

REDD+ project baselines accurately correspond with observed forest loss globally

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Abstract

The REDD+ (Reducing Emissions from Deforestation and Forest Degradation) mechanism has shown promise as a climate mitigation strategy, yet concerns persist regarding project baseline estimates. Studies have suggested that REDD+ projects overestimate baselines, resulting in over-crediting and exaggerated climate impacts. This study introduces a new approach to assessing REDD+ avoided unplanned deforestation (AUD) baselines on a global scale, by comparing them with observed forest loss in surrounding jurisdictions. Analyzing 45 projects representing 71% of verified AUD projects by area and 63% of total AUD verified emissions reductions, we compare normalized baseline deforestation rates with actual jurisdiction-level forest loss between 2002–2022. Integrated across this time period, our findings demonstrate that net REDD+ baseline deforestation rates ($0.70 \pm 0.12\%/year$) correspond closely with observed jurisdictional forest loss ($0.71 \pm 0.24\%/year$), although country- and project-level results show significant variability, with Colombia project baselines exceeding observed forest loss and Madagascar project baselines below observed forest loss. Overall, REDD+ projects had an annual forest loss of $0.07 \pm 0.02\%/year$, a factor ten lower than either baseline or observed jurisdiction-average forest loss. These findings contrast with other studies, suggesting that at a systemic level, emissions reductions from the voluntary project-based REDD+ mechanism have been robust.

Keywords: REDD+, avoided unplanned deforestation, baseline assessment, emissions reduction, global scale, data uncertainties, climate change mitigation.

Introduction

Deforestation contributes 1.8 billion tonnes of carbon emissions (Gt CO₂e) per annum¹, much of which is occurring in the tropics², driven by commodities and shifting agriculture³. This compares to 10Gt CO₂e from fossil fuel burning emissions¹. Recent projections suggest that if current population, consumption and demand trends continue, another 25% of natural ecosystems could be converted by 2050 releasing more than 40Gt CO₂e into the atmosphere prior to 2030^{4,5}, by which time the signatories to the Glasgow Leaders' Declaration on Forests and Land Use - 145 nations, covering over 90% of the Earth's forest cover - have committed to halting forest loss⁶. It is clear that effective action must be vastly scaled in a short period of time if there is to be any realistic chance of curbing deforestation in line with these commitments.

REDD+ (*reducing emissions from deforestation and forest degradation*) is an established voluntary market-based mechanism used to safeguard at-risk tropical forests⁷⁻¹¹. REDD+ crediting systems are designed to enable results-based payments to flow to forest stakeholders by incentivizing forest protection over deforestation⁵. Voluntary market-supported REDD+ has grown substantially in recent years, with annual corporate retirements of REDD+ verified carbon units (VCUs) increasing by 1,180% between 2015-2021, from 5M tCO₂e to 64M tCO₂e¹². While the scale of the market remains small relative to the full extent of global deforestation, these growth rates suggest the potential to expand within this decade to a magnitude approaching the full scale of the problem.

REDD+ VCUs are generated when projects registered under a voluntary crediting system such as the Verified Carbon Standard (VCS) are verified, through third-party audits, to have reduced forest loss and emissions against a counterfactual “baseline” or business as usual (BAU) scenario. The VCS is a global, ISO-accredited standard for GHG emissions reductions and removal projects, with underlying methodologies developed by technical experts and independently reviewed and audited prior to release¹³. Under VCS, REDD+ baselines are established by estimating BAU deforestation and resulting GHG emissions scenarios using a

control area (“Reference Area”, RA) that is statistically matched to the REDD+ site (REDD+ “Project Area”, PrA) prior to intervention, based on the application of detailed methodological protocols that must be validated through third-party independent audit. Since baseline predictions establish an upper bound on the quantity of REDD+ VCUs that can be generated, monetized by REDD+ projects, and purchased by companies to make claims relative to “net zero” and similar public-facing climate commitments, investigating REDD+ baselines is an important area of research.

At a fundamental level, it is impossible to fully “validate” a baseline in retrospect, simply because by definition a counterfactual scenario is what did not happen where an intervention has taken place. Therefore, REDD+ baseline research aims to assess, in hindsight, the reasonableness of the without-project BAU forest loss scenarios against which REDD+ projects aim to perform, in light of forest loss that has taken place in some comparison or control area. This area of research remains relatively new, and there is neither a generally accepted scientific standard for what constitutes a “good” baseline when evaluated in retrospect, nor a generally accepted approach for establishing a valid comparison area against which to evaluate a baseline scenario.

Two recent studies of REDD+ baselines have applied a Synthetic Control Method (SCM) to identify REDD+ control sites by matching REDD+ project area geospatial data variables with other areas of land within the same country^{14,15}, then evaluating the statistical correspondence between control site deforestation, project area deforestation, and predicted baseline deforestation. These studies have concluded that REDD+ project baselines generally overstate the forest protection and emissions reduction impacts of the interventions, calling into question the efficacy of the REDD+ mechanism as a whole. However, these studies have also sparked criticism, focused on inappropriate matching and control selection, inadequate communication of modeling and geospatial errors, and other methodological and analytic issues¹⁶⁻¹⁹.

Here we present a new, simpler approach to assessing REDD+ avoided unplanned deforestation (AUD) baselines on a global scale, which avoids the difficulties of control area matching entirely. Instead, we compare the predicted forest loss rates of REDD+ baseline scenarios with the actual forest loss rates observed in the jurisdictions surrounding the REDD+ projects (i.e., legal districts or regions containing the projects).

Beyond the problems of establishing a valid control using the SCM discussed above, in any small-scale control area selected (including those matched previously in West et al. 2020¹⁴, 2023¹⁵) forest loss may occur faster or slower than predicted within the context of the deforestation drivers that are present in the broader landscape. By taking jurisdiction-level forest loss as our basis of comparison, we avoid the numerous problems associated with establishing a valid small-scale control while also providing a more complete view of the actual threat level in the landscapes surrounding REDD+ projects.

Based on this approach, and utilizing the same open-source global forest loss dataset as applied in recent baseline studies¹⁵, we assess: (1) how REDD+ baseline projections compare to actual observed forest loss in surrounding jurisdictions over a twenty-year period (2002-2022), and (2) how actual forest loss in REDD+ areas compares to forest loss within the surrounding jurisdictions, and to the REDD+ baselines against which project crediting performance is assessed.

Methods

Data Collection

REDD+ projects were selected for analysis from the VCS Registry

(<https://registry.terra.org/app/search/VCS>) with the following criteria: (1) REDD+ avoided unplanned deforestation, (2) at least four years of forest loss data available since project start date (most recent start date included: 2017), (3) registered, validated and verified to the VCS Standard, (4) excluding dryland forests due to limitations in the accuracy of open source forest cover and forest loss datasets in drylands^{20,21}.

A total of 50 registered REDD+ projects from 7 countries (Peru, Colombia, Cambodia, Brazil, Guatemala and Madagascar) were originally selected from the VCS Registry. A further 5 projects were removed from the subset as they had not yet verified their first credits.

Altogether, application of the selection criteria resulted in a total of 45 projects covering 10,198,521ha, representing over 71% of all AUD project area and 63% of total AUD verified emissions reductions (Supplementary Table 1).

Early projects (2002-2010) were predominantly located in Brazil, Madagascar, and Peru.

Following a significant expansion of REDD+ development from 2012 onward, this subset grew to include the additional 4 countries, with the majority remaining in South America followed by Africa and then Southeast Asia; Peru (3,466,342ha; 36.8%), Colombia (1,652,844ha; 17.2%), Brazil (2,209,109ha; 23.0%), Cambodia (700,613ha; 7.3%), Madagascar (865,304ha; 9.2%) and Guatemala (636,976ha; 6.6%) (Figure 1).

Project metadata was collected from the VCS database, including ID, project area, start year, relevant state/province, project area shapefiles (.kml), total emissions reductions, total buffer pool contributions, global buffer pool releases and baseline deforestation rate. The baseline deforestation rate was collected from the project description document and averaged up to 2022 (the final study year) or for the first 10 years of the project. Most projects only projected

for the first baseline period (10 years), however, in cases when the entire project period was estimated only the first 10 years were used.

State/province-level tree cover loss data were collected from Hansen et al. (2013)²², available at: <https://glad.earthengine.app/view/global-forest-change>. Analysis of total tree cover loss per year was undertaken in QGIS (version 3.28.0). The error in the forest loss was predicted based on results from Tyukavina et al. (2015)²³ which are set at a national level, resulting in a range of potential forest loss for the state/province and project areas over the relevant periods.

