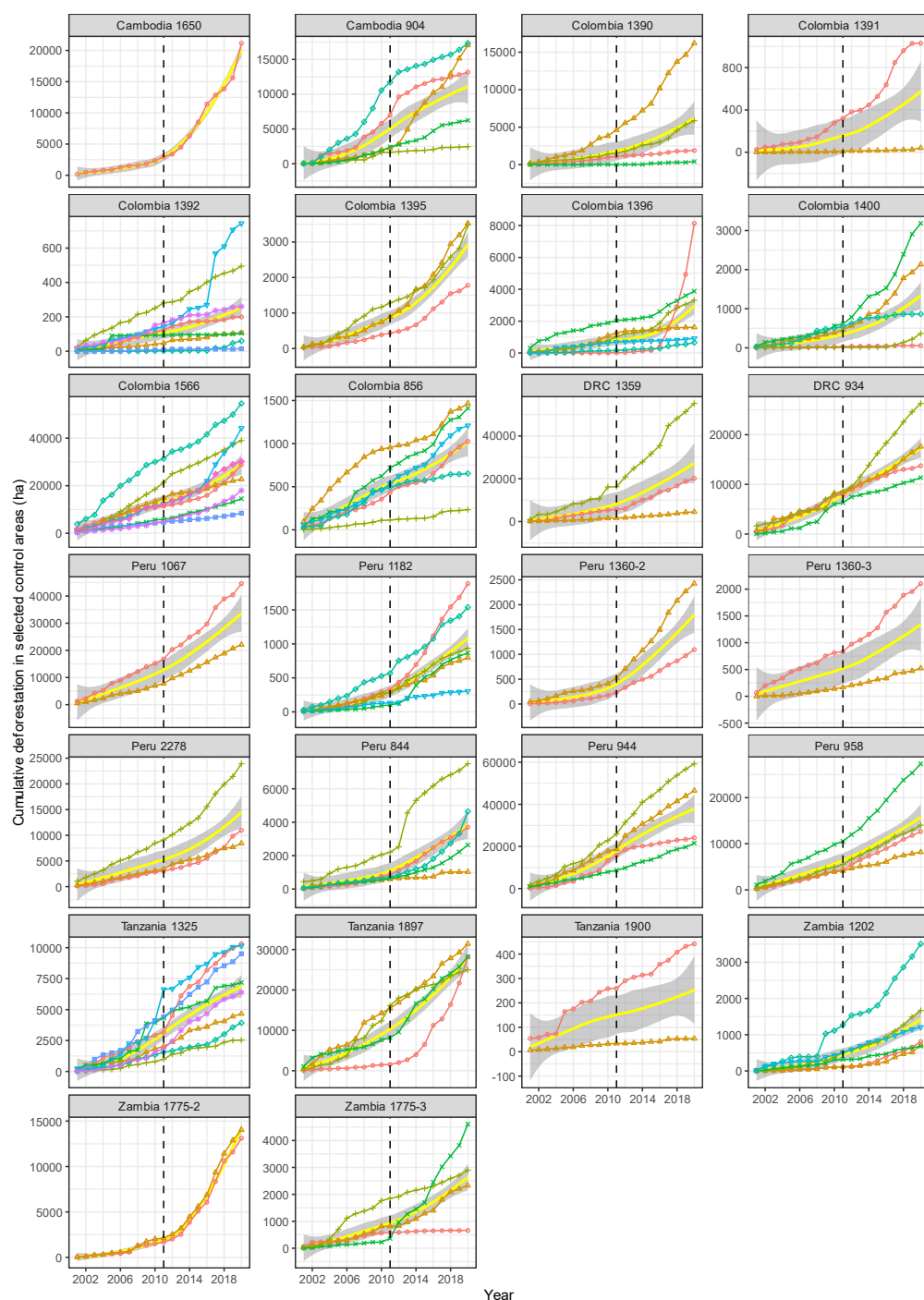


Fig. S4. Selected donor areas (displayed in blue) for the construction of the individual synthetic controls. REDD+ project areas displayed in red.



345

346 **Fig. S5.** Deforestation trends in selected donor areas that compose the individual synthetic
 347 controls. Yellow lines and shaded areas are locally estimated scatterplot smoothing
 348 (LOESS) trends and their 95% confidence intervals, respectively. (Increases in
 349 deforestation rates in the selected donor areas result in more conservative estimates of
 350 project effectiveness.)

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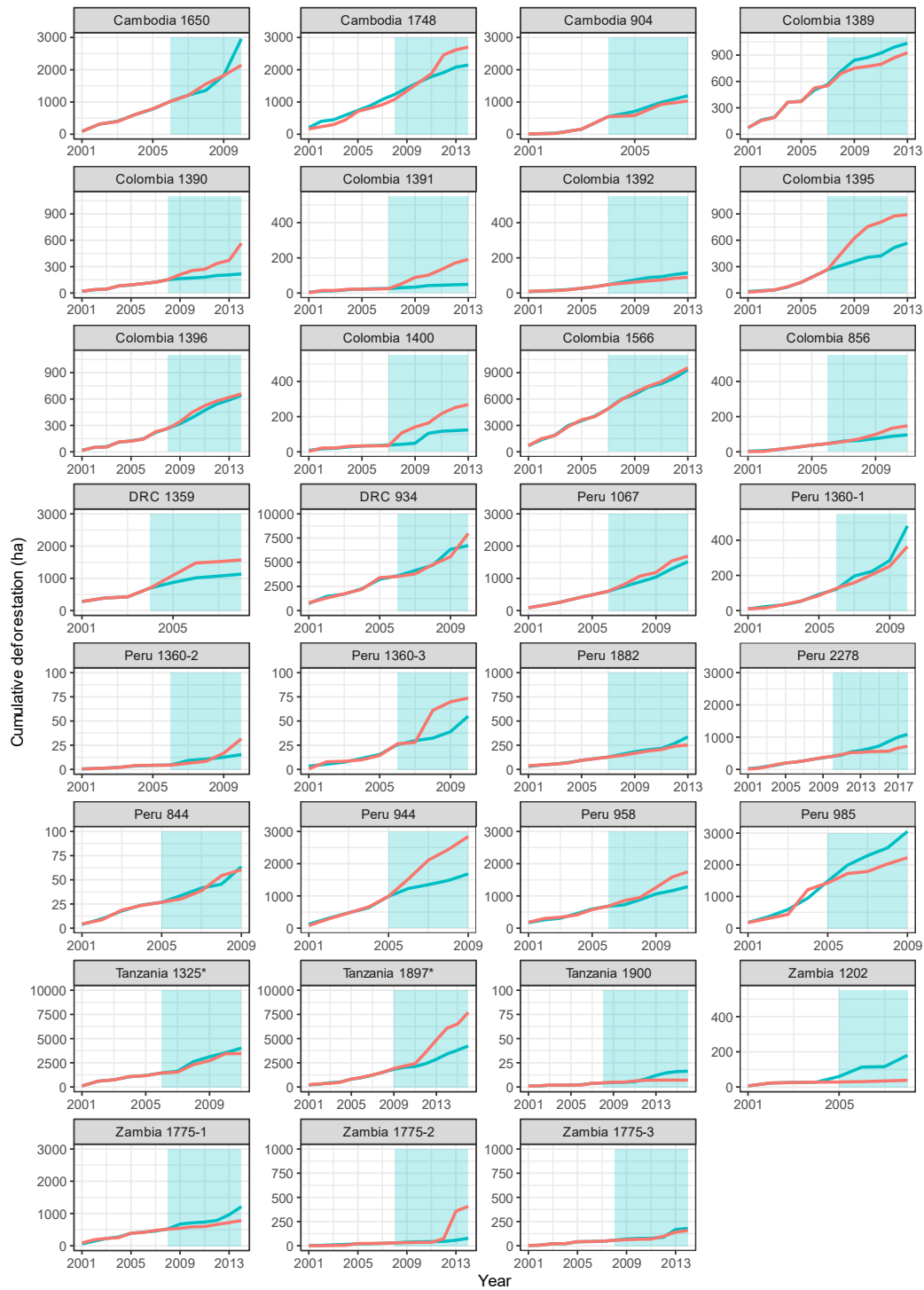


Fig. S6. “Validation” of the synthetic control method in each REDD+ project. Pre-REDD+ deforestation in “to-be” REDD+ project areas (red) versus synthetic controls (blue). Shaded blue areas represent the validation periods (note: scales differ). Asterisks indicate projects that failed the test (see Table S3 for details).

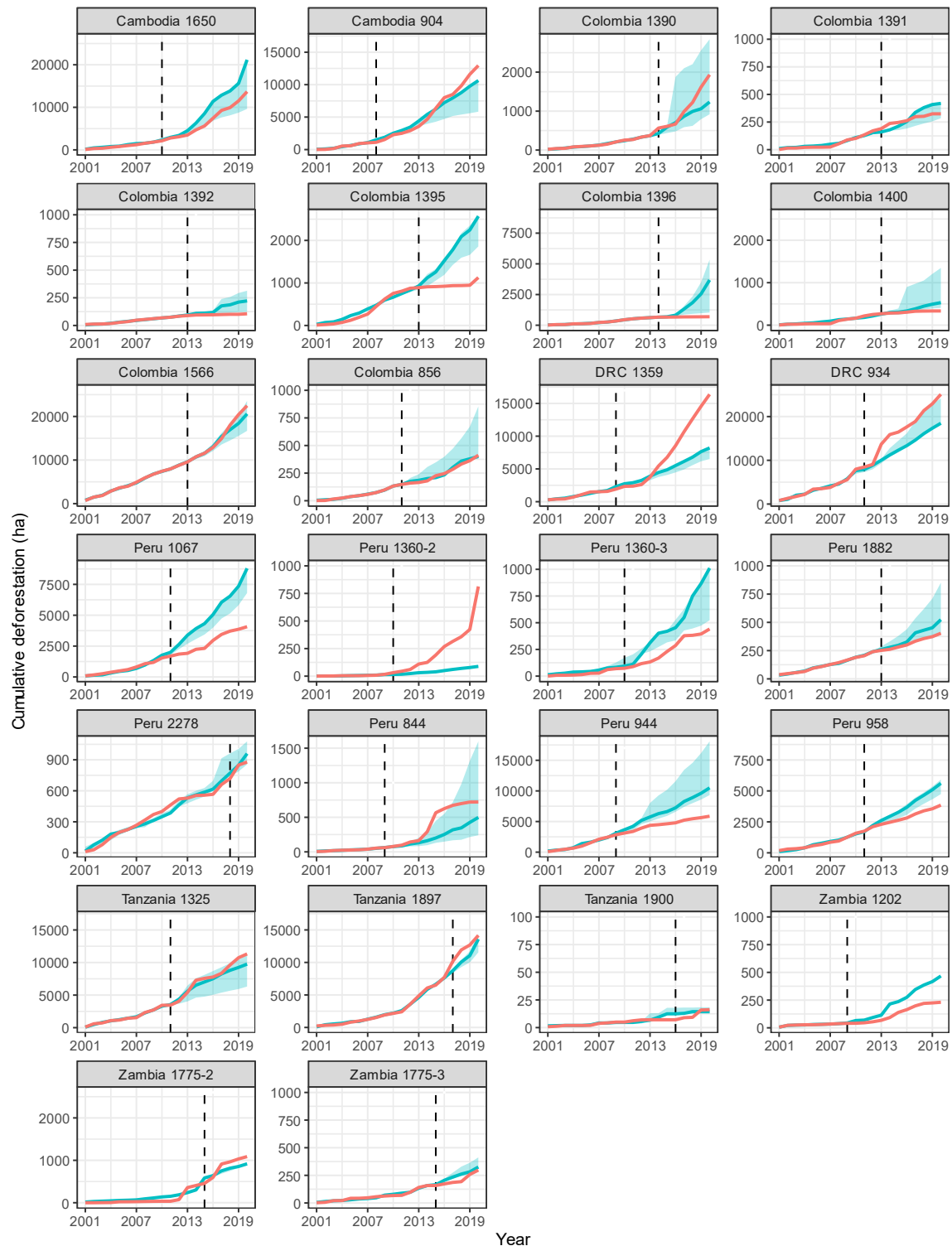


Fig. S7. Cumulative post-2000 deforestation in REDD+ project areas (red) versus synthetic controls (blue). Blue shaded areas are “possibility intervals” (see SI for details). Dashed black lines indicate the project implementation year (note: scales differ).

