DEPARTMENT OF GEOGRAPHICAL SCIENCES

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Peer-Reviewed Offset Protocol
Maryland Reforestation/Afforestation Projects

Submit for Review: April 29, 2022

Table of Contents

Chapter 1. Purpose and Definition

1.1 Purpose

(a) This Protocol was originally developed by the California Environmental Protection Agency Air Resources Board as a Compliance Offset Protocol for U.S. Forest Projects. It was Adopted in June 2015 and approved by the Climate Action Reserve.

(b) This Protocol has been modified by the University of Maryland, College Park Department of Geographical Sciences and University of Maryland Office of Sustainability to integrate a high-resolution remote sensing and modeling based quantification methodology into the voluntary carbon offset market for forest projects.

(c) This quantitative methodology uses spatially explicit data available through NASA's Carbon Monitoring System (CMS) to quantify forest carbon sequestration potentials and monitor annual forest carbon fluxes. The protocol is designed for use in the State of Maryland but can be extended to other locations where the underlying data exists.

(d) This Protocol is designed for use within the Second Nature Peer Offset Network. All universities that belong to Second Nature's Climate Leadership Network are able to use this protocol and participate in third party verification.

1.2 Definitions

For the purposes of this protocol, the following definitions apply:

(a) "Above-Ground Biomass" means the total mass of biomass in live trees including the stem, branches, and leaves or needles, brush and other woody live plants above ground.

(b) "Carbon Pool" means a greenhouse gas reservoir.

(c) "Carbon Sequestration Potential" means 95% of the maximum forest aboveground biomass a site reaches during succession.

(d) "Carbon Sequestration Potential Gap" means the remaining amount of forest carbon that could be captured and stored in a specific area given its current above ground biomass.

(e) "Confidence Deduction" means a deduction applied to the project's onsite forest carbon stocks for each reporting period to account for statistical uncertainty associated with the remote sensing and modeling based framework to ensure that estimates of GHG removals are conservative.

(f) "Forest Owner" means the owner of any interest in the real (as opposed to personal) property involved in a forest offset project. Generally, a Forest Owner is the owner in fee

of the real property involved in a forest offset project. In some cases, one entity may be the owner in fee while another entity may have an interest in the trees or the timber on the property, in which case all entities or individuals with interest in the real property are collectively considered the Forest Owners, however, a single Forest Owner must be identified as the Offset Project Operator.

(g) "Forest Project" means a planned set of activities designed to increase removals of CO2 from the atmosphere through increasing forest carbon stocks.

(h) "Native Forest" means forests occurring naturally in an area, as neither a direct or indirect consequence of human activity post-dating European settlement.

(i) "Primary Effect" means the forest project's intended changes in carbon stocks, greenhouse gas emissions, or greenhouse gas removals.

(j) "Project Area" means the property associated with the geographic boundaries of a forest project, as defined following the requirements in Chapter 2 of this protocol.

(k) "Project Life" means the period of time between offset project commencement and a period of 50 years following the issuance of any registry offset credit for GHG removal enhancements achieved by the offset project.

(l) "Public Lands" means lands that are owned by a public governmental body such as a municipality, county, state, or country.

(m)"Reforestation/Afforestation Project" means a type of forest project involving the restoration of tree cover on land that currently has no, or minimal, tree cover.

(n) "Secondary Effects" means unintended changes in greenhouse gas emissions caused by the forest project.

(o) "Significant Disturbance" means any natural impact that results in a loss of at least 20 percent of the above-ground biomass that is not the result of intentional or grossly negligent acts of the forest owner.

(p) "Standing Live Tree Carbon Stocks" means the carbon in standing live trees. Live trees include the stem, branches, and roots, regardless of species.

(q) "Stocks" or "Carbon Stocks" means the quantity of carbon contained in an identified greenhouse gas reservoir (or carbon pool).

(r) "Tree" means a woody perennial plant, typically large and with a well- defined stem or stems carrying a more or less definite crown with the capacity to attain a minimum diameter at breast height of 5 inches and a minimum height of 15 feet with no branches

within 3 feet from the ground at maturity.

For purposes of this protocol, the following acronyms apply:

"AGB" means aboveground biomass.

"C" means carbon.

"CH_4" means methane.

"CO_2" means carbon dioxide.

"CO_2e" means carbon dioxide equivalent.

"CMS" means Carbon Monitoring System (as part of NASA CMS).

"CSP" means carbon sequestration potential.

"CSPG" means carbon sequestration potential gap.

"FIA" means USDA Forest Service Forest Inventory and Analysis program.

"GHG" means greenhouse gas.

"GIS" means geographic information systems.

"MT" means metric ton.

"N_2O" means nitrous oxide.

"NASA" means U.S. National Aeronautics and Space Administration.

"NAIP" means National Agricultural Imagery Program.

"OPDR" means Offset Project Data Report.

"SSR" means GHG sources, sinks, and reservoirs.

"QA/QC" means quality assurance and quality control.

"USFS" means United States Forest Service.

Chapter 2. Eligible Activities – Quantification Methodology

This protocol includes Reforestation/Afforestation activities designed to increase removals of CO2 from the atmosphere through increasing forest carbon stocks. The following is eligible:

2.1 Reforestation/Afforestation

This protocol applies to forest offset projects that restore tree cover on land that is not at stocking levels optimal for climate change mitigation.

(a) To be eligible under this protocol, a Reforestation/Afforestation project must involve tree planting or removal of impediments to natural regeneration, on land that:

(i) Has had less than 10 percent tree canopy cover for a minimum of 10 years; or

(ii) Has been subject to a significant disturbance within the last 10 years that resulted in a loss of at least 20 percent of the land's above-ground biomass.

(b) To be eligible under this protocol, a Reforestation/Afforestation project must not:

(i) Involve rotational harvesting of reforested trees or any harvesting of pre- existing carbon in live trees during the first 30 years after offset project commencement unless such harvesting is needed to prevent or reduce an imminent threat of disease. Such harvesting may only occur if the Offset Project Operator or Authorized Project Designee provides a written statement from the government agency in charge of forestry regulation in the state where the project is located stipulating that the harvesting is necessary to prevent or mitigate disease; or

(ii) Undertake tree planting or removal of impediments to natural Reforestation/Afforestation if the tree planting or removal activity follows a commercial harvest of healthy live trees within the Project Area that has occurred within the past 10 years or since the occurrence of a significant disturbance, whichever period is shorter.