Comparative Analysis

All together, the average baseline deforestation rates of the analyzed projects were compared to the average actual REDD+ provincial/state forest loss on national and global levels. This analysis was undertaken both on an annual level (Supplementary Information) and integrated across the entire study period (2002–2022). Adjustments were also made to the project baseline deforestation rates (taking into account the effect of buffer contributions) and actual forest loss rates in jurisdictions and REDD+ projects (taking into account the effect of leakage forest loss) to more accurately reflect carbon accounting procedures and potential conservation spillover, respectively.

The baseline deforestation rates for each project were integrated on a country level on an annual basis, based on the weighted average proportional (%) area of each REDD+ project within the country of question each year. For example, if Project A covered 50% of the total REDD+ area in Peru in 2010, then the Peru average 2010 REDD+ baseline would be 50% weighted by the Project A baseline (Equation 1).

$$vb_j = \left(vb_1 \times \frac{A_1}{A_j} \right) + \left(vb_2 \times \frac{A_2}{A_j} \right) + \left(vb_3 \times \frac{A_3}{A_j} \right) + \dots \left(vb_x \times \frac{A_x}{A_j} \right) \quad \text{Equation 1}$$

Where vb_j represents the weighted average baseline deforestation rate of all the projects studied within the country in a single year, $vb_{1,2,3...x}$ represents the project-level baseline deforestation rates of x number of individual projects and A denotes the total area of all REDD+ projects operating within the country (A_j) and the area of each individual project ($A_{1,2,3...x}$). This was calculated each year from 2002–2022 and integrated globally across the entire study period to estimate the total 20-year weighted average baseline deforestation rate for the full set of projects (gvb_j).

The national REDD+ jurisdictional (NRJ) area was defined as the total area of the states/provinces housing the analyzed REDD+ projects within a given country. In cases where an analyzed REDD+ project occupied a large portion (>40%) of the state/province, adjacent states were included in the analysis. The geospatial bounds of the REDD+ project areas (PrAs) were removed from the jurisdictional area to ensure REDD+ interventions were compared to surrounding non-REDD+ forests. The area of each NRJ expanded over time as new projects were added from different provinces/states. For each country studied, the annual average forest loss for its NRJ area was calculated based on state/province rates of forest loss, weighted by the % of that country's total REDD+ project area contained in each province/state for that year. For example, if 70% of the REDD+ project area in Peru was located in Madre de Dios (MDD) state in 2010, annual forest loss for Peru's NRJ in 2010 would be 70% attributed to MDD (Equation 2).

$$vd_{nrj} = \left(vd_1 \times \frac{A_i}{A_{nrj}} \right) + \left(vd_2 \times \frac{A_{ii}}{A_{nrj}} \right) + \left(vd_3 \times \frac{A_{iii}}{A_{nrj}} \right) + \dots \left(vd_x \times \frac{A_{xx}}{A_{nrj}} \right) \quad \text{Equation 2}$$

Where vd_{nrj} represents the average deforestation rate of the NRJ in a single year, $vd_{1,2,3...xx}$ represents the state/province deforestation rates of x number of states/provinces, and A denotes the national REDD+ jurisdictional area (A_{nrj}) and the total area of states/provinces containing active projects ($A_{i,ii,iii...xx}$) excluding the project area sites. This was calculated each

year from 2002–2022. All of the NRJs were averaged using the same weighting approach to approximate the global NRJ (gNRJ) deforestation rate (vd_{gNRJ}); the gNRJ was calculated on an annual basis and averaged across the entire study period (2002–2022)

The overall, weighted average annual forest loss for the REDD+ project area contained within each NRJ was calculated by normalizing the % of REDD+ project area operating in that year (Equation 3).

$$vd_r = \left(vdr_1 \times \frac{Ar_i}{A_r} \right) + \left(vdr_2 \times \frac{Ar_{ii}}{A_r} \right) + \left(vdr_3 \times \frac{Ar_{iii}}{A_r} \right) + \dots \left(vdr_x \times \frac{Ar_{xx}}{A_r} \right) \quad \text{Equation 3}$$

Where vd_r represents the average deforestation rate of the project area in a single year, $vdr_{i,ii,iii,\dots,xx}$ represents the REDD+ forest loss rates each individual REDD+ project and $Ar_{i,ii,iii,\dots,xx}$ denotes the total area of each REDD+ project within an NRJ, and A_r represents the total area of all REDD+ projects operating within the NRJ. This was calculated each year from 2002–2022 and integrated globally across the entire study period to estimate the total 20-year weighted average annual REDD+ project forest loss rate (gvd_r).

Adjustments: Buffer contributions & Leakage forest loss

A major criticism of REDD+ projects and other conservation interventions is the potential for “leakage” or the spillover of deforestation into surrounding regions²⁵. Projects under the VCS system are required to establish leakage belts and set baseline deforestation projections, against which forest loss in those leakage belts must be monitored for each monitoring period. When observed forest loss is found to exceed the baseline, a project must report net leakage emissions, which on verification are deducted from its emission reduction performance for that monitoring period²⁶. Analysis of project monitoring and verification reports indicates that projects generally report negligible leakage across the sample, with such reports verified by third-party audits.

To our knowledge, only one study has evaluated actual leakage forest loss attributed to REDD+ interventions⁷, evaluating observed forest loss in 10 km-wide leakage belts around REDD+ project areas for a sub-set of projects analyzed in the study. The authors find some evidence of leakage deforestation in the first 5 years after project implementation, with higher rates of deforestation observed for 3 of 5 project sites in the leakage belt within this period compared to pre-project. We applied the highest observed post-implementation leakage deforestation rate found within 5 years of project start (0.025%/year) to the total leakage area established for the projects in this study, for all years, as the “Leakage Scenario”, in order to assess the potential impact of a conservative leakage rate on project performance. It is important to note that the selected value is relatively conservative as the authors of the abovementioned study found that any observed leakage dissipated 10 years post-implementation.

Leakage areas (total hectares) were reported for 38 of the 45 projects within the final subset. For those projects where the total leakage area was not reported, an area was estimated using the average leakage area:project area ratio within the country where the project resides.

For the leakage scenario, the annual forest loss within each projects' leakage area predicted between project start and 2022 was summed for all projects active within a country subset to estimate the total forest loss within the NRJ that occurred as a result of REDD+ project leakage (LK_{NRJ}). LK_{NRJ} was subtracted from the average annual forest loss within the NRJ (vd_{nrj}) and added to the forest loss of the REDD+ project subset (vb_j) so that LK_{NRJ} was attributed to the projects rather than the jurisdiction. The same calculation was undertaken at the global level to estimate global REDD+ leakage (LK_{gNRJ}); deducting the annual LK_{gNRJ} from the gvd_r and adding it to the vd_r .

The average total % of emissions reductions discounted for buffer pool contributions was estimated by dividing the net buffer contributions (excluding removals; collected from the VCS registry; $B_{1,2,3...x}$) by the total emissions reductions on a national (ER_{NRJ} ; equation 5) and global basis (ER_{gNRJ} ; equation 6).

$$B_{NRJ} = \left(\frac{(B_1 + B_2 + B_3 + \dots B_x)}{ER_{NRJ}} \right) \quad \text{Equation 5}$$

$$B_{gNRJ} = \left(\frac{(B_{NRJ1} + B_{NRJ2} + B_{NRJ3} + \dots B_{NRJx})}{ER_{gNRJ}} \right) \quad \text{Equation 6}$$

Results

Global results

The REDD+ baselines averaged $0.70 \pm 0.12\%$ /year from 2002–2022, corresponding closely with the estimated actual average gNRJ forest loss ($0.71 \pm 0.24\%$ /year; Figure 2).

In the VCS system, a portion of the verified emissions reductions (VERs) achieved by a project within a monitoring period is withheld and deposited into a system-level credit buffer pool as a form of insurance against risks of reversals (e.g., fire). That “permanence” risk is determined on a project level and expressed as a percentage likelihood of reversal²⁴, which is then applied to the VERs generated during a monitoring period. In total, the analyzed REDD+ projects generated a total of 240,285,247 tCO₂e of VERs (equivalent to 1.17tCO₂e/ha/year) according to project monitoring and verification reports (Supplementary Table 2). Application of the permanence risk score for all projects resulted in a total of 29,885,029 tCO₂e being deposited into the Verra buffer pool; 2,738,689tCO₂e of which were released, resulting in a net buffer pool contribution of 25,980,521tCO₂e. The overall net permanence risk across the projects was 10.8% (Supplementary Table 2). Applying the net buffer contribution to the gross ERs, the VERs available to be issued and sold was 210,400,218 tCO₂e over the period from 2002–2022. By reducing the total number of issuable credits, the buffer pool effectively reduces the baseline under which the projects operate. When the impact of buffer pool contributions is considered, the effective net REDD+ baseline rate is reduced from $0.70 \pm 0.12\%$ /year to $0.62 \pm 0.09\%$ /year.

