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ORIGINAL ARTICLE

Probability-based accounting for carbon in forests to consider wildfire and other stochastic events: synchronizing science, policy, and carbon offsets

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Abstract

Forest carbon offset protocols reward measurable carbon stocks to adhere to accepted greenhouse gas (GHG) accounting principles. This focus on measurable stocks threatens permanence and shifts project-level risks from natural disturbances to an offset registry's buffer pool. This creates bias towards current GHG benefits, where greater but potentially high-risk stocks are incentivized vs. medium-term to long-term benefits of reduced but more stable stocks. We propose a probability-based accounting framework that allows for more complete risk accounting for forest carbon while still adhering to International Organization for Standardization (ISO) GHG accounting principles. We identify structural obstacles to endorsement of probability-based accounting in current carbon offset protocols and demonstrate through a case study how to overcome these obstacles without violating ISO GHG principles. The case study is the use of forest restoration treatments in fire-adapted forests that stabilize forest carbon and potentially avoid future wildfire emissions. Under current carbon offset protocols, these treatments are excluded since carbon stocks are lowered initially. This limitation is not per se required by ISO's GHG accounting principles. We outline how real, permanent, and verifiable GHG benefits can be accounted for through a probability-based framework that lowers stressors on a registry's buffer pool.

Keywords Risk · Wildfire · Carbon offsets · Greenhouse gas accounting · Forest restoration

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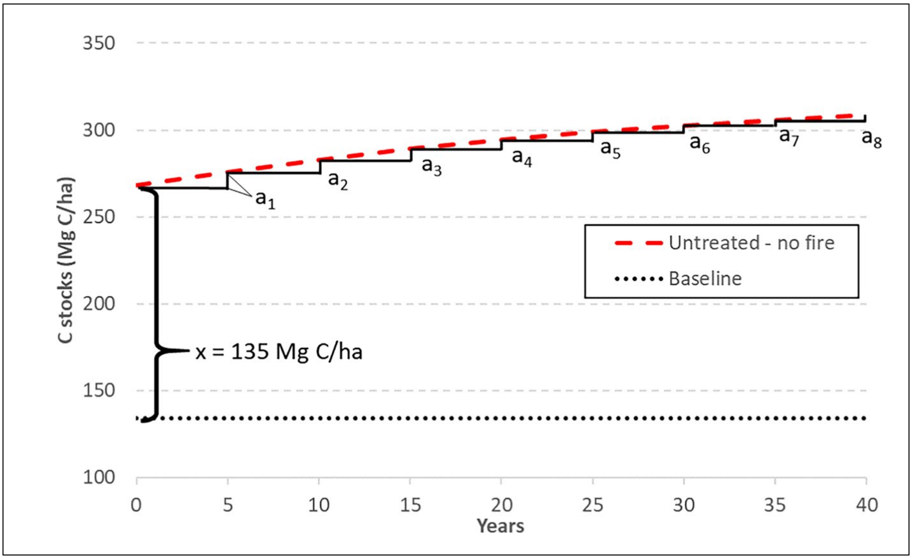


Fig 1 Forest carbon stock measurement accounting approach for IFM carbon offset protocols (generic example). An initial credit volume (x) is issued for above-baseline carbon stocking (with credit issuance drawn out over around 7 years under ACR's IFM protocol; 2018a). Periodic stock increases over the minimum project period (40 years under ACR's IFM protocol) can trigger additional credit issuance ($a_{1\text{-}8}$)

1 Introduction

1.1 Carbon accounting for forest-based offset markets

Carbon offset markets have a proven track record to incentivize atmospheric greenhouse gas (GHG) reductions by increasing forest carbon stocks through reforestation or improved forest management (IFM) activities compared to a baseline projection (Anderson et al. 2017). Additionally, methodologies that account for the avoided future loss of forest carbon stocks by preventing conversion of forest to non-forest are also available and have been employed in numerous offset transactions to date (ACR 2020). Contrary to other ecosystem markets (e.g., green bonds, corporate social responsibility commitments), carbon offset markets are the best-established ecosystem service markets in terms of rigor and price paid, for instance, per megagram (Mg) of carbon dioxide equivalents (CO_2e) delivered.

Current forest carbon offset protocols for IFM (e.g., ACR 2018a) rely on a carbon stock measurement GHG accounting framework to show verifiable and permanent atmospheric emission reductions. Carbon offset credits are generated through demonstrating above-baseline initial project carbon stocks (Figure 1; variable x) and periodic increments of carbon stocks (Figure 1; variable $a_{1\text{-}8}$) throughout the assessment period or project lifetime (40 years in case of ACR's IFM protocol). Depending on the registry, the baseline can be established based on regional average stocking, legal minimum stocking requirements, management approaches optimizing net-present-value, or conversion to non-forest. External risks or stochastic events such as wildfire, droughts, insect infestations, or storms affecting carbon stock permanence over the project lifetime are generically considered (and not quantified) and insured by a contribution to a registry-wide buffer pool. For instance, if a wildfire occurs, this is categorized as an unintentional reversal, and carbon credit forfeiture is recovered from the registry's collective buffer pool (externalized risk) and ultimately results in a project termination with no further liabilities to a project proponent (Hurteau et al. 2012). From a carbon offset project proponent's perspective, this carbon stock measurement GHG accounting framework incentivizes and rewards high initial carbon stocks while disregarding potential increased risks associated with these high carbon stock volumes in fire-adapted forests.

We propose a probability-based GHG accounting framework that would integrate carbon dynamics including risk (e.g., wildfire) would benefit registries as a whole, since risks to depleting the buffer pool would be minimized. It would also provide an incentive to project proponents to implement fire-adapted management. The goal of this paper is to demonstrate that a probability-based GHG accounting framework is an improvement over a carbon stock measurement GHG accounting framework; is feasible from an accounting, registry, and project proponent perspective; and could improve IFM protocols. Since all existing carbon offset protocols rely on ISO GHG accounting principles (2019), we introduce these principles first. Using the American Carbon Registry's (ACR) standard (ACR 2018b) and IFM protocol (ACR 2018a), we then provide context as to how ISO GHG principles are met by a proposed probability-based "avoided wildfire emissions" (AWE) GHG accounting framework, as an example of a disturbance-specific forest management protocol. Numerical examples are further provided in Section 2.2.4 (see Figure 3 for a conceptual example and SI 1, SI 2, and Figure 4 for a project example).