(c) The project area for a Reforestation/Afforestation project:

(i) May be situated on either private or public lands;

(ii) The boundary that is set shall be the project area boundary for the duration of the project, provided that all lands included in the project area were initially included in the project area during listing; and

(iii) Can be contiguous or separated into tracts.

Chapter 3. Reforestation/Afforestation Eligibility

Reforestation/Afforestation Offset projects must adhere to the eligibility requirements below.

3.1 General Eligibility Requirements

(a) In order to be eligible under this protocol, a forest offset project must

(i) Occupy a minimum area of 2.5 acres; and

(ii) Meet the natural forest management criteria set forth in table 3.1;

Table 3.1. Natural Forest Management Criteria for Forest Offset Projects

Natural Forest Management Criteria	Timeline for Meeting Criteria
Native Species*	
Project consists of at least 95% native species based on the sum of carbon in standing live tree carbon stocks. The assessment must be conducted using estimates of stems per acre for Reforestation/Afforestation projects. Native Species are identified in consultation with the Maryland Department of Natural Resources or other qualified independent resource, recognized as expert by academic, private and government organizations.	Project must demonstrate continuous progress towards meeting requirements and must meet criterion within 2 reporting periods. Project is not eligible unless it is demonstrated that management activities will enable this goal to be achieved within 2 reporting periods. Projects must continue to meet requirements for the duration of the project life.
Composition of Native Species*	
To the extent seed is available, and/or physical site characteristics permit, Reforestation/Afforestation projects that involve planting of seedlings must plant a mixture of species. Where seed is unavailable, the Reforestation/Afforestation project is based on natural	Project must demonstrate continuous progress towards meeting requirements and must meet criterion within 2 reporting periods. Project is not eligible unless it is demonstrated that management activities will enable this goal to be

regeneration, and a written statement from the government agency in charge of forestry regulation in the state where the project is located, or other qualified independent resource, stipulating that seed is unavailable must be submitted. Where supported by scientific peer-reviewed research, the planting of native species outside of their current distribution is allowed as an adaptation strategy due to climate change. Such planting must be done in accordance with a state- or federally-approved adaptation plan, or a local plan that has gone through a transparent public review process.	achieved within 2 reporting periods. Projects must continue to meet requirements for the duration of the project life.
*Assessed at time of planting.	

(iii) Maintain or increase carbon stocks within the project area over any 10 consecutive year period during the project life except as allowed for in subchapter 3.1(b)(1);

(iv) Reforestation/Afforestation projects on lands that have undergone a significant disturbance must assess their eligibility using the standardized approach presented below to determine whether Reforestation/Afforestation activities are likely to be "business as usual" based on the net present value for the timber expected to be produced from Reforestation/Afforestation.

(1) A Reforestation/Afforestation project is considered "business as usual" if the net present value for expected timber is $0 or more.

(2) To determine whether a Reforestation/Afforestation project is eligible, perform the following steps:

a) Identify whether site preparation costs are high or low:

i) Site preparation costs are high if competing species management (including mechanical removal and/or use of herbicides) has been or will be conducted on 50 percent or more of the project area; or soil ripping has occurred or will occur on more than 50 percent of the project area.

ii) Site preparation costs are low for all other projects.

(b) To be eligible under this protocol, a forest offset project must not:

(i) Experience a decrease in the carbon stocks over any 10 consecutive year period, as evaluated in the first reporting period that is at least 10 years after project commencement and every subsequent reporting period, by comparing the current reporting period's 10-year average carbon stocks to the previous reporting period's 10-year average carbon stocks, except if the decrease in carbon stocks is due to one of the following causes[1]:

(1) The decrease is demonstrably necessary to substantially improve the project area's resistance to wildfire, insect, and/or disease risks where:

a) The actions that will be taken to reduce the risks are documented; and

b) The techniques used to improve resistance are supported by relevant published peer reviewed research;

(2) The decrease is associated with a planned balancing of age classes (regeneration, sub-merchantable, and merchantable) and is detailed in a long-term management plan that demonstrates harvest levels are necessary to reduce imminent threat of disease, adhering to section 2.1.b of this protocol, and that is sanctioned and monitored by a state or federal agency where:

a) Documentation is submitted at the time of the forest project's listing, indicating that a balancing of age classes, resulting in a decrease in the carbon stocks, is planned at the initiation of the forest project;

b) Over any 10 consecutive year period, average carbon stocks are maintained at or above the carbon stocks at the initiation of the project;

(3) The decrease is due to an unintentional reversal; or

(4) The decrease in carbon stocks occurs after the final crediting period (during the required 50 year monitoring period) and the residual live carbon stocks are maintained at a level that assures all credited carbon stocks are permanently maintained;

[1] These exceptions in no way change or affect the requirements related to compensating for reversals as detailed in subchapter 3.5.3.

(ii) Experience a decrease in carbon stocks that results in the carbon stocks falling to the forest project's carbon stocks at the project's initiation, which should be zero; and

(iii) Take place on land that was part of a previously listed compliance offset forest project, unless the previous forest project was terminated due to an unintentional reversal or is an early action offset project transitioning to this protocol.

(c) Offset Project Operators or Authorized Project Designees that use this protocol must:

(i) Provide the reporting information required by Chapter 7.1 of this protocol;

(ii) Monitor GHG emission sources, sinks, and reservoirs within the Offset project boundary as delineated in Chapter 6;

(iii) Quantify GHG emission reductions and GHG removal enhancements per Chapter 5; and

(iv) Obtain offset peer-verification services per the requirements in Chapter 8.

3.2 Location

(a) Projects located in the state of Maryland are eligible under this protocol.

(b) Forest projects in non-Maryland states are eligible under this protocol if the underlying NASA CMS data required for baseline mapping (Appendix B) and monitoring (Appendix C) calculations are available across those domains.

(c) All forest projects on public lands must be approved by the government agency or agencies responsible for management activities on the land.

3.3 Offset Project Operator or Authorized Project Designee

(a) The Offset Project Operator or Authorized Project Designee is responsible for project listing, monitoring, reporting, and verification.

(b) The Offset Project Operator or Authorized Project Designee must submit the information required by Chapter 7.

(c) The Offset Project Operator must have the legal authority to implement the offset project.

(d) The Offset Project Operator may identify an Authorized Project Designee, to assist or consult with implementation of the forest project.

(e) A single forest owner must be identified as the Offset Project Operator. If there are multiple forest owners, all forest owners are ultimately responsible for all forest project commitments.

