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Current Forest Carbon Offset Buffer Pool Contributions Do Not Adequately Insure Against Disturbance-Driven Carbon Losses

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ABSTRACT

Nature-based climate solutions in Earth's forests could strengthen the land carbon sink and contribute to climate mitigation, but must adequately account for climate risks to the durability of carbon storage. Forest carbon offset protocols use a "buffer pool" to insure against disturbance risks that may compromise durability. However, the extent to which current buffer pool tools and allocations align with current scientific data or models is not well understood. Here, we use a tropical forest stand biomass model and an extensive set of long-term tropical forest plots to test whether current buffer pool contributions are adequate to insure against observed disturbance regimes. We find that forest age and disturbance regime both influence necessary buffer pool sizes. In the majority of disturbance scenarios in a major carbon registry buffer pool tool, current buffer pools are substantially smaller than required by carbon cycle science. Buffer pool tools and estimates urgently need to be updated to accurately assess disturbance regimes and climate change impact on disturbances based on rigorous, open scientific datasets for nature-based climate solutions to succeed.

1 | Introduction

Earth's forests currently serve as a substantial carbon sink, absorbing roughly a quarter of human carbon emissions annually from the atmosphere (Bonan 2008; Pan et al. 2011; Pugh et al. 2019). Alongside critical and necessary efforts to dramatically reduce fossil fuel emissions, forests can contribute to climate change mitigation as "nature-based climate solutions" (NbCS), which are a suite of potential changes in management decisions to increase forest carbon stocks (Griscom et al. 2017; Nolan et al. 2021; Seddon 2022). The most common forest-based NbCS to date are (i) avoided conversion/loss where forests are protected from degradation or deforestation, (ii) improved forest management where management changes are implemented to increase carbon stocks, and (iii) afforestation/reforestation where forests are actively planted and restored (Griscom et al. 2017; Buma et al. 2024; Ellis et al. 2024; Novick et al. 2024). The potential for NbCS is considered to be largest in tropical forests where there is widespread interest in leveraging NbCS efforts to reduce and stop deforestation through Reducing Emissions from Deforestation and Degradation (REDD+) efforts (Griscom et al. 2020; Haya, Alford-Jones, et al. 2023; Roopsind et al. 2019). Despite the potential for NbCS, widespread quality concerns about ongoing efforts (Anderegg et al. 2020; Badgley, Chay, et al. 2022; Badgley, Freeman, et al. 2022; Coffield et al. 2022; Haya, Alford-Jones, et al. 2023; Stapp et al. 2023; West et al. 2023) highlight the urgent need of rigorous carbon cycle science underpinning the tools and protocols that fund and implement NbCS projects.

To serve effectively as climate mitigation, forest NbCS projects must achieve a level of durability in carbon storage and account for any potential carbon losses, frequently through a buffer pool approach. Individual projects contribute a portion of credits into a common buffer pool that serves as an insurance policy and then those credits are retired (i.e., permanently removed from the marketplace after a credit has been used to offset emissions) when a reversal (loss) of carbon occurs in a project. Durability is particularly crucial when the NbCS effort is funded as part of a carbon offset, because the carbon stored in the forest is intended to offset fossil fuel carbon emissions that warm the climate for centuries to millennia (Archer et al. 2009; Solomon et al. 2009) and must be generally sustained through when global temperatures peak to avoid excess warming (Cullenward et al. 2023; Matthews et al. 2022). A frequent timescale used as a gold standard for durability by NbCS project protocols is a 100-year time horizon (Anderegg et al. 2020; Haya, Evans, et al. 2023). For buffer pools to effectively insure project durability, they urgently need to accurately account for the frequency and severity of climate-sensitive disturbances such as fire or drought, and also the carbon cycle consequences of those disturbances. Disturbance plays a fundamental role in mediating forest carbon balance in many regions across the globe (Pugh et al. 2019). Crucially, the frequency and severity of these disturbances is projected to worsen under climate change over the 21st century (Seidl et al. 2017; Anderegg et al. 2020).