1.2 Stabilizing carbon through forest restoration treatments

To understand the probability-based GHG accounting framework we discuss below, it is necessary to establish forest management and disturbance regimes common in western North America and elsewhere. In California, for example, forest carbon stocks declined by 0.8% per year from 2001 to 2010, where wildfire accounted for two-thirds of the loss of live tree forest carbon (Gonzalez et al. 2015). Forest restoration treatments including mechanical thinnings and prescribed fire can restore forests to desired ecological conditions and fire regimes (Goodwin et al. 2020; Jeronimo et al. 2019; Schoennagel et al. 2017; North 2012; Noss et al. 2006). The goal is to increase stored carbon in trees that are larger and more resistant to wildfire, drought, or insects (Foster et al. 2020; Hurteau and North 2010; Stephens et al. 2009; see

Box 1). These treatments stabilize forest carbon by retaining a larger share of forest carbon stocks in the live carbon pool and maintaining continuous sequestration potential.

Box 1 Wildfire-related forest restoration treatments and carbon

Fire is a key ecological process in forests in the western USA and beyond (Safford and Van de Water 2014). Over the last two decades, fire-adapted forests have been increasingly affected by large and severe wildfires, often beyond the range of historic variability (Reilly et al. 2017). This change in fire behavior is due to fire suppression, harvesting history (Stephens et al. 2018), and climate change (Stevens-Rumann et al. 2018). Consequences abound, such as declining forest carbon stocks further contributing to climate change (Liang et al. 2017), threats to built infrastructure and human life (Moritz et al. 2014), diminished wildlife habitat (Chiono et al. 2017; Ganey et al. 2017; North et al. 2017; Stephens et al. 2016), changing hydrological regimes (McKenzie and Littell 2017), and reduced soil health (Cobb et al. 2016). In the context of wildfire, the goal of forest restoration treatments is not to suppress wildfire but to change wildfire behavior. Forest restoration treatments that shift forest stands from small-diameter, high-density, and shade-tolerant species towards larger diameter, low density, and fire-tolerant species modify fire behavior such that severity and size are reduced compared to the baseline of no restoration treatment activity (Liang et al. 2018; Stephens et al. 2012; Moghaddas et al. 2010; Safford et al. 2009). Type, size, and distribution of restoration treatments greatly affect their effectiveness in changing fire behavior (Coen et al. 2018; Thompson et al. 2017). While ignition risk remains unchanged by forest restoration treatments (Mann et al. 2016), the altered fire behavior can result in significantly reduced or absent fire suppression needs.

With increasing emphasis on forest restoration treatments as a tool in climate change adaptation, their large-scale implementation required to effect change (Vaillant and Reinhardt 2017) is hampered by a lack of funds (Thompson et al. 2017) and a lack of streamlined methods to efficiently and reliably quantify their ecosystem service benefits. These benefits can include climate change mitigation such as reduced wildfire emissions (Krofcheck et al. 2019) and stabilized carbon stocks on the landscape (Campbell et al. 2012; Mitchell et al. 2009). A full accounting of these outcomes must include longer term dynamics, however, or key carbon-related benefits go unrecognized. A similar case can be made for silvicultural treatments designed to address other forest health threats where fire is not necessarily an expected component of the disturbance regime. One such example is salvage harvesting with the intent to reduce severity of insect outbreaks (e.g., Dobor et al. 2020), though salvage harvesting also can have the opposite effect by increasing the likelihood and magnitude of subsequent disturbances (Leverkus et al. 2021).

However, forest restoration treatments lower initial carbon stocks (Figure 2; solid green line) and hence potential (initial) carbon liability. With wildfire, the absence of forest restoration treatments can result in a large shift of live carbon to the dead carbon pool if fire occurs—resulting in a continuous decline of forest carbon stocks due to decomposition (assumed in Figure 2, red solid line) or salvage logging. Furthermore, high-intensity wildfires can also cause high levels of tree mortality and soil impacts that result in delayed reforestation, i.e. a vegetation type change from forest to grassland or shrub types lasting at least several decades (Collins and Roller 2013; Coppoletta et al. 2016; Roccaforte et al. 2012; Rother and Veblen 2016, p. 20; Tubbesing et al. 2019; van Wagtendonk et al. 2012; Welch et al. 2016).

While stand carbon loss due to the forest restoration treatment (green solid line; year 0 to 5) can be comparable to wildfire-induced carbon loss in untreated stands (red solid line; year 20), over 70% of carbon remains in the live carbon pool in the treatment scenario and continues to sequester carbon. In contrast, over 90% of the carbon in the untreated stand is transferred to the dead carbon pool during the wildfire event, and growth of surviving live carbon stock is surpassed by carbon emissions due to decay, resulting in net carbon emissions over the following years. Despite this fact, the implementation of effective forest restoration treatments (in terms of area treated and carbon removed per hectare) count as an intentional reversal under ACR's standard (ACR 2018b). The carbon stock measurement GHG accounting framework currently applied for forest-based carbon offset projects therefore excludes proactive wildfire, drought, or insect-related management in principle.

Forest restoration treatments are discouraged in several contexts under the carbon stock measurement GHG accounting framework as detailed above. From a carbon offset registry's perspective, there should be a strong incentive to integrate stochastic events such as