(f) All information submitted to The Offset Network or an Offset Project Registry must reference the Offset Project Operator and all forest owner(s) who are ultimately responsible for the accuracy and completeness of the information submitted.

3.4 Additionality

Offset projects must meet the additionality requirements in this protocol. Eligible offsets must be generated by projects that yield additional GHG emission reductions or removal enhancements that exceed any GHG emission reductions or removal enhancements otherwise required by law or regulation or any GHG emission reductions or removal enhancements that would otherwise occur in a conservative business-as-usual scenario. These requirements are assessed through the Legal Requirement Test in subchapter 3.4.1 and the Performance Standard Evaluation in subchapter 3.4.2 of this protocol.

3.4.1 Legal Requirement Test

(a) Emission reductions or removals enhancements achieved by a forest project must exceed those required by any law, regulation, or other legally binding mandate.

(b) Legally binding mandates may include, but are not limited to conservation easements or deed restrictions, except where such conservation easements have been enacted within one year of offset project commencement in support of the forest project.

(c) The legal requirement test is satisfied if project activities are not legally required (as defined in Chapter 3.4) at the time of offset project commencement.

3.4.2 Performance Standard Evaluation

(a) Emission reductions or removals enhancements achieved by a forest project must exceed those likely to occur in a conservative business-as-usual scenario.

(b) The performance standard evaluation is satisfied if the following requirements are met:

(i) A Reforestation/Afforestation project that occurs on land that has had less than 10 percent tree canopy cover for at least 10 years automatically satisfies the performance standard evaluation.

(ii) A Reforestation/Afforestation project that occurs on land that has undergone a significant disturbance satisfies the performance standard evaluation if:

(1) The forest project corresponds with the requirements and methods in Appendix E, indicating that it is "eligible"; or

(2) The forest project occurs on a type of land for which the forest owner(s) has not historically engaged in or allowed timber harvesting.

3.5 Permanence

(a) Credited GHG emission reductions removals must be "permanent." For purposes of this protocol, 50 years is considered permanent.

(b) Permanence of forest project GHG emission reductions and removals is addressed through two mechanisms:

(i) The requirement for all offset projects to remotely monitor onsite carbon stocks, submit Offset Project Data Reports, and undergo third-party peer verification of those reports with monitoring using remote sensing for the duration of the project life; and

(ii) The maintenance of a forest buffer account by The Offset Network to provide insurance against reversals of GHG emission reductions and removals due to unintentional causes.

3.5.1 Project Life and Minimum Time Commitment

(a) Forest projects must continue to monitor, report, and verify offset project data for the duration of the project life.

(b) Two exceptions to this minimum time commitment:

(i) Purchasing of third-party verified offsets equivalent to the carbon accumulated from trees since the beginning of the project and the future offsets that would be generated for the remainder of the project.

(ii) A forest project automatically terminates if project lands or timber rights are sold to an entity that does not elect to take over the forest project responsibilities and commitments.

3.5.2 Identifying a Reversal

(a) GHG emission reductions and GHG removal enhancements can be reversed if the stored carbon associated with them is released (back) to the atmosphere.

(b) If the reporting finds a reversal indicated by a loss detected via remote sensing, the

Project Operator must follow the following procedure:

(i) Determine the cause of the reversal, and if biologically caused, consult a trained forester to identify the cause of the reversal and ensure additional project trees will not be affected (in the case of pests/diseases, etc.).

(ii) The Project Operator must then assess the carbon cost of the reversal using methods outlined in Appendix C, the appropriate action needed to recover project assets from the buffer pool, and estimate the future impact on the project's estimated carbon sequestration.

(iii) To determine if a reversal has occurred, refer to Appendix C.

3.5.3 Compensating for a Reversal

(a) Unintentional reversals are insured against by a forest buffer account, a holding account administered by The Offset Network for offset credits issued to forest projects.

(i) All forest projects must contribute a percentage of offset credits to the Forest Buffer Account any time offset credits are issued for verified GHG emission reductions and removals. Each forest project's contribution is based on a project-specific risk rating, determined according to Appendix E.

(ii) If a forest project experiences an unintentional reversal of credited GHG emission reductions and GHG removal enhancements, offset credits from the forest buffer account will be retired in an amount equal to the total amount of carbon that was reversed (measured in metric tons of CO2e).

(b) If a forest project is terminated for any reason except an unintentional reversal, the forest owner(s) must replace any offset credits that have previously been issued based on the following provision:

(i) A quantity of additional reductions equal to the total number of offset credits lost.

3.6 Offset Project Commencement

(a) For this protocol, offset project commencement is defined as the date on which the earliest activity is first implemented that will lead to increased GHG emission reductions or GHG removal enhancements relative to the forest project's baseline. For a Reforestation/Afforestation project, whichever of the following actions occurs first denotes an offset project commencement date:

(i) Planting trees;

(ii) Removing impediments to natural regeneration; or

(iii) Initiating site preparation for the planting of trees.

(b) Adequate documentation denoting the offset project commencement date must include, where applicable, deeds of trust, title reports, conservation easement documentation, dated forest management plans, and/or other relevant contracts or agreements.

3.7 Project Crediting Period

(a) The offset project crediting period is the period of time over which emission reductions are quantified for the purpose of determining creditable GHG emission reductions.

(b) The offset project crediting period for this protocol is 50 years.

(c) For this protocol, the initial crediting period begins on the first day of the first reporting period as identified in the first verified Offset Project Data Report received by The Offset Network or an approved Offset Project Registry.

Chapter 4. Offset Project Boundary – Quantification Methodology

The GHG assessment boundary, or offset project boundary, delineates the GHG emission Sources, Sinks, and Reservoirs (SSRs) that must be included or excluded when quantifying the net changes in GHG emissions associated with the sequestration of carbon achieved by increasing and/or conserving forest carbon stocks. The following offset project boundaries apply to all Reforestation/Afforestation projects:

4.1 Reforestation/Afforestation

(a) Table 4.1 lists the SSRs for Reforestation/Afforestation projects.

(b) If an SSR is designated as a reservoir, source or sink, GHG emission reductions and removals are accounted for by quantifying changes in carbon stock levels.

