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Optimal durations of reference and crediting periods for estimating emission reductions from forests

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Abstract

Accurate quantification of emission reductions from jurisdictional-scale forest mitigation efforts depends, among many other things, on selecting appropriate durations for the reference period, which determines the historical baseline, and the crediting period, during which performance is measured. Selecting the durations of these periods is problematic. Periods that are too long may not adequately represent deforestation rates in countries where these rates are changing, as rates from the distant past may no longer reflect conditions during the crediting period; periods that are too short are sensitive to interannual variability. Carbon standards and reporting frameworks currently have varying requirements (e.g. 5- or 10-year periods), but the implications of reference and crediting period durations remain underexplored. Using a global remote sensing dataset of deforestation rates for 71 tropical countries and territories from 1990 to 2025, we evaluated how the duration of reference and crediting period durations affect changes in deforestation rates, using a sliding window approach. We compared deforestation rates during hypothetical crediting periods against historical rates during hypothetical reference periods for all possible combinations of period durations for each country. We report the period durations that minimized the difference between the two rates, which we call the Reference-Crediting Period Discrepancy (RCPD). We did this for all countries together, then for countries with and without deforestation trends, and finally for each country separately. Both very short and very long reference periods resulted in high RCPD. On average, the lowest RCPD (51%) occurred at a 12-year reference and 7-year crediting period, and a 10-year reference and 5-year crediting period were almost as good as optimal (56% RCPD). Shorter reference periods were worse; a 5-year reference period gave an average RCPD of 69%. Stratifying countries based on detected trends resulted in shorter optimal periods for countries with a trend and longer periods for countries dominated by noise, as expected, with a slight reduction in RCPD (50%). Customizing period durations for each country reduced average RCPD to 11%, but carbon crediting requires a more standardized approach. These results suggest that longer reference periods (10 or more years) are better than shorter ones, especially for countries without a trend in their historical deforestation rates.

1. Introduction

Forests play a critical role in mitigating climate change by serving as carbon sinks and reducing atmospheric greenhouse gas concentrations. To address the emissions produced by deforestation and forest degradation, international climate frameworks such as REDD+ (Reducing Emissions from Deforestation and forest Degradation) have incentivized countries to quantify and report their reductions in emissions from forests. A fundamental challenge in this process is determining robust methodologies for estimating emission reductions and validating the impact of forest conservation efforts.

Reductions of greenhouse gas emissions under jurisdictional-scale REDD+ are quantified by comparing emissions during a crediting period against a benchmark of baseline emissions (Olander *et al* 2008, Balmford *et al* 2023). The baseline is used to estimate what emissions would have been if no action had been taken. Under Article 6 of the Kyoto Protocol (Decision 9/CMP.1, Appendix B), the baseline is defined as 'the scenario that reasonably represents the anthropogenic emissions by sources or anthropogenic removals by sinks of greenhouse gases that would occur in the absence of the proposed project.' Building on this framework, the 2009 Copenhagen Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) (Decision 4/CP.15) emphasized that baseline emissions for REDD+ should be established transparently using historical data and taking national circumstances into account. Most countries (>80%) have used historical averages as reference levels (FAO 2022) to approximate the rate of deforestation at the start of the project (Griscom *et al* 2009).

Carbon standards and reporting frameworks (we refer to these together as 'carbon standards' henceforward) define methods for quantifying, reporting and verifying emission reductions, including from jurisdictional-scale forest mitigation programs, for the provision of results-based payments or the issuance of carbon credits. These standards mainly set crediting baselines using historical averages over reference periods of varying durations (table 1). The methodological framework of the Forest Carbon Partnership Facility's (FCPF) Carbon Fund, first released in 2013, requires a 10-year reference period, except under specific circumstances (FCPF 2020). The Architecture for REDD+ Transactions' The REDD+ Environmental Excellence Standard (ART-TREES) requires a 5-year reference period (Architecture for REDD+ Transactions 2021). The 2024 version of Verra's Verified Carbon Standard (VCS) for Jurisdictional and Nested REDD+ (JNR) requires a 4–6-year reference period (Verra 2024). For REDD+ reporting to the UNFCCC, countries have mostly used 10-year reference periods, although shorter and longer periods are also common (FAO 2022).

Compared with reference periods, the duration of crediting periods has been more uniform. A 5-year crediting period is mandatory in ART-TREES and 4–6 years is required by Verra's VCS-JNR (Architecture for REDD+ Transactions 2021, Verra 2024). Although there is flexibility under the UNFCCC and the FCPF Carbon Fund, most countries use crediting periods close to 5 years in those contexts (World Bank 2021, FAO 2022).

Current guidelines for selecting reference and crediting periods have come under scrutiny

Table 1. Reference and crediting period durations required by major carbon standards or reporting frameworks for jurisdictional REDD+.