The average annual PrA deforestation from 2002–2022 was $0.07 \pm 0.02\%$ /year; increasing from $0.04 \pm 0.01\%$ over the first decade of the study period (2002–2010) to $0.09 \pm 0.02\%$ from 2011–2022. Overall, the PrA forest loss was 10-fold lower than baseline deforestation rates and the net actual forest loss in the gNRJ.

The total leakage area of the project subset is 9,716,687ha, slightly lower than the total PrA area (10,265,549ha) and 1.88% of the total gNRJ area (518,178,739ha). Applying the average

annual leakage forest loss rate specified in the leakage scenario to the leakage area of the project subset yields estimated leakage forest loss of 2,429ha per annum. Given the large size of the gNRJ, this leakage has no appreciable impact on the total annual gNRJ forest loss rate (-0.0005% and 0.0019%, respectively). Adjusted for this leakage scenario, the PrA forest loss rate increases from 0.07% to 0.09%, approximately 8-fold lower than both the baseline deforestation rates and the actual forest loss in the gNRJ.

Country level results

Peru

Peru has historically had relatively low rates of forest loss since REDD+ was initiated (average₂₀₀₇₋₂₀₂₂: $0.22 \pm 0.05\%$ /year; Supplementary Table 3), however average annual forest loss has been increasing steadily over the past two decades, from $0.15 \pm 0.03\%$ in 2007 to $0.30 \pm 0.06\%$ in 2022. Within those provinces housing REDD+ projects (San Martín, Madre de Dios, Huánuco, Loreto and Ucayali; Supplementary Table 4) forest loss has been nearly two-fold higher on average ($0.53 \pm 0.11\%$ /year), but has remained stable through this period. Only the high leakage scenario (LK₂) had an appreciable impact on the NRJ forest loss, reducing it to $0.52 \pm 0.11\%$ /year. The majority of Peruvian REDD+ projects (7 projects; 2.3 million hectares) demonstrated baseline deforestation rates within the error bounds of this jurisdictional forest loss (subset average: $0.29 \pm 0.06\%$ /year; range: 0.01-0.62%/year; IDs: 1882, 1218, 1799, 2502, 1067, 958, 985) The three remaining projects (1,003,507ha) reported estimated baseline rates that were more than double the actual jurisdictional average ($1.54 \pm 0.23\%$ /year; range: 1.15-2.23%/year; IDs: 944, 844, 868). Normalized by relative REDD+ area, the Peru gross and net (following buffer credit discounting) baseline deforestation rates are within the error bounds of actual estimated forest loss in the relative jurisdictions (Figure 3a). Accounting for leakage, the actual forest loss in REDD+ project areas was 12-fold lower (LK average₂₀₀₇₋₂₀₂₂: $0.04 \pm 0.01\%$) than Peru's NRJ forest loss over the same period.

Colombia

Similar to Peru, annual forest loss rates in Colombia have been relatively low since REDD+ was initiated (average₂₀₁₀₋₂₀₂₂: $0.31 \pm 0.07\%$ /year) with a slight increase in recent years (average₂₀₁₇₋₂₀₂₂: 0.39% /year; Supplementary Table 3). Forest loss in Colombia's NRJ (Chocó, Mataven, Valle del Cauca, Nariño and Antioquia; Supplementary Table 4) was comparable - averaging $0.27 \pm 0.06\%$ /year and $0.38 \pm 0.08\%$ /year, respectively; thus the REDD+ projects are not necessarily located in current deforestation hotspots. The leakage forest loss ($0.001-0.003\%$ /year) had no detectable impact on the average annual forest loss within the NRJ. Normalized by relative REDD+ area, the Colombia REDD+ gross and net baseline rates (gross $0.87 \pm 0.13\%$ /year; net: $0.73 \pm 0.11\%$ /year) were higher than the actual estimated NRJ forest loss (Figure 3b); demonstrating no overlap with the upper bounds of the uncertainty threshold, although three projects (IDs: 1389, 1390, 1395) estimated baselines that were lower than the jurisdictional forest loss average. After accounting for leakage, the actual forest loss in REDD+ project areas was 7-fold lower (LK average₂₀₁₃₋₂₀₂₂: $0.05 \pm 0.01\%$) than Colombia's NRJ forest loss over the same period.

Madagascar

Country-level forest loss in Madagascar nearly tripled in the most recent decade (average₂₀₁₀₋₂₀₂₂: $1.73 \pm 1.37\%$ /year) compared to the previous (average₂₀₀₂₋₂₀₁₀: $0.62 \pm 0.49\%$ /year), with a peak occurring between 2014-2018 (average: $2.30 \pm 1.82\%$ /year; Supplementary Table 3). This increase was echoed in the Madagascar NRJ (Toamasina and Fianarantsoa); averaging $0.58 \pm 0.46\%$ /year and $1.97 \pm 1.56\%$ /year, respectively. The leakage forest loss ($0.001-0.002\%$ /year) had no detectable impact on the average annual forest loss within the NRJ. The three REDD+ projects analyzed (total area: 865,304ha) selected an average baseline deforestation rate of $0.69 \pm 0.10\%$ /year (net: $0.61 \pm 0.09\%$ /year), which is significantly lower than the actual forest loss occurring within the Madagascar jurisdiction (average₂₀₀₅₋₂₀₂₂: $1.48 \pm 1.17\%$ /year; Supplementary Table 5, Figure 3c). Considering leakage, the actual forest loss in REDD+ projects was 7-fold lower (LK average₂₀₀₅₋₂₀₂₂: $0.23 \pm 0.18\%$) than the Madagascar NRJ.

Cambodia

Cambodia has historically had a very high rate of annual deforestation, with forest loss averaging $1.39 \pm 0.44\%$ /year over the past two decades (2002–2022; Supplementary Table 3), peaking between 2010–2016 (average: $2.10 \pm 0.67\%$ /year). The Cambodia NRJ tends to have higher annual forest loss rates (average_{2010–2012}: $2.22 \pm 0.73\%$ /year; Supplementary Table 5) compared to the country average as REDD+ projects have typically been located in deforestation hotspots. Only the high leakage scenario (LK₂) had an appreciable impact on the NRJ forest loss, reducing it to $2.21 \pm 0.08\%$ /year. The area normalized baseline deforestation rates of the three REDD+ projects analyzed (total area: 700,613ha) average $2.09 \pm 0.32\%$ /year (net: $1.86 \pm 0.28\%$ /year), which is slightly lower and within the uncertainty bounds of the predicted jurisdictional forest loss - demonstrating reasonable predictions of BAU deforestation. Two of the three projects utilized the Cambodia Forest Reference Emissions Level (FREL) deforestation rate of 2.38% /year. After accounting for leakage, the actual forest loss in project areas was 11-fold lower (LK average_{2010–2022}: $0.21 \pm 0.97\%$) than the jurisdictional forest loss over the same period (Figure 3d).

Brazil

Forest loss across Brazil has been relatively stable over the past two decades, increasing slightly from $0.56 \pm 0.05\%$ /year (2001–2010) to $0.59 \pm 0.05\%$ /year (2010–2022; Supplementary Table 3). Within the Brazil NRJ (Pará, Amazonas, Mato Grosso, Acre, Amapá and Rondônia), forest loss rates are similar (average_{2001–2010}: $0.60 \pm 0.05\%$ /year; Supplementary Table 5) and thus do not represent deforestation hotspots. The leakage forest loss (0.001% /year) had no detectable impact on the average annual forest loss within the NRJ. Actual area normalized REDD+ baseline deforestation rates are marginally lower (average: $0.57 \pm 0.09\%$ /year; net: $0.50 \pm 0.08\%$ /year) than the actual jurisdictional forest loss. When accounting for leakage, the actual forest loss in REDD+ project areas was 6-fold lower (LK average_{2002–2022}: $0.11 \pm 0.01\%$) than the Brazil NRJ (Figure 2e).