Table 4.1. List of the Greenhouse Gas Sources, Sinks, and Reservoirs for Reforestation/Afforestation Projects

Description	Type	Quantification Method
Primary Effect Sources, Sinks, and Reservoirs		
Carbon in above ground portions of living trees	Reservoir	Baseline: Initial baseline mapping and projections Project: Updated through monitoring estimates at least every three years
Secondary Effect Sources, Sinks, and Reservoirs		
Biological emissions from site preparation activities	Source	Baseline: N/A Project: Quantified based on measured carbon stock changes in reservoirs
Mobile combustion emissions from site preparation activities	Source	Baseline:N/A Project: Estimated using default emission factors
Biological emissions from clearing of forestland outside the project area	Source	Baseline: N/A Project: Estimated using default land-use conversion factors for non-project land
Biological emissions from decomposition of forest products	Source	Quantified as a component of calculating carbon stored for 50 years in wood products and landfills

Chapter 5. Quantifying Net GHG Emission Removals – Quantification Methodology

(a) Offset Project Operators and Authorized Project Designees must use the activity type-specific quantification methods provided in this protocol to:

(i) Quantify baseline onsite carbon stocks;

(ii) Estimate changing carbon stocks throughout life of the project;

(iii) Calculate the forest project's secondary effect;

(iv) Monitor annual changes in forest carbon flux; and

(v) Determine applicable confidence deductions and discount factors.

(b) The length of time over which GHG emission reductions are quantified is called the "reporting period." GHG emission reductions must be quantified over a consecutive twelve month period.

(c) All forest project types must quantify the net GHG emission reductions and GHG removal enhancements eligible for offset crediting for each reporting period using the methodology outlined in Appendix C. Net GHG emission reductions and removals must be quantified and reported in metric tons of CO_2e.

Equation 5.1. Net GHG Removals

Quantified net GHG emission removals = Carbon gains (MT CO_2e) - Carbon loses (MT CO_2e) - Secondary Effects (MT CO_2e)

Carbon Gains = growth over the treed fraction of the gridcell

Carbon Losses = loss due to fraction of gridcell disturbed

5.1.1 Estimating Baseline Onsite Carbon Stocks

The Offset Project Operator or Authorized Project Designee for a Reforestation/Afforestation project must estimate baseline onsite carbon stocks according to the following methodology:

(a) Provide a qualitative characterization of the likely vegetative conditions and activities that would have occurred without the project. The qualitative characterization must take into consideration any laws, statutes, regulations, or other legal mandates that would require Reforestation/Afforestation on the project area.

(b) Quantify the carbon stocks in each of the forest project's required carbon pools

(identified in table 4.1), following the requirements in Appendix B.

(c) The baseline for a forest project under this version of the protocol is valid for the duration of the project life following a successful initial verification where the offset project receives a positive verification statement.

(i) If a subsequent verification(s) detects correctable errors of greater than 5.00 percent to the baseline or to quantified GHG removal enhancements, the baseline must be adjusted prior to a verification statement being issued. The corrected baseline would then supersede the originally verified baseline for the purpose of determining GHG emission removal enhancements going forward.

(1) In no case will additional offset credits be issued until the new baseline has been exceeded.

(ii) If a forest project seeks renewal of its crediting period, the Offset Project Operator or Authorized Project Designee must conform to the most recent version of the Offset Protocol. Any changes in the baseline that result from the use of the most recent version of the Offset Protocol that affect GHG emission removal enhancements from the previous crediting period are not subject to invalidation or additional crediting.

5.1.2 Determining Onsite Carbon Stocks

For each reporting period, the Offset Project Operator or Authorized Project Designee for a Reforestation/Afforestation project must determine the forest project's onsite carbon stocks by updating the project area's forest carbon stocks according to the following methodology:

(a) Use annual forest carbon data to estimate new net growth from the end of the previous reporting period, per the requirements of Appendix C;

(b) Apply an appropriate confidence deduction for the inventory based on its statistical uncertainty, following the requirements and methods in Appendix A.

5.1.3. Calculating Secondary Effects

For each reporting period after the completion of an estimated inventory of all required carbon stocks, the Offset Project Operator or Authorized Project Designee for a Reforestation/Afforestation project must quantify the secondary effects associated with the project.

(a) Secondary effects will almost always be negative (i.e., they will reflect an increase in GHG emissions caused by the offset project). For Reforestation/Afforestation projects,

significant secondary effects can arise from:

(i) Mobile combustion emissions associated with machinery used in site preparation

(b) If the addition of negative secondary effect emissions results in a negative amount for total net quantified GHG emission removal enhancements in the first reporting period (QR1), the negative amount must be carried over into future reporting periods until sufficient GHG emission reductions and GHG removal enhancements are accrued to achieve a positive balance. Negative GHG emission reductions and GHG removal enhancements due to site preparation emissions are not considered a reversal.

Equation 5.2. Combustion Emissions Associated with Site Preparation

$MC_y = (-1) \times (EF_{mc} \times PA)$
Where,
MC_y = Secondary effect emissions due to mobile combustion from site preparation in reporting period y (MT CO2e)
EF_{mc} = Mobile combustion emission factor from table 5.1 (MT CO2e/acre)
y = Reporting period
PA = The size of the project area (acres)

Table 5.1. Mobile Combustion Emissions for Reforestation/Afforestation Projects

SITE PREP - Reforestation/Afforestation PROJECTS Emissions Associated with Mobile Combustion		
Average Metric Tons CO2e per Acre		
Light	Medium	Heavy
0-25% Brush Cover	>25-50% Dense Brush Cover	>50% Brush Cover, Stump Removal
0.090	0.202	0.429