Carbon standard or reporting framework	Reference period	Crediting period
FCPF carbon Fund	10 years, except with justification	Flexible, 5 years often used
ART-TREES	5 years	5 years
Verra's VCS-JNR	4–6 years	4–6 years
REDD+ reporting to the UNFCCC	Flexible, 10 years often used, but shorter and longer periods also common	Flexible, 5 years often used

(Balmford *et al* 2023, Zhao *et al* 2025). Much attention has focused on the project scale since an analysis of VCS projects in the Brazilian Amazon (West *et al* 2020) and in other countries (West *et al* 2023) found that baseline deforestation trends were often not maintained beyond the project boundaries, leading to the unfair crediting of reductions calculated only by comparison to unrealistic baselines. Similar problems with baseline setting have been seen elsewhere, as in California's cap-and-trade program (Badgley *et al* 2022, Coffield *et al* 2022). Spatial aggregation at the jurisdictional scale reduces the variability in deforestation rates that makes baseline-setting at the project scale so sensitive to period selection (Teo *et al* 2023), which helps to avoid the credibility challenges faced by local REDD+ projects.

For jurisdictional-scale forest mitigation programs, there is no geographical area to use as the counterfactual reference (Zhao *et al* 2025), and baseline setting relies on historical average deforestation measurements from within the program area. To ensure the integrity of carbon credits, establishing appropriate durations for the reference and crediting periods is essential. Clarity is key because there is an incentive to select a reference period characterized by a high rate of deforestation to inflate the apparent success of conservation efforts during the crediting period (Santilli *et al* 2005). The Integrity Council for the Voluntary Carbon Market (ICVCM) recently published Core Carbon Principles that laid out the need for an appropriate duration of the reference and crediting periods (criterion 10.3) and called for approaches to estimating baseline emissions and removals to be based on historical information, with attention to uncertainty in these estimates (ICVCM 2024).

Long reference periods (e.g. 20 years) may produce baselines that no longer reflect contextual conditions during the crediting period, leading to inaccurate estimates of emission reductions (Dudley 2010, Angelsen 2017). For example, in regions where annual deforestation rates are rising, long reference periods include older data that tend to underestimate rates at the time that mitigation activities began. A low reference rate makes it unattractive to participate in carbon programs because a performance period with no change or a slight improvement could appear as a failure when in fact it was a success (Dezécache *et al* 2018). Conversely, where deforestation trends are downwards, outdated deforestation measurements overestimate the effect of new mitigation activities (Dudley 2010, West *et al* 2020).

Very short reference periods (e.g. 1-year periods) are also problematic (Houghton 2005), because deforestation rates fluctuate from year to year (Olander *et al* 2008, Huettner *et al* 2009). Thus, the reported deforestation rate for a very brief period is unlikely to represent the baseline deforestation rate. Similar reasoning applies to very short crediting periods.

The goal of this study was to identify what durations of reference and crediting periods could best enable accurate carbon crediting for jurisdictional-scale, result-based payment programs, using a global remote sensing dataset of deforestation rates for 71 tropical countries and territories. A sliding window approach compared observed deforestation rates during hypothetical crediting periods against historical baselines derived from hypothetical reference periods. We aimed to identify a compromise of reference and crediting period duration that would minimize the risks associated with being either too long or too short.

2. Methods

2.1. Data source

For this study of jurisdictional-scale forest cover change dynamics, we needed a dataset with annual deforestation area estimates for a large number of countries in the tropics. We selected the tropical moist forest (TMF) dataset, a product of the Joint Research Centre (Vancutsem *et al* 2021, European Commission 2025), which provides annual change maps in tropical moist forest cover from 1990 through 2025. The analysis was restricted to countries and territories fully covered by the TMF tile grid. Country and territory identification followed the United Nations M49 standard (UNSD 2024). We excluded Sao Tome and Principe because data were available only until 2021. The final dataset comprised 71 countries and territories (figures S1–S3).

We used estimates of annual change in forest area for each country. We considered only the deforestation component of the dataset and ignored forest degradation. We refer to the annual change in forest area as the deforestation rate. Although greenhouse-gas emissions are the ultimate focus of climate mitigation activities, we used deforestation area for this analysis because annual emissions from deforestation are typically calculated as the product of deforested area and emissions per unit area (e.g. Fearnside 2005). While deforestation rates vary over time, emissions per unit area are usually treated as constants within a forest type; thus, change over time in estimated emissions is driven by change in the underlying area data. To the degree that the proportion of forest types undergoing deforestation changes from year to year, there is some variation in the relationship between emissions and deforested area. Our analysis of optimal period durations would be biased by this variation only if the signal-to-noise ratio in deforestation rates over time varies systematically with the rate of emissions per unit area across various forest types, which seems unlikely.

The map-based approach underlying the TMF dataset differs from the sample-based map area estimates that most carbon standards now require (Bey *et al* 2016, FAO 2022). Sample-based area estimation is labor-intensive because it requires augmented visual interpretation, and many countries have produced such estimates only for the durations required (5–10 years for reference and crediting periods). The TMF dataset, although map-based, had a reported overall accuracy of 91% for forest degradation and deforestation based on the original Landsat Collection 1 product (Vancutsem *et al* 2021). The reprocessed TMF product used here, based on the improved Landsat Collection 2 archive with an 11%–20% increase in usable observations depending on region, likely has even better accuracy, but a formal accuracy assessment has not yet been reported (European Commission 2025). We did not account for possible differences in map accuracy over time (image quality was lower in the 1990s than in the 2000s) or among countries (commodity-driven clearing in South America being easier to detect than small-scale shifting agriculture in the Congo basin; Zalles *et al* 2024), as it is not clear how this would introduce a bias, in either direction, in identification of optimal period durations.