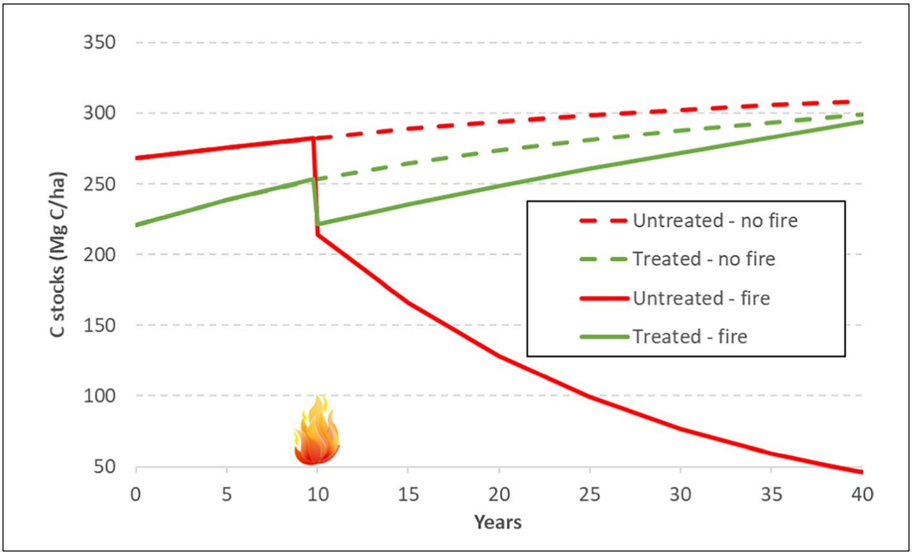


Fig 2 Example for forest carbon stocking (above and belowground) over time in the absence (dotted lines) and presence of high-severity wildfire (solid lines) with (green lines) and without forest restoration treatments (red lines) and delayed reforestation following a stand-replacing wildfire at year 10 (red solid line). Total stocking (above and belowground; live and dead carbon pools) and carbon loss due to forest restoration treatments and high-severity wildfire are based on 19 sites sampled in the Sierra Nevada mountains by North and Hurteau (2011), while post-fire carbon flux data is model-based (see e.g., Harmon et al. 1987) for decay rates and assumes delayed reforestation for an untreated stand

wildfire into project accounting, rather than handling it as an external risk, burdening the buffer pool. The risks to registries are real, especially under the protocols that require 100-year permanence (e.g., CARB 2015). For instance, recent data suggest an average wildfire risk exceeding 40% over the entire 100-year project term for all California-based IFM projects registered under the compliance market with California's Air Resources Board (CARB).[1] A total of 16% of all IFM projects registered with CARB (2020b) are affected by this risk for involuntary reversal.

When implementing forest restoration treatments, the decreased risk of carbon loss due to wildfire is not benefiting the project proponent since carbon losses due to stochastic events such as wildfire are externalized. In the case of a wildfire, the project proponent is released from all carbon credit sale-related responsibilities such as permanence while the buffer pool covers for losses. Benefits associated with forest restoration treatments therefore accrue to the registry as a whole through a decreased risk to the buffer pool.

Once stochastic events are acknowledged as an integral (rather than external) risk to carbon offset projects in affected forests, it becomes apparent the high average stocking of

[1] The CAL FIRE wildfire risk map (CAL FIRE 2016) suggests a 0.41% average annual wildfire probability for the Northern Sierra Nevada, northern coastal range, and Klamath Mountains, where all California-based IFM projects are located (CARB 2020a). This wildfire risk map and the approach to use a pixel-average as a fireshed-wide annual wildfire probability are widely considered conservative since a pixel-based average might underestimate a fireshed-wide fire risk. A more realistic alternative to fireshed-wide fire risk quantification could be to use the 75th percentile value or the product of the pixel values.

a maximum carbon stock projection is misleading. If specific forest restoration treatments can predictably provide long-term atmospheric GHG reductions that are measured against the same standards as currently endorsed forest protocols—and the associated GHG emissions can be cost-effectively proven through adherence to a stringent accounting protocol—a probability-based carbon offset protocol, or elements of it, should by definition be endorsable by carbon offset registries.

2 Accounting for GHG emissions in carbon offset markets

2.1 ISO GHG accounting principles

In the USA, all carbon offset registries (e.g., American Carbon Registry [ACR], Climate Action Reserve [CAR], Verra, Gold Standard, Plan Vivo, World Resources Institute), whether they deal with voluntary or compliance grade credits, are based on the same set of general (ISO) GHG accounting principles (ISO 2019). In the context of IFM carbon offset projects, the market-dominant registries in the USA (ACR, CAR, Verra) provide a close-to-identical approach in how they implement ISO GHG accounting principles under their overarching standards and registry-specific IFM protocols.

Project-level ISO GHG accounting principles (ISO 2019) entail relevance (data and methods appropriate to the needs), completeness (include all relevant GHGs within relevant spatial and temporal boundaries and other information), consistency (enable meaningful GHG-related comparisons), accuracy (reduce bias and uncertainty while ensuring practicality), transparency (disclose relevant information), and conservativeness (ensure that project GHG benefits are not over-estimated).

A host of literature points out that these principles are subject to the accounting framework (Marland et al. 2013) and to relative weighting depending on the accounting purpose (Buchholz et al. 2014; Wise et al. 2019). For instance, for carbon offset projects, completeness might be paramount to conservativeness if potentially significant but uncertain GHG sources, sinks, or reservoirs (SSR) are excluded. Weighting of principles is especially relevant during system boundary delineation (Eve et al. 2014) and baseline assessments (Ascui and Lovell 2011).

Besides the overarching accounting principles, the standard (ISO 2019) further provides important additional guidance on the following:

- Boundary delineation, i.e. the identification of all “relevant GHG sources and sinks controlled by the project, as well as those related to or affected by the project” (ISO 2019). This assessment step includes leakage accounting.
- Baseline and project determination, quantification, and uncertainty assessment. A conservative baseline scenario should be chosen over other plausible baseline scenarios that perform equally in terms of other GHG accounting principles. Baseline and project periods “should be long enough to ensure that the variability in operating patterns are accounted for”. To stay program neutral, the ISO standard does not use the term “additionality” in this context. Adhering to the accounting principles needs to drive the quantification while actual measurements are not required per se. To ensure appropriate data quality, in-depth uncertainty analysis becomes more important if SSR measurements are not feasible (e.g., GHG emissions across a

landscape). Reversal risk or permanence assessment of GHG emission reduction or removal enhancement is part of this step.

- Monitoring, reporting, and verification (MRV). While monitoring plans are required and guidance is provided, verification is optional. However, if a public statement is made that a project adheres to ISO 14064-2 standards, both a public GHG report using a specified outline and a third-party verification are mandatory.

2.2 Implementing ISO GHG principles in carbon offset standards and IFM protocols

2.2.1 Adhering to ISO GHG principles under a probability-based carbon accounting framework

ISO GHG accounting principles underlie all relevant carbon offset registries to date. A probability-based carbon accounting framework would need to adhere to ISO GHG principles to the same extent as currently employed carbon stock measurement GHG accounting frameworks.

Relevance and completeness A carbon offset methodology based on a probability-based carbon accounting framework would need to cover and document all relevant information for the accounting of GHG reductions or removals across all mandatory (aboveground live tree, dead wood, harvested wood products) and optional (belowground live tree) SSRs with a specified *de minimis* threshold of the final calculation of emission reductions. Relevant and mandatory GHG emissions include CO_2, CO, CH4, and optional emissions from non-methane hydrocarbons, particulate matter, and NO_x. To adhere to the completeness principle, any decreases in carbon pools and/or increases in GHG emission sources must be included if they exceed the *de minimis* threshold.