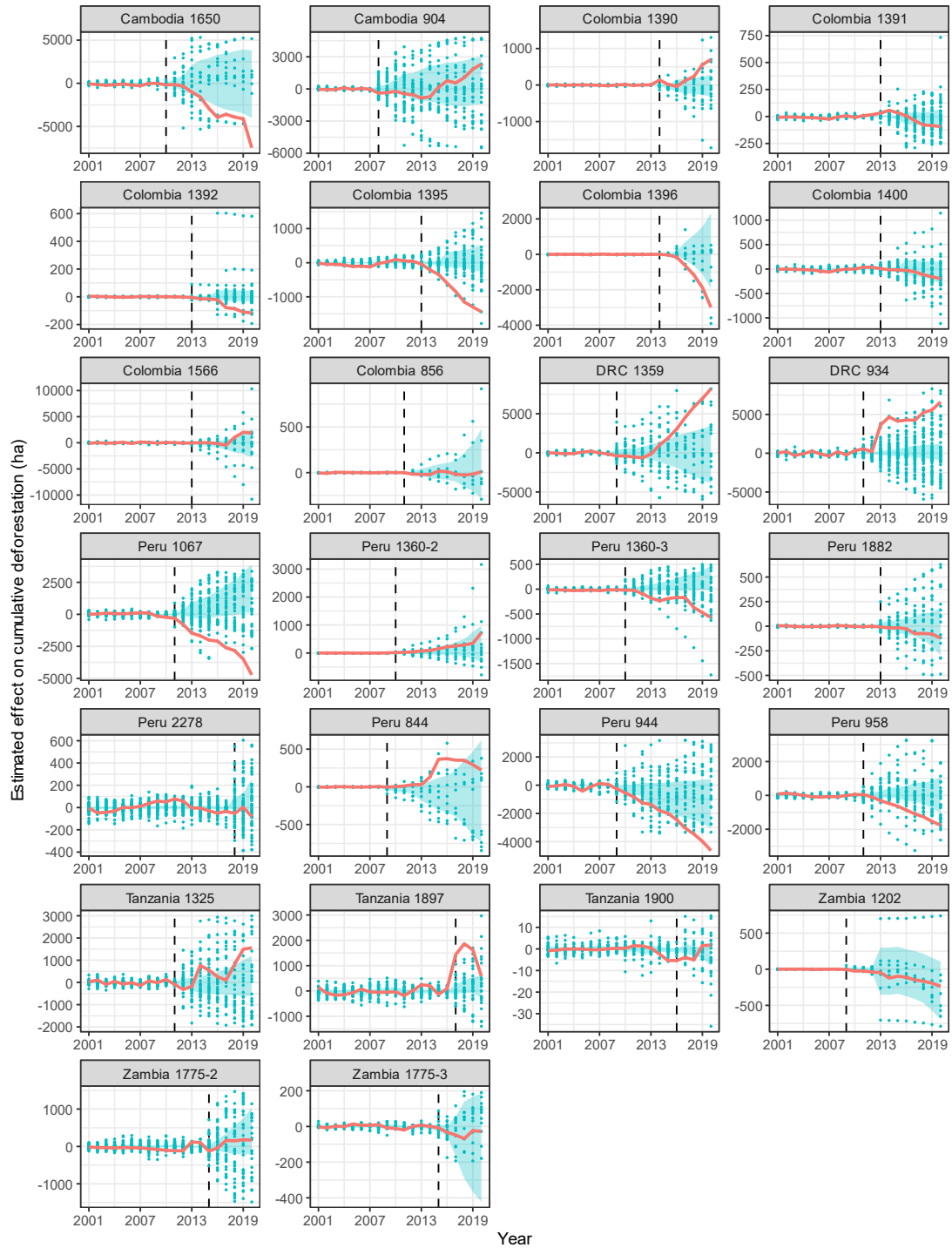


Fig. S8. Placebo tests: cumulative deforestation in REDD+ project areas minus deforestation in their respective synthetic controls (red), and cumulative deforestation in placebos minus deforestation in their respective synthetic controls (blue dots). Dashed black lines indicate the project implementation year (assumed the same for placebos). Blue shaded areas represent 95% confidence intervals around the placebos' mean (note: scales differ).

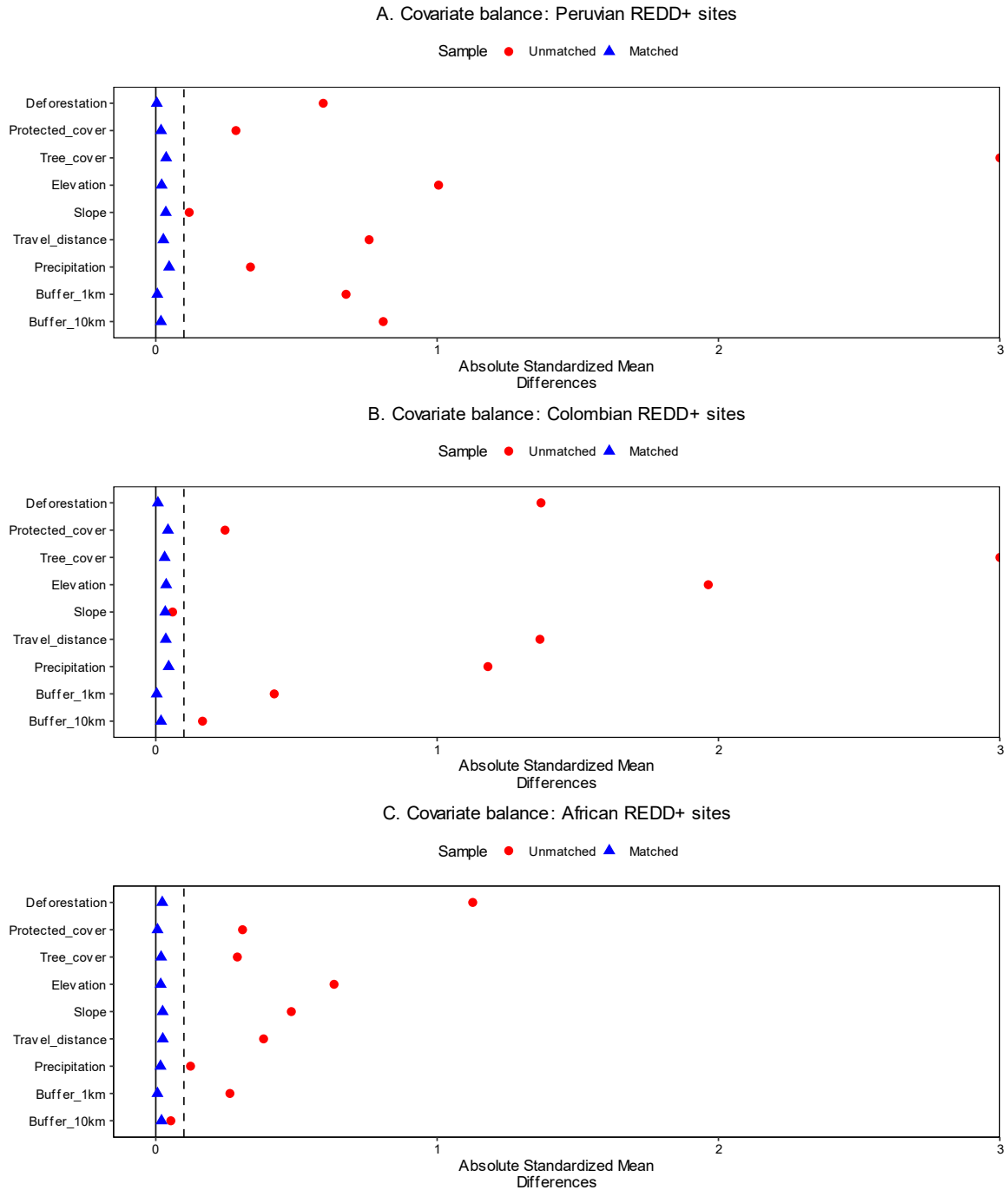
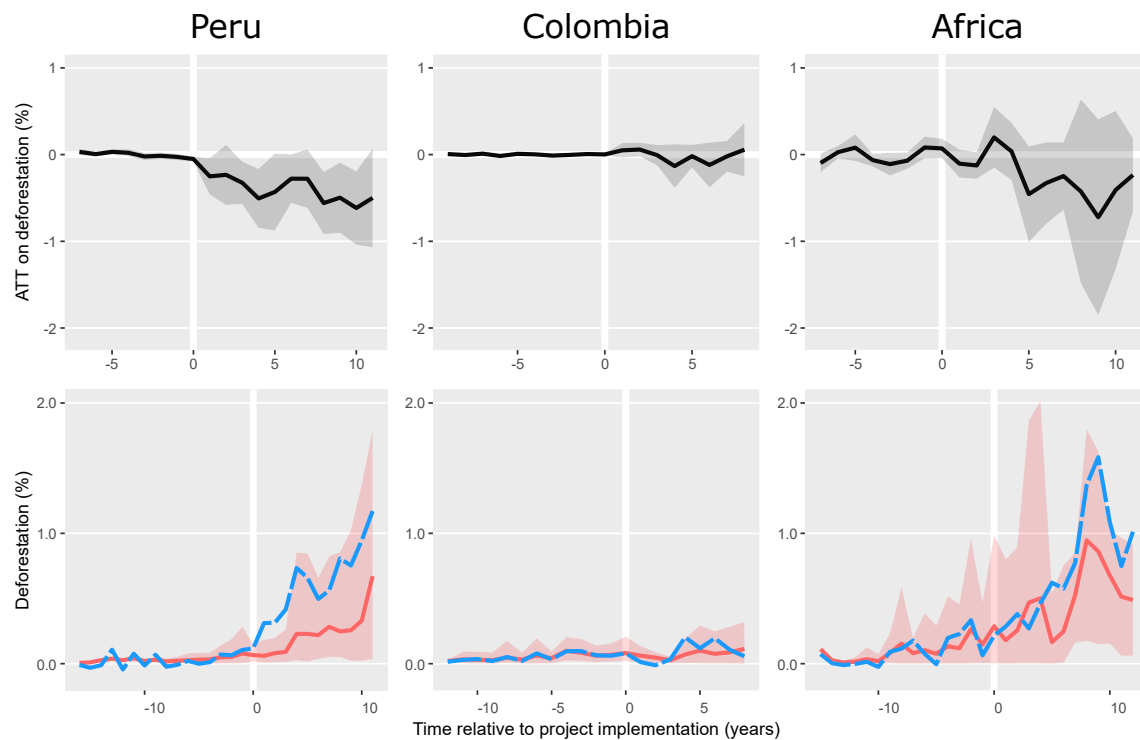


Fig. S9. Covariate balance for the Peruvian (A), Colombian (B), and African (C) projects before and after cardinality matching. Absolute standardized mean differences within the vertical-line interval (0.1) generally indicate well-balanced sets.



376

377 **Fig. S10.** Estimated average impacts of REDD+ projects from Peru, Colombia, and Africa
 378 on annual deforestation, using the generalized synthetic control (GSC) method and selected
 379 controls from the *cardinality matching*. Upper panels display the average treatment effect
 380 on the treated (ATT) project areas. Lower panels display projects' (solid red line) and
 381 counterfactuals' (dashed blue line) deforestation averages. Shaded red areas represent
 382 bootstrapped 95% confidence intervals around the projects' deforestation average.