Guatemala

Guatemala forest loss has been consistently high over the past few decades ($0.99 \pm 0.24\%$ /year average from 2001–2010 and 2010–2022; Supplementary Table 3) with a few peak years between 2016–2020 (average $1.34\% \pm 0.32\%$ /year). The Guatemala NRJ area (Izabal and Peten) has demonstrated slightly higher annual forest loss rates ($1.45\% \pm 0.35\%$ /year) since REDD+ was locally initiated in 2012. Only the high leakage scenario (LK₂) had an appreciable impact on the NRJ forest loss, reducing it to $1.42 \pm 0.34\%$ /year. The area normalized REDD+ baseline deforestation rates are marginally higher (gross: $1.66\% \pm 0.25\%$ /year; net: $1.52\% \pm 0.22\%$ /year; Supplementary Table 5) but remain within error bounds of actual jurisdictional forest loss. Two of the three projects analyzed (total area: 173,737ha) selected relatively high baseline rates (2.40% /year), but this was balanced by the accurate baseline rate (1.42% /year) of the remaining larger project (total area: 463,239ha) which represents the majority (72%) of REDD+ area in the country. After accounting for leakage, the actual forest loss in Guatemalan REDD+ projects (LK average_{2011–2022}: $0.29 \pm 0.07\%$) was 5-fold lower than the Guatemala NRJ (Figure 3f).

Discussion

We find that weighted average net REDD+ baseline deforestation rates across six countries ($0.70 \pm 0.12\%$ /year: 2002–2022, $n_{\text{projects}} = 45$) correspond closely with the estimated average net forest loss in corresponding jurisdictions, and are well within the error thresholds of the underlying data ($0.71 \pm 0.24\%$ /year: 2002–2022; Figure 2).

When the impact of leakage and project buffer pool contributions on jurisdictional forest loss and REDD+ project baselines, respectively, are taken into account, REDD+ baselines were lower than jurisdictional forest loss rates over the study period (net REDD+ baseline: $0.62 \pm 0.09\%$ /year; net jurisdictional forest loss $0.69 \pm 0.20\%$ /year). Had the projects, taken as a whole, been operating within a nested jurisdictional system subject to an accurately-predicted jurisdictional baseline over this twenty-year period, these findings suggest that project crediting levels would have been essentially identical.

The results also show that REDD+ project-level forest loss across all six countries was substantially lower in comparison to their corresponding NRJs. During the study period (2002–2022), the 45 REDD+ projects had an average forest loss of $0.07 \pm 0.02\%$ /year – 10-fold lower than the actual forest loss within all the REDD+ jurisdictions. It is important to note that while the systematically low rate of project-level forest loss observed in this study suggests strong conservation performance, it could also reflect relatively low site-specific threat levels. Each project must provide a detailed assessment of the site-specific threats and drivers of forest loss in its Project Design Document, which is validated through independent third-party audits. In addition, some peer-reviewed studies have provided further evidence of high site-specific threat levels and have directly assessed REDD+ project conservation effectiveness in specific countries^{7,27}. However, further project-specific analyses are needed to draw broader conclusions and remain an important area for further research.

There is also substantial year-to-year variability in the correspondence between baseline prediction and actual gNRJ forest loss (Supplementary Table 5). However, when integrated across twenty years of that year-on-year variability, the overall correspondence between baseline and actual forest loss is quite close (Figure 2). This result has implications for the concept of “dynamic baselining”²⁸, which has been proposed as a way to adjust baseline periods at high frequency in order to respond to interannual changes in deforestation rates. Our results suggest that dynamic baselining would not have been needed to achieve a close correspondence between baseline and actual deforestation rates over the twenty-year period of this study. On the other hand, by creating significant interannual variability in crediting levels, dynamic baselining may compromise the success of deforestation reduction activities by introducing substantial uncertainty for communities and governments regarding potentially available incentive levels. This highlights a core tension in the design of REDD+ crediting systems, which must meet the long-term financing needs of forest communities and governments on the ground in order to durably and effectively reduce forest loss, while also meeting the needs of market actors seeking assurance about the climate impacts of their investments.

The significant project-level variability highlighted in this study indicates that the systemic adoption of project baselines allocated on the basis of risk from jurisdictional forest emission reference levels (FRELs), as planned for the VCS program²⁹, is a sensible methodological evolution for the REDD+ mechanism. Another benefit of this approach is that it will enable project-level REDD+ efforts to be integrated within jurisdictional and national-level program and accounting frameworks. Notably, however, this study suggests that this new approach to baseline development is not needed in order to address a system-level misalignment between project-level baseline predictions and observed jurisdiction-level forest loss.

This study encompasses the substantial majority of AUD REDD+ projects (71% of registered and verified projects by area and 63% by annual emissions reduction volume). However, avoided planned deforestation (APD) REDD+ projects, which are not considered in the current study, are also a significant component of the voluntary REDD+ mechanism: while APD projects represent only 6.25% of all registered REDD+ project area, they generate 23.31% of all REDD+ annual emissions reductions (see Supplementary Table 1). This is because in most Planned Deforestation scenarios a much greater proportion of the forest area protected is scheduled to be lost in the baseline scenario (for example, slated for total clearance for palm oil). In previous matching studies^{14,15}, APD project baselines have to date been assessed using the same approach as for AUD projects, with synthetic controls established assuming unplanned deforestation scenarios. However, APD projects are established as an alternative to large-scale legal conversion of forests authorized through concessionary contracts (e.g. logging, agriculture, mining); the baseline scenarios of which are based on the management plans, legally authorized harvest scenarios, etc. that are associated with these concessions in the national context. Because of this, neither the approach used in this study, nor as implemented by West et al. (2023)¹⁵, are valid for assessing APD baselines against real-world forest loss. This is an area for further research.

The earth observation data²² utilized in this study captures forest cover on a pixel basis rather than identifying individual trees - thus it is highly uncertain in low density forests such as drylands. As a result, many relatively large REDD+ projects situated in dryland forests (e.g. Tanzania, Kenya) could not be analyzed in this study. This data also only identifies forest loss (not degradation) and does not quantify carbon variability (storage, removals, regrowth) - thus missing important elements of REDD+ project interventions. Ideally, further research would include higher quality geospatial data that could accurately map these variables for more all-encompassing results.

In conclusion, this study presents a comprehensive assessment of the REDD+ avoided unplanned deforestation mechanism on a global scale. The close correspondence between REDD+ baseline projections and actual jurisdiction-level forest loss, combined with the apparent success of voluntary REDD+ projects in avoiding forest loss and emissions across six countries over twenty years, suggests that the REDD+ mechanism is substantially more effective than recent studies have claimed. These findings hold significant implications for the scientific community, climate policymakers, the REDD+ community of practice, and the voluntary carbon markets.

References

1. Friedlingstein, P., O'sullivan, M., Jones, M.W., Andrew, R.M., Gregor, L., Hauck, J., Le Quéré, C., Luijkx, I.T., Olsen, A., Peters, G.P. and Peters, W., 2022. Global carbon budget 2022. *Earth System Science Data Discussions*, 2022, pp.1-159.
2. Pacheco, P., Mo, K., Dudley, N., Shapiro, A., Aguilar-Amuchastegui, N., Ling, P.Y., Anderson, C. and Marx, A. *Deforestation fronts: Drivers and responses in a changing world*. WWF, Gland, Switzerland (2021).
3. Pendrill, F., Persson, U. M., Godar, J., Kastner, T., Moran, D., Schmidt, S., & Wood, R. (2019). Agricultural and forestry trade drives large share of tropical deforestation emissions. *Global Environmental Change*, 56, 1-10.
4. Food and Land Use Coalition (2019), *Growing Better: Ten Critical Transitions to Transform Food and Land Use*.
5. Pauly, M. and Tosteson, J. (2022), *Safeguarding natural forests through the voluntary REDD+ scheme*. *Nature Plants*.
6. UN Climate Change Conference (2021). Glasgow Leaders' Declaration on Forests and Land Use. The National Archives. Available: <https://webarchive.nationalarchives.gov.uk/ukgwa/20230221141550/https://ukcop26.org/glasgow-leaders-declaration-on-forests-and-land-use/>
7. Guizar-Coutiño, Guizar-Coutiño, A., Jones, J.P., Balmford, A., Carmenta, R. and Coomes, D.A. A global evaluation of the effectiveness of voluntary REDD+ projects at reducing deforestation and degradation in the moist tropics. *Conservation Biology* **36.6** (2022).
8. Gosnell, G., Dickson, R., Hu, J., Hird, T., and Basnak, M. The REDD+ framework for reducing deforestation and mitigating climate change: overview, evaluation, and cost-effectiveness. *Rethink Priorities*, (2022). Available at: <https://forum.effectivealtruism.org/posts/LmjsyFvQavLQnYSTp/the-redd-framework-for-reducing-deforestation-and-mitigating>
9. Boyd, W., Stickler, C., Duchelle, A.E., Seymour, F., Nepstad, D., Bahar, N. and Rodriguez-Ward, D., *Jurisdictional approaches to REDD+ and low emissions development: Progress and prospects*. Washington, DC: *World Resources Institute*, (2018).