Carbon offset protocols developed by carbon registries are the most prominent and widely used mechanism currently to fund forest NbCS projects (Haya, Evans, et al. 2023; Ruseva et al. 2017). The carbon registry Verra, the largest registry in the world in the voluntary carbon market, recently released a new tool for calculating buffer pool based on different disturbance severity and frequencies (Verra 2023), which is expected to have a large influence on carbon markets and climate policy broadly. Previous Verra protocols (VM0006, VM0007, VM0009 and VM0015) have been criticized for buffer pools that were generally smaller than currently available science (Haya, Alford-Jones, et al. 2023), but more scientific quantification, models, and datasets are needed in this space. Thus, rapid and urgent evaluation of the robustness of the new Verra tool is a key scientific need with enormous policy relevance.

Here, we use a forest carbon model parameterized with extensive data from 125 tropical forest plots across multiple countries to ask: (1) Do existing buffer pool estimates conform with historical data-constrained models of tropical forest carbon cycle dynamics? (2) What buffer pool contributions would be needed to adequately insure different disturbance frequencies and severities, while accounting for a wide range in observed forest growth and mortality rates? (3) How does forest age affect buffer pool contributions within established forests?

2 | Methods

We simulated the carbon cycle dynamics of tropical forests assuming growth/regrowth based on historical estimates in response to different disturbance scenarios articulated by Verra's Non-Permanence Risk Tool version 4.2 (Table S1 reproduced from table 10 in AFOLU Non-Permanence Risk Tool V4.2 (Verra 2023)). This tool requires project developers to estimate the frequency (return time) and severity (carbon lost) of key natural disturbances including fire, pest and disease outbreaks, extreme weather events such as droughts and hurricanes, and geological risks such as earthquakes and volcanoes, and provides 25 categories of buffer pool contributions for each combination of frequency and severity for each relevant disturbance (Table S1) (Verra 2023). The stated goal of a carbon offset buffer pool's “natural risks” contributions is to insure against carbon losses from disturbances, such that a portfolio of projects remains able to deliver the promised climate mitigation benefits. In other words, the protocol will likely fail from a durability point of view if the total buffer pool declines to zero, driven by qualifying losses of biomass (unintended “reversals”) and indicating that climate risks (termed “natural risks” in the protocol) exceeded the allotted buffer pool. Note that offset protocols also must meet rigorous criteria in additionality, leakage, net climate impacts, and monitoring/verification to succeed for climate mitigation (Cook-Patton et al. 2023; Haya, Alford-Jones, et al. 2023; West et al. 2023). Currently, it is unclear whether the buffer pool contribution numbers per disturbance category provided in table 10 of the Non-Permanence Risk Tool (Table S1) are based on scientific data (i.e., no citation presented in reference material). Verra reports they are a mix of internal data and expert opinion, but have never been independently assessed, and no public information is available on the degree of scientific rigor that underpins them.

To contextualize the geographic coverage and breadth of Verra's current forest offset projects, we first extracted the geographic location and project type (e.g., improved forest management, avoided conversion/loss, afforestation/reforestation) of the 256 currently active forest offset projects in Verra's registry as of 1 December 2023. We overlaid these locations on a global forest age map in 2010 at 1000 m resolution (Besnard et al. 2021) and extracted an estimated mean forest age for each project based on the boundaries of project shapefiles or the 3×3 pixels with the centroid coordinates of the project as the center pixel when the project shapefile is not available. We note that these projects were developed under previous methodologies with different (and generally lower) buffer pool contribution rules (Haya, Alford-Jones, et al. 2023), but they provide a useful starting point for understanding the age distributions of different project categories for informing the model initiation. We plotted current projects on a previously generated global map of stand-replacing (e.g., stand-clearing) disturbance risk (Anderegg, Chegwidden, et al. 2022) to contextualize the range of integrated 100-year disturbance risk and return interval of stand-replacing disturbance. Our focus here is primarily on established forests and is thus most directly relevant to “improved forest management” and “reducing emissions from deforestation and degradation” project types.