The data reflect a wide range in both the degree of interannual variability ('noise') and the rate of long-term change over time ('trend') (figure 1), which are the two characteristics of deforestation time series determining the optimal durations of reference and crediting periods.

This dataset includes countries with ongoing efforts to reduce deforestation, which, if effective, would contribute to downward trends. Our approach ignores those mitigation efforts, consistent with the treatment by leading carbon standards such as Verra's VCS-JNR and ART-TREES, where baseline setting ignores mitigation efforts. In practice, as time goes on, this year's crediting period becomes next year's

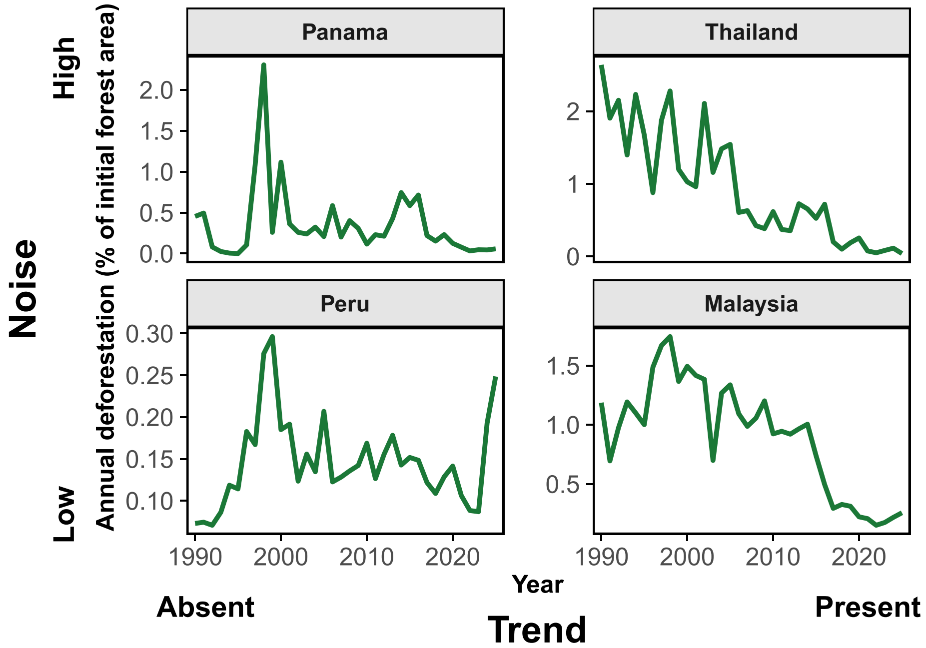

Figure 1. Noise versus signal in country deforestation patterns illustrated with four deforestation time series differing in inter-annual variation (noise, top vs. bottom) and the presence of a long-term trend (right vs. left). Annual deforestation is expressed relative to the undisturbed tropical moist forest area in 1991, the first year of the dataset. Note that the countries that differ by more than an order of magnitude in deforestation rates.

reference period, as is the case in our sliding window approach (described below).

2.2. Assessing Reference-Crediting Period Discrepancy in deforestation rates

We analyzed deforestation rates at various intervals of reference and crediting periods within the 36-year dataset. By systematically shifting these periods across the dataset using a sliding window approach (figure 2), we explored all possible temporal configurations of contiguous reference and crediting periods and compared deforestation rates between them.

Let D_t denote the deforestation rate (measured in area units) in year t. The analysis involved defining a range of potential durations for both the reference period and the crediting period. The reference period, of duration n_{r}, immediately precedes the start of the crediting period starting at year t_0. Hence, the reference period spans from year $t_0 - n_{\mathrm{r}}$ to $t_0 - 1$. The crediting period, of duration n_{c}, is the period over which the RCPD was assessed, spanning from initial year t_0 to year $t_0 + n_{\mathrm{c}} - 1$.

The analysis proceeded iteratively across different combinations of reference and crediting period durations (n_{r} and n_{c}, respectively). For each pair $\{n_{\mathrm{r}}, n_{\mathrm{c}}\}$, n_{r} and n_{c} were drawn from the sets of possible durations. The combined duration of these two intervals could not exceed the dataset's duration, thus $n_{\mathrm{r}} + n_{\mathrm{c}} \leqslant 36$. We report values for all possible period durations, even though those close to 35 years reflect only one or a few windows for each country.