10. Meyer, C. and Miller, D., Zero deforestation zones: The case for linking deforestation-free supply chain initiatives and jurisdictional REDD+. *Journal of Sustainable Forestry*, **34**, 559-580 (2015).
11. Piris-Cabezas, P., Lubowski, R.N. and Leslie, G., Estimating the potential of international carbon markets to increase global climate ambition. *World Development*, 167, p.106257, 10.1016/j.worlddev.2023.106257, (2023).
12. Trove, (2023). Trove Intelligence Platform. Available at: <https://trove-research.com/>
13. VCS, (2023) Verified Carbon Standard (VCS), version 4.4. Available at: <https://verra.org/programs/verified-carbon-standard/>
14. West, T.A., Börner, J., Sills, E.O., & Kontoleon, A. Overstated carbon emission reductions from voluntary REDD+ projects in the Brazilian Amazon. *Proceedings of the National Academy of Sciences of the United States of America*, **117.39**, 24188–24194, 10.1073/pnas.2004334117 (2020).
15. West, T.A., Wunder, S., Sills, E.O., Börner, J., Rifai, S.W., Neidermeier, A.N., & Kontoleon, A. Action needed to make carbon offsets from tropical forest conservation work for climate change mitigation. *Science*. **381.6660**, 873-877 (2023).
16. Verra. Technical Review of West et al. 2020 and 2023, Guizar-Coutiño 2022, and Coverage in Britain's Guardian. Verra News (31 January 2023). Available at: <https://verra.org/technical-review-of-west-et-al-2020-and-2023-guizar-coutino-2022-and-coverage-in-britains-guardian/>
17. Furey, A. Sylvera response to The Guardian's Analysis of Rainforest Offsets. *Sylvera: Market Insight* (19 January 2023). Available at: <https://www.sylvera.com/blog/guardian-offsets-response>
18. Mitchard, E.T.A. The tropical forest carbon cycle and climate change. *Nature*, 559.7715, 527-534, 10.1038/s41586-018-0300-2 (2018).
19. Pauly, M. Recent challenges in the retrospective evaluation of forest carbon credit baselines. *Integrated Environmental Assessment and Management: Debates, Dilemmas, and Discoveries*. 10.1002/ieam.4801 (2023).

20. McNicol, I.M., Ryan, C.M. & Mitchard, E.T. Carbon losses from deforestation and widespread degradation offset by extensive growth in African woodlands. *Nature communications*, **9.1**, 3045, 10.1038/s41467-018-05386-z, (2018).
21. Fagan, M.E. 2020. A lesson unlearned? Underestimating tree cover in drylands biases global restoration maps. *Global Change Biology* <https://doi.org/10.1111/gcb.15187>
22. Hansen, M. C., P. V. Potapov, R. Moore, M. Hancher, S. A. Turubanova, A. Tyukavina, D. Thau, S. V. Stehman, S. J. Goetz, T. R. Loveland, A. Kommareddy, A. Egorov, L. Chini, C. O. Justice, and J. R. G. Townshend. High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science* **342**, 850–53 (2013). Data available from: earthenginepartners.appspot.com/science-2013-global-forest
23. Tyukavina, A., Baccini, A., Hansen, M.C., Potapov, P.V., Stehman, S.V., Houghton, R.A., Krylov, A.M., Turubanova, S. and Goetz, S.J., Aboveground carbon loss in natural and managed tropical forests from 2000 to 2012. *Environmental Research Letters*, 10.7, 10.1088/1748-9326/10/7/074002, (2015).
24. Verra, 2019. Verified Carbon Standard (VCS) AFOLU Non-Permanence Risk Tool. Available at: <https://verra.org/digitized-afolu-non-permanence-risk-tool/>
25. Streck, C., 2021. REDD+ and leakage: debunking myths and promoting integrated solutions. *Climate Policy*, 21(6), pp.843-852.
26. Verra, 2020. VM0007 REDD+ Methodology Framework (REDD+MF), v1.6. Available at: <https://verra.org/methodologies/vm0007-redd-methodology-framework-redd-mf-v1-6/>
27. Pauly, M., Crosse, W. and Tosteson, J., 2022. High deforestation trajectories in Cambodia slowly transformed through economic land concession restrictions and strategic execution of REDD+ protected areas. *Scientific Reports*, 12(1), p.17102.
28. Li, X., Wang, W., Zhang, H., Wu, T. and Yang, H., 2022. Dynamic baselines depending on REDD+ payments: a comparative analysis based on a system dynamics approach. *Ecological Indicators*, 140, p.108983.
29. Verra. JNR Program Guide: Jurisdictional & Nested REDD+. (15 April 2021). Available at: <https://verra.org/programs/jurisdictional-nested-redd-framework/>

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Data availability statement: Data is available in the supplementary information.

Competing Interest Statement: MP, JT, WC, ZR and JM are employed at Everland LLC, an organization that works with REDD+ developers.

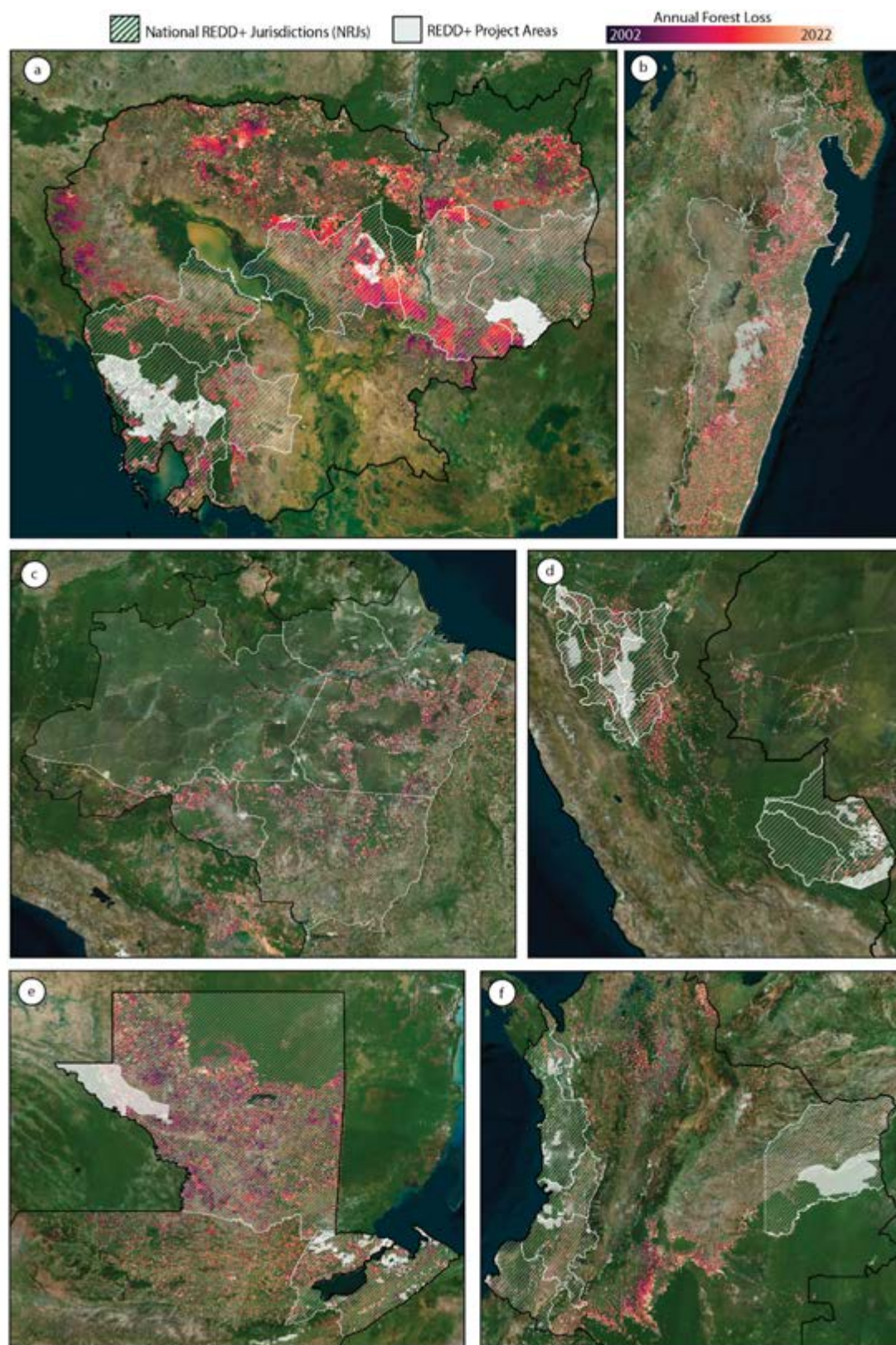
Figure Captions

Figure 1. Location of the REDD+ projects analyzed (a), REDD+ project area (%) by country within the gNRJ (b).