Consistency and transparency Consistency would need to be ensured by providing a detailed step by step description of the carbon offset methodology and detailed documentation requirements. The carbon offset methodology would need to specify both baseline and project accounting steps and strive for a uniform data input and modeling approach with minimum expert opinion input.

Accuracy and conservativeness The reliance of model-based calculation of SSRs under both baseline and project scenarios under a probability-based carbon accounting framework would require heightened efforts to ensure data accuracy. Accuracy can be ensured by restricting project-specific expert opinion inputs to a minimum and by specifying conservative model parameters to the largest extent possible. Wherever possible (e.g., aboveground live tree carbon), modeled stocks are measured periodically across the entire crediting period. Conservativeness is further ensured by detailed instructions for uncertainty quantification (error propagation by accounting element) as far as practicality allows. Uncertainties around emission reductions are captured by appropriate buffer pool and conservative emission savings estimates. In the context of forest restoration treatments for example, leakage effects through activity shifting or market effects can most likely be ignored since forest restoration treatment project activities typically include greater removal of forest products than assumed under the baseline scenario.

2.2.2 ACR implementation of ISO GHG accounting principles

Using the ACR standard (ACR 2018b) and IFM protocol (ACR 2018a) as an example for a leading carbon offset registry in the USA, we highlight (i) how registries currently implement ISO GHG accounting principles; (ii) how a probability-based carbon accounting framework, without violating ISO GHG principles, can be incorporated under revised standards as a stand-alone protocol for forest restoration treatments to, for example, lower emissions from wildfires; and (iii) how probability-based accounting can further assist in overcoming wildfire-related challenges in the current IFM accounting procedure.

Project-level ISO GHG accounting guidelines explicitly state that "in order to have broad and flexible application to different GHG project types and scales, this document outlines principles and specifies process requirements rather than prescribing specific criteria and procedures" (ISO 2019). In this context, the ACR standard and IFM protocol acknowledge ISO GHG accounting principles as the accounting foundation. The ACR standard implements these principles along a subset of eligibility requirements:

- Real. The project yields quantifiable and verifiable emission reductions/removals;
- Emission or removal origin. The project proponent has direct and effective control over SSRs;
- Additional. GHG reductions and removal enhancements would not have occurred in the absence of the project;
- Permanence. Unintentional and intentional reversal risks are defined, considered, and mitigated. Monitoring for and reporting of reversals is in place and compensation mechanisms are defined;
- Leakage. Effects of project activities outside of project boundary are accounted for if beyond a defined threshold;
- Independently verified. Verification of emission assertions for a specific reporting period.

Below, we focus on the eligibility requirements for *real*, *permanent*, and *verifiable* emission reductions/removals. These are the eligibility elements where accounting for wildfire-related probability-based emissions challenges ACR's current implementation of ISO GHG principles.

2.2.3 Real emission reductions

A carbon offset project must provide quantifiable GHG emission reductions or removals. Credits can only be issued once the emission mitigation activity has been conducted (e.g., ACR 2018b). Under an AWE probability-based carbon offset methodology, the mitigation activity is the forest restoration treatment management plan over the entire crediting period, starting with the initial round of forest restoration treatments. Once the project proponent commits to this management plan, and verification confirms completion of the initial forest restoration treatments, credits could be issued without violating the exclusion rule of "ex-ante" crediting, i.e. the issuance of credits "for GHG emissions reductions or removals when an emission mitigation activity has not occurred or is not yet verified" (ACR 2018b).

A potentially delayed GHG emission reduction can further pose a conceptual challenge where net GHG emission reductions get realized at a later stage during the crediting period due to an initial reduction of forest carbon stocks induced by the forest restoration treatments. In the context of an AWE carbon offset methodology, this initial stock loss tends to be higher for mechanical thinnings compared to prescribed burns (Goodwin et al. 2020; Liang et al. 2018) and can be delayed, particularly if contemporary wildfire probabilities are low (Krofcheck et al. 2017).

If concerns remain regarding the delay in GHG benefits from a climate benefit or risk perspective, future credits could be discounted based on when net benefits materialize. Though being a physical flow, discounting emissions is common practice (Timmons et al. 2016; US Environmental Protection Agency 2014) since a tonne of CO_2 is in this case a proxy for a monetized damage caused by climate change. In this context, Tol (2009) notes discounting does not reduce the present value of future climate effects if the costs of such effects grow faster than the discount rate. However, the steep decline of long-term costs caused by a constant annual discount rate does not reflect true social values (Gowdy 2005). Hence, hyperbolic discounting or declining discount rates, where a high value is placed on near future benefits, followed by a sharp drop in the medium, and an asymptotic flattening into the distant future, can and has been widely applied in a climate change context (Arrow et al. 2014; HM Treasury 2018). The relatively short minimum crediting period of 40 years under the ACR IFM protocol (ACR 2018a) in principle fully discounts (eliminates) any climate benefits from project activities beyond this timeframe—which stands in stark contrast with a general consensus amongst sociology and economics scientists to apply comparatively small discount rates to potential damages in the distant future (Stern 2006).

Credit issuance could be based on initial forest restoration treatment completion. This early-stage issuance would be independent of the temporal aspects where positive net GHG emission reductions will occur at some time in the future. This approach is conceptually in line with a probability-based carbon accounting framework such as the AWE carbon offset methodology. It challenges, though only hypothetical in nature, an accounting approach that heavily relies on measured carbon stocks to verify real emission reductions. The issuance of credits in the first period of a project for carbon stocks above a common practice baseline is a case in point for a bias towards measurable carbon stocks under the current forest carbon offset market concepts of all major registries (see also Section 2.2.5 on verification). While arguably ensuring maintenance of above-average carbon stocks on the landscape, this accepted and current approach taken by all registries challenges additionality requirements where GHG emission reductions need to be directly tied to project activities executed during the crediting period. A discount rate for early-stage credits could partially assist in overcoming concerns associated with early-stage issuance.