For each possible combination of n_{r} and t_0, as well as n_{c} and t_0, the average annual deforestation rate for the reference period was:

$$D_{\mathrm{r}}^{n_{\mathrm{r}},t_0} = \frac{1}{n_{\mathrm{r}}} \sum_{t=t_0-n_{\mathrm{r}}}^{t_0-1} D_t \qquad (1)$$

and the average annual deforestation rate for the crediting period was:

$$D_{\mathrm{c}}^{n_{\mathrm{c}},t_0} = \frac{1}{n_{\mathrm{c}}} \sum_{t=t_0}^{t_0+n_{\mathrm{c}}-1} D_t \,. \qquad (2)$$

The RCPD for each combination of $\{n_{\mathrm{r}}, n_{\mathrm{c}}\}$ was the weighted mean absolute difference over all t_0:

$$\frac{\sum_{t_0} \left| D_{\mathrm{c}}^{n_{\mathrm{c}},t_0} - D_{\mathrm{r}}^{n_{\mathrm{r}},t_0} \right|}{\sum_{t_0} D_{\mathrm{r}}^{n_{\mathrm{r}},t_0}} \,. \qquad (3)$$

RCPD (equation (3)) is thus the average absolute difference in annual deforestation between paired periods, expressed as a fraction of the average deforestation observed in the reference periods across all windows. Hence, it is not a measure of statistical uncertainty but of empirical sensitivity: it captures how much the apparent emission reductions depend on the timing and duration of the reference and crediting periods, expressed relative to the reference level because, in carbon accounting, the reference period deforestation rate is the benchmark against which claimed reductions are measured. Minimizing RCPD therefore identifies the period durations that reduce

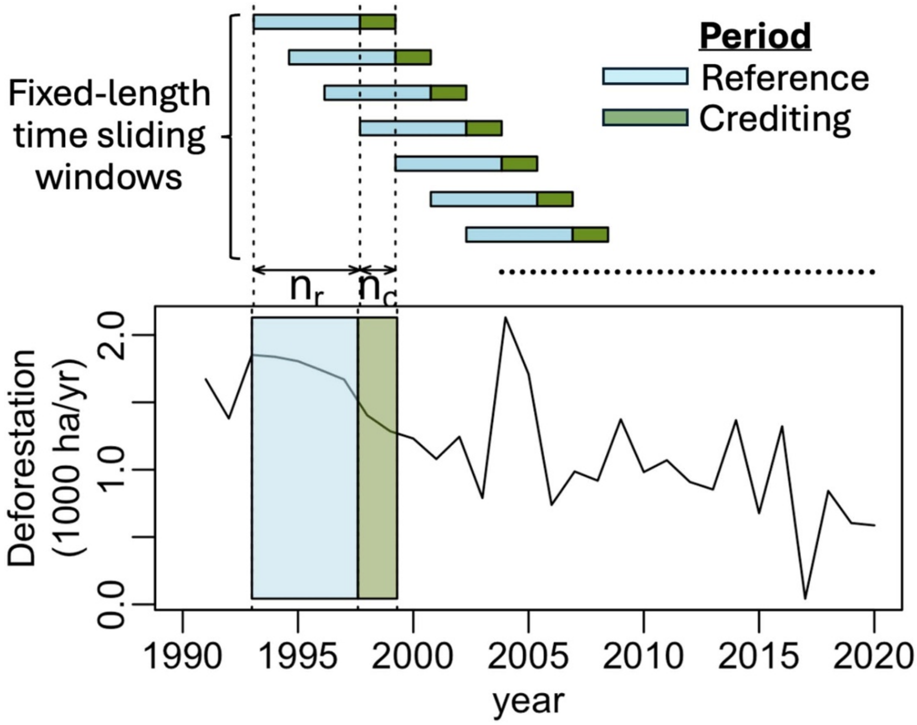

Figure 2. Sliding window approach for comparing deforestation in the reference and crediting periods of duration n_r and n_c, respectively. For both periods average deforestation rates are calculated. The method loops through different n_r and n_c across the entire time series.

the influence of period selection on estimated emission reductions, improving the ability to distinguish genuine mitigation from baseline artifacts.

In some years for some countries, the deforestation rates in the TMF dataset were zero. To avoid dividing by zero, we found the minimum non-zero area per year reported in the entire dataset and replaced zeros with half of that value. Finally, we averaged RCPD across the 71 countries for which we had data.

2.3. Identifying trends

We explored whether the optimal choice of reference and crediting period durations varied depending on whether a country's deforestation time series displayed a long-term trend (figures S1–S3). We fitted autoregressive integrated moving average (ARIMA) models to each country's deforestation time series using the 'forecast' package in R (Hyndman *et al* 2025). The ARIMA integration order parameter d (the number of times the series must be differenced to achieve stationarity) serves as a transparent, data-driven indicator of trend presence: $d = 1$ (or more) indicates a non-stationary, trending series, while $d = 0$ indicates a stationary series without a persistent trend (Shumway and Stoffer 2000). This classification is used only to stratify countries for the analysis; the ARIMA model is not used to generate predictions or to characterize the form of each time series.

3. Results

3.1. Sources of Reference-Crediting Period Discrepancy

There are two sources of RCPD: interannual variability ('noise') and trends over time (figure 1). For a deforestation time series free of any trend and consisting of pure noise, the RCPD would be smallest for the longest durations of reference and crediting periods. At the other extreme, a deforestation time series with a long-term trend and no noise, i.e., a sloped line, would have the smallest RCPD for the shortest possible durations of reference and crediting periods. Real deforestation time series display trends and noise to varying degrees, resulting in minimal average RCPD at a wide variety of period durations.