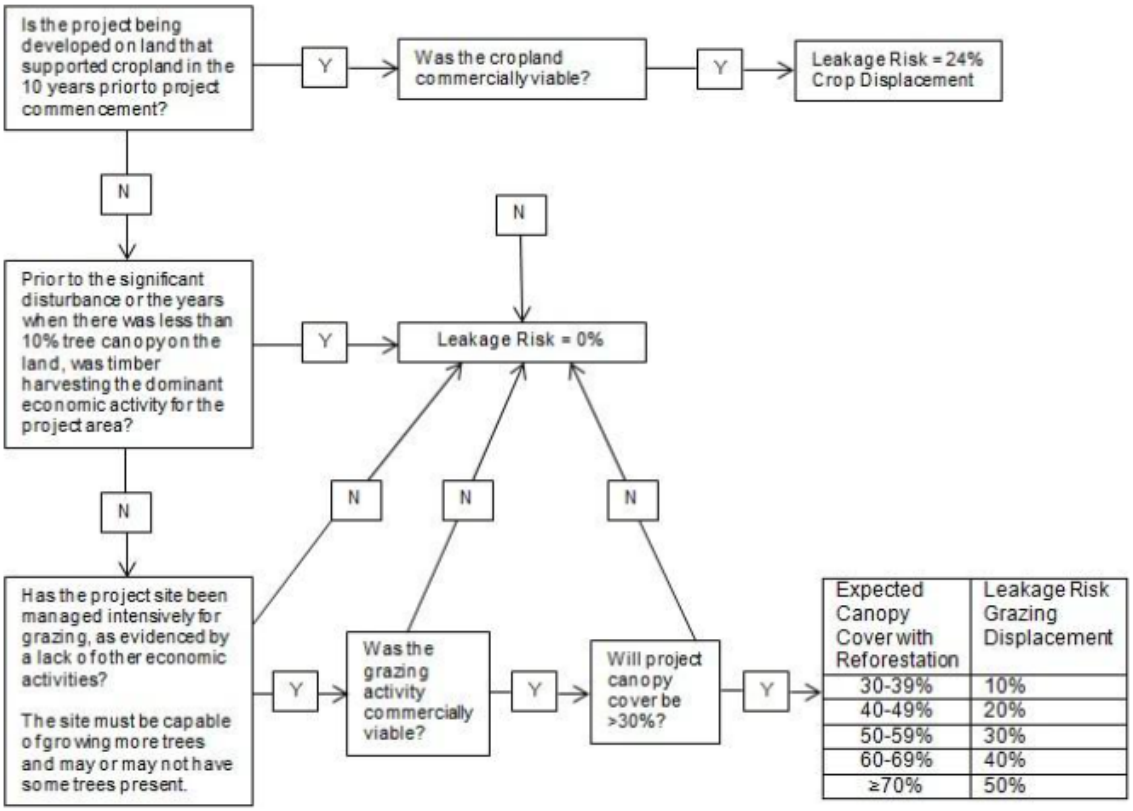
(c) The leakage risk percentage is determined once, at offset project commencement, and remains constant for the duration of the project life.

Equation 5.3. Emissions from Shifting Cropland and Grazing Activities

$AS_y = (-1) \times L \times (\Delta \text{ AConsite} - \Delta \text{ BConsite})$
Where,

AS_y = Secondary effect emissions due to shifting of cropland or grazing activities in reporting period y (MT CO2e)
L = Leakage risk percentage, as determined from figure 5.1 (%)
y = Reporting period
Δ AConsite = Annual difference in actual onsite carbon as defined in equation 5.1 (MT CO2e)
Δ BConsite = Annual difference in baseline onsite carbon as defined in equation 5.1 (MT CO2e)

Figure 5.1. Activity Shifting Leakage Risk Assessment for Reforestation/Afforestation Projects



(d) Secondary effects must be quantified using equation 5.4.

Equation 5.4. Total Secondary Effect Emissions

$SE_y = MIN[(ASy + MC_y), 0]$

Where,
SE_y = Secondary effect GHG emissions caused by the project activity in reporting period y (MT CO2e)
y = Reporting period
MIN = The lowest value in the set of values being evaluated.
ASy_y = Secondary effect emissions due to shifting of cropland or grazing activities in reporting period y (MT CO2e)
MC_y = Secondary effect emissions due to mobile combustion from site preparation in reporting period y (MT CO2e)

Chapter 6. Monitoring

The Offset Project Operator or Authorized Project Designee must conduct monitoring activities at least every three years in accordance with this protocol.

(a) Monitoring is required for a period of 50 years following the final issuance of any Offset Network credits to an offset project.

(b) For forest projects, monitoring activities consist primarily of updating a project's forest carbon inventory. This complete inventory must be maintained and updated throughout the project life.

(c) Annual onsite carbon stock estimates are computed from NASA Carbon Monitoring System Forest Carbon Monitoring data (See Appendix C).

(d) Specific methods used to update the forest inventory must follow the inventory methodologies approved at the time the project is initially verified. Modifications to inventory methodologies must achieve an equal or greater accuracy relative to the original method and be approved in advance by a third-party verification body, and documented in the change log.

(e) The Offset Project Operator or Authorized Project Designee is required to keep all documentation and information outlined in this protocol.

Chapter 7. Reporting

Reforestation/Afforestation offset projects must adhere to the project listing and reporting requirements below.

(a) The Offset Project Operator or Authorized Project Designee must submit Offset Project Monitoring Reports to the Second Nature Offset Network at least every three years.

(b) A forest project is considered automatically terminated if the Offset Project Operator or Authorized Project Designee does not report data at required intervals.

(c) The monitoring information is subject to peer verification at the initial and all subsequent offset project verifications.

7.1 Offset Project Monitoring Report

All Reforestation/Afforestation projects must provide

(a) Offset project name

(b) Offset project type (Reforestation/Afforestation)

(c) Contact information, including name, phone number, mailing address, physical address (if different from mailing address) and email address for:

(i) Offset Project Operator;

(ii) The person submitting the information; and

(iii) Any technical consultants

(d) Indicate whether the Offset Project Operator is the owner of the project area;

(i) If yes, provide documentation (e.g., deed of trust, title report) showing the Offset Project Operator's ownership interest in the property and its interest in the trees and standing timber on the property;

(ii) If no, explain how the entity identified as the Offset Project Operator has the legal authority to implement the offset project and provide documentation supporting the explanation;

(e) Name and mailing address of all forest owners including in fee as well as third parties with existing property interests within the project area that may have an effect on the trees and standing timber located in the project area (e.g., mineral rights, timber rights, easements, rights of way, leases, etc.);

(f) Physical address of the project site (if available);

(g) Indicate if the offset project occurs on public or private lands, Land that is "Indian lands" of a Tribe, as defined by 25 U.S.C. §81(a)(1); or

(h) If the forest project is located on public land, describe the approval process and public vetting processes necessary to evaluate management and policy decisions concerning the offset project that has or will take place in order to obtain approval of the offset project's management activities and baseline;

(i) Identify the assessment area(s) in which the project area is located including:

(i) How many acres of project lands fall within each assessment area (if aggregating more than one project site); and

(ii) The total project area acreage;

(j) Descriptions and a georeferenced GIS shapefile of the project area boundary, of adequate resolution to clearly identify the following features:

(i) Governing jurisdictions, and latitude/longitude coordinates;