We then used a forest biomass model to quantify biomass dynamics in different disturbance scenarios from table 10 of

Verra's Non-Permanence Risk Tool using a Monte Carlo approach and the mean stand age estimated for current Verra Improved Forest Management or Reducing Emissions from Deforestation and Degradation projects. The forest biomass model used here was developed at Barro Colorado Island in Panama to quantify tropical forest age-biomass dynamics across spatial scales using a range of growth and mortality rates (Knapp et al. 2022). This model is a standard statistical demographic model that simulates distributions of biomass trajectories based on input rates of carbon gains (growth and recruitment) and carbon losses (mortality) at a range of spatial scales as a function of age, whereby the change in aboveground biomass is described as a differential equation involving a biomass gain parameter and a mortality parameter (Fisher et al. 2008; Knapp et al. 2022). The model successfully recreates biomass distributions across spatial scales using the long-term plot data in Panama (Knapp et al. 2022) and is ideally suited for an examination of the impacts of age, growth rates, and disturbance frequency and severity on biomass and carbon trajectories in tropical forests.

To quantify forest growth and biomass dynamics across a wide range of climate and biogeographic variability in the Monte Carlo analysis, we used the published tropical forest carbon gain and carbon losses from mortality that comprise 125 long-term monitoring plots in tropical forests across North and South America (Yu et al. 2019). This allows us to quantify the estimated buffer pool contributions needed across a wide range of observed climate, soils, topography, and species composition, though our goal is not to directly examine any existing offset projects per se here. We further verified that the model reasonably reproduced aboveground biomass patterns in these 125 tropical forest plots, even absent on-site information about stand age (Figure S1), further giving confidence in the appropriateness of the model.

In the Monte Carlo analysis, we sampled across all carbon gain and carbon loss measurements of the 125 long-term tropical forest plots (925 plot-by-census combinations) with 1000 iterations per plot-by-census combination, yielding 925,000 simulations for any given initial forest age. In each Monte Carlo iteration, we sampled a uniform distribution with a given range of disturbance probabilities derived directly from Verra's table 10 scenarios and a uniform distribution that covered the range of carbon losses from disturbance from the same table of scenarios. This provides a probabilistic set of assessments that captures the wide range of potential biomass trajectories in a given disturbance regime over 100 years for a given tropical forest set of demographic rates (carbon gains and carbon losses) informed by observations of the 125 long-term forest plots. We first chose a representative forest age of 189 years old, the mean age for avoided conversion and improved forest management existing projects from the same dataset. Finally, to quantify the effects of age directly, we ran a set of scenarios with stand ages of 50, 100, 150, and 200 years old.

We plotted the biomass remaining (%) 100 years after project initiation, given its frequent policy relevance, and plotted variability across the stand biomass model Monte Carlo as boxplots, adding in lines for the mean and 20th percentile biomass remaining, which would provide more conservative guidance for what a buffer pool contribution would need to successfully insure 80% of projects (Galik et al. 2016). Finally, Verra allows increases of buffer pool contributions due to climate risks by up to 40% based on IPCC ‘climate impact drivers’ (Ruane et al. 2022) that attempt to coarsely capture climate-driven amplification of durability risks. Verra also allows reductions of buffer pool contributions by up to 75% based on projects' risk mitigation activities (Verra 2023). Thus, we plot the full potential buffer pool contribution range in our figures as well. For example, if a project determined the baseline risk was a 5% buffer pool contribution for a given risk, the full range of potential buffer pool contributions could be 1.25%–7% (i.e., 5% × 0.25 = 1.25% for risk mitigation actions and 5% × 1.4 = 7% for climate amplification), based on justifications provided by the project developer.

3 | Results

Current Verra forest carbon offset projects are located across all biomes, though heavily concentrated in tropical forests, and are exposed to a substantial level of risk for stand-replacing disturbances based on a previously generated global dataset (Figure 1). Stand biomass model inputs spanned a large range of carbon gains and carbon loss estimates in the 925 plot-by-census combinations in our tropical forest dataset (Figure 1). After accounting for this large variation in observed growth and mortality rates in our model simulations, we found that severe carbon losses from disturbance have major impacts on the forest carbon storage in a given tropical forest after 100 years. Figure 2 provides an example scenario for the simulated biomass trajectories from the Monte Carlo at a single forest site (i.e., combination of age, carbon gain, and carbon loss) over 100 years in the scenario with biomass losses of 50%–70% from disturbance occurring once every 25–50 years. In this frequent and severe disturbance scenario, our stand model estimates that an average of 57% (±29% SD) of initial biomass remains after 100 years (red line; Figure 2B). In contrast, the Verra buffer pool contribution for this scenario assumes that > 96% of biomass is remaining on average and more than 93% of biomass scenarios from our model fall below the insured level in Verra's buffer pool (blue line; Figure 2B).