3.2. Optimal durations of reference and crediting periods

For each country, we evaluated the RCPD for varying durations of the reference and crediting periods. The shape of these curves varied by country (figure 3), as shown for the four cases pictured in figure 1. In countries with a long-term trend (Thailand and Malaysia, on the right in figure 3), longer reference periods produced higher RCPD because longer historical averages misrepresent current conditions. In countries without a trend (Panama and Peru, on the left), the lowest RCPD occurs at longer durations of reference periods than for countries with a trend. In the other dimension, countries with greater noise (Panama and

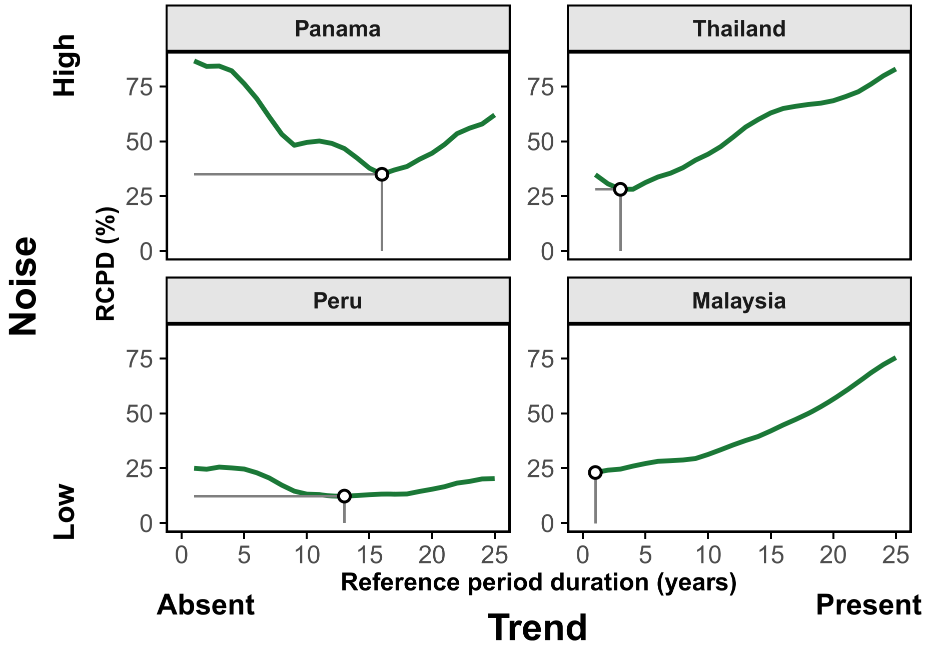

Figure 3. Reference-Crediting Period Discrepancy for varying reference periods and a 5-year crediting period, for the four countries pictured in figure 1. The dot marks the minimum RCPD for each country.

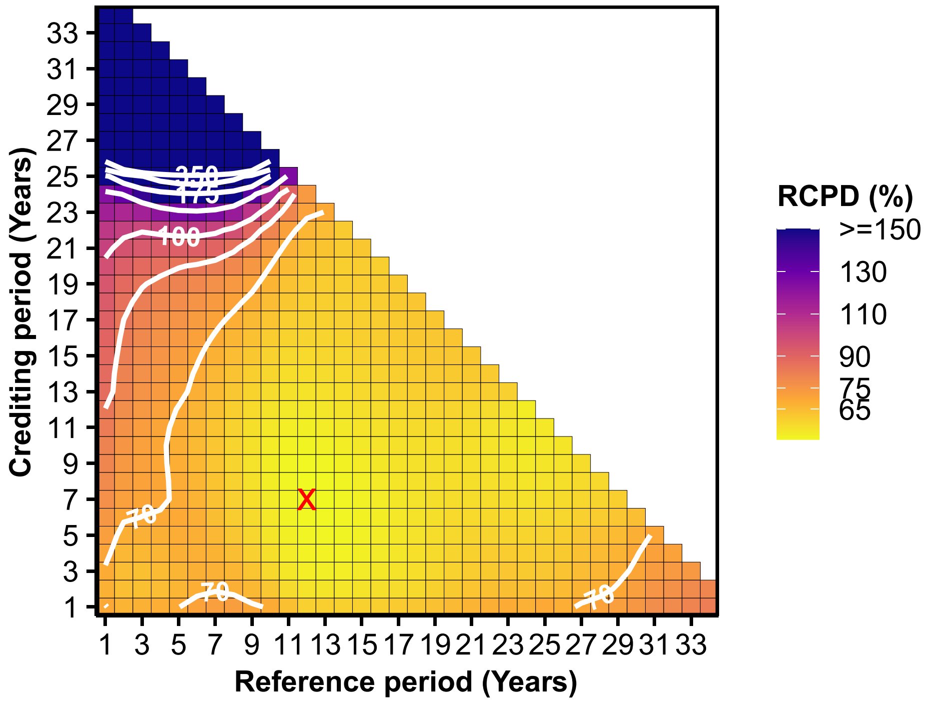

Figure 4. Average Reference-Crediting Period Discrepancy (%) across 71 countries for all possible combinations of reference and crediting periods. The red 'X' marks the combination of reference and crediting period durations giving the minimum RCPD.

Thailand, on top) had slightly higher optimal period durations than their less noisy counterparts (Peru and Malaysia, on the bottom), because a longer duration averages out the interannual variation, resulting in lower RCPDs.