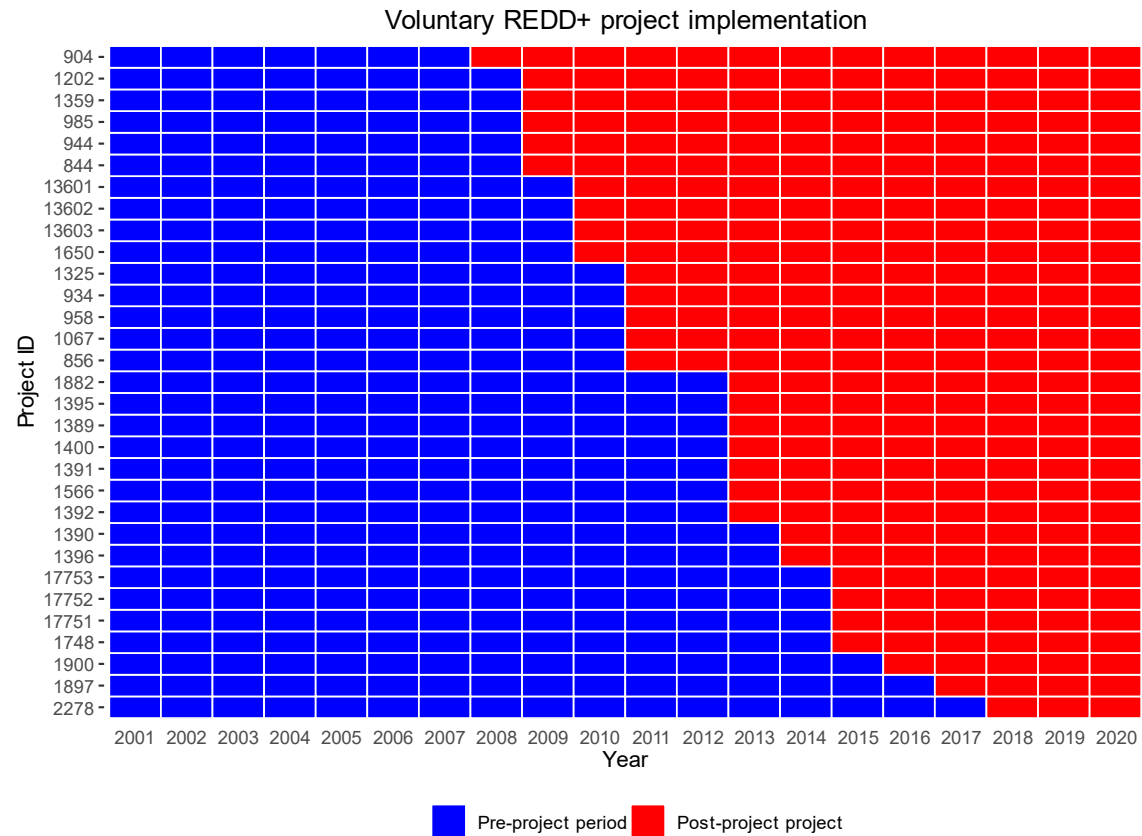


Fig. S11. Treatment history: VCS-certified REDD+ project implementation.

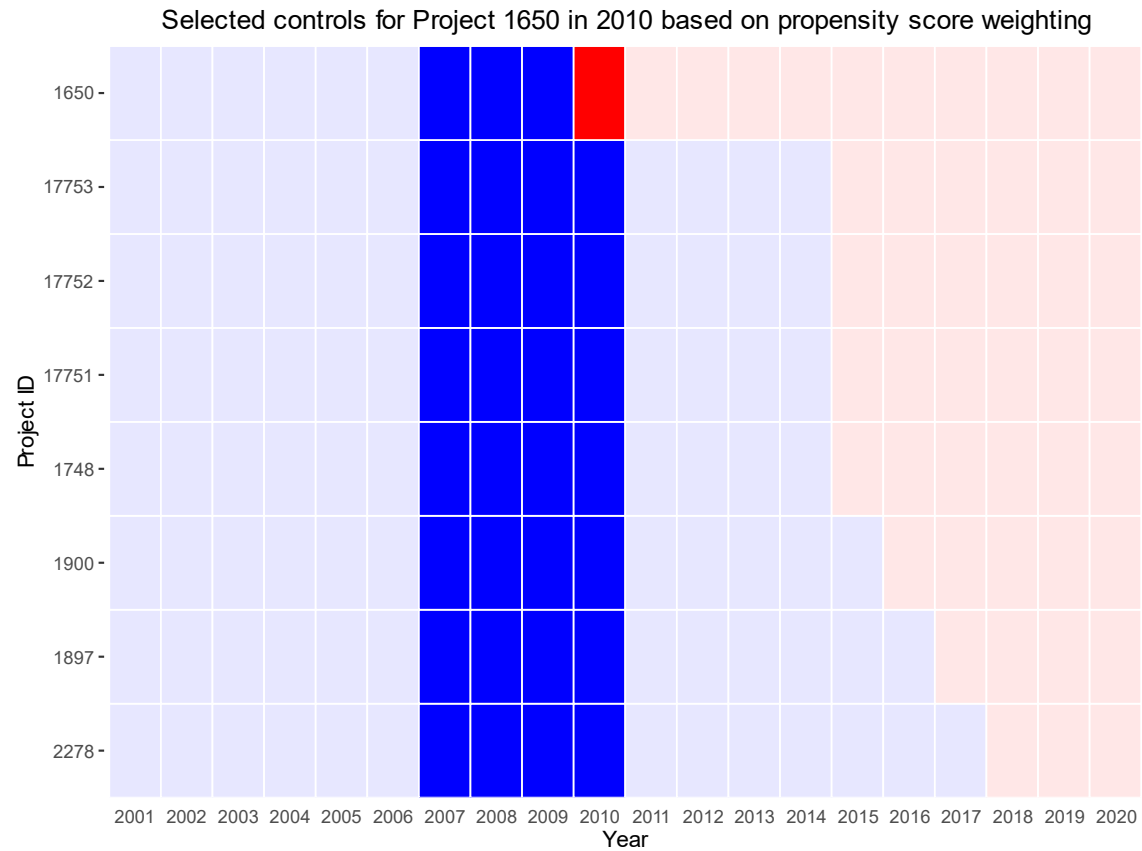


Fig. S12. Example of selected controls (“to-be” REDD+ sites; blue) for the cross-sectional evaluation (in 2010) of operational Project 1650 (red). Highlighted 2007–2009 period (blue) is the interval used for the identification of the control areas via matching.

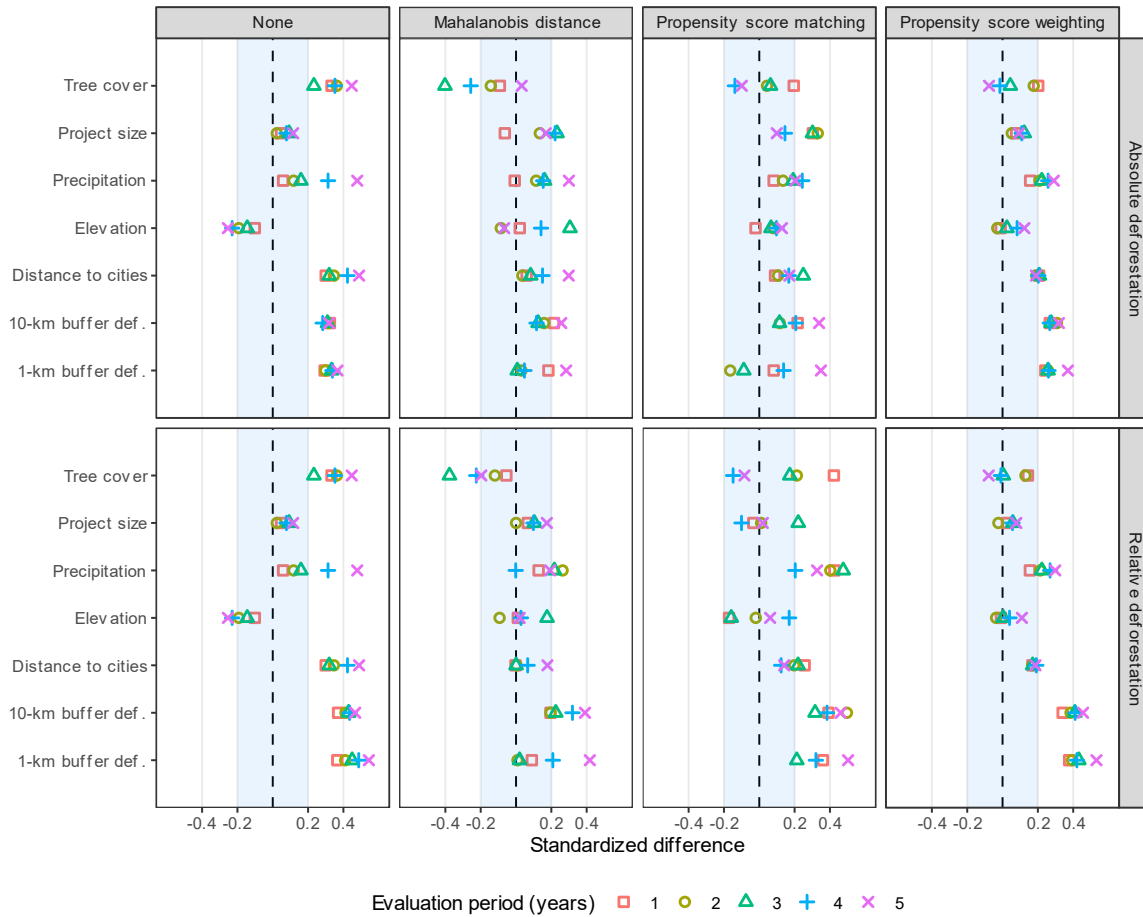


Fig. S13. Covariate balance from propensity score matching, Mahalanobis distance, and propensity score weighting based on absolute (ha year^{-1}) and relative deforestation ($\% \text{ year}^{-1}$) for different evaluation periods (years). Time-varying covariates are represented by averages over the 5-year interval prior to project implementation used for the matching analyses. “None” represents the original unmatched sample. Standardized differences within the shaded intervals generally indicate well-balanced sets.

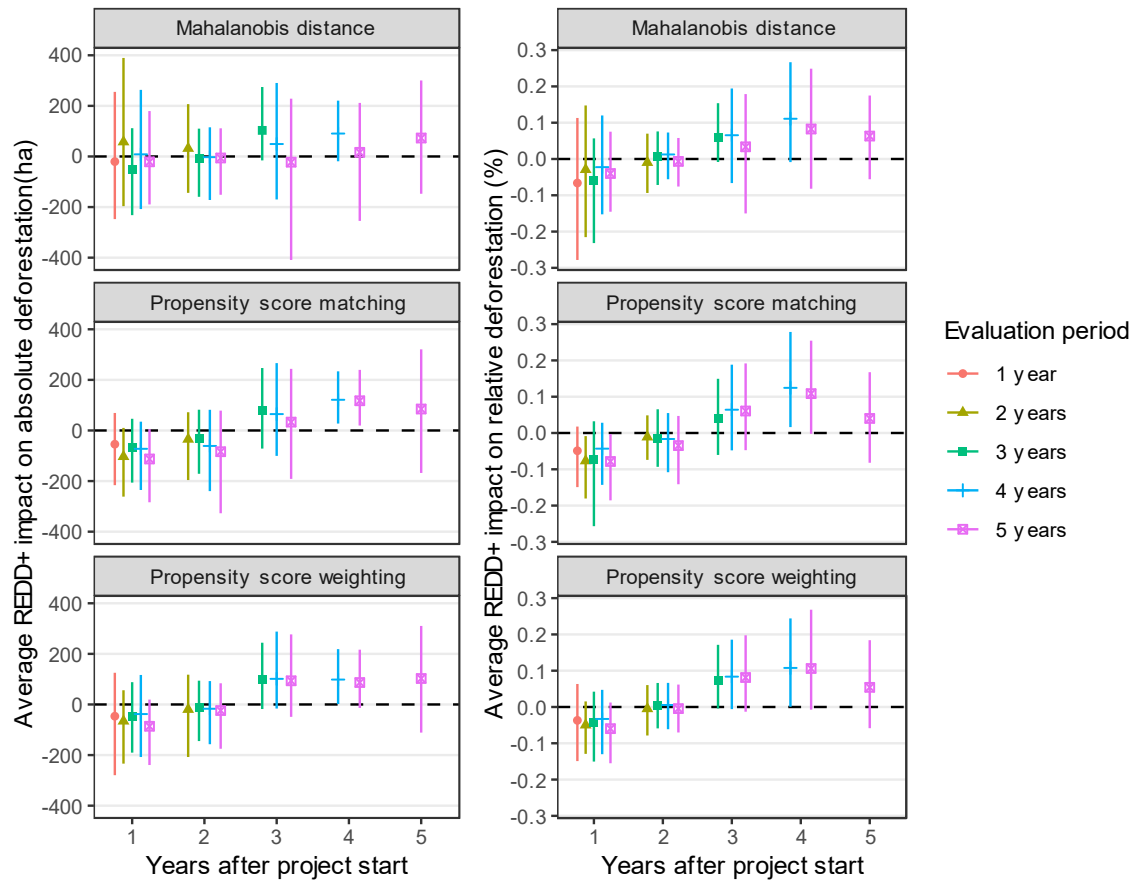


Fig. S14. Estimated impacts of the REDD+ projects on the annual absolute and relative deforestation per evaluation period based on Mahalanobis distance, propensity score matching, and propensity score weighting [see Imai et al (18) for details]. Vertical colored lines are bootstrapped 95% confidence intervals. Impact estimates for the same year after project start vary across the evaluation periods due to changes in sample sizes.