2.2.4 Permanent emission reductions

2.2.4.1 Managing reversal Initial stock reduction In the example AWE framework we describe below, forest carbon stocks initially would be reduced through forest restoration treatments designed to affect wildfire behavior. ACR's forest carbon offset protocols allow initial but short-term carbon stock reductions to accommodate project preparation activities such as vegetation removal for afforestation or reforestation projects (ACR 2017). ACR's IFM protocol allows for an initial negative project stock change prior to the first credit issuance. However, "after the first offset issuance, negative project stock change is a Reversal" (ACR 2018a). This exclusion of initial carbon stock reductions is a major barrier for implementing forest restoration treatments with the objective of reducing long-term GHG emissions. Under this concept, the forest restoration treatments are considered an intentional reversal since initial carbon stocks are lowered—disregarding potential long-term effects for stabilizing carbon stocks above the baseline.

When implementing forest restoration treatments, carbon stocks could remain below a baseline for a prolonged period. For a successful AWE carbon offset project, this stock reduction would be offset by a positive (probability-based) balance of aggregated GHG emissions over the crediting period and should not be categorized as a reversal. The prominence of avoiding carbon stock losses under current standards and protocols is rooted in verification concerns. Probability-based modeling of SSRs over time requires alternative verification steps compared to physical stock changes that can be measured (see verification Section 2.2.5 below for more details). The requirement to avoid carbon stock reductions below the baseline and beyond the short term is protocol-specific and standard-specific and not per se required by ISO's GHG accounting principles. The hypothetical nature of baseline development, particularly for avoided conversion projects (CARB 2015), provides an example for overcoming a carbon stock-based bias, while adhering to ISO GHG principles (see also Section 2.2.5 on verification). For avoided conversion projects, an anticipated baseline is developed that assumes future carbon stock loss associated with land use change.

In the context of existing IFM protocols, as mentioned above, the currently practiced carbon stock measurement GHG accounting framework disincentivizes landowners willing to implement forest restoration treatments prior to or as part of an IFM project implementation. Carbon offset credits are generated in two ways: Initial credits are derived from carbon stocks above a given baseline (example in Figure 3a; variable x) followed by periodic credits generated through proven forest carbon stock increases (variable y). If forest restoration treatments would be implemented at the beginning of an IFM project, fewer initial credits could be sold (Figure 3b vs. Figure 3a).

A probability-based GHG accounting framework could overcome this challenge by providing an average carbon stocking level expected over time (Figure 3c; red dotted line). This average carbon stock would be considerably lower than the initial carbon stock of an untreated stand (Figure 3b; red dot). It could be potentially increased substantially for a treated stand (Figure 3d; green dotted line). For the treated stand, adding both carbon credit types (Figure 3d; variable x and y) results in an only slightly lowered initial carbon credit potential compared to an untreated stand (Figure 3a; variable x) based on an alternative probability-based GHG accounting framework.

Note that Figure 3 provides a stand-level example for a wildfire occurring 10 years after project initiation. For a complete probability-based GHG accounting including wildfire emissions, stand-level carbon stocks and fluxes would need to be modeled out periodically across the entire project lifetime (e.g., every 5 years), for both treated and untreated stands within the assessment area and multiplied by the period-specific wildfire probability ($PWF_{y=0\text{-}z}$). This fire probability can be static or variable to account for increased fire risk over time due to climate change. While the example presented here is restricted to a wildfire occurrence at year 10, a full probability-based GHG accounting framework would need to integrate annual wildfire probability over the entire project lifetime.

Reversal due to wildfire or other stochastic events—responsibilities and GHG accounting solutions Carbon offset registries handle wildfire occurrence and other stochastic events as an unintentional reversal. While the occurrence of these stochastic events might be beyond a forest owner's control, their outcome can frequently be mitigated by

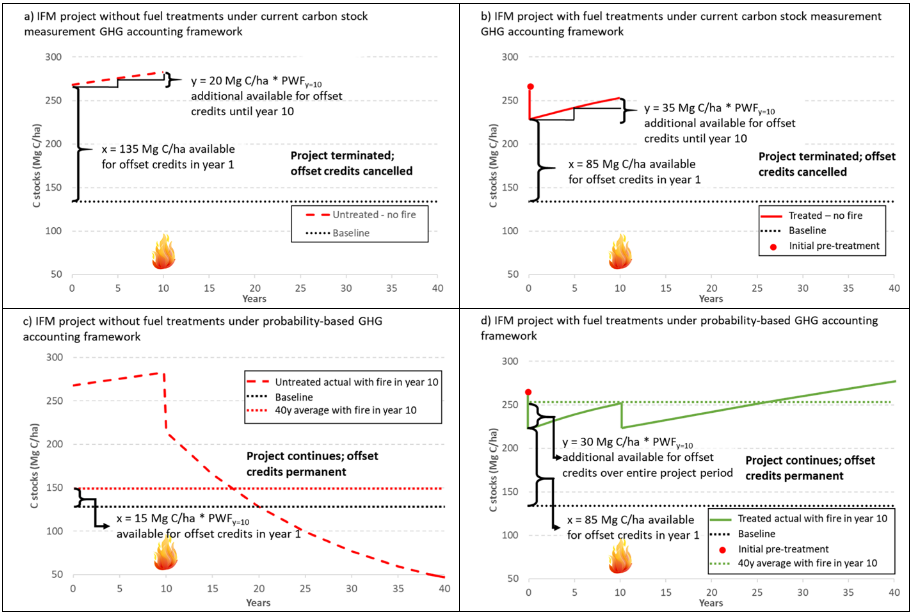


Fig 3 Average carbon stocks for stands affected by a wildfire in year 10 based on the generic example presented in Figure 1 and Figure 2. A carbon stock measurement GHG accounting framework as applied under the current ACR standard and IFM protocol results in project reversal (**a**) in case of wildfire occurrence (year 10) and discourages forest restoration treatments (**b**). As in existing IFM protocols, initial above-baseline credit creation (variable *x*) would be paired with periodic credits (variable *y*) based on future carbon stocks and fluxes. All numbers are based on North and Hurteau (2011), generic in nature, and only intended to serve for conceptual guidance. A probability-based GHG accounting framework would not only offer the option to avoid project reversal in case of wildfire occurrence and absence of forest restoration treatments (**c**), but also provide incentives to implement forest restoration treatments (**d**). For a complete probability-based GHG accounting including wildfire emissions, stand-level carbon stocks and fluxes would need to be modeled out periodically across the entire project lifetime (e.g., every 5 years) for both treated and untreated stands and multiplied by the period-specific wildfire probability (PWF)