Figure 2. Weighted average gross global REDD+ jurisdiction (gNRL) forest loss compared to weighted average gross REDD+ baseline deforestation rates and REDD+ project area (PrA) forest loss for all jurisdictions. The dashed line represents net values: REDD+ baselines excluding national-level buffer pool contribution discounts, global jurisdictional forest loss excluding predicted leakage forest loss and PrA forest loss with leakage forest loss from two scenarios added (LK = Leakage Scenario).

Figure 3. Weighted average REDD+ jurisdiction forest loss (NRJ) compared to weighted average REDD+ baseline deforestation rates (vbj) and REDD+ project area (PrA) forest loss for (a) Peru, (b) Colombia, (c) Madagascar, (d) Cambodia, (e) Brazil and (f) Guatemala. Solid lines represent average, slashed lines represent average net: national baseline excluding buffer pool contributions, and jurisdictional forest loss excluding predicted leakage forest loss.

Supplementary Information



Supplementary Figure 1. The location of REDD+ project areas, annual forest loss and national jurisdictions within each analyzed country: (a) Cambodia, (b) Madagascar, (c) Guatemala, (d) Peru, (e) Brazil and (f) Colombia.

Supplementary Table 1: A summary of Avoided Unplanned Deforestation (AUD) and Avoided Planned Deforestation (APD) REDD+ projects currently registered on the VCS database.

Type	Annual Emissions Reductions (tCO2e)	Total Area (ha)	Average Annual Emissions Reductions per area (tCO2e/ha)
AUD	48,542,966	14,382,126	3.76
APD	14,755,761	958,782	15.39

Supplementary Table 2: A summary of Net Emissions Reductions (NERs), total global buffer pool contributions, proportion of NERs contributed towards the global buffer pool and total buffer credits released. Projects without monitoring reports were excluded from the table.

ID	Total NERs (tCO ₂ e)	Total Buffer (tCO ₂ e)	Buffer Released (tCO ₂ e)
1882	368,652	53,981	0
1218	299,896	88,506	0
2502	3,850,755	415,897	0
1067	5,350,120	626,870	151,361
958	629,826	62,983	9,447
944	8,405,814	840,589	0
844	10,251,891	1,165,819	0
868	18,935,913	2,515,761	0
985	49,919,092	4,068,005	0
1400	622,548	154,179	0
1566	15,682,275	4,724,188	1,878,938
1396	648,915	81,629	0
1395	1,852,924	232,723	0
1392	531,415	102,351	0
1389	1,166,316	112,788	0
1390	779,818	98,252	0
1391	1,167,834	146,687	0
1399	503,343	63,734	0
1748	27,627,236	3,093,780	0
1650	21,171,578	2,288,670	0
1689	645,410	72,305	0
1094	1,747,417	641,865	193,846
981	9,582,742	1,348,671	0
977	22,384,502	969,805	0
1118	-452,554	48,366	24,183
875	5,429,148	1,280,878	245,832
1113	1,079,263	272,570	0
963	861,283	115,623	0
1112	1,474,189	141,293	0
1115	2,377,110	280,890	0
1329	582,840	131,600	0
1503	1,515,303	154,063	0
1654	1,507,931	306,674	0
1571	1,423,829	187,531	0
1686	2,801,469	347,924	0
2558	412,441	41,564	0
2252	6,240,621	801,787	0
1953	941,618	119,549	0
1622	6,900,404	873,635	235,082
1541	1,577,470	43,809	0
1384	1,107,525	123,058	0
1215	1,955,374	255,342	0
1311	-3,915,496	46,993	0
1047	2,037,516	222,721	0

Supplementary Table 3: Country-level forest loss from Hansen et al. (2013)

Year	Peru	Colombia	Madagascar	Cambodia	Brazil	Guatemala
2001	0.10%	0.28%	0.51%	0.32%	0.53%	0.69%
2002	0.10%	0.22%	0.52%	0.62%	0.68%	0.72%
2003	0.10%	0.15%	0.49%	0.65%	0.63%	1.30%
2004	0.13%	0.31%	0.48%	0.90%	0.74%	0.73%
2005	0.21%	0.23%	0.55%	0.73%	0.67%	1.30%
2006	0.11%	0.23%	0.41%	0.91%	0.55%	0.68%
2007	0.15%	0.33%	1.10%	0.88%	0.50%	1.60%
2008	0.16%	0.28%	0.72%	0.95%	0.47%	1.00%
2009	0.23%	0.29%	0.80%	1.40%	0.35%	1.10%
2010	0.18%	0.24%	0.63%	2.70%	0.52%	0.78%
2011	0.16%	0.23%	0.95%	2.20%	0.37%	0.53%
2012	0.35%	0.28%	0.75%	2.20%	0.56%	1.10%
2013	0.27%	0.17%	1.70%	2.20%	0.37%	0.72%
2014	0.26%	0.25%	2.40%	1.80%	0.52%	0.80%
2015	0.21%	0.17%	1.80%	1.50%	0.43%	0.70%
2016	0.30%	0.36%	2.20%	2.10%	1.00%	2.30%
2017	0.39%	0.52%	3.00%	1.30%	0.87%	1.00%
2018	0.27%	0.43%	2.10%	1.30%	0.57%	0.92%
2019	0.30%	0.33%	1.50%	1.60%	0.52%	1.20%
2020	0.36%	0.40%	1.40%	1.60%	0.63%	1.30%
2021	0.29%	0.32%	1.40%	1.60%	0.58%	0.65%
2022	0.30%	0.32%	1.50%	1.20%	0.64%	0.60%

Supplementary Table 4: States/provinces included in jurisdictions for global baseline analysis, added as REDD+ projects were initiated. Jurisdictional forest loss estimated based on state/province forest loss normalized by % REDD+ area within each state/province.

Country	State/Province	Year added
Peru	San Martín	2007
	Madre de Dios	2008
	Loreto	2008
	Huánuco	2008
	Ucayali	2008
Colombia	Chocó	2010
	Mataven	2013
	Valle del Cauca	2015
	Nariño	2013
	Antioquia	2013
Cambodia	Môndól Kiri	2010
	Kratie	2010
	Kâmpóng Thum	2015
	Kaôh Kong	2015
	Pouthisat	2015
	Kâmpôt	2015
	Krong Preah Sihanouk	2015
	Kâmpóng Spœ	2015
	Preah Vihear	2015
	Siem Reap	2015
Brazil	Pará	2002
	Amazonas	2009
	Mato Grosso	2009
	Acre	2011
	Amapá	2011
	Rondônia	2016
Guatemala	Izabal	2012
	Peten	2012
Madagascar	Toamasina	2005
	Fianarantsoa	2007

Supplementary Table 5: Jurisdictional average annual % forest loss (NRJ; relative to remaining forest cover; Hansen et al. 2013), average REDD+ project baseline deforestation rate (R^+_{baseline} ; % predicted change per year in the first baseline setting period: project year 1-10); and average REDD+ project area actual forest loss (R^+_{actual} ; relative to remaining forest cover; Hansen et al. 2013); all data normalized by % REDD+ area.