(ii) Towns (map only);

(iii) Topography (map only);

(iv) Existing land cover and land use;

(v) Forest vegetation types description;

(vi) Site classes description;

(vii) Historical land uses, current zoning, and projected land use within project area and surrounding areas (description with optional map);

(k) Offset project commencement date and specification of the action(s) that identify the offset project commencement date. Explain and justify the commencement date;

(l) Initial reporting period start and end dates;

(m) Description of the planting and management activities that will lead to increased carbon stocks in the project area, compared to the baseline;

(n) Description of a maintenance plan for the duration of the offset project;

(o) Description of how the offset project meets (or will meet) the natural forest management

criteria (refer to table 3.1);

(p) Matrix documenting any and all legal constraints affecting forest management activities in the project area. Matrix must include:

(i) A description of each constraint;

(ii) The applicable geographic range for each constraint and the local, state, or federal agency associated with each constraint; and

(q) Qualitative description and quantitative estimate of the forest project's baseline onsite carbon stocks;

(r) Anticipated changes to baseline carbon stocks portrayed in a graph depicting time (50 years) in the x-axis and metric tons CO2e in the y-axis. The graph must be supported with written characterizations that explain any annual changes in baseline carbon stocks over time.

(s) Calculation of the offset project's reversal risk rating;

(t) Declaration that the project is not being implemented and conducted as the result of any law, statute, regulation, court order, or other legally binding mandate? If yes, explain;

(u) Disclose if any GHG emission reductions associated with land within the project area have ever been:

(i) Listed or registered by another registry or program for the purpose of greenhouse gas mitigation or reduction goals, whether in a voluntary or regulatory context;

(ii) Credited or claimed by another registry or program for the purpose of greenhouse gas mitigation or reduction goals, whether in a voluntary or regulatory context;

(iii) Sold to a third party prior to listing; and

(iv) If yes to any of the above, identify the registry or program, reporting period(s), number of credits issued, vintage(s) of credits, and verification bodies that have performed verification services

(v) Explanation of how the project area, at the time of offset project commencement, meets the project eligibility requirements of: a) less than 10 percent tree canopy cover for a minimum of 10 years; or b) subject to a significant disturbance that has resulted in the loss of at least 20 percent of the area's above-ground biomass using estimates from GFW or NAFD. The explanation must include why the forest had been reduced to less than 10 percent tree canopy cover or a description

of the disturbance if a significant disturbance occurred;

(i) For a Reforestation/Afforestation project that occurs on land that has undergone a recent significant disturbance, indicate the level of eligibility as identified in Appendix E or a provide a description of how the forest project occurs on a type of land for which the forest owner(s) has not historically engaged in or allowed timber harvesting; and

(ii) Qualitative characterization of baseline conditions, including an assessment of the likely vegetative conditions and activities that would have occurred in the absence of the project, taking into consideration any laws, statutes, regulations, or other legal mandates that would require Reforestation/Afforestation on the project area.

7.2.1 Monitoring Reporting

(a) The Offset Project Operator or Authorized Project Designee must submit the information listed in Section 7.1 at least every three years following the project commencement date.

Chapter 8. Verification

(a) Offset Project Data Reports must be verified for the duration of the project life in accordance with the verification requirements in this protocol.

(b) It is required that a third-party verification body review and assess all reported data and information for a forest project every three years utilizing the same methods outlined in Appendix C.

(c) The Offset Verification Statement for the initial reporting period must be received by the Offset Network within 2 years after the conclusion of the Reporting Period for which offset verification services were performed. An Offset Verification Statement for all subsequent reporting periods must conform with the timing for submission of Offset Verification Statements

(d) Failure to conform to any requirements in this protocol, as applicable, will result in an adverse verification statement.

(e) A forest project is considered automatically terminated if the project does not undergo verification at required intervals.

8.1 Verification of Multiple Reporting Periods

If verification is less frequent than every three years, the verification team must issue individual Offset Verification Statements for each reporting period.

8.2 Verification Team

Each verification team must include the following:

(a) The Offset Network Peer Verifiers should consist of three university carbon offset initiative managers or similar sustainability-related roles. Potential university verifiers include:

(i) Duke University

(ii) American University

(iii) Elon University

(b) At least one individual with demonstrated knowledge of and competence in the use of forest growth models, and demonstrated experience working with the model used in the forest carbon inventory being verified.

(c) At least one individual with demonstrated knowledge of and competence in the use of

satellite derived data products, remote sensing analysis, and capacity in Python programming.

(d) The required experience and expertise may be demonstrated by a single individual, or by a combination of individuals.

Appendix A. Confidence Deduction

(a) When compared to inventoried changes in U.S. Forest Inventory and Analysis Plots, the median statewide uncertainty related to annual change in aboveground biomass projected each year by the Ecosystem Demography model is 10% (Hurtt et al., 2019; Ma et al., 2021).

(b) The confidence deduction for all annual carbon stock estimates regardless of location is 10%.

(c) The percent confidence deduction must be applied to the inventory estimate of onsite carbon stocks each year for the purpose of calculating GHG emission removals.

(d) A confidence deduction is not applied to baseline carbon stocks, which should be zero over the non-treed fraction of the project area.

(e) The confidence deduction may be updated each time the offset project is subject to verification, but must remain unchanged between verifications.

(f) If there is a lower confidence deduction at the time of verification, the lower deduction must be applied to inventory estimates in the most recent reporting period subject to verification at that time. Registry offset credits may be issued in the most recent reporting period for any verified increase in quantified GHG emission removals associated with the new (lower) confidence deduction.

Appendix B. Estimating Carbon Stock Baselines

B.1. Data and Models

(a) Unlike previously established protocols that rely on field based measurements for quantifying baseline carbon stocks and monitoring changes in carbon stocks, this protocol leverages recent advances in remote sensing and ecosystem modeling to perform these calculations.

(b) The Ecosystem Demography (ED) model:

(i) The ED model is an individual-based prognostic ecosystem model. By integrating submodules of growth, mortality, hydrology, carbon cycle, and soil biogeochemistry, ED can track plant dynamics including growth, mortality, competition, and reproduction (Hurtt *et al* 2002, 2004, 2010, 2016, Fisk *et al* 2013, Flanagan *et al* 2019, Ma et al 2022, Moorcroft *et al* 2001).