management actions. Research over the past decade shows that a failure to better integrate wildfire management into carbon offset protocols poses a significant threat to the forest carbon offset market (e.g., Hurteau et al. 2012). IFM protocols approach wildfire (and other disturbance) risk as external and therefore collectivize losses through a buffer pool. In case of wildfire occurrence, the project is terminated and the project proponent has no further liabilities (see also Figure 3a and b). Project contributions in terms of a percentage of generated credits are frequently minimal and based on a generic approach. Employing a generic wildfire risk assessment tool and treating wildfire occurrence as an external threat provided a bridge to operationalize forest carbon offsets in the first place. However, outsourcing risk and a simplistic risk assessment sets up registries for a perilous future with little understood risks to the buffer pool under an imminent climate that deviates from historic norms. For instance, Hurteau et al. (2012) estimate that total liability of a wildfire-induced reversal for one project "would require buffer pool contributions from more than seven comparable projects to fully protect the registry". Both subjects (outsourcing risk, generic risk assessment) emerge as major liabilities for carbon offset protocols. In terms of alternatives for generic risk assessments, recent advancements in data availability and modeling capacity provide cost-effective and powerful tools for fine-scaled project-level wildfire risk mapping (Hurteau et al. 2019). In terms of outsourcing wildfire risk, the current approach creates perverse incentives in light of inherently unstable and high-risk carbon stocks. The current practice of letting forest owners tap into the buffer pool (involuntary reversal) defies landowner's responsibilities towards stabilizing carbon stocks at healthy levels in forests with an inherent fire ecology.

A probability-based GHG accounting framework for IFM projects could both (i) incentivize forest restoration treatments and (ii) provide a pathway to eliminate wildfire occurrence as an involuntary reversal. By using an average carbon stock estimate over the entire project lifetime (Figure 3d; green dotted line) including wildfire occurrence and discounted by wildfire probability, rather than initial carbon stocks (Figure 3b; red dot)—this approach would substantially ease the strain on buffer pools. Even if no active risk reduction for wildfire emissions is undertaken by implementing forest restoration treatments, a probability-based GHG accounting framework could overcome wildfire-induced risks to the buffer pool (Figure 3d).

Under the current carbon stock measurement GHG accounting framework, the involuntary reversal of a project in a wildfire-driven ecoregion poses a challenge to the entire offset registry. At the same time, the large spatial scale of individual and aggregated carbon offset projects that incentivize forest restoration treatments through a probability-based carbon accounting framework could reduce the risk to the buffer pool for the region as a whole substantially. In consequence, stochastic events such as wildfire occurrence within a carbon offset project boundary would not be classified as reversal in the first place, but as an integral part of the ecological process.

2.2.4.2 Long-term permanence IFM projects under ACR currently provide strong incentives for high current and near-term carbon stocks. Long-term permanence within and beyond the minimum crediting period of 40 years is dealt with through continuous MRV activities and the buffer pool in case of involuntary reversals. Considering the latest science (Graves et al. 2020; Krofcheck et al. 2019; McCauley et al. 2019), AWE carbon offset projects in wildfire-adapted ecosystems provide a stronger case for permanence then currently incentivized IFM projects, through a more deliberate shift towards stable carbon pools (reduced trees per acre, increased mean bole diameter)—not only in terms of potential carbon losses due to wildfire and other stochastic events. This climate beneficial outcome (e.g., Figure 4, black line) can be realized not only despite, but because of, an initial reduction in carbon stocks (Figure 4, light green bars). The current practice in carbon offset protocols and standards to value measurable carbon stocks above defensible probability-based carbon stock projections provides a temporal disadvantage to forest restoration treatments. Forest restoration treatments have a later-stage and permanent GHG benefit (see Section 2.2.3 on discounting future GHG benefits above) over projects with clear evidence of current, but potentially highly volatile and less permanent, "above average" carbon stocks. Any long-term GHG benefit beyond the project lifetime is discounted by 100% under current IFM protocols. The question remains how to truly assess permanence in the context of credits generated at different points in time within the project lifetime.

2.2.5 Verifiable emission reductions

Verifying GHG emission reductions is comparatively straight forward for carbon offset projects where aggregated SSRs are dominated by physical carbon stocks. Terrestrial carbon offset projects are frequently measured against this "standard" in terms of real and

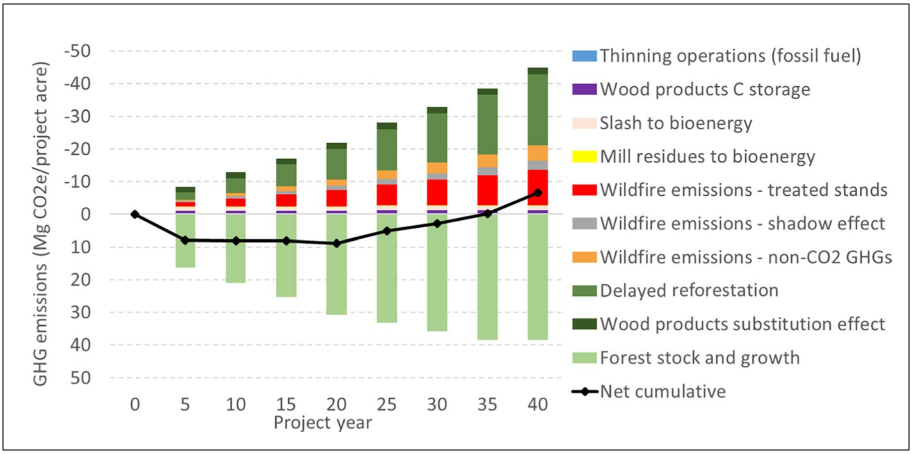


Fig 4 Case study example of full GHG accounting for AWE due to fuel treatments, employing a probability-based carbon accounting framework, in the mixed conifer forests of the mid-elevation Sierra Nevada Mountain Range, USA (see also SI 2). Columns present cumulative additional GHG emissions (positive values) and GHG emission savings (negative values) from fuel treatments over a baseline (no fuel treatments) scenario. Initial stock reductions followed by forgone carbon sequestration due to a reduction in forest stocks (light green columns) are balanced over time by GHG emission reductions; most notably delayed reforestation (dark green columns) and wildfire emissions (red, orange, gray columns). Aggregated net GHG emissions for the entire fireshed including untreated stands are negative over time (black line). GHG emission savings are modeled for wildfire occurrence over the entire fireshed in 5-year intervals and discounted by an annual constant fire probability

verifiable emission reductions. For instance, even the ISO GHG standard (ISO 2006) suggests that in terrestrial GHG removal projects, "only the sum of changes of carbon stocks in GHG reservoirs or carbon pools are likely to be considered. Resulting GHG removal enhancements would then be the sum of changes in carbon stocks in the GHG reservoirs or carbon pools less any increase in GHG emissions of all GHGs by GHG sources". This bias towards carbon stock measurement GHG accounting frameworks puts probability-based GHG accounting frameworks into an initial bind in terms of verifiability.