Year	Peru			Colombia			Cambodia			Brazil			Madagascar			Guatemala			Global		
	NRJ	R^+_{actual}	R^+_{baseline}	NRJ	R^+_{actual}	R^+_{baseline}	NRJ	R^+_{actual}	R^+_{baseline}	NRJ	R^+_{actual}	R^+_{baseline}	NRJ	R^+_{actual}	R^+_{baseline}	NRJ	R^+_{actual}	R^+_{baseline}	gNRJ	R^+_{actual}	R^+_{baseline}
2002										0.72%	0.003%	0.32%							0.72%	0.003%	0.32%
2003										0.58%	0.008%	0.32%							0.58%	0.008%	0.32%
2004										0.90%	0.017%	0.32%							0.90%	0.017%	0.32%
2005										0.87%	0.007%	0.32%	0.48%		0.18%				0.56%	0.001%	0.21%
2006										0.71%	0.010%	0.32%	0.13%		0.18%				0.24%	0.002%	0.57%
2007	0.83%	0.01%	1.15%							0.62%	0.008%	0.32%	1.10%	0.248%	0.76%				1.02%	0.175%	0.90%
2008	0.33%	0.06%	0.48%							0.65%	0.022%	1.20%	0.57%	0.041%	0.76%				0.42%	0.053%	0.65%
2009	0.52%	0.01%	0.48%							0.30%	0.056%	0.80%	0.66%	0.082%	0.76%				0.52%	0.034%	0.64%
2010	0.38%	0.01%	0.61%				2.65%	0.08%	1.86%	0.51%	0.023%	0.80%	0.55%	0.139%	0.76%				0.50%	0.035%	0.73%
2011	0.34%	0.01%	0.61%				3.84%	0.16%	1.86%	0.31%	0.025%	0.68%	0.90%	0.171%	0.76%				0.55%	0.046%	0.72%
2012	0.76%	0.02%	0.61%				2.52%	0.07%	1.86%	0.43%	0.031%	0.70%	0.72%	0.106%	0.76%	1.25%	0.165%	1.66%	0.81%	0.052%	0.82%
2013	0.51%	0.03%	0.60%	0.19%	0.02%	0.92%	3.20%	0.10%	1.86%	0.30%	0.041%	0.61%	2.05%	0.318%	0.76%	1.12%	0.125%	1.66%	0.68%	0.070%	0.81%
2014	0.53%	0.02%	0.60%	0.25%	0.03%	0.87%	2.75%	0.30%	1.86%	0.47%	0.064%	0.61%	2.45%	0.181%	0.76%	1.10%	0.117%	1.66%	0.75%	0.061%	0.79%
2015	0.43%	0.03%	0.60%	0.17%	0.02%	0.87%	1.60%	0.06%	2.26%	0.41%	0.090%	0.61%	2.15%	0.279%	0.76%	0.93%	0.082%	1.66%	0.67%	0.070%	0.89%
2016	0.54%	0.03%	0.60%	0.35%	0.03%	0.87%	2.45%	0.26%	2.26%	0.85%	0.129%	0.55%	2.90%	0.228%	0.76%	3.10%	0.193%	1.66%	1.13%	0.097%	0.87%
2017	0.65%	0.03%	0.59%	0.53%	0.05%	0.87%	1.49%	0.27%	2.26%	0.90%	0.074%	0.57%	3.70%	0.566%	0.76%	1.45%	0.187%	1.66%	1.08%	0.190%	0.86%
2018	0.50%	0.02%	0.63%	0.41%	0.06%	0.87%	1.47%	0.19%	2.26%	0.56%	0.108%	0.57%	2.35%	0.458%	0.76%	1.20%	0.162%	1.66%	0.79%	0.110%	0.87%
2019	0.48%	0.03%	0.63%	0.33%	0.05%	0.87%	1.91%	0.25%	2.26%	0.54%	0.071%	0.57%	1.55%	0.214%	0.76%	1.55%	0.552%	1.66%	0.74%	0.110%	0.87%
2020	0.59%	0.03%	0.63%	0.40%	0.05%	0.87%	1.73%	0.28%	2.26%	0.71%	0.169%	0.57%	1.43%	0.314%	0.76%	1.90%	0.396%	1.66%	0.84%	0.132%	0.87%
2021	0.52%	0.03%	0.63%	0.32%	0.04%	0.87%	1.76%	0.37%	2.26%	0.67%	0.123%	0.57%	1.50%	0.226%	0.76%	0.90%	0.163%	1.66%	0.73%	0.105%	0.87%
2022	0.53%	0.03%	0.63%	0.31%	0.04%	0.87%	1.26%	0.24%	2.26%	0.69	0.147%	0.57%	1.60%	0.234%	0.76%	0.71%	0.154%	1.66%	0.72%	0.101%	0.87%
Median	0.52%	0.03%	0.61%	0.35%	0.04%	0.87%	1.91%	0.24%	2.26%	0.62%	0.04%	0.57%	1.47%	0.23%	0.76%	1.20%	0.16%	1.66%	0.72%	0.061%	0.80%
Average	0.53%	0.02%	0.63%	0.35%	0.04%	0.87%	2.22%	0.20%	2.09%	0.60%	0.06%	0.57%	1.48%	0.26%	0.69%	1.45%	0.21%	1.66%	0.71%	0.068%	0.70%
Exclusions scenario	0.53%	0.04%	0.57%	0.35%	0.05%	0.82%	2.22%	0.21%	1.86%	0.60%	0.11%	0.50%	1.48%	0.29%	0.61%	1.45%	0.23%	1.52%	0.71%	0.092%	0.62%

Supplementary Table 6: REDD+ projects for the global baseline analysis; REDD+ baseline deforestation rate ($R_{+baseline}$); actual jurisdictional forest loss ($J_{+baseline}^*$) during the project period.

VCS ID	Name	Area (ha)	Country	$R_{+baseline}$	$J_{+baseline}^*$	$R_{+baseline}$ vs. $J_{+baseline}^*$	Start Year
1882	Alto Huayabamba	53,410	Peru	0.28±0.04%	0.53±0.11%	lower	2013
1218	Evio	7,653	Peru	0.62±0.09%	0.53±0.11%	Within range	2011
1799	Belgica Community	53,563	Peru	0.18±0.03%	0.55±0.12%	lower	2017
2502	Tahuamany Amazon	171,584	Peru	0.48±0.07%	0.55±0.12%	Within range	2017
1067	Tambopata	573,299	Peru	0.21±0.03%	0.51±0.10%	lower	2008
958	Biocorridor Martin	303,699	Peru	0.01±0.0%	0.52±0.10%	lower	2010
944	Alto Mayo	182,000	Peru	1.15±0.17%	0.53±0.11%	higher	2007
844	Madre de Dios	96,906	Peru	2.23±0.33%	0.52±0.10%	higher	2006
868	Brazil Nut	724,601	Peru	1.23±0.18%	0.52±0.10%	higher	2010
985	Cordillera Azul	1,353,190	Peru	0.50±0.08%	0.51±0.10%	Within range	2008
1400	Concosta	52,212	Colombia	1.09±0.16%	0.33±0.07%	higher	2013
1566	Resguardo Indigena	1,856,836	Colombia	1.02±0.15%	0.33±0.07%	higher	2013
1396	Rio Pepe y Acaba	48,177	Colombia	0.73±0.11%	0.34±0.07%	higher	2014
1395	Bajo Calima	83,452	Colombia	0.43±0.06%	0.33±0.07%	Within range	2013
1392	Cajambre	60,316	Colombia	0.57±0.09%	0.33±0.07%	Within range	2013
1389	Acapa Bajo Mira	58,212	Colombia	0.27±0.04%	0.33±0.07%	Within range	2013
1390	Carmen del Darién	118,318	Colombia	0.23±0.03%	0.34±0.07%	lower	2014
1391	SUPP	47,667	Colombia	0.88±0.13%	0.33±0.07%	Within range	2013
1399	Mutató	34,288	Colombia	0.40±0.06%	0.33±0.07%	Within range	2013
1748	Southern Cardamom	465,839	Cambodia	2.38±0.36%	1.76±0.56%	Within range	2015
1650	Keo Seima Wildlife Sanctuary	166,983	Cambodia	1.86±0.28%	2.22±0.71%	Within range	2010
1689	Tumring	67,791	Cambodia	2.38±0.36%	1.76±0.56%	Within range	2015
1094	Ecomapua Amazon	86,270	Brazil	0.32±0.05%	0.60±0.05%	lower	2002
981	Pacajai	135,106	Brazil	0.33±0.05%	0.54±0.05%	lower	2009
977	RMDLT Portel Para	151,105	Brazil	1.70±0.26%	0.55±0.05%	higher	2008
1118	Suruf Forest	31,994	Brazil	1.06±0.16%	0.54±0.05%	higher	2009
875	Florestal Santa Maria	71,714	Brazil	0.27±0.04%	0.54±0.05%	lower	2009
1113	Valparaiso	28,096	Brazil	0.13±0.02%	0.57±0.05%	lower	2011
963	Purus	34,702	Brazil	0.67±0.10%	0.57±0.05%	Within range	2011
1112	Russas	41,976	Brazil	0.28±0.04%	0.57±0.05%	lower	2011
1115	Jari Amapa	65,982	Brazil	0.27±0.04%	0.57±0.05%	lower	2011
1329	Maísa	28,752	Brazil	0.68±0.10%	0.59±0.05%	Within range	2012
1503	Rio Preto-Jacunda	94,289	Brazil	1.16±0.17%	0.59±0.05%	higher	2012
1654	Fortaleza Ituxi	46,592	Brazil	0.30±0.04%	0.61±0.05%	lower	2013
1571	Manoa	730,387	Brazil	0.53±0.08%	0.61±0.05%	Within range	2013
1686	Agrocortex	186,067	Brazil	0.59±0.09%	0.64±0.06%	Within range	2014
2566	Serra do Amolar	76,850	Brazil	0.47±0.07%	0.70±0.06%	lower	2016
2558	ABC Norte	140,691	Brazil	0.90±0.01%	0.68±0.06%	higher	2017
2252	Rio Anapu-Pacaja	165,707	Brazil	0.02±0.00%	0.70±0.06%	lower	2016
1953	Floresta Verde	53,528	Brazil	0.40±0.06%	0.70±0.06%	lower	2016
1622	Conservation Coast	128,448	Guatemala	2.23±0.33%	1.38±0.33%	higher	2012
1541	Lacandon	45,289	Guatemala	2.57±0.39%	1.38±0.33%	higher	2012
1384	Guatcarbon	463,239	Guatemala	1.42±0.21%	1.38±0.33%	Within range	2012
1215	Marika Forest	360,060	Madagascar	0.18±0.03%	1.49±1.18%	lower	2005
1311	CAZ	370,032	Madagascar	1.21±0.18%	1.64±1.30%	Within range	2007
1047	COFAV	135,212	Madagascar	1.03±0.15%	1.64±1.30%	Within range	2007