Table S1. VCS-certified REDD+ projects based on avoided unplanned deforestation and degradation.

Country	Project ID	Project name	Start year	Adopted VCS methodology	Included in the analysis	Reported project area (ha)	Project polygon area (ha)	Area overlap	Project polygon average tree cover in 2000*
Peru	1882	REDD+ Project in the Alto Huayabamba Conservation Concession (CCAH)	2013	VM0015	Yes	53,410	53,357	100%	85%
	1360	Forest Management to reduce deforestation and degradation in Shipibo Conibo and Cacataibo indigenous communities of Ucayali region	2010	VM0015	Partially‡	127,004	127,098	100%	99%
	2278	The Jaguar Amazon REDD Project	2018	VM0006	Yes	183,015	183,120	100%	99%
	1067	Reduction of deforestation and degradation in Tambopata National Reserve and Bahuaja-Sonene National Park within the area of Madre de Dios region–Peru	2011	VM0007	Yes	541,620	557,250	97%	98%
	985	Cordillera Azul National Park REDD Project	2009	VM0007	No†	1,351,964	1,352,298	100%	97%
	958	Biocorredor Martin Sagrado	2011	VM0015	Yes	295,654	295,412	100%	93%
	944	Alto Mayo Conservation Initiative	2009	VM0015	Yes	182,000	177,533	103%	89%
	844	Madre De Dios Amazon Redd Project	2009	VM0007	Yes	98,932	97,998	101%	99%
Colombia	1400	Concosta REDD+ Project	2013	VM0006	Yes	54,623	63,961	85%	97%
	1566	REDD+ Project Resguardo Indígena Unificado de la Selva de Matavén (RIU-SM)	2013	VM0007	Yes	1,150,212	1,753,035	66%	85%
	856	The Chocó-Darién Conservation Corridor REDD Project	2011	VM0009	Yes	13,465	12,710	106%	95%
	1396	Rio Pepe y ACABA REDD+ Project	2014	VM0006	Yes	48,177	57,051	84%	98%
	1395	Bajo Calima y Bahía Málaga (BCBM) REDD+ Project	2013	VM0006	Yes	83,452	91,831	91%	98%
	1392	Cajambre REDD+ Project	2013	VM0006	Yes	661,69	60,316	110%	98%
	1391	Sivirú, Usaragá, Pizarro y Pilizá (SUPP) REDD+ Project	2013	VM0006	Yes	47,667	55,104	87%	98%
	1390	Carmen del Darién (CDD) REDD+ Project	2014	VM0006	Yes	118,318	131,828	90%	94%
	1389	ACAPA – Bajo Mira y Frontera (ACAPA-BMF) REDD+ Project	2013	VM0006	No†	58,212	68,602	85%	95%

Table S1 (continued). VCS-certified REDD+ projects based on avoided unplanned deforestation and degradation.

Country	Project ID	Project name	Start year	Adopted VCS methodology	Included in the analysis	Reported project area (ha)	Project polygon area (ha)	Area overlap	Project polygon average tree cover in 2000*
Cambodia	1748	Southern Cardamom REDD+ Project	2015	VM0009	No†	445,339	458,408	97%	93%
	904	Reduced Emissions from Deforestation and Degradation in Community Forests – Oddar Meanchey, Cambodia	2008	VM0006	Yes	56,050	66,205	85%	42%
	1650	Reduced Emissions from Deforestation and Degradation in Keo Seima Wildlife Sanctuary	2010	VM0015	Yes	166,983	193,503	86%	73%
DRC	934	The Mai Ndombe REDD+ Project	2011	VM0009	Yes	299,640	301,263	99%	89%
	1359	Isangi REDD+ Project	2009	VM0006	Yes	187,571	188,489	100%	100%
Tanzania	1325	Mjumita Community Forest Project (LINDI)	2011	VM0015	Yes	41,924	65,279	64%	51%
	1900	Makame Savannah REDD	2016	VM0007	Yes	104,065	107,152	97%	10%
	1897	Ntakata Mountains REDD	2017	VM0007	Yes	216,994	204,203	106%	50%
Zambia	1775	Luangwa Community Forests Project	2015	VM0009	Partially‡	943,676	943,674	100%	23%
	1202	Lower Zambezi REDD+ Project	2009	VM0009	Yes	40,126	40,103	100%	24%

* Processed in Google Earth Engine based on the 2000 Percent Tree Cover map from the Global Forest Change dataset (Hansen et al., 2013).

† Discarded due to the poor quality of the synthetic control counterfactual.

‡ Project composed of multiple sites, some of which were discarded due to the poor quality of the synthetic control counterfactual.

Source: Verified Carbon Standard (VCS) project database (<https://registry.terra.org/>).

Table S2. Data source.

Variable	Description	Geographical coverage	Source
Annual seforestation and average tree cover in 2000	2000–2020 forest cover and change, time-variant	Global	Global Forest Change dataset (Hansen et al., 2013), available in Google Earth Engine
Travel time to urban centers	Friction surface of land-based travel time (days); time-invariant	Global	Global Friction Surface 2019 (Weiss et al., 2018), available in Google Earth Engine
Elevation and slope	Average elevation and slope in project and control areas (m); time-invariant	Global	Global Multi-resolution Terrain Elevation Data (GMTED2010), available in Google Earth Engine
Protected area cover	Location of protected areas; time-invariant	Peru	National Service of Natural Areas Protected by the State (SERNANP; Spanish acronym)
		Colombia	Colombian Environmental Information System (SIAC; Spanish acronym)
		Cambodia	Open Development Cambodia (https://opendevelopmentcambodia.net/)
		DRC, Tanzania, Zambia	Protected Planet (https://www.protectedplanet.net/)
Indigenous land cover	Location of Indigenous lands; time-invariant	Peru	Body for the Formalization of Informal Property (COFOPRI; Spanish acronym)
		Colombia	National Land Agency (ANT; Spanish acronym)
		DRC	Map for Environment (https://mapforenvironment.org/)
Mining concession cover	Location of mining concessions; time-invariant	Peru, Colombia, DRC	Global Forest Watch (https://www.globalforestwatch.org/)
		Cambodia	Open Development Cambodia (https://opendevelopmentcambodia.net/)
		Tanzania	Map for Environment (https://mapforenvironment.org/)
Logging concession cover	Location of logging concessions; time-invariant	Peru	Map for Environment (https://mapforenvironment.org/)
		DRC	Global Forest Watch (https://www.globalforestwatch.org/)
Palm oil concession cover	Location of palm oil concessions; time-invariant	Colombia	Map for Environment (https://mapforenvironment.org/)
		Indonesia	Global Forest Watch (https://www.globalforestwatch.org/)
General concession cover	Location of multiple land concessions; time-invariant	Cambodia	Map for Environment (https://mapforenvironment.org/)
Precipitation	Annual cumulative precipitation (mm); time-variant	Global	Monthly Global Precipitation Measurement (GPM) v.6, available in Google Earth Engine
REDD+ jurisdictional programs and other conservation interventions	Central Africa Regional Program for the Environment (CARPE) in RDC, DRC's jurisdictional Maï Ndombe Emission Reduction Program, and DRC's Forest Investment Program; time-invariant	DRC	Map for Environment (https://mapforenvironment.org/)
Other REDD+ interventions	Other REDD+ intervention areas used for exclusion of control areas; time-variant	DRC	Map for Environment (https://mapforenvironment.org/)
Soil fertility	3-class ordinal map of soil fertility; time-invariant	Cambodia	Map for Environment (https://mapforenvironment.org/)

Table S3. Synthetic control “validation”: difference between project and synthetic control deforestation in the final year of the validation period.

Country	Project ID	Final year of the validation period	Project deforestation (ha)	Synthetic control deforestation (ha)	Difference between project and synthetic control deforestation	
					(ha)	(% of project area)
Cambodia	1650	2010	2389.8	2142.0	247.8	0.1
Cambodia	1748	2015	3089.9	2700.8	389.0	0.1
Cambodia	904	2007	1122.3	1032.2	90.0	0.1
Colombia	1389	2013	929.9	927.2	2.7	0.0
Colombia	1390	2014	365.1	565.6	-200.5	-0.2
Colombia	1391	2013	55.2	190.9	-135.8	-0.2
Colombia	1392	2013	132.0	89.0	43.0	0.1
Colombia	1395	2013	554.8	890.7	-335.8	-0.4
Colombia	1396	2014	643.3	659.2	-16.0	0.0
Colombia	1400	2013	89.7	268.5	-178.7	-0.3
Colombia	1566	2013	10,761.7	9563.2	1198.5	0.1
Colombia	856	2011	88.6	147.9	-59.4	-0.5
DRC	1359	2008	1509.9	1572.4	-62.4	0.0
DRC	934	2010	8234.9	7975.1	259.8	0.1
Peru	1067	2011	1953.1	1687.8	265.4	0.0
Peru	1182	2013	243.6	252.3	-8.8	0.0
Peru	1360-1	2010	381.2	364.8	16.3	0.0
Peru	1360-2	2010	34.7	31.6	3.0	0.0
Peru	1360-3	2010	73.2	73.8	-0.5	0.0
Peru	2278	2018	995.8	718.3	277.4	0.2
Peru	844	2009	50.8	60.5	-9.7	0.0
Peru	944	2009	2626.6	2843.2	-216.6	-0.1
Peru	958	2011	1504.6	1749.0	-244.4	-0.1
Peru	985	2009	2914.3	2224.3	690.0	0.1
Tanzania	1325	2011	2913.9	3456.2	-542.3	-0.8*
Tanzania	1897	2017	4279.0	7701.1	-3422.2	-1.7*
Tanzania	1900	2016	16.3	7.1	9.2	0.0
Zambia	1202	2009	193.5	37.7	155.8	0.4
Zambia	1775-1	2015	1526.2	779.7	746.6	0.1
Zambia	1775-2	2015	136.5	406.9	-270.4	-0.2
Zambia	1775-3	2015	197.2	157.8	39.4	0.0

*Projects with difference between project and synthetic control deforestation >0.5% of the project area are assumed to have failed validation.

Table S4. VCS-certified REDD+ projects: carbon offsets issued and retired as of November 2021.

Country	Project ID	Project name	Start year	Adopted VCS methodology	Carbon offsets issued	Carbon offsets retired	Retired proportion (%)
Peru	1882	REDD+ Project in the Alto Huayabamba Conservation Concession (CCAH)	2013	VM0015	171,673	14,443	8.4
	1360	Forest Management to reduce deforestation and degradation in Shipibo Conibo and Cacataibo indigenous communities of Ucayali region	2010	VM0015	4,852,836	763,786	15.7
	2278	The Jaguar Amazon REDD Project	2018	VM0006	0	0	–
	1067	Reduction of deforestation and degradation in Tambopata National Reserve and Bahuaja-Sonene National Park within the area of Madre de Dios region–Peru	2011	VM0007	3,678,270	704,766	19.2
	985	Cordillera Azul National Park REDD Project	2009	VM0007	25,240,371	6,323,967	25.1
	958	Biocorredor Martin Sagrado	2011	VM0015	566,843	335,957	59.3
	944	Alto Mayo Conservation Initiative	2009	VM0015	5,282,313	3,625,820	68.6
	844	Madre De Dios Amazon Redd Project	2009	VM0007	9,658,069	975,539	10.1
Colombia	1400	Concosta REDD+ Project	2013	VM0006	544,278	303,004	55.7
	1566	REDD+ Project Resguardo Indígena Unificado de la Selva de Matavén (RIU-SM)	2013	VM0007	22,274,745	6,068,608	27.2
	856	The Chocó-Darién Conservation Corridor REDD Project	2011	VM0009	435,188	158,822	36.5
	1396	Rio Pepe y ACABA REDD+ Project	2014	VM0006	567,286	419,209	73.9
	1395	Bajo Calima y Bahía Málaga (BCBM) REDD+ Project	2013	VM0006	1,620,202	747,709	46.1
	1392	Cajambre REDD+ Project	2013	VM0006	477,432	290,483	60.8
	1391	Sivirú, Usaragá, Pizarro y Pilizá (SUPP) REDD+ Project	2013	VM0006	1,021,146	625,751	61.3
	1390	Carmen del Darién (CDD) REDD+ Project	2014	VM0006	681,565	398,348	58.4
	1389	ACAPA – Bajo Mira y Frontera (ACAPA-BMF) REDD+ Project	2013	VM0006	783,133	323,456	41.3

Table S4 (continued). VCS-certified REDD+ projects: carbon offsets issued and retired as of November 2021.