However, as Marland et al. (2013) point out, "it is an adage of accounting to monitor what you can measure, but there is concern that some elements can potentially be very important, yet very difficult, to evaluate." In this context, a probability-based GHG accounting approach breaks new ground vs. a carbon stock measurement GHG accounting framework and requires alternative pathways for verification.

As for carbon stock measurement GHG accounting frameworks, tracking of carbon stocks (potentially restricted to unburnt areas) will remain a vital verification tool throughout the crediting period. Forest carbon stock tracking outcomes can inform if growth and yield modeling assumptions require updates and confirm if management commitments were met (e.g., follow-up forest restoration treatments implemented over time). For instance, an intentional reversal can be triggered by a failure of following through with the original management plan. In this context, it would be important to keep management obligations flexible to allow for incorporating new scientific insights into future forest restoration treatment types and placements while meeting protocol requirements.

MRV requirements should also endorse additional future credit issuance if newly developed and relevant datasets or models provide sufficient evidence for their existence. For instance, we expect rapid advancements in probability-based calculations of AWEs due to delayed reforestation following high-severity wildfires (Tubbesing et al. 2019), and modeling non-CO_2 GHG emissions such as particulate matter (Schweizer et al. 2018).

Until now, the reliance of probability-based GHG accounting frameworks on large datasets and complex modeling approaches was a major obstacle in terms of practicality or, in terms of ISO GHG principle-based language—accuracy. The recent advent of both modeling platforms such as ArcFuels10 (Vaillant et al. 2013) and large consistent datasets such as region-wide tree lists (e.g., Riley et al. 2018) provide the foundation for this new approach to carbon offset protocol development.

2.3 Example for probability-based carbon accounting based on ISO GHG principles: avoided wildfire emissions

2.3.1 Outlining a suggested AWE carbon offset methodology

Besides improvements to existing IFM methodologies discussed above, a probability-based carbon accounting framework can be employed, for instance, to co-finance forest restoration treatments that lower wildfire emissions through carbon offset markets. To achieve this goal, it is essential that the ISO GHG principles outlined above can be met in an AWE carbon offset methodology (see SI 1).

We suggest an AWE carbon offset methodology that employs probability-based wildfire models to calculate GHG emissions in the absence (baseline scenario) and presence (project scenario) of forest restoration treatments that are additional to current practice (see SI 1 for an in-depth description of the AWE accounting methodology). Using field data, modeling, and probabilistic functions, this approach is fundamentally different from IFM methodologies where landscape carbon stock changes are solely identified using measured data. GHG emission savings are calculated prior to the project start and issued following the forest restoration treatment implementation. For instance, modeled on the IFM carbon offset protocol of the American Carbon Registry (ACR 2018a; see SI 1), GHG emission savings are quantified for each 5-year interval over the entire crediting period of 40 years. Wildfires covering the entire landscape are modeled for each interval under defined weather scenarios, GHG emission-relevant metrics are collected and processed, and wildfire-related GHG emissions are discounted by the location-specific wildfire probability. GHG emission savings can be refined and verified based on subsequent project area measurement assessments to confirm stand growth response to initial forest restoration treatments.

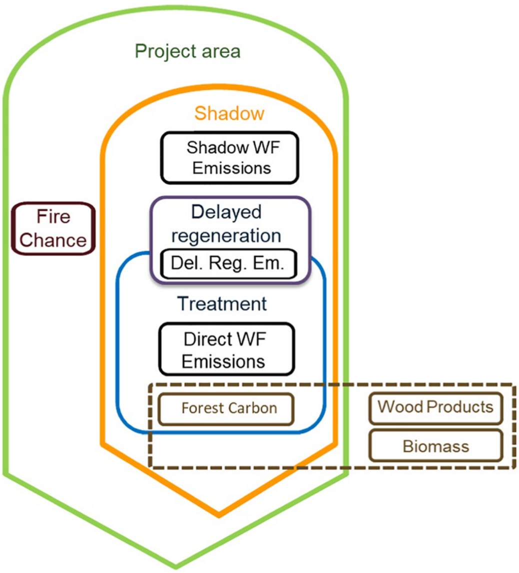
When assessing AWE reductions from forest restoration treatment implementation, the following relevant SSRs can in principle be quantified (
Box 2):

- Forest carbon. Increase in stored carbon on the designated landscape (project area) over time, particularly in larger, more fire-resistant trees (Foster et al. 2020; Hurteau and North 2010; Stephens et al. 2009). This results from reducing individual wildfire severity and potentially size on both the directly treated areas and untreated areas through fuel limitation (Collins et al. 2008). Treating even a small portion of the landscape can result in a decrease in probability of areas outside those treated areas being burned severely, referred to as the "treatment shadow effect" (Finney et al. 2007; Moghaddas et al. 2010). A decline in forest restoration treatment effectiveness over time (e.g., Collins et al. 2011) can be countered by follow-up treatments.

- Wood products and renewable energy. Utilization of forest restoration treatment byproducts as (i) long-lived wood products that sequester carbon and displace fossil fuel-intensive alternatives to wood products such as concrete and steel; and (ii) renewable energy production that displaces fossil fuel energy alternatives (Buchholz et al. 2016).
- Fossil fuel emissions required for harvesting and processing of wood. This also requires accounting for fossil fuel emissions associated with harvest and processing of wood products.
- Change in non-CO_2 GHG emissions. Wildfires can contribute substantial non-CO_2 GHG emissions such as particulate matter ($PM_{2.5}$), CH_4, CO, NO_x, and SO_2 (McClure and Jaffe 2018; Urbanski et al. 2018). Changing low-frequency high-severity wildfire patterns to higher-frequency lower-intensity wildfires can reduce non-CO_2 GHG emissions including particulate matter, i.e. smoke (Pierce et al. 2017; Schweizer et al. 2018).
- Preservation of forest. Forest restoration treatments can reduce the amount of forest that experiences delayed reforestation, i.e. a vegetation type change from forest to grassland or shrub types lasting at least several decades, compared to the baseline, through moderating fire severity and size.