Considering all disturbance severity and frequency categories, current buffer pool contributions dramatically underestimate the carbon cycle impacts of disturbance, especially at high levels of carbon losses and higher frequencies of disturbance for a stand age of 189 (which represents the mean age of IFM and REDD+ projects; Figure S2A) (Figure 3). Our calculated average buffer pool contributions were 2.5–7-fold higher than Verra's in the most severe biomass loss (> 70%) scenario and 1.25–11-fold higher in the moderate (25%–50%) biomass loss scenario (Figure 3; Tables S1 and S2). The default Verra buffer pool contribution was inadequate to insure the mean biomass trajectory in 75% of disturbance regime scenarios and inadequate to insure at least 80% of biomass trajectories (i.e., 80th percentile of disturbance risk, 20th percentile of biomass remaining) in 87.5% of disturbance regime scenarios (Figure 3). We posit that a buffer pool that does not include the mean project biomass trajectory is substantially undercapitalized and that generally a buffer pool may want to aim to insure > 80%–90% or more of projects' biomass trajectories (Galik et al. 2016), though this is ultimately a normative decision.

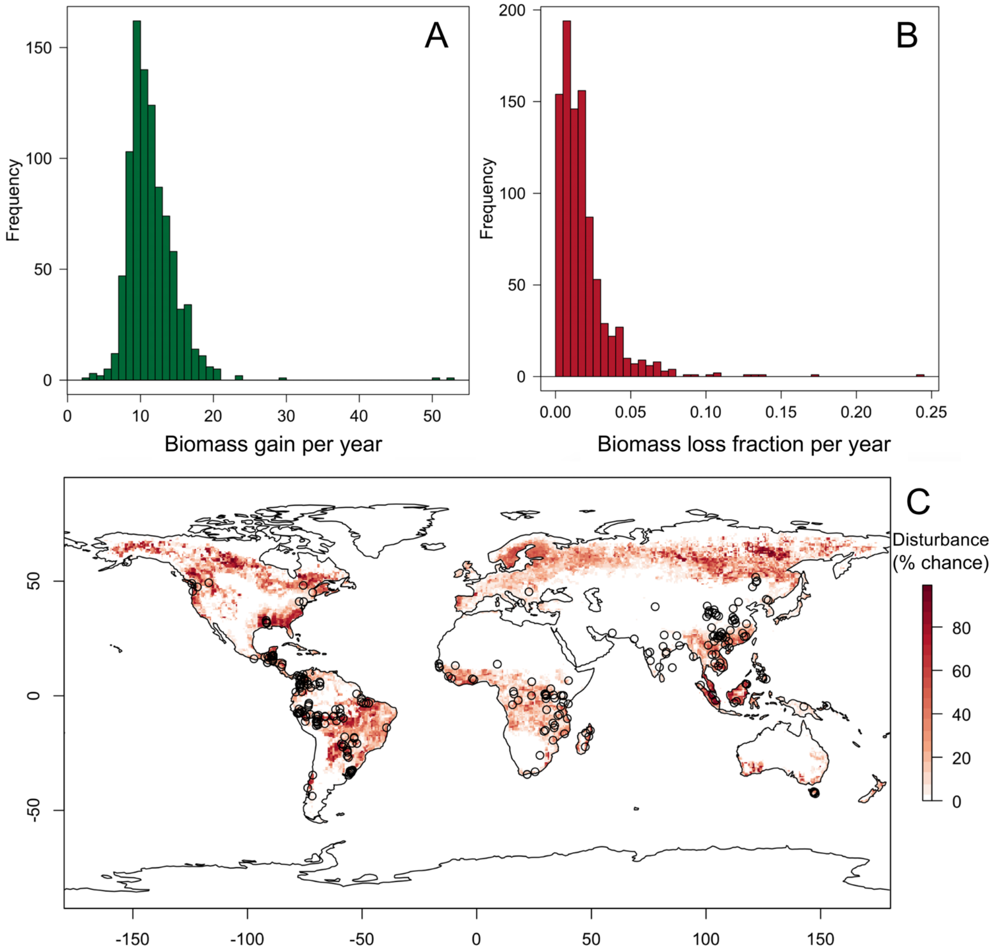

FIGURE 1 | Key inputs of the simple forest model and location of current Verra forest offset projects. (A) Distribution of tropical forest plots' biomass gain (tons biomass/ha*year) and (B) biomass loss (fraction biomass/year) from long-term plot data. These distributions form the basis of the Monte Carlo runs in all analyses. (C) Observed spatial distribution of Verra's current registered forest offset projects ($N=265$) overlaid on the 100-year estimated integrated stand-clearing disturbance risk (% chance of at least one stand-clearing disturbance over 100 years) from Anderegg, Wu, et al. (2022).