Country	Project ID	Project name	Start year	Adopted VCS methodology	Carbon offsets issued	Carbon offsets retired	Retired proportion (%)
Cambodia	1748	Southern Cardamom REDD+ Project	2015	VM0009	23,785,965	2,365,202	9.9
	904	Reduced Emissions from Deforestation and Degradation in Community Forests – Oddar Meanchey, Cambodia	2008	VM0006	48,000	44,297	92.3
	1650	Reduced Emissions from Deforestation and Degradation in Keo Seima Wildlife Sanctuary	2010	VM0015	14,568,314	154,747	1.1
DRC	934	The Mai Ndombe REDD+ Project	2011	VM0009	13,322,276	2,572,569	19.3
	1359	Isangi REDD+ Project	2009	VM0006	1,620,202	747,709	46.1
Tanzania	1325	Mjumita Community Forest Project (LINDI)	2011	VM0015	10,000	2246	22.5
	1900	Makame Savannah REDD	2016	VM0007	150,425	80,000	53.2
	1897	Ntakata Mountains REDD	2017	VM0007	726,000	84,115	11.6
Zambia	1775	Luangwa Community Forests Project	2015	VM0009	6,147,649	1,911,839	31.1
	1202	Lower Zambezi REDD+ Project	2009	VM0009	1,570,196	689,134	43.9
TOTAL	–	–	–	–	139,804,377	38,154,319	22.3

Source: Verified Carbon Standard (VCS) project database (<https://registry.verra.org/>).

Table S5. Carbon offsets generated by a voluntary REDD+ project (i.e., that a project is entitled to sell) can be calculated by comparing the observed cumulative deforestation in the project area to either the project baseline (*ex-ante*) or the project synthetic control (*ex-post*) through 2020.

Country	Project ID	Observed deforestation in the project area (ha)	Observed deforestation in the synthetic control area (<i>ex-post</i> ; ha)	Project baseline deforestation* (<i>ex-ante</i> ; ha)	Expected carbon offsets based on projects' ex-ante baseline† (Mg CO ₂)	Expected carbon offsets per hectare of avoided deforestation (Mg CO ₂ ha ⁻¹)	Evidence of significant reductions in deforestation‡	Avoided deforestation based on the synthetic control (ha)	Carbon offsets based on the synthetic control (Mg CO ₂)
Peru	1882	403	524	1,268	356,960	282	No	0	0
	2278	878	960	13,299	5,891,253	443	No	0	0
	1067	4,070	8,797	13,581	4,817,471	355	Yes	4,727	1,676,610
	958	3,391	5,614	2,924	630,937	216	Yes	2,223	479,713
	944**	5,454	8,911	23,685	5,151,165	217	Yes	3,457	751,791
	844**	699	347	125,561	12,475,134	99	No	0	0
Colombia	1400	334	531	12,425	1,657,098	133	No	0	0
	1566	22,473	20,594	103,908	31,325,923	301	No	0	0
	1396	693	3,685	8,076	1,489,786	184	Yes	2992	551,949
	1395	1,129	2,569	16,835	2,791,723	166	Yes	1440	238,809
	1392	105	222	10,722	1,455,141	136	Yes	117	15,822

Table S5 (continued). Carbon offsets generated by a voluntary REDD+ project (i.e., that a project is entitled to sell) can be calculated by comparing the observed cumulative deforestation in the project area to either the project baseline (*ex-ante*) or the project synthetic control (*ex-post*) through 2020.

Country	Project ID	Observed deforestation in the project area (ha)	Observed deforestation in the synthetic control area (<i>ex-post</i> ; ha)	Project baseline deforestation* (<i>ex-ante</i> ; ha)	Expected carbon offsets based on projects' <i>ex-ante</i> baseline† (Mg CO ₂)	Expected carbon offsets per hectare of avoided deforestation (Mg CO ₂)	Evidence of significant reductions in deforestation‡	Avoided deforestation based on the synthetic control (ha)	Carbon offsets based on the synthetic control (Mg CO ₂)
Cambodia	904**	12,950	10,632	21,252	1,626,420	77	No	0	0
	1650	11,499	15,609	30,446	12,432,277	408	Yes	4,110	1,678,415
DRC	1359**	16,385	8,204	11,949	4,735,361	396	No	0	0
Tanzania	1325	11,318	9,756	10,578	359,834	34	No	0	0
	1900	16	14	11,407	348,019	31	No	0	0
	1897	14,161	13,577	35,472	1,406,892	40	No	0	0
TOTAL					88,951,394				5,393,108

* Reported by official project documents plus the cumulative post-2000 deforestation observed in the project site (see Table S6 for details).

** Projects with baselines ending before 2020 (e.g., 2018) were compared to their respective observed and synthetic control cumulative deforestation for the last available baseline year.

† Reported by official project documents.

‡ Based on the results from the synthetic control analyses and placebo tests.

Note: Projects 856 and 1390 from Colombia, 934 from DRC, 1748 from Cambodia, and the Zambian projects are excluded from this table due to insufficient public information about *ex-ante* baseline deforestation rates.

Table S6. Cumulative baseline and observed deforestation from the Global Forest Change dataset in the voluntary REDD+ project sites.

Country	Project ID	Observed cumulative deforestation in the project area in 2020 (ha)	Observed cumulative pre-project deforestation in the project area (ha)	Project cumulative baseline deforestation from project start to 2020* (<i>ex-ante</i>)		Project cumulative baseline deforestation in 2020 used in Table S5† (<i>ex-ante</i> ; ha)
				ha	Reference from the Project Description document†	
Peru	1882	403	252	1,016	Table 8	1,268
	2278	878	718	12,581	Table 40	13,299
	1067	4,070	1,988	11,893	Table 41	13,581
	958	3,391	1,749	1,525	Table 16	2,924
	944	5,454	2,843	20,842	Table 9.b	23,685
	844	699	60	125,501	Chart 25	125,561
Colombia	1400	334	268	12,157	Table 39	12,425
	1566	22,473	9,563	94,345	Table 61	103,908
	1396	693	659	7,417	Table 37	8,076
	1395	1,129	891	15,944	Table 37	16,835
	1392	105	89	10,633	Table 40	10,722
Cambodia	904	12,950	12	20,142	Table 43	21,252
	1650	11,499	2,142	28,304	Table 5.3b	30,446
DRC	1359	16,385	1,919	10,030	Section 5.3.5.1	11,949
Tanzania	1325	11,318	3,456	7,122	Table 9.b	10,578
	1900	16	7	11,400	Table 3.11	11,407
	1897	14,161	10,171	25,301	Table 3.10	35,472

* Reported by official project documents. For projects without baseline deforestation information for 2020, the latest baseline year was used.

† Sum of columns “Observed cumulative pre-project deforestation in the project area (ha)” and “Project cumulative baseline deforestation in 2020* (*ex-ante*; ha).”

Table S7. Generalized synthetic control (GSC) estimate of the average REDD+ effect of the *Peruvian projects* on annual deforestation rates based on the selected control areas from the individual synthetic controls.

Years relative to project implementation	Average REDD+ effect on forest loss (ATT*; %)	Standard error	Confidence interval		p-value	Number of operational projects
			Lower	Upper		
-7	0.0572	0.0173	0.0232	0.0911	0.001	0
-6	0.0098	0.0145	-0.0185	0.0381	0.4982	0
-5	0.0536	0.0202	0.0141	0.0931	0.0078	0
-4	0.0011	0.0223	-0.0426	0.0448	0.9599	0
-3	-0.0378	0.0243	-0.0854	0.0099	0.1202	0
-2	-0.0047	0.0233	-0.0504	0.041	0.8394	0
-1	-0.0272	0.025	-0.0763	0.0219	0.278	0
0	-0.073	0.0231	-0.1183	-0.0276	0.0016	0
1	-0.1741	0.0761	-0.3233	-0.025	0.0221	10
2	-0.1657	0.091	-0.3441	0.0127	0.0687	10
3	-0.222	0.0782	-0.3752	-0.0687	0.0045	10
4	-0.2918	0.142	-0.5701	-0.0135	0.0399	9
5	-0.2825	0.1647	-0.6053	0.0404	0.0864	9
6	-0.1683	0.1182	-0.3999	0.0634	0.1545	9
7	-0.1158	0.1377	-0.3856	0.1541	0.4005	9
8	-0.3672	0.1593	-0.6794	-0.055	0.0212	9
9	-0.2908	0.1978	-0.6785	0.0969	0.1415	8
10	-0.2992	0.2338	-0.7575	0.1591	0.2007	8
11	-0.0031	0.2694	-0.5312	0.5249	0.9908	6
12	-0.743	0.4552	-1.6352	0.1491	0.1026	3
Mean ATT*	-0.2362	0.1276	-0.4863	0.0140	0.0642	—

*Average treatment effect on the treated.

Table S8. Generalized synthetic control (GSC) estimate of the average REDD+ effect of the *Colombian projects* on annual deforestation rates based on the selected control areas from the individual synthetic controls.

Years relative to project implementation	Average REDD+ effect on forest loss (ATT*, %)	Standard error	Confidence interval		p-value	Number of operational projects
			Lower	Upper		
-9	0.0062	0.011	-0.0154	0.0277	0.5755	0
-8	-0.0145	0.0115	-0.037	0.008	0.2063	0
-7	0.0344	0.0146	0.0057	0.063	0.0188	0
-6	-0.028	0.0133	-0.0541	-0.0019	0.0358	0
-5	0.0052	0.0158	-0.0258	0.0362	0.7423	0
-4	0.0177	0.0188	-0.0192	0.0546	0.348	0
-3	-0.0141	0.0166	-0.0466	0.0184	0.3943	0
-2	-0.0049	0.015	-0.0344	0.0245	0.7422	0
-1	0.009	0.0161	-0.0226	0.0406	0.5762	0
0	0.0051	0.0111	-0.0167	0.0269	0.6462	0
1	0.0241	0.0221	-0.0191	0.0673	0.275	9
2	0.0147	0.0231	-0.0305	0.0599	0.5235	9
3	0.0044	0.0302	-0.0548	0.0636	0.8842	9
4	-0.0555	0.0551	-0.1635	0.0524	0.3134	9
5	-0.0609	0.0432	-0.1455	0.0237	0.1581	9
6	-0.1029	0.0608	-0.2221	0.0163	0.0908	9
7	-0.0502	0.0576	-0.163	0.0626	0.383	9
8	-0.0199	0.0884	-0.1931	0.1533	0.8218	7
9	0.0368	0.0897	-0.1391	0.2127	0.6816	1
10	0.2029	0.1432	-0.0777	0.4835	0.1564	1
Mean ATT*	-0.0269	0.0347	-0.0949	0.0412	0.4387	—

*Average treatment effect on the treated.

Table S9. Generalized synthetic control (GSC) estimate of the average REDD+ effect of the *African projects* on annual deforestation rates based on the selected control areas from the individual synthetic controls.