(ii) Along with plant dynamics, ED can track the carbon cycle, including carbon uptake by leaf photosynthesis, carbon allocation to biomass growth in leaves, roots and stems, carbon redistribution from plants to soil based on plant tissue turnover from dead plants due to mortality and disturbance, carbon decomposition in various pools (metabolic litter pool, structural litter pool, soil slow pool, soil passive pool, wood product pool, harvested crop pool, etc) as well as carbon combustion from fire.

(iii) ED distinguishes itself from most other ecosystem models by explicitly tracking vegetation structure and scaling fine-scale physiological processes to large-scale ecosystem dynamics (Hurtt *et al* 1998, Moorcroft *et al* 2001, Fisher *et al* 2018).

(c) NASA Carbon Monitoring System Science:

(i) The NASA Carbon Monitoring System (CMS) provides carbon stock and flux estimates to characterize the state of and potential changes to carbon to improve overall monitoring of the global carbon cycle. NASA satellite observations and remote sensing technology are used to develop carbon Monitoring Reporting and Verification systems (MRV) quantifying and predicting global carbon sources and sinks.

(ii) NASA CMS forest carbon products use mapped 3D vegetation structures and aboveground biomass (AGB) from airborne LiDAR and NAIP optical imagery as reference data (Huang et al. 2019; Tang et al. 2021). NASA CMS products utilize lidar data and NAIP optical imagery to measure existing canopy height and generate contemporary AGB over the tree cover fraction. Once initialized with

this data, the ED model predicts annual net growth under local environmental and climate conditions (Hurtt et al. 2019; Ma et al, 2021). It can also estimate carbon sequestration potentials on the treed and non-treed fraction of the pixel.

(iii) These estimates are calibrated and validated using the USDA Forest Service Forest Inventory and Analysis (FIA) field plots.

(d) Annual Changes in Forest Disturbance:

(i) Landsat based forest disturbance products can be used with NASA CMS products. Three examples are the North American Carbon Program North American Forest Dynamics (NAFD) dataset (Goward et al. 2016), the Global Land Analysis and Discovery (GLAD) Global Forest Change dataset (Hansen et al. 2013), and the USDA Landchat Monitoring Assessment Projection (LCMAP) dataset (Brown et al. 2020).

(ii) The forest disturbance dataset that is used to generate annual forest carbon fluxes within the State of Maryland's Greenhouse Gas Inventory is recommended for use.

(iii) These datasets provide annual 30m estimates of area with forest disturbance or regrowth. Annual updates are published regularly.

B.2. Baseline Assessment of Carbon Stocks

(a) A forest project's carbon inventory is used as the basis for establishing a forest project's current baseline stocks and used to quantify changes to these carbon stocks during the project life (following the requirements of Chapter 5).

(b) The baseline assessment includes two steps to 1) establish existing aboveground biomass (AGB) within the project area and 2) estimate the carbon sequestration potential of the project area within the crediting period.

(c) Annual NASA CMS forest growth trajectories are derived from Ma et al. (2021).

(d) Offset Project Operators or Authorized Project Designees must perform the following steps when developing the forest project's baseline carbon inventory:

(i) Draw the project's geographical boundaries and represent it as vector data. The project geographical boundaries should follow the project eligibility requirements in Chapter 3. Record the size of the project area.

(ii) Select two data layers from the NASA CMS dataset: (1) the first data layer at time zero and (2) the layer 50 years from the project start year.

(iii) Use a geographical information system (GIS) software to isolate the AGB raster data within the project area using the project geographical boundary represented as a vector.

(iv) Calculate the difference between the total amount of carbon within the project boundary in the end year from the total amount of carbon in the project boundary in the base year. The result is the total projected amount of carbon that will be accumulated over the project time period, available in both summary table and vector formats.

(v) Using a disturbance dataset (see Appendix B.1.d), evaluate and document if any disturbance has occurred within the project area during the past 10 years.

(vi) If detected disturbance was due to prohibited activity as defined in Chapter 2 (e.g. no harvesting), exclude this pixel from the project boundary.

(vii) Example code and links to data are found here: https://github.com/UMDgel/Campus-Forest-Carbon-Project

(e) A complete carbon inventory methodology must include:

(i) A description of the Offset Project Boundary and a list of all onsite carbon pools included in the Offset Project Boundary. See table 4.1 to determine which onsite carbon pools are included and quantified for inventory measurement.

(ii) Forest carbon inventory methodology and procedures for each required onsite carbon pool, with references clearly documented. These procedures must be detailed enough so that any institution would be able to accurately repeat the previous calculations.

(iii) Description of data management systems and processes, all remote sensing based analytic methods, calculation methodologies, and models used for each of the carbon pools included in the offset boundary;

(iv) A documented quality assurance/quality control (QA/QC) plan including procedures for internal review to ensure that standard operating procedures are being followed. The QA/QC plan must include procedures for:

(1) Procedures for data entry and analysis and data maintenance and archiving; and

(2) Any other relevant procedures to ensure quality and consistency in the collection and maintenance of data used to compile Offset Project Data

Reports;

(f) Inventory methods, once established and approved at verification, must be consistent over the life of the project. If new methodologies are adopted, they must achieve an equal or greater accuracy relative to the original approach. Any changes to inventory methods or calculations must be documented and justified in the change log.

(g) Offset Project Operators or Authorized Project Designees must keep a distinct inventory for the required above-ground biomass carbon pool.

Appendix C. Updating Forest Carbon Inventory

C.1. Data and Models

(a) NASA CMS Monitoring Data

(i) The NASA CMS Monitoring products for forest carbon fluxes are based on the established remote sensing and modeling framework outlined in B.1.c.

(ii) Annual forest carbon fluxes are quantified after digesting annual tree cover changes identified by forest disturbance and regrowth data (see B.1.d) and real time meteorology and atmospheric CO2 concentrations (Hurtt et al. 2020; Hurtt et al. 2022, in prep). This product is constrained by lidar remote sensing data on forest canopy height and tree cover.

C.2. Assessment of Updated Forest Carbon Stocks

(a) Offset Project Operators or Authorized Project Designees must perform the following steps when developing the forest project's carbon inventory at least every three years:

(i) Obtain the project boundary vector as defined in B.2.d.i.

(ii) Select the most recent annual monitoring map from the NASA CMS Monitoring dataset.

(iii) Use a geographical information system (GIS) software to isolate the raster data within the project area using the project geographical boundary represented as a vector.