Box 2: Avoided wildfire emissions accounting concept.

To quantify forest restoration treatment impacts on reducing emissions from wildfires (WF), all relevant carbon pools -- forest carbon, wood products, and biomass -- are accounted for across the entire fireshed/project area. This requires an ecologically relevant integration of wildfire probability (fire chance), wildfire behavior, delayed reforestation, and forest carbon accounting. Treatments to reduce high-severity fires will impact fire behavior within their direct footprint, and indirectly beyond their direct footprint ("treatment shadow effect"). Benefits from reduced atmospheric CO2 concentrations through avoided delayed reforestation following high-severity fires are also considered in this methodology.



2.3.2 Implementing an AWE carbon offset methodology

To implement an AWE carbon offset methodology, a few major elements deviate from current practices under carbon stock measurement GHG accounting frameworks.

Boundary delineation The project area would need to be a contiguous spatial unit. Through the wildfire shadow effect, AWE benefits can be expected substantially beyond the forest restoration treatment locations. This fact provides an incentive to maximize the project area across a larger landscape and use one or multiple firesheds to maximize offset credit generation. A fireshed is delineated based on fire regime, condition class, fire history, fire hazard and probability, and potential wildland fire behavior of a scale that allows the ecologically relevant integration of wildfire probability, wildfire hazard, and forest carbon accounting (Bahro et al. 2007). Trade-offs between project acreage and credit generation occur when a threshold is crossed where only minimal additional AWE benefits can be accounted for while at the same time data collection and monitoring, reporting, and verification (MRV) costs exceed additional project revenues. This relationship provides a built-in automation towards conservativeness in AWE accounting, i.e., forgoing potential AWE benefits which are due to project activities, but realized beyond the project boundary. There is also no risk of double counting AWE carbon benefits beyond the treatment area itself. If other IFM carbon offset projects are located adjacent to an AWE carbon offset project (i.e., within the fireshed), a carbon offset registry would in fact experience a reduced risk to its overall buffer pool for involuntary reversals due to a reduced risk of carbon loss due to wildfire based on fuel treatment activities in adjacent locations (see also Section 2.2.4.1 for reversals due to wildfire). Leakage effects are unlikely to occur in AWE carbon offset projects (see previous Section 2.2.1).

Baseline and project determination, quantification, and uncertainty assessment Two important topics for AWE baseline and project quantification include risk and uncertainty assessments. For instance, carbon offset project risks include reversals, i.e. situations where the project results in higher GHG emissions than the baseline. In case of intentional reversals, i.e. reversals due to a project proponent's choice of activities, sold offset credits have to be redeemed (internalized risk), whereas unintentional reversals result in a project termination with no further liabilities to a project proponent (externalized risk). The active management for wildfire behavior under an AWE carbon offset project (internal risk management) provides a challenge for existing carbon offset registries since wildfire is currently handled as an unintentional reversal, i.e. a limited responsibility for wildfire behavior on behalf of a project proponent.

Uncertainties in AWE carbon offset methodology are prominent since GHG offsets are modeled based on probabilistic functions. This stands in contrast to a "measured carbon stock" approach that dominates current forest-based carbon offset protocols where current and future carbon stock projections can be verified through inventories. A defensible AWE carbon offset methodology therefore relies on extensive uncertainty assessments in its modeling procedure and data input. Uncertainties in potential AWE carbon offset projects are further augmented by potentially delayed AWE benefits into late stages of the crediting period.

Monitoring, reporting, and verification The probabilistic nature of AWE credit generation provides unique MRV challenges. While only indirectly related to credit generation, periodically repeated project carbon stock measurements would validate model assumptions. Furthermore, we expect rapid advancements in data availability (e.g., climate forecasts, wildfire probabilities) and modeling approaches in the coming decade. Optional updating of AWE calculations periodically with new data/models could provide opportunities for additional refined credit generation throughout the project lifetime.

Additionally, AWE benefits are likely to be reliant on repeated forest restoration treatments throughout the project to maintain treatment effectiveness (Collins et al. 2011). Confirming the implementation of scheduled forest restoration treatments would be an important element of MRV plans.

Application to other disturbance mitigation management scenarios Forest management activities can also mitigate long-term ecosystem carbon losses in disturbance contexts that include more complex forest health interactions between other disturbance agents (e.g., insects) and wildfire. For example, salvage harvesting following eastern spruce budworm (*Choristoneura fumiferana*) mortality in balsam fir (*Abies balsamea*) and spruce (*Picea* spp.) stands can lead to reduced life cycle (i.e., including harvested wood products) carbon emissions over 40 years compared to not salvaging under certain stand structural conditions (Gunn et al. 2020). However, this comes at the cost of greater near-term emissions (10-20 years), similar to the AWE example above. The probability of future fire occurrence following spruce budworm mortality is quite variable depending on many factors, but the framework we present here potentially could be applied to salvage decisions where stability of future carbon stocks are explicitly considered alongside economics and salvage harvests result in significantly reducing future fire risk (James et al. 2017).

3 Conclusion

Stochastic events such as wildfire, drought, or insect damage can pose a major threat to carbon stocks in forests. Forest carbon offset methodologies account for these threats as external forces, and their occurrence and subsequent carbon stock loss results in an involuntary project reversal, with the carbon liabilities transferred to a registry-wide buffer pool, and project termination. This approach is based on a carbon stock measurement GHG accounting framework endorsed by leading carbon offset registries that prioritizes (i) high initial and (ii) measurable carbon stocks. As a solution, we demonstrate how a probability-based GHG accounting framework can provide a framework to integrate stochastic events in carbon accounting for offset registries without violating ISO GHG accounting principles. Besides improving permanence metrics and a reduced threat to a registry's buffer pool, such a probability-based approach could also incentivize forest restoration treatments in cases where their implementation results in long-term carbon stabilization. Using a proposed avoided wildfire emission carbon offset methodology that would incentivize forest restoration treatments to lower wildfire emissions through reduced wildfire severity and size, we show how a probability-based GHG accounting framework can be implemented cost-effectively and meet verification standards.

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