Years relative to project implementation	Average REDD+ effect on forest loss (ATT*, %)	Standard error	Confidence interval		p-value	Number of operational projects
			Lower	Upper		
-7	-0.0471	0.0288	-0.1036	0.0094	0.1024	0
-6	0.011	0.0245	-0.037	0.0591	0.6528	0
-5	0.0036	0.0378	-0.0705	0.0778	0.9233	0
-4	-0.0557	0.0273	-0.1093	-0.0022	0.0414	0
-3	-0.0863	0.0443	-0.1731	6.00E-04	0.0515	0
-2	-0.0123	0.0294	-0.07	0.0453	0.6748	0
-1	0.0548	0.0448	-0.0331	0.1427	0.2215	0
0	0.0494	0.0438	-0.0364	0.1353	0.2592	0
1	-0.095	0.0632	-0.2189	0.029	0.1332	9
2	-0.0996	0.0709	-0.2385	0.0393	0.16	9
3	0.1658	0.1547	-0.1374	0.469	0.2838	9
4	0.0678	0.1882	-0.301	0.4367	0.7185	9
5	-0.327	0.1805	-0.6808	0.0269	0.0701	8
6	-0.2612	0.1936	-0.6405	0.1182	0.1772	7
7	-0.2625	0.1551	-0.5665	0.0414	0.0905	4
8	-0.2069	0.3621	-0.9167	0.5029	0.5678	4
9	-0.4077	0.3698	-1.1325	0.317	0.2701	4
10	-0.2377	0.3431	-0.9102	0.4347	0.4884	4
11	-0.1772	0.2275	-0.6231	0.2686	0.4359	2
12	-0.392	0.2776	-0.936	0.1521	0.1579	2
Mean ATT*	-0.1365	0.1277	-0.3868	0.1139	0.2853	—

*Average treatment effect on the treated.

Table S10. Generalized synthetic control (GSC) estimate of the average REDD+ effect of the *Peruvian projects* on annual deforestation rates based on the selected control areas from the cardinality matching.

Years relative to project implementation	Average REDD+ effect on forest loss (ATT*, %)	Standard error	Confidence interval		p-value	Number of operational projects
			Lower	Upper		
-7	0.0309	0.0181	-0.0046	0.0665	0.0883	0
-6	0.0051	0.0139	-0.0221	0.0323	0.7154	0
-5	0.0316	0.0152	0.0019	0.0613	0.0372	0
-4	0.0209	0.0201	-0.0185	0.0603	0.299	0
-3	-0.0214	0.0211	-0.0628	0.02	0.3107	0
-2	-0.0135	0.0186	-0.05	0.0229	0.4662	0
-1	-0.0267	0.0185	-0.063	0.0096	0.1489	0
0	-0.0512	0.014	-0.0786	-0.0238	3.00E-04	0
1	-0.251	0.1068	-0.4603	-0.0418	0.0187	10
2	-0.2336	0.1759	-0.5784	0.1112	0.1843	10
3	-0.3255	0.1239	-0.5683	-0.0827	0.0086	10
4	-0.5057	0.1735	-0.8457	-0.1657	0.0036	9
5	-0.431	0.2256	-0.8731	0.0111	0.056	9
6	-0.2776	0.1427	-0.5573	0.0021	0.0518	9
7	-0.2785	0.1711	-0.6138	0.0568	0.1035	9
8	-0.5592	0.1823	-0.9165	-0.2019	0.0022	9
9	-0.4968	0.2063	-0.9012	-0.0924	0.016	8
10	-0.616	0.2154	-1.0383	-0.1937	0.0042	8
11	-0.4997	0.2907	-1.0694	0.0699	0.0855	6
12	-1.0382	0.5632	-2.1419	0.0656	0.0653	3
Mean ATT*	-0.4158	0.1456	-0.7012	-0.1305	0.0043	—

*Average treatment effect on the treated.

Table S11. Generalized synthetic control (GSC) estimate of the average REDD+ effect of the *Colombian projects* on annual deforestation rates based on the selected control areas from the cardinality matching.

Years relative to project implementation	Average REDD+ effect on forest loss (ATT*, %)	Standard error	Confidence interval		p-value	Number of operational projects
			Lower	Upper		
-9	0.0058	0.0071	-0.0081	0.0197	0.4148	0
-8	-0.0049	0.0069	-0.0185	0.0086	0.4759	0
-7	0.0107	0.0081	-0.0052	0.0265	0.1886	0
-6	-0.0158	0.0076	-0.0307	-8.00E-04	0.0388	0
-5	0.0086	0.007	-0.0052	0.0224	0.2219	0
-4	0.0027	0.0099	-0.0167	0.0222	0.7826	0
-3	-0.0114	0.0113	-0.0335	0.0107	0.311	0
-2	-0.0033	0.0055	-0.014	0.0075	0.5516	0
-1	0.0064	0.0108	-0.0147	0.0275	0.553	0
0	0.0019	0.0057	-0.0093	0.0131	0.7358	0
1	0.0493	0.0426	-0.0342	0.1328	0.247	9
2	0.0585	0.0401	-0.0201	0.1371	0.1447	9
3	-0.0065	0.0595	-0.123	0.1101	0.9136	9
4	-0.1328	0.1278	-0.3833	0.1178	0.299	9
5	-0.0181	0.0663	-0.148	0.1119	0.7853	9
6	-0.1195	0.1315	-0.3772	0.1381	0.3632	9
7	-0.02	0.0903	-0.197	0.1569	0.8243	9
8	0.0568	0.1568	-0.2506	0.3641	0.7174	7
9	0.1245	0.1177	-0.1062	0.3553	0.2902	1
10	0.3255	0.1602	0.0116	0.6395	0.0421	1
Mean ATT*	-0.0119	0.0711	-0.1514	0.1276	0.8676	—

*Average treatment effect on the treated.

Table S12. Generalized synthetic control (GSC) estimate of the average REDD+ effect of the *African projects* on annual deforestation rates based on the selected control areas from the cardinality matching.

Years relative to project implementation	Average REDD+ effect on forest loss (ATT*, %)	Standard error	Confidence interval		p-value	Number of operational projects
			Lower	Upper		
-7	-0.0969	0.0549	-0.2045	0.0106	0.0774	0
-6	0.0276	0.036	-0.043	0.0982	0.4433	0
-5	0.08	0.0779	-0.0728	0.2327	0.3048	0
-4	-0.0634	0.0367	-0.1354	0.0085	0.084	0
-3	-0.11	0.0667	-0.2407	0.0206	0.0988	0
-2	-0.0698	0.0474	-0.1627	0.0232	0.1411	0
-1	0.0824	0.0635	-0.0421	0.2069	0.1947	0
0	0.0713	0.0569	-0.0403	0.1829	0.2106	0
1	-0.1045	0.0822	-0.2656	0.0565	0.2034	9
2	-0.1252	0.078	-0.2782	0.0277	0.1084	9
3	0.1982	0.1779	-0.1504	0.5468	0.2652	9
4	0.0382	0.1685	-0.292	0.3684	0.8208	9
5	-0.4562	0.2804	-1.0057	0.0934	0.1037	8
6	-0.3284	0.2392	-0.7972	0.1404	0.1698	7
7	-0.2475	0.1985	-0.6365	0.1416	0.2125	4
8	-0.4255	0.541	-1.4858	0.6348	0.4316	4
9	-0.7224	0.5759	-1.8511	0.4063	0.2097	4
10	-0.4089	0.4655	-1.3213	0.5036	0.3798	4
11	-0.2354	0.2157	-0.6581	0.1874	0.2752	2
12	-0.5231	0.3531	-1.2151	0.1689	0.1384	2
Mean ATT*	-0.2059	0.1675	-0.5342	0.1223	0.2187	—

*Average treatment effect on the treated.

Appendix A. Optimized V-weights from the individual synthetic control (SC) analyses and covariate balance between the voluntary REDD+ project sites and SCs from 2001 to project implementation year (note: missing covariates indicate no covariate variation between the project and control areas).

Table A1. Covariate balance for Project 844 from Peru.

Covariate	V-weights	Project area	Synthetic control*	Control set average
Average tree cover (%)	8.04E-09	0.99	0.981	0.793
Indigenous land cover (%)	0.001062	0	0.006	0.154
Protected area cover (%)	8.04E-09	0	0.534	0.188
Mining concession cover (%)	0.803873	0	0	0.055
Slope (degree)	8.04E-09	2.271	2.302	10.413
Elevation (m)	0.000264	331.537	245.639	1027.763
Timber concession cover (%)	8.04E-09	1	0.406	0.091
Travel distance to urban centers (days)	8.04E-09	0.038	0.038	0.046
Average annual deforestation (ha)	0.025548	6.785	6.38	80.571
Average cumulative deforestation (ha)	0.088212	25.668	26.404	341.568
Annual precipitation (mm)	4.96E-06	1874	2325.915	2066.562
Average annual buffer deforestation (ha)	0.081035	139.75	139.745	121.91
Average cumulative buffer deforestation (ha)	8.04E-09	445.125	539.677	512.055

*Based on five control areas from a pre-subset pool of 142 potential donors.

Table A2. Covariate balance for Project 944 from Peru.

Covariate	V-weights	Project area	Synthetic control*	Control set average
Average tree cover (%)	5.92E-09	0.89	0.944	0.9
Indigenous land cover (%)	9.88E-05	0.011	0.444	0.157
Protected area cover (%)	5.92E-09	0.98	0.111	0.077
Mining concession cover (%)	1.36E-05	0	0.029	0.067
Slope (degree)	5.92E-09	17.249	12.561	8.849
Elevation (m)	5.92E-09	1751.28	1155.386	661.372
Timber concession cover (%)	5.59E-05	0	0.188	0.095
Travel distance to urban centers (days)	5.92E-09	0.076	0.064	0.049
Average annual deforestation (ha)	0.592404	304.811	297.826	1085.439
Average cumulative deforestation (ha)	0.407427	1069.94	1136.148	4490.298
Annual precipitation (mm)	5.92E-09	1208.125	1332.231	1799.905
Average annual buffer deforestation (ha)	5.92E-09	1444.625	899.245	1275.296
Average cumulative buffer deforestation (ha)	5.92E-09	5440.25	3678.49	5140.562

*Based on four control areas from a pre-subset pool of 54 potential donors.

Table A3. Covariate balance for Project 958 from Peru.

Covariate	V-weights	Project area	Synthetic control*	Control set average
Average tree cover (%)	9.30E-09	0.93	0.734	0.837
Indigenous land cover (%)	0.003971	0	0.088	0.196
Protected area cover (%)	9.30E-09	0	0.034	0.138
Slope (degree)	9.30E-09	23.243	20.099	10.722
Elevation (m)	9.30E-09	1831.213	2256.768	1061
Mining concession cover (%)	0.060823	0	0.021	0.063
Timber concession cover (%)	0.000219	1	0.202	0.088
Travel distance to urban centers (days)	0.003126	0.087	0.075	0.051
Average annual deforestation (ha)	9.30E-09	158.09	152.822	550.58
Average cumulative deforestation (ha)	0.929849	712.794	711.536	2803.392
Annual precipitation (mm)	9.30E-09	1139.8	1397.511	1830.01
Average annual buffer deforestation (ha)	9.30E-09	482.1	479.555	462.755
Average cumulative buffer deforestation (ha)	0.002012	2305	2425.142	2324.838

*Based on four control areas from a pre-subset pool of 40 potential donors.

Table A4. Covariate balance for Project 1067 from Peru.

Covariate	V-weights	Project area	Synthetic control*	Control set average
Average tree cover (%)	8.21E-09	0.98	0.985	0.844
Indigenous land cover (%)	8.21E-09	0.002	0.019	0.19
Protected area cover (%)	8.21E-09	0.939	0.014	0.141
Slope (degree)	8.21E-09	0.929	1.604	11.508
Elevation (m)	8.21E-09	234.969	186.731	1120.772
Mining concession cover (%)	8.21E-09	0.001	0	0.054
Timber concession cover (%)	8.21E-09	0.124	0.731	0.108
Travel distance to urban centers (days)	7.71E-06	0.038	0.039	0.052
Average annual deforestation (ha)	0.178866	154.182	176.482	1374.262
Average cumulative deforestation (ha)	0.821126	658.882	642.699	6784.841
Annual precipitation (mm)	8.21E-09	2825.3	3309.608	1841.981
Average annual buffer deforestation (ha)	8.21E-09	1172.9	705.164	972.285
Average cumulative buffer deforestation (ha)	8.21E-09	5819.4	3352.26	4756.742

*Based on two control areas from a pre-subset pool of 52 potential donors.