(iv) Calculate the difference between the total amount of carbon within the project boundary in the current inventory year from the total amount of carbon in the project boundary in the base year (or the most recent inventory year). The result is the total projected amount of carbon that has been accumulated since that last inventory.

(b) While the carbon impact of detected disturbance is included with the annual NASA CMS Monitoring products, the forest disturbance dataset should also be viewed directly over the project area. If a disturbance occurred, it may prompt further steps for compensating for reversals outlined in 3.5.2 and 3.5.3.

(c) Landsat-derived forest disturbance datasets may not detect early stage forest regrowth until the canopy signal is strong enough to be reflected on satellite imagery and detection

algorithms. To confirm regrowth during early project years, high resolution optical imagery (e.g., Google Earth, NAIP and other aerial imagery) should be used to confirm tree presence and monitor for potential disturbances.

(d) Example code and links to data are found here: https://github.com/UMDgel/Campus-Forest-Carbon-Project

(e) A complete carbon inventory methodology includes all elements as described in B.2.e.

Appendix D. Determination of a Forest Project's Reversal Risk Rating

A conservative buffer pool is used to protect against unavoidable reversals in the project. The Offset Network reserves the right to review the scale and scope of all buffer pool contributions during project lifetime. Offset credits will be contributed to the Forest Buffer Account. The quantity of the contribution is determined by a project's reversal risk rating based on the potential for reversals associated with different types of risks and project-specific circumstances.

(a) The Offset Project Operator or Authorized Project Designee is required to determine the project's reversal risk rating prior to listing, and recalculate it every time the forest project undergoes verification.

(b) If estimated risk values and associated mitigation measures are updated as improvements in quantifying risks or changes in risks are determined, any adjustments to the reversal risk ratings will affect only current and future year contributions to the Forest Buffer Account.

(c) Risks that may lead to reversals are classified into the categories identified in table E.1.

Table D.1. Forest Project Risk Types

Risk Category	Risk Type	Description
Financial	Financial Failure Leading to Bankruptcy	Financial failure can lead to bankruptcy and/or alternative management decisions to generate income that result in reversals through over-harvesting or conversion
Management	Illegal harvesting	Loss of project stocks due to timber theft
	Conversion to non-forest uses	Alternative land uses are exercised at project carbon expense
	Over-harvesting	Exercising timber value at expense of project arbon
Social	Social risks	Changing government policies, regulations, and general economic conditions

Natural Disturbances	Wildfire	Loss of project carbon through wildfire
	Disease/Insects	Loss of project carbon through disease and/or insects
	Other episodic catastrophic events	Loss of project carbon from wind, snow and ice, or flooding events

(d) The project reversal risk rating must be determined using the tables in this appendix which are designed to identify and quantify the specific types of risks that may lead to a reversal, based on project-specific factors. The Offset Project Operator or Authorized Project Designee must determine the contribution to the reversal risk rating for each risk type below.

(i) Financial Risk: Financial failure of an organization resulting in bankruptcy can lead to dissolution of agreements and forest management activities to recover losses that result in reversals. Forest projects that employ a qualified conservation easement or that occur on public or tribal lands have lower risk.

Table D.2. Financial Risk

Project Specific Circumstances	Contribution to Reversal Risk Rating
Forest project with a qualified conservation easement	1%
Forest project on public or tribal lands	1%
Forest project without a qualified conservation easement and not on public or tribal lands	5%

(ii) Management Risk: Management failure is the risk of management activities that directly or indirectly could lead to a reversal

(iii) Management Risk I – Illegal Removals of Forest Biomass: Illegal logging occurs when biomass is removed either by trespass or outside of a planned set of management activities that are controlled by regulation. Illegal logging is exacerbated by lack of controls and enforcement activities.

Table E.3. Risk of Illegal Removals of Forest Biomass

Project Specific Circumstances	Contribution to Reversal Risk Rating
Forest Project within the United States	0%

(iv) Management Risk II – Conversion of Project Area to Alternative Land Uses: High values for development of housing and/or agriculture may compete with timber and carbon values and lead to a change in land use that affects carbon stocks. The risk of conversion of any project area to other non-forest uses is related to the probability of alternative uses, which are affected by many variables, including population growth, topography, proximity to provisions and metropolitan areas, availability of water and power, and quality of access to the project area.

Table D.4. Risk of Conversion to Alternative Land Use

Project Specific Circumstances	Contribution to Reversal Risk Rating
Forest project with a qualified conservation easement that explicitly encumbers all development rights	0%
Forest project on public or tribal lands	0%
Forest project without a qualified conservation easement that explicitly encumbers all development rights and not on public or tribal lands	2%

(v) Management Risk III – Over-Harvesting: Favorable timber values, among other reasons, may motivate an Offset Project Operator or Authorized Project Designee to realize timber values at the expense of managing carbon stocks for which ARB or registry offset credits have been issued. Additionally, reversals can occur as the result of harvest associated with fuels treatments.

Table D.5. Risk of Over-Harvesting

Project Specific Circumstances	Contribution to Reversal Risk Rating

Forest project with a qualified conservation easement that explicitly encumbers all timber harvesting associated with project stocks	0%
Forest project on public or tribal lands	0%
Forest project without a qualified conservation easement that explicitly encumbers all timber harvesting associated with project stocks and not on public or tribal lands	2%

(vi) Social Risk: Social risks exist due to changing government policies, regulations, and general economic conditions. The risks of social or political actions leading to reversals are low, but could be significant.

Table D.6. Social Risk

Project Specific Circumstances	Contribution to Reversal Risk Rating
Forest Project within the United States	0%

(vii) Natural Disturbance Risk: Natural disturbances can pose a significant risk to the permanence of the GHG emission reductions and removals. Natural disturbance risks are only partially controllable by management activities. Management activities that improve resiliency to wildfire, insects, and disease can reduce these risks. Management activities that shift harvesting practices from live sequestering trees to trees that have succumbed to natural disturbances reduce or negate the reversal depending on the size and location of the disturbance.

(viii) Natural Disturbance Risk I – Wildfire: A wildfire has the potential to cause significant reversals, especially in certain carbon pools. These risks can be reduced by certain techniques including reducing surface fuel loads, removing ladder fuels, adding fuel breaks, and reducing tree density. However, these techniques cannot reduce emission risk to zero because all landowners will not undertake fuel treatments, nor can they prevent wildfires from occurring.

Table D.7. Natural Disturbance Risk I – Wildfire

Project Specific Circumstances	Contribution to Reversal Risk Rating