We calculated the average RCPD across all countries for every possible combination of reference and crediting period durations (figure 4). The minimum RCPD (51%) occurred at a reference period of 12 years and a crediting period of 7 years; similar values (up to 55%) were found for reference periods of 10–16 years and crediting periods of 3–11 years.

These average rates conceal a range of RCPD values across the 71 countries. The minimum RCPD (51%) had a 95% bootstrapped C.I. of 45%–56%. With both periods set at 5 years (figure 5(A)), RCPD

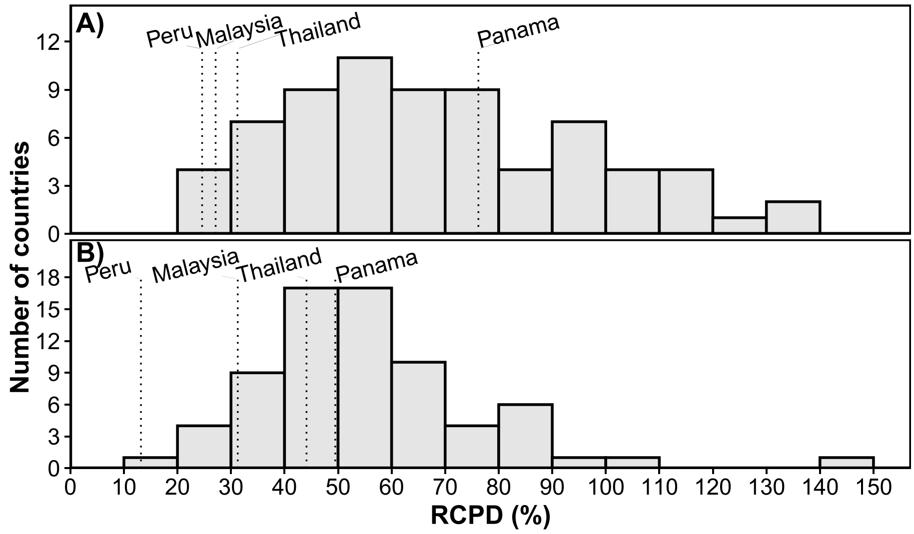

Figure 5. Distribution of Reference-Crediting Period Discrepancy for 71 countries for (A) a 5-year reference period and (B) a 10-year reference period, using a 5-year crediting period. The location of countries shown in figure 1 is indicated.

was notably worse, averaging 69% (64%–75%). A 10-year reference and 5-year crediting period (figure 5(B)) was better, with RCPD averaging 56% (51%–61%). Judging from these confidence intervals, a 10-year reference period is indistinguishable from optimal, but a shorter reference period gives more countries high RCPD (figure 5).

3.3. Tailoring periods to country circumstances

Selecting the duration of reference and crediting periods requires balancing the risks associated with periods that are too long or too short. The optimal duration varies substantially across countries, depending on the presence of trends (requiring shorter durations) and the degree of variability ('noise') in their deforestation time series (figures 1 and 3). To improve guidance on the selection of these durations, we explored two additional approaches: (1) distinguishing countries with and without trends in deforestation rates; and (2) identifying the minimum RCPD for countries individually.

3.4. Distinguishing countries with and without trends

In carbon crediting discussions, considerable attention has been given to tailoring approaches for specific country groups. For example, the FCPF Carbon Fund, ART-TREES, and the Green Climate Fund all provide differentiated crediting methodologies for high forest, low deforestation (HFLD) countries.

In this paper, we tested the value of breaking countries into two groups based on whether their deforestation rates displayed trends. We used ARIMA models for assessing presence or absence of trends in each country's deforestation time series and found 6 countries with an upward trend, 21 countries with a downward trend, and 44 countries without a trend in their deforestation time series. As expected, for countries without a trend, long period durations were optimal (16 for the reference, 20 for the crediting period), consistent with the benefit of averaging out interannual variability over longer period durations. For countries with a trend, RCPD was lowest for reference and crediting periods of only 3 years, because deforestation rates changed over the time series in these countries. Figure 6 shows RCPD for both groups for all durations of reference periods and a crediting period of 5 years; Figure S4 shows, for both groups, RCPD for all combinations of period durations.

In theory, this classification could guide the selection of period durations. The performance gain, however, was negligible. With a 5-year crediting period, for countries with a trend, the minimal RCPD was 48%, at a reference period of 3 years, while for countries without a trend, the minimal RCPD was 52% at a reference period duration of 14 years (figure 6). The overall average RCPD for all countries, with these differentiated reference periods, would be 50%, which is not very different from the global minimum RCPD for a 5-year crediting period: 52% for a reference period of 12 years (figure 4). A greater improvement in RCPD could be achieved by assigning a longer crediting period to countries without a trend (figure S4), but this would delay their ability to claim payments.