Established but younger forests need modestly lower buffer pools compared with older forests due to faster growth rates (e.g., 50 years in Figure 4; 71 years in Figure S2). For 71-year-old forests, 67% of disturbance scenarios had buffer pool contributions that were inadequate to insure 80% of biomass trajectories (Figure S2). Furthermore, current buffer pool estimates were still generally not adequate to insure younger forests (e.g., 50 years old) in moderate and high disturbance regimes (Figure 4B). Of existing Verra projects, there was a bimodal age distribution with reforestation/afforestation projects clustering at low stand ages; improved forest management and avoided conversion projects clustered at high stand ages (Figure S2). We note that the global forest age product used (Besnard et al. 2021) has a cap at 300 years old and thus does not meaningfully distinguish values above that age.

Finally, with the aim of improving science-based policy and protocols, we provide as supplemental tables the buffer pool contributions needed to cover the mean and 80th percentile of forest biomass trajectories based on our analyses in tropical forests (Tables S2 and S3) and a global map of stand-clearing disturbance return intervals based on forest losses between 2002 and 2014 that can be directly incorporated into any updated tool or table as a conservative estimate of combined disturbance risk (Figure S1; see Data statement). We note these estimates exclude land-use change, include forest management activities, and are very likely underestimates of the true risk because they do not incorporate climate change-driven trends in disturbance (see Anderegg, Wu, et al. 2022 for full details).

4 | Discussion

We leveraged a forest biomass model and extensive tropical long-term forest plots to probabilistically quantify the impacts of disturbance on 100-year biomass trajectories compared with a widely used tool in forest offset projects. We find that the buffer pool contributions in Verra's risk tool are inconsistent with forest biomass trajectories from a validated stand development model in the large majority of disturbance scenarios, especially at moderate or high frequency or severity of disturbance that are increasingly likely under climate change. The inadequacy of the current buffer pool estimates is much larger for older forests, such as those likely to be enrolled in avoided conversion or improved forest management, but still substantial in established but younger forests. This central finding that current