Table A5. Covariate balance for Project 1882 from Peru.

Covariate	V-weights	Project area	Synthetic control*	Control set average
Average tree cover (%)	5.60E-09	0.85	0.786	0.784
Indigenous land cover (%)	0.00013	0	0.017	0.165
Protected area cover (%)	5.60E-09	0	0.534	0.158
Slope (degree)	5.60E-09	26.758	22.674	10.985
Elevation (m)	1.98E-06	2855.566	2379.519	1091.892
Mining concession cover (%)	0.001249	0	0.002	0.064
Timber concession cover (%)	5.60E-09	1	0.038	0.099
Travel distance to urban centers (days)	2.72E-06	0.091	0.076	0.047
Average annual deforestation (ha)	0.216582	20.024	20.044	46.266
Average cumulative deforestation (ha)	0.221771	123.477	123.394	252.416
Annual precipitation (mm)	0.000116	1319.333	1416.252	2020.959
Average annual buffer deforestation (ha)	2.59E-05	115.333	109.498	107.616
Average cumulative buffer deforestation (ha)	0.560122	677	677.002	590.92

*Based on six control areas from a pre-subset pool of 101 potential donors.

Table A6. Covariate balance for Project 2278 from Peru.

Covariate	V-weights	Project area	Synthetic control*	Control set average
Average tree cover (%)	9.77E-09	0.99	0.965	0.862
Indigenous land cover (%)	0.977343	0	0	0.218
Protected area cover (%)	0.011434	0	0	0.133
Slope (degree)	9.77E-09	2.153	3.034	10.155
Elevation (m)	9.77E-09	361.254	452.229	949.285
Mining concession cover (%)	2.19E-06	0	0.034	0.06
Timber concession cover (%)	9.77E-09	1	0.954	0.122
Travel distance to urban centers (days)	0.006855	0.039	0.039	0.051
Average annual deforestation (ha)	0.000615	38.871	40.897	538.241
Average cumulative deforestation (ha)	0.003751	346.858	344.573	3803.924
Annual precipitation (mm)	1.76E-07	1980.765	3084.993	1891.379
Average annual buffer deforestation (ha)	9.77E-09	749.941	234.841	580.549
Average cumulative buffer deforestation (ha)	9.77E-09	5171.529	1287.853	4031.998

*Based on three control areas from a pre-subset pool of 172 potential donors.

Table A7. Covariate balance for Project 1360-2 from Peru.

Covariate	V-weights	Project area	Synthetic control*	Control set average
Average tree cover (%)	9.99E-09	0.99	1	0.916
Indigenous land cover (%)	9.99E-09	0.998	0.349	0.226
Protected area cover (%)	4.07E-06	0	0.001	0.114
Mining concession cover (%)	0.998817	0	0	0.031
Slope (degree)	9.99E-09	0.634	1.723	8.815
Elevation (m)	2.42E-07	169	197.704	738.592
Timber concession cover (%)	9.99E-09	0.001	0	0.133
Travel distance to urban centers (days)	9.99E-09	0.037	0.038	0.051
Average annual deforestation (ha)	7.01E-05	1.859	1.58	66.026
Average cumulative deforestation (ha)	0.001108	5.266	5.405	300.644
Annual precipitation (mm)	9.99E-09	1625.778	2156.448	1947.459
Average annual buffer deforestation (ha)	9.99E-09	292	213.611	282.821
Average cumulative buffer deforestation (ha)	9.99E-09	1307.667	932.363	1270.729

*Based on two control areas from a pre-subset pool of 46 potential donors.

Table A8. Covariate balance for Project 1360-3 from Peru.

Covariate	V-weights	Project area	Synthetic control*	Control set average
Average tree cover (%)	1.00E-08	0.99	0.977	0.906
Indigenous land cover (%)	1.00E-08	0.989	0.203	0.171
Protected area cover (%)	0.99986	0	0	0.024
Mining concession cover (%)	1.00E-08	0	0.821	0.117
Slope (degree)	1.00E-08	0.726	4.336	7.854
Elevation (m)	1.00E-08	183.504	412.574	578.512
Timber concession cover (%)	1.00E-08	0	0.431	0.134
Travel distance to urban centers (days)	5.65E-08	0.037	0.042	0.046
Average annual deforestation (ha)	0.00014	7.757	9.204	89.47
Average cumulative deforestation (ha)	1.00E-08	25.114	44.374	410.975
Annual precipitation (mm)	1.00E-08	1641.556	4526.388	2305.322
Average annual buffer deforestation (ha)	1.00E-08	491.333	458.916	477.606
Average cumulative buffer deforestation (ha)	1.00E-08	1545.556	2017.51	2184.875

*Based on two control areas from a pre-subset pool of 40 potential donors.

Table A9. Covariate balance for Project 856 from Colombia.

Covariate	V-weights	Project area	Synthetic control*	Control set average
Average tree cover (%)	3.40E-06	0.95	0.92	0.617
Indigenous land cover (%)	1.00E-08	0.003	0	0.049
Protected area cover (%)	4.67E-08	0.961	0.802	0.102
Slope (degree)	1.00E-08	14.87	8.946	5.207
Elevation (m)	1.00E-08	443.552	643.577	447.091
Travel distance to urban centers (days)	1.63E-07	0.061	0.054	0.025
Average annual deforestation (ha)	0.999609	13.448	13.448	49.997
Average cumulative deforestation (ha)	0.000388	58.197	58.621	293.955
Annual precipitation (mm)	1.15E-07	2837.455	2745.287	2667.147
Average annual buffer deforestation (ha)	1.00E-08	332	302.966	319.368
Average cumulative buffer deforestation (ha)	4.48E-08	1819.091	1610.866	1883.188

*Based on six control areas from a pre-subset pool of 62 potential donors.

Table A10. Covariate balance for Project 1390 from Colombia.

Covariate	V-weights	Project area	Synthetic control*	Control set average
Average tree cover (%)	4.94E-09	0.94	0.967	0.576
Indigenous land cover (%)	4.94E-09	0.002	0.001	0.106
Protected area cover (%)	4.94E-09	0	0.626	0.133
Slope (degree)	2.34E-06	0.936	1.834	8.9
Elevation (m)	1.14E-07	23.101	255.41	1009.857
Mining concession cover (%)	0.494015	0	0	0.002
Travel distance to urban centers (days)	0.494015	0.038	0.037	0.032
Average annual deforestation (ha)	0.000999	28.59	28.374	178.222
Average cumulative deforestation (ha)	0.010968	161.489	161.673	1284.22
Annual precipitation (mm)	4.94E-09	4587	2662.707	2352.755
Average annual buffer deforestation (ha)	4.94E-09	235.231	196.72	233.208
Average cumulative buffer deforestation (ha)	4.94E-09	1595.692	1247.988	1688.764

*Based on four control areas from a pre-subset pool of 109 potential donors.

Table A11. Covariate balance for Project 1391 from Colombia.

Covariate	V-weights	Project area	Synthetic control*	Control set average
Average tree cover (%)	1.73E-05	0.98	0.977	0.623
Indigenous land cover (%)	1.00E-08	0.007	0.619	0.293
Protected area cover (%)	1.00E-08	0.513	0	0.16
Slope (degree)	1.00E-08	4.314	1.661	6.757
Elevation (m)	1.79E-06	56.516	120.435	1020.077
Palm oil concession cover (%)	1.00E-08	0.166	0	0.005
Mining concession cover (%)	0.999972	0	0	0.013
Travel distance to urban centers (days)	1.00E-08	0.039	0.038	0.036
Average annual deforestation (ha)	2.09E-06	14.192	12.819	21.904
Average cumulative deforestation (ha)	6.72E-06	55.714	60.846	141.402
Annual precipitation (mm)	1.00E-08	6758.25	4982.011	2918.984
Average annual buffer deforestation (ha)	1.00E-08	52.5	47.307	52.257
Average cumulative buffer deforestation (ha)	1.00E-08	237.833	288.669	341.149

*Based on two control areas from a pre-subset pool of 58 potential donors.

Table A12. Covariate balance for Project 1392 from Colombia.

Covariate	V-weights	Project area	Synthetic control*	Control set average
Average tree cover (%)	0.352179	0.98	0.98	0.981
Indigenous land cover (%)	3.52E-09	0	0.694	0.715
Protected area cover (%)	3.49E-06	0.014	0.042	0.224
Slope (degree)	3.52E-09	6.369	3.064	2.386
Elevation (m)	4.10E-08	65.338	148.735	171.273
Travel distance to urban centers (days)	0.301659	0.039	0.039	0.039
Average annual deforestation (ha)	2.53E-05	6.984	7.104	6.035
Average cumulative deforestation (ha)	4.99E-05	42.199	41.857	35.302
Annual precipitation (mm)	7.44E-09	5160.333	4037.512	3548.618
Average annual buffer deforestation (ha)	7.49E-07	13.75	13.501	14.216
Average cumulative buffer deforestation (ha)	0.346083	66.833	66.833	86.361

*Based on eight control areas from a pre-subset pool of 46 potential donors.

Table A13. Covariate balance for Project 1395 from Colombia.

Covariate	V-weights	Project area	Synthetic control*	Control set average
Average tree cover (%)	1.63E-05	0.98	0.971	0.895
Indigenous land cover (%)	1.00E-08	0	0.495	0.366
Protected area cover (%)	1.52E-06	0.279	0.257	0.119
Slope (degree)	1.00E-08	2.891	3.931	7.186
Elevation (m)	1.00E-08	53.587	230.951	858.956
Palm oil concession cover (%)	1.00E-08	0.377	0.005	0.016
Mining concession cover (%)	0.999953	0	0	0.023
Travel distance to urban centers (days)	1.00E-08	0.038	0.041	0.045
Average annual deforestation (ha)	1.66E-05	72.962	69.522	60.188
Average cumulative deforestation (ha)	1.27E-05	352.45	379.959	378.28
Annual precipitation (mm)	2.57E-08	6213.583	3273.178	3018.375
Average annual buffer deforestation (ha)	1.00E-08	123.667	127.313	123.177
Average cumulative buffer deforestation (ha)	1.35E-07	552.833	740.151	798.288

*Based on three control areas from a pre-subset pool of 50 potential donors.

Table A14. Covariate balance for Project 1396 from Colombia.

Covariate	V-weights	Project area	Synthetic control*	Control set average
Average tree cover (%)	3.83E-09	0.98	0.958	0.911
Indigenous land cover (%)	3.63E-07	0.001	0.009	0.095
Protected area cover (%)	0.383205	0	0	0.225
Slope (degree)	3.83E-09	3.318	7.137	11.62
Elevation (m)	3.83E-09	48.842	501.921	836.012
Mining concession cover (%)	0.383205	0	0	0.007
Palm oil concession cover (%)	1.05E-07	0.018	0.037	0.032
Travel distance to urban centers (days)	3.83E-09	0.039	0.05	0.056
Average annual deforestation (ha)	0.197691	47.55	47.55	106.77
Average cumulative deforestation (ha)	0.035898	269.257	269.255	775.306
Annual precipitation (mm)	3.83E-09	7466.846	3898.415	2812.821
Average annual buffer deforestation (ha)	8.02E-08	297	263.905	279.438
Average cumulative buffer deforestation (ha)	5.35E-07	1755.308	1813.711	1993.859

*Based on six control areas from a pre-subset pool of 36 potential donors.

Table A15. Covariate balance for Project 1400 from Colombia.

Covariate	V-weights	Project area	Synthetic control*	Control set average
Average tree cover (%)	6.41E-09	0.97	0.932	0.962
Indigenous land cover (%)	0.641418	0.041	0.041	0.335
Protected area cover (%)	3.15E-07	0.5	0.627	0.169
Slope (degree)	5.54E-07	2.812	9.918	5.887
Elevation (m)	6.41E-09	50.619	1452.192	440.685
Mining concession cover (%)	6.41E-09	0	0.064	0.016
Palm oil concession cover (%)	6.41E-09	0.18	0.002	0.051
Travel distance to urban centers (days)	6.41E-09	0.038	0.059	0.046
Average annual deforestation (ha)	0.00018	20.939	18.011	48.804
Average cumulative deforestation (ha)	0.000693	88.433	97.038	334.993
Annual precipitation (mm)	6.41E-09	7152.667	2997.049	3390.871
Average annual buffer deforestation (ha)	4.26E-06	131.5	124.019	132.004
Average cumulative buffer deforestation (ha)	0.357703	646.417	646.418	847.776

*Based on five control areas from a pre-subset pool of 38 potential donors.