3.5. Identifying the minimum Reference-Crediting Period Discrepancy for countries individually

As a theoretical exercise, we identified, for each country individually, the duration of the reference and crediting periods that produced the minimum RCPD. Optimal reference and crediting periods extended across the whole data range we have estimates for,

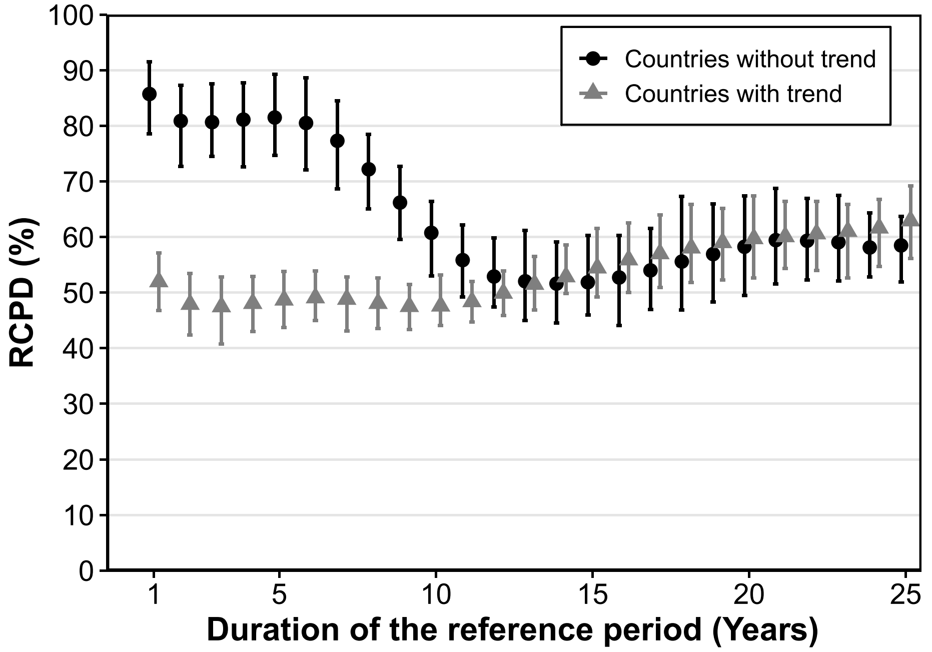

Figure 6. Reference-Crediting Period Discrepancy for varying reference periods and a 5-year crediting period applied separately to two groups of countries, those with and without trends. Error bars represent bootstrapped 95% C.I.

from 1 to 34 years. The average RCPD across the 71 countries, allowing for country-specific reference and crediting periods, was only 11% (C.I. 9%–15%). Some of these optima are not very robust, where they correspond to durations with few replicate sliding-window combinations. In any case, carbon standards tend to constrain the duration of reference and crediting periods rather than allowing each country to choose these durations freely, which reduces the risk of opportunistic selection of periods that maximize the claimed emission reductions.

4. Discussion

4.1. Durations of reference and crediting periods

Our analysis showed that a 10-year reference period and 5 year crediting period is close to optimal: based on the 71 countries in the data set, the very best combination was a 12-year reference period and a 7-year crediting period, with an average RCPD of 51%. A 5-year reference period, which is also common (table 1) did not perform as well, giving an average RCPD of 69%, compared to 56% for a 10 year reference period with the same 5-year crediting period). Note, however, that longer reference periods require the use of earlier Earth Observation products with higher uncertainty, which reduces the quality of emission reduction estimates. Thus, the choice of a reference period duration requires balancing the advantages of averaging over longer periods against the disadvantages of using older data.

The choice of reference period durations could be refined to account for trends in deforestation over time: in countries exhibiting trends, the average RCPD was minimal at shorter combinations of reference and crediting periods, while those without trends had much longer optimal period durations (figures 6 and S4). The advantage of longer reference periods is thus greatest for countries with high noise and low long-term change in deforestation rates.

4.2. Noise and trend both contribute to Reference-Crediting Period Discrepancy

Some of the RCPD we observed is due to trends in deforestation rates, and some is due to interannual variability. Interannual variability in deforestation rates has many causes, including patterns in forest fires associated with El Niño events, changes in local policy, and other drivers of land-use change. Trends are present in the data; global deforestation rates are decreasing (FAO 2025); the TMF dataset we used had more countries with decreasing than increasing trends. Surprisingly, countries with trends had lower RCPD than those without a trend, in the range of period durations relevant to carbon standards (figures 6 and S4 shows all combinations of period durations). If the difference in RCPD between these two groups of countries is due to noise in the countries not determined to have a trend by ARIMA modeling, then the contribution of trends to RCPD is smaller than the contribution of noise, in the range of period durations relevant to carbon standards. There are other possible approaches to identifying trends and grouping countries than the ARIMA modeling we used, which could be explored for their potential to improve reporting of emission reductions against a reference level.

Where countries have been successful at reducing deforestation rates, the RCPD we report partly reflects those trends. Our analysis covers 1990–2025, a period spanning both the pre-mitigation era dominated by economic, climatic, and demographic drivers, and the post-2013 scale-up of jurisdictional-scale REDD+ programs following the Warsaw Framework and the 2015 Paris Agreement. We do not attempt to separate these two signals: the sliding window approach treats all years equivalently, consistent with how carbon standards apply historical average baselines without accounting for whether the baseline reflects mitigation results.