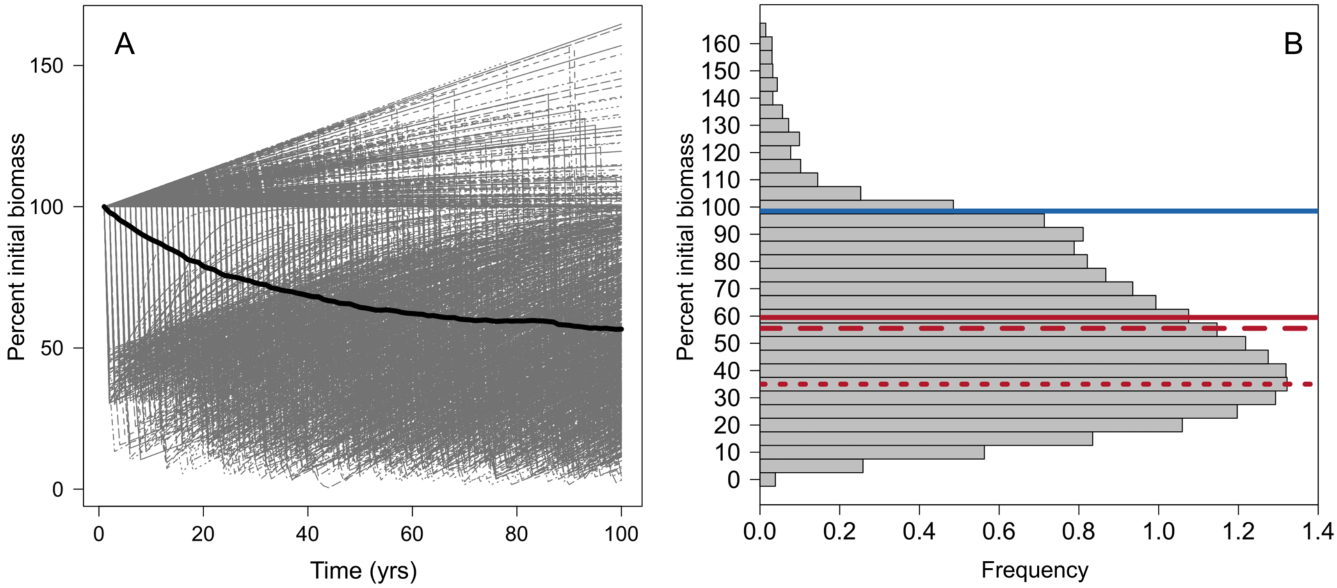

FIGURE 2 | Stand biomass is strongly impacted by moderate and high severity disturbances. (A) Model simulations of the percent initial biomass remaining over a 100-year period in the scenario of biomass losses of 50%–70% once every 25–50 years across the 1000 Monte Carlo iterations (black line is the mean). (B) Distribution of the percent initial biomass remaining at 100 years. Blue line indicates the lowest biomass levels insured with the current baseline buffer pool from Verra for this scenario. Solid red line indicates the buffer pool levels needed to insure the mean of the distribution, thick dashes is the median, and thin dashes is the mode.

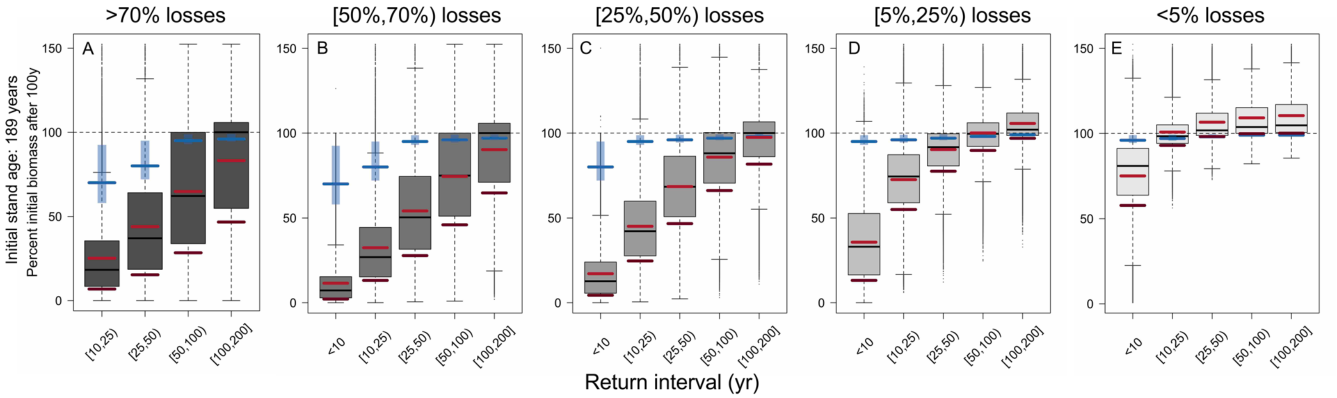

FIGURE 3 | Current buffer pool values are far below levels needed in moderate and high disturbance scenarios. Percent of initial biomass remaining after 100 years as a function of different disturbance severities (darkness of gray from left to right: (A) > 70% biomass losses, (B) [50, 70%] losses, (C) [25, 50]% losses, (D) [5, 25]% losses, and (E) < 5% losses) and disturbance return intervals (< 10, [10, 25], [25, 50], [50, 100], and [100, 200] years) for a stand age of 189 (which represents the mean age of IFM and REDD projects; Figure S2A). Blue lines indicate the lowest biomass levels insured with the current baseline buffer pool from Verra and polygons show the range of possible buffer pool contributions. Light red bars indicate the buffer pool levels needed to insure the mean of the distribution in each scenario and dark red bars the 80 percentile of the distribution.

forest offset protocols do not adequately consider risks to forest permanence aligns with substantial recent work in other regions and globally (Anderegg et al. 2020; Anderegg, Chegwidden, et al. 2022; Badgley, Chay, et al. 2022; Coffield et al. 2021; Cooley et al. 2012; Galik and Jackson 2009; Gren and Aklilu 2016; Hurteau et al. 2009; Wu, Coffield, et al. 2023).