Supplementary Table 7: REDD+ credits vs. estimated crediting potential emissions reductions based on forest loss rate within NRJs

Country	REDD+ Project Subset actual Net Emissions Reductions	% difference subset baseline vs. NRJ forest loss	Estimated Emissions Reductions from NRJ
Peru	98,313,690	-17%	81,600,363
Colombia	22,955,388	-56%	10,100,371
Cambodia	49,444,224	+12%	55,377,531
Brazil	59,909,152	+23%	73,688,257
Madagascar	3,992,890	+59%	6,348,695
Guatemala	9,585,399	-7%	8,914,421
Global subset	240,285,247	+11%	266,716,624

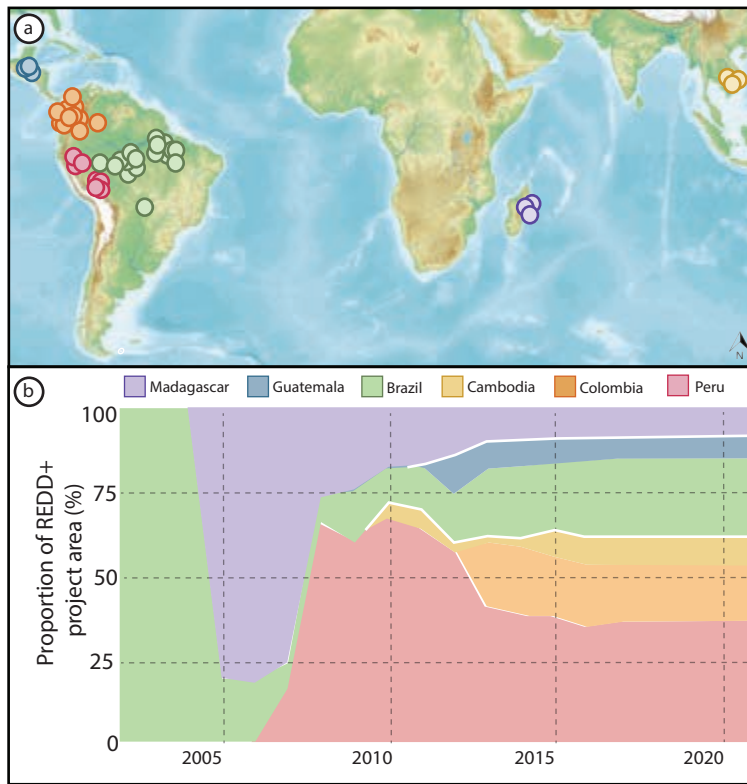


Figure 1. Location of the REDD+ projects analyzed (a), REDD+ project area (%) by country within the gNRJ (b).

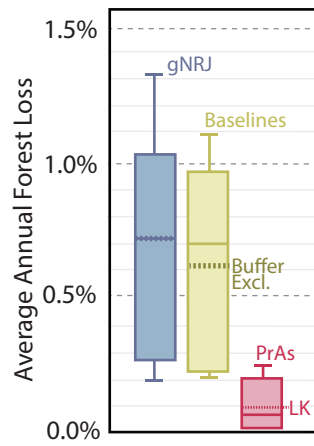


Figure 2. Weighted average gross global REDD+ jurisdiction (gNRJ) forest loss compared to weighted average gross REDD+ baseline deforestation rates and REDD+ project area (PrA) forest loss for all jurisdictions. The dashed line represents net values: REDD+ baselines excluding national-level buffer pool contribution discounts, global jurisdictional forest loss excluding predicted leakage forest loss and PrA forest loss with leakage forest loss from two scenarios added (LK = Leakage Scenario).

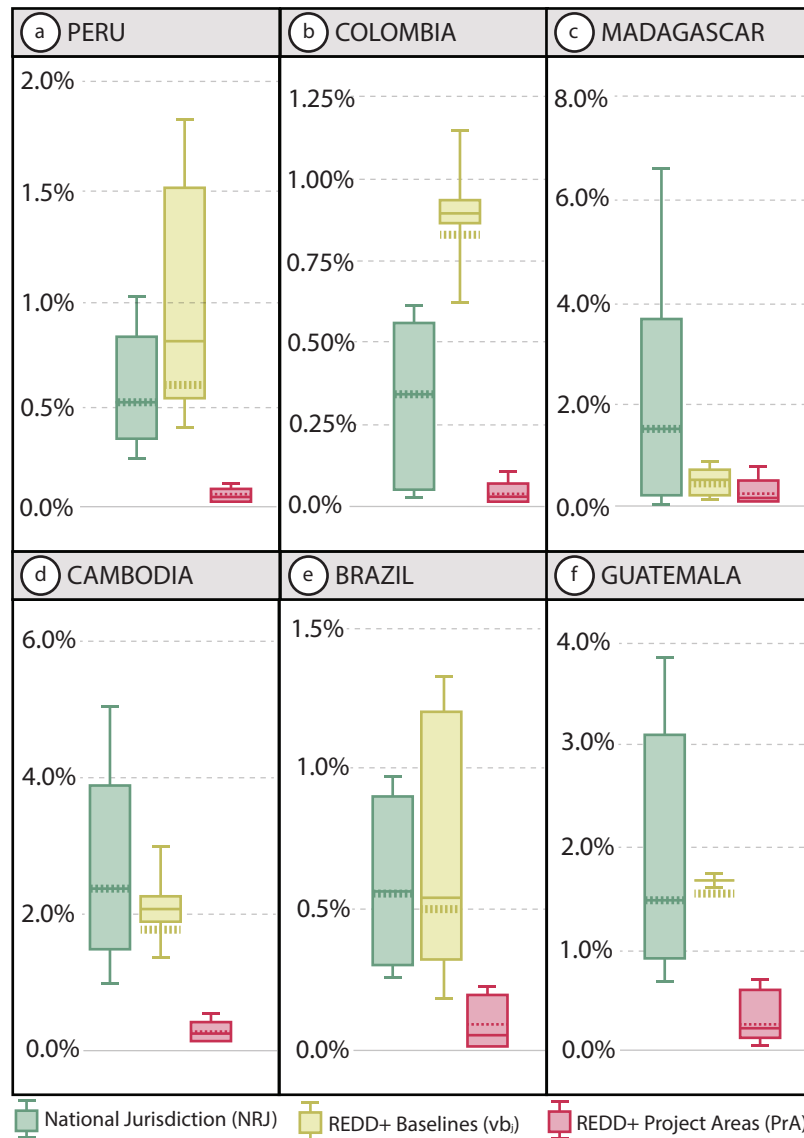


Figure 3. Weighted average REDD+ jurisdiction forest loss (NRJ) compared to weighted average REDD+ baseline deforestation rates (vbj) and REDD+ project area (PrA) forest loss for (a) Peru, (b) Colombia, (c) Madagascar, (d) Cambodia, (e) Brazil and (f) Guatemala. Solid lines represent average, slashed lines represent average net: national baseline excluding buffer pool contributions, and jurisdictional forest loss excluding predicted leakage forest loss.