4.3. Addressing interannual variability in uncertainty analysis

The selection of reference and crediting period durations contributes uncertainty to emission reduction estimates. Carbon standards commonly require countries to conduct detailed uncertainty analyses of claimed emission reductions (Yanai *et al* 2020), but interannual variability has not been included as an error source. More research is needed to understand the degree to which interannual variability in deforestation rates is due to map accuracy limitations rather than genuine year-to-year changes in forest cover. The original TMF product reports omission (9.4%) and commission (8.1%) error rates (Vancutsem *et al* 2021); no formal accuracy reassessment has been published for the reprocessed TMF product used here (European Commission 2025), but accuracy is likely even better due to improvements in the Landsat Collection 2. To the degree that interannual variability reflects actual changes in deforestation rates, no improvement in map accuracy would reduce it: it represents real variation that any carbon accounting framework must contend with. A formal assessment of whether map accuracy biases the identification of optimal period lengths is not feasible for the TMF dataset, which is a wall-to-wall map product rather than a probabilistic or sample-based estimate. The bootstrapped confidence intervals we report, derived by resampling across the 71 countries, provide the best estimate of confidence in our findings.

More frequent measurements of forested area are becoming more common. For example, ART-TREES mandates annual reporting during both reference and crediting periods, though it also allows interpolation such that countries may still collect data only at intervals of several years (Architecture for REDD+ Transactions 2021). Verra's VCS-JNR requires biennial data collection for both reference and crediting periods (Verra 2024). These requirements will improve the basis for incorporating interannual variability into uncertainty assessments.

4.4. Risk of inflated emission reduction estimates

Our findings bear directly on the foundational condition of additionality in carbon credit integrity: the selection of reference and crediting periods affects how well observed emission reductions can be distinguished from baseline variation. High interannual variability contributes uncertainty to calculated emission reductions, and opportunistic selection of reference and crediting periods could artificially inflate emission reduction estimates beyond any real mitigation effects (Balmford *et al* 2023, Cabiyo and Field 2025). Recall that the RCPD we report represents the variation in estimated emission reductions that results from sliding the window for reference and crediting periods.

The optimal average RCPD was high compared with the reductions in deforestation reported by countries participating in REDD+ programs. In submissions to the UNFCCC, most programs reduce emissions by 10%–40% below the reference level (Neeff 2021). Our results indicate that the average difference in deforestation rates between a reference period and a crediting period (the RCPD) is 51% just due to the selection of those periods. To the degree that emissions scale with the rate of loss of forested area, this means that the uncertainty from period selection alone is of the same order of magnitude as the emission reductions, making it difficult to build robust emission reduction estimates. Adopting longer reference periods would reduce this uncertainty, strengthening our ability to distinguish genuine emission reductions from artifacts of period selection, thereby improving the integrity of carbon credits.

Carbon standards can use several mechanisms to mitigate this risk. First, backcrediting should be limited: for instance, ART-TREES allows up to 4 years prior to concept note, Verra's VCS-JNR allows up to 5 years, while the World Bank does not purchase carbon credits generated prior to emission reductions payment agreements (FCPF 2020, Architecture for REDD+ Transactions 2021, Verra 2024). Second, standards should require credible evidence linking the chosen mitigation start date to actual mitigation activities to avoid opportunistic period selection. Finally, a better understanding of interannual variability in deforestation rates would allow more accurate quantification of uncertainty in estimated emissions, potentially revealing opportunities to reduce uncertainty due to this source.

Carbon credit integrity in jurisdictional REDD+ rests on conditions beyond additionality. Permanence (whether credited carbon remains sequestered beyond the crediting period) can be addressed by post-crediting adjustments and buffer mechanisms in carbon standards. Another source of credit inflation that is outside the purview of our analysis is international leakage, which occurs when emission reductions in one jurisdiction replace deforestation elsewhere through commodity trade. Although it is difficult to quantify, it is not insignificant, as shown for forest product trade in the context of China (Yin 2024).

5. Conclusions

The durations of the reference and crediting periods are critical parameters in quantifying emission reductions from reduced deforestation. Selecting appropriate durations is challenging: too long a period may be inadequate in countries where deforestation rates are trending upward or downward, while too short a period is sensitive to interannual variability, leading to unreliable estimates.

Carbon standards such as ART-TREES and Verra's VCS-JNR currently apply uniform reference and crediting period durations across all countries. Our analysis indicates that reference periods of 12 years and crediting periods of 7 years produced the lowest average RCPD across the 71 countries studied. Results varied widely across countries, both in the magnitude of RCPD and the optimal period durations based on minimizing RCPD. However, on average, it appears that confidence in emission reductions would be improved by increasing the duration of reference periods from 5 to 10 years, while retaining a crediting period of 5 years, based on our analysis of the TMF dataset. Consideration should be given to whether extending reference periods back in time incurs a loss in quality of area estimation.

Beyond examining the duration of reference and crediting periods, there are other important improvements needed to carbon standards. Robust rules governing mitigation start dates, requirements for evidence of real mitigation actions, and limits on back-crediting are critical to maintain the integrity of carbon crediting. Incorporating interannual variability in deforestation rates in assessing uncertainty in emission reductions will require a better understanding of its sources.

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Data availability statement

The R code and data used in this analysis are available on Zenodo https://doi.org/10.5281/zenodo.17713475 (Gamarra and Neeff 2026).

No new data were created or analysed in this study.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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