Moving forward, NbCS urgently need to be grounded in rigorous data and carbon cycle science. We provide here initial numbers that would be more likely to insure the mean or most (e.g., 80%) biomass trajectories (Tables S2 and S3), but crucially, global maps of reversal risk that include climate change are currently being developed (Wu, Badgley, et al. 2023; Wu et al. in review) and would greatly strengthen offset protocols if directly incorporated into protocols via formal tools. We note that a previous analysis on 67 Verra REDD+ projects found a mean of 2% contributions to the buffer pool to insure all natural risk categories (Haya, Alford-Jones, et al. 2023). More detailed research on individual disturbance risks globally, including fire, drought, biotic agents, storms, and sea-level rise, is urgently needed to update such tools (Seidl et al. 2017). Furthermore, factors that either amplify or reduce required buffer pool contributions should generally be based on rigorous and region-specific data. Verra's current Non-Permanence Risk Tool allows 50% reductions in buffer pool contributions if risk "prevention measures are in place" and an additional 50% reduction in buffer pool contributions if "the project has a proven

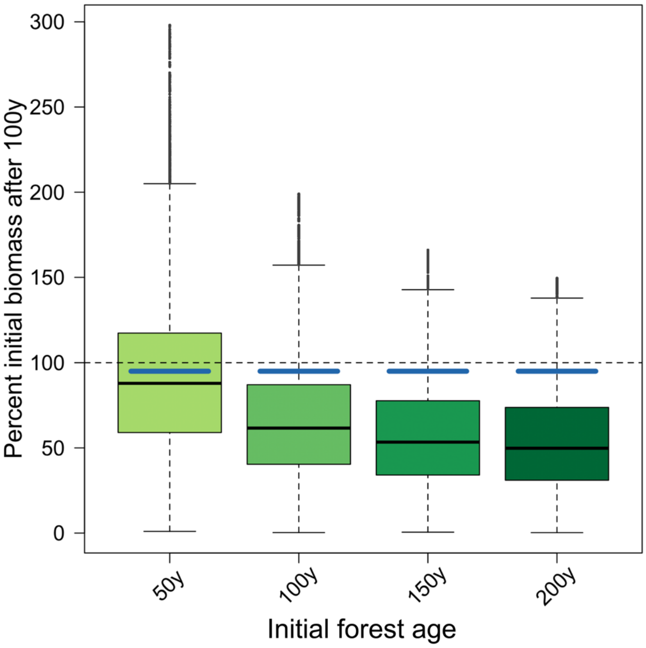

FIGURE 4 | Effects of forest age on simulated biomass trajectories. Percent of initial biomass remaining after 100 years as a function of different stand ages (50, 100, 150, and 200 years old) at hypothetical project initiation in the same disturbance scenario as Figure 2 (biomass losses of 50%–70% once every 25–50 years). Blue lines indicate the lowest biomass levels insured with the current baseline buffer pool from Verra.

history of effectively containing natural risk" (Verra 2023). For fire risk, examples of evidence that project developers can provide include fuel removal, establishment of fire breaks, or access to fire-fighting equipment. However, the extent to which these management activities can reduce climate risks, such as fire, is an open scientific question and the data supporting a 50%–75% reduction in fire risk for implementing one or more of these strategies is not provided and is highly unlikely to be conservative. We emphasize that flexibility in allowing project developers to claim buffer pool reductions for poorly defined management activities is likely to further lead to an inadequate buffer pool. Furthermore, it is unclear that risk mitigation for disturbances such as fire or drought or biotic agents is actually effective in many tropical forests (e.g., Moreau et al. 2022; Nair 2007).