Table A16. Covariate balance for Project 1566 from Colombia.

Covariate	V-weights	Project area	Synthetic control*	Control set average
Average tree cover (%)	1.15E-08	0.85	0.579	0.507
Indigenous land cover (%)	1.67E-08	0.901	0.248	0.133
Protected area cover (%)	1.13E-06	0	0.056	0.122
Slope (degree)	0.429012	1.076	1.076	5.679
Elevation (m)	0.013463	128.519	129.135	752.092
Mining concession cover (%)	0.157795	0.002	0.002	0.002
Travel distance to urban centers (days)	4.29E-09	0.037	0.024	0.022
Average annual deforestation (ha)	0.000172	732.768	736.774	2167.316
Average cumulative deforestation (ha)	0.000748	4694.777	4696.716	13801.74
Annual precipitation (mm)	0.398809	2828	2827.999	2482.57
Average annual buffer deforestation (ha)	9.34E-07	653.75	603.469	665.963
Average cumulative buffer deforestation (ha)	4.29E-09	4758.5	3876.692	4279.342

*Based on nine control areas from a pre-subset pool of 146 potential donors.

Table A17. Covariate balance for Project 934 from the Democratic Republic of Congo.

Covariate	V-weights	Project area	Synthetic control*	Control set average
Average tree cover (%)	2.22E-08	0.89	0.589	0.639
Protected area cover (%)	0.835655	0	0	0.091
Slope (degree)	8.36E-09	0.787	2.623	2.361
Elevation (m)	8.36E-09	319.012	903.379	713.075
Mining concession cover (%)	3.62E-08	0	0.642	0.441
Indigenous land cover (%)	8.36E-09	0.697	0.016	0.25
Logging concession cover (%)	1.28E-08	1	0	0.051
REDD+ jurisdiction or other conservation program(s) cover (%)	3.21E-08	1	0.094	0.184
Travel distance to urban centers (days)	8.36E-09	0.038	0.022	0.024
Average annual deforestation (ha)	4.88E-06	797.509	764.554	360.083
Average cumulative deforestation (ha)	0.16434	3506.279	3506.282	1766.389
Annual precipitation (mm)	7.75E-08	1691.8	1380.623	1501.567
Average annual buffer deforestation (ha)	8.36E-09	294.2	329.185	291.748
Average cumulative buffer deforestation (ha)	8.36E-09	1345.8	1479.023	1429.909

*Based on four control areas from a pre-subset pool of 166 potential donors.

Table A18. Covariate balance for Project 1359 from the Democratic Republic of Congo.

Covariate	V-weights	Project area	Synthetic control*	Control set average
Average tree cover (%)	1.00E-08	1	0.981	0.83
Protected area cover (%)	7.82E-05	0	0.255	0.013
Slope (degree)	1.00E-08	1.522	4.072	2.732
Elevation (m)	0.000153	432.489	631.843	556.565
Mining concession cover (%)	1.00E-08	0.006	0.396	0.575
Indigenous land cover (%)	1.00E-08	0	0.133	0.206
Logging concession cover (%)	1.00E-08	1	0	0.095
REDD+ jurisdiction or other conservation program(s) cover (%)	6.64E-05	0.052	0.791	0.297
Travel distance to urban centers (days)	1.00E-08	0.039	0.042	0.034
Average annual deforestation (ha)	1.00E-08	196.545	213.683	1378.81
Average cumulative deforestation (ha)	0.999703	932.066	942.98	5828.416
Annual precipitation (mm)	1.00E-08	1728.75	1727.138	1516.734
Average annual buffer deforestation (ha)	1.00E-08	2367.125	1309.851	1538.826
Average cumulative buffer deforestation (ha)	1.00E-08	11344.88	6596.921	6608.888

*Based on three control areas from a pre-subset pool of 48 potential donors.

Table A19. Covariate balance for Project 1325 from Tanzania.

Covariate	V-weights	Project area	Synthetic control*	Control set average
Average tree cover (%)	5.47E-09	0.51	0.421	0.262
Protected area cover (%)	0.387054	0.176	0.176	0.247
Slope (degree)	5.47E-09	3.681	3.611	1.679
Elevation (m)	1.12E-06	313.465	485.775	808.852
Mining concession cover (%)	5.47E-09	0.086	0.036	0.031
Travel distance to urban centers (days)	0.54697	0.014	0.014	0.011
Average annual deforestation (ha)	2.34E-07	314.2	322.122	385.374
Average cumulative deforestation (ha)	4.72E-05	1689.107	1691.01	1968.003
Annual precipitation (mm)	4.36E-06	948	956.914	924.771
Average annual buffer deforestation (ha)	4.47E-06	807	803.258	752.509
Average cumulative buffer deforestation (ha)	0.065919	4272.727	4272.727	3816.71

*Based on eight control areas from a pre-subset pool of 75 potential donors.

Table A20. Covariate balance for Project 1897 from Tanzania.

Covariate	V-weights	Project area	Synthetic control*	Control set average
Average tree cover (%)	0.000103	0.5	0.325	0.258
Slope (degree)	0.589418	5.122	5.117	2.198
Elevation (m)	4.72E-05	1389.528	1319.223	934.263
Mining concession cover (%)	5.89E-09	0.044	0.001	0.016
Travel distance to urban centers (days)	5.89E-09	0.016	0.015	0.012
Average annual deforestation (ha)	5.89E-09	481.319	475.931	706.79
Average cumulative deforestation (ha)	0.377348	2574.946	2588.453	5184.995
Annual precipitation (mm)	0.011534	1101.062	1113.8	903.495
Average annual buffer deforestation (ha)	5.89E-09	751.375	814.131	740.75
Average cumulative buffer deforestation (ha)	0.02155	3662.5	3713.207	5446.848

*Based on four control areas from a pre-subset pool of 83 potential donors.

Table A21. Covariate balance for Project 1900 from Tanzania.

Covariate	V-weights	Project area	Synthetic control*	Control set average
Average tree cover (%)	0.333299	0.1	0.1	0.156
Protected area cover (%)	0.333299	1	1	0.581
Slope (degree)	3.74E-05	0.804	0.804	2.526
Elevation (m)	3.33E-09	1172.476	1109.468	1068.004
Mining concession cover (%)	3.33E-09	0	0.041	0.028
Travel distance to urban centers (days)	0.333299	0.014	0.014	0.014
Average annual deforestation (ha)	3.33E-09	0.441	0.778	26.448
Average cumulative deforestation (ha)	6.65E-05	4.327	5.061	241.384
Annual precipitation (mm)	3.33E-09	551.562	581.125	779.517
Average annual buffer deforestation (ha)	3.33E-09	23.188	22.812	22.856
Average cumulative buffer deforestation (ha)	3.33E-09	147.75	107.062	196.002

*Based on one control area from a pre-subset pool of 90 potential donors.

Table A22. Covariate balance for Project 1202 from Zambia.

Covariate	V-weights	Project area	Synthetic control*	Control set average
Average tree cover (%)	0.002879	0.24	0.24	0.254
Protected area cover (%)	7.83E-09	0.128	0.87	0.286
Slope (degree)	3.39E-05	4.378	2.122	1.276
Elevation (m)	7.83E-09	1093.45	925.286	1179.245
Travel distance to urban centers (days)	7.83E-09	0.015	0.015	0.013
Average annual deforestation (ha)	0.050949	4.716	4.716	40.79
Average cumulative deforestation (ha)	0.162489	26.411	26.351	152.984
Annual precipitation (mm)	0.783331	859.875	859.875	1070.829
Average annual buffer deforestation (ha)	0.000318	109.875	98.997	109.381
Average cumulative buffer deforestation (ha)	7.83E-09	530.375	328.277	398.26

*Based on six control areas from a pre-subset pool of 74 potential donors.

Table A23. Covariate balance for Project 1775-2 from Zambia.

Covariate	V-weights	Project area	Synthetic control*	Control set average
Average tree cover (%)	9.75E-09	0.26	0.592	0.247
Protected area cover (%)	0.017502	0.995	0.975	0.199
Slope (degree)	9.75E-09	2.384	1.153	1.215
Elevation (m)	9.75E-09	697.335	1175.69	1202.202
Travel distance to urban centers (days)	0.974804	0.014	0.014	0.012
Average annual deforestation (ha)	9.75E-09	29.063	21.558	305.833
Average cumulative deforestation (ha)	0.007695	75.096	109.56	1808.967
Annual precipitation (mm)	9.75E-09	948.643	1214.721	1109.714
Average annual buffer deforestation (ha)	9.75E-09	331.786	299.896	333.088
Average cumulative buffer deforestation (ha)	9.75E-09	2034.071	2073.964	1936.154

*Based on two control areas from a pre-subset pool of 115 potential donors.

Table A24. Covariate balance for Project 1775-3 from Zambia.

Covariate	V-weights	Project area	Synthetic control*	Control set average
Average tree cover (%)	9.99E-09	0.2	0.423	0.198
Slope (degree)	5.76E-07	1.186	1.043	1.095
Elevation (m)	9.99E-09	657.042	1182.804	1001.683
Travel distance to urban centers (days)	9.99E-09	0.013	0.014	0.014
Average annual deforestation (ha)	0.99903	11.275	11.275	106.349
Average cumulative deforestation (ha)	0.000968	59.63	60.052	685.327
Annual precipitation (mm)	9.99E-09	911	1224.422	976.04
Average annual buffer deforestation (ha)	2.04E-08	110.714	117.908	111.107
Average cumulative buffer deforestation (ha)	1.32E-06	678.714	672.593	706.651

*Based on four control areas from a pre-subset pool of 70 potential donors.

Table A25. Covariate balance for Project 904 from Cambodia.

Covariate	V-weights	Project area	Synthetic control*	Control set average
Average tree cover (%)	0.000498	0.42	0.477	0.399
Protected area cover (%)	0.157606	0.443	0.442	0.169
Slope (degree)	8.35E-09	0.869	2.147	1.477
Elevation (m)	8.35E-09	69.484	106.046	96.806
Mining concession cover (%)	0.00411	0.153	0.116	0.125
Soil fertility level	8.35E-09	1.75	1.888	2.157
Other economic concessions cover (%)	0.002572	0.025	0.127	0.119
Travel distance to urban centers (days)	0.000616	0.012	0.017	0.005
Average annual deforestation (ha)	8.35E-09	147.463	152.14	1163.323
Average cumulative deforestation (ha)	0.834598	467.113	482.857	4554.692
Annual precipitation (mm)	8.35E-09	1407.286	1844.49	1824.241
Average annual buffer deforestation (ha)	8.35E-09	2541	1755.709	2107.064
Average cumulative buffer deforestation (ha)	8.35E-09	8162.571	6316.207	8230.669

*Based on five control areas from a pre-subset pool of 51 potential donors.

Table A26. Covariate balance for Project 1650 from Cambodia.

Covariate	V-weights	Project area	Synthetic control*	Control set average
Average tree cover (%)	0.000498	0.73	0.76	0.679
Protected area cover (%)	0.157606	0.97	0.732	0.677
Slope (degree)	8.35E-09	2.566	1.155	2.268
Elevation (m)	8.35E-09	197.462	86	144.59
Mining concession cover (%)	0.00411	0.736	0.208	0.248
Soil fertility level	8.35E-09	1.714	2	2.069
Other economic concessions cover (%)	0.002572	0.005	0.159	0.197
Travel distance to urban centers (days)	0.000616	0.014	0.037	0.024
Average annual deforestation (ha)	8.35E-09	214.199	232.645	1338.094
Average cumulative deforestation (ha)	0.834598	993.492	1135.273	5807.584
Annual precipitation (mm)	8.35E-09	2124.5	1800.2	1850.923
Average annual buffer deforestation (ha)	8.35E-09	3167.3	1343	1687.065
Average cumulative buffer deforestation (ha)	8.35E-09	12213.2	5575.8	7342.892

*Based on one control area from a pre-subset pool of 26 potential donors.