Our analysis on the impact of forest age on buffer pool size did not extend to very young stands, such as those recently planted for reforestation and afforestation project categories, because our forest carbon cycle model is designed primarily to simulate established-to-mature forests. Analysis of these very young forests will require careful modeling of recruitment and survival over the first 10–20 years, including the climate, site, species, and practice-level predictors of when and where projects might fail due to high mortality rates (Banin et al. 2023; Preece et al. 2023). One assumption of our model is that trees will always regrow following disturbance, which would likely be too optimistic at dry range edges and biomes where climate may no longer be suitable to forests in a changing climate (Hurteau et al. 2009; Brodribb et al. 2020; Wu, Coffield, et al. 2023). Buffer pool contributions in afforestation/reforestation project types could potentially be modestly lower than mature forests, at least in that regrowth rates after disturbance could be rapid and carbon lost due to disturbance is much smaller and thus less of a risk of depleting the buffer pool, at least for the first decade or two, but a more detailed analysis is needed to better capture the range of growth and mortality rates of afforestation/reforestation projects and thus their buffer pool dynamics in the first decade of project establishment.

An alternative approach to buffer pools in addressing the nonpermanence risks inherent in forest NbCS is to structure protocols to where forest NbCS activities are credited only as temporary carbon offsets, as was done in the UN Clean Development Mechanism (CDM) (Gillenwater and Seres 2011). Under the CDM, offset credits from afforestation/reforestation activities were set as temporary and were required to be replaced with either other temporary credits or more permanent credits from other sectors at the end of the credit lifetime (Gillenwater and Seres 2011; Galik et al. 2016). Because this approach raises the cost of the credit to the buyer compared to a permanent credit and reduces the monetary value of the credit and revenue to the project, a combination of financial, administrative, and governance constraints likely led to very few afforestation/reforestation projects occurring under the CDM (Thomas et al. 2010; Galik et al. 2016). Yet temporary crediting approaches are likely more physically accurate and defensible regarding the long-term climate mitigation benefit of the forest NbCS activity in a rapidly changing climate (Galik et al. 2016; Balmford et al. 2023; Cullenward et al. 2023; Blanchard et al. 2024). Thus, there may be some important advantages of temporary crediting mechanisms compared to buffer pool approaches with assumed permanent credits.

Our analyses aim to capture a wide range of impacts of disturbance on tropical forest carbon dynamics empirically and are likely conservative estimates, but many additional mechanistic processes are likely to be important. Our validated stand biomass model explores a wide range of forest demographic rates but does not include forest composition, mechanistic processes (e.g., competition for light or water, lianas, impacts of severe droughts or pests, effects of rising atmospheric CO_2 concentrations), or belowground or soil carbon dynamics. More mechanistic and detailed modeling work using dynamic vegetation models and demographic models is needed to explore and further quantify these dynamics and how global change drivers are likely to further influence forest carbon in the 21st century (Brodribb et al. 2020; Fisher et al. 2018; Walker et al. 2021). We emphasize that climate change is projected to increase the frequency and severity of many disturbances (Seidl et al. 2017) and, given that our models are based solely on historical demographic rates, our analyses are likely to be underestimates of the risk profiles. Our models assume that forests always regrow at historical rates after disturbance, which is increasingly not the case in many regions (Davis et al. 2019; Batllori et al. 2020; Coop et al. 2020).

In conclusion, rigorous NbCS urgently need (1) to ensure buffer pool contributions reflect carbon cycle science and are based on rigorous and publicly available scientific datasets, (2) to use external and rigorous estimates of disturbance probability and frequency that are standardized by a third party and not chosen by project developers, and (3) to ensure that any risk amplification or deduction factors are based on rigorous science as well. The stand-clearing disturbance return interval presented here (Figure 1; Figure S3; Supporting Information) and Tables S1 that provide required buffer pool estimates based on this analysis can start to help address #1 and #2, but more work that includes climate change trends is urgently needed here. Finally, we note that alternate funding mechanisms for NbCS efforts that are not carbon offsets, such as contribution approaches, are another promising pathway because the uncertainty and rising risks to forest carbon durability are much less of a concern due to the decoupling of forest carbon from fossil fuel emissions (Blanchard et al. 2024; Anderson et al. 2022).

Author Contributions

William R. L. Anderegg: conceptualization, formal analysis, funding acquisition, investigation, methodology, project administration, visualization, writing – original draft, writing – review and editing. **Anna T. Trugman:** conceptualization, methodology, writing – review and editing. **German Vargas G.:** conceptualization, methodology, writing – review and editing. **Chao Wu:** conceptualization, methodology, writing – review and editing. **Linqing Yang:** conceptualization, formal analysis, methodology.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data and source code to reproduce our analysis is available in https://figshare.com/s/84eb29456d2d52a56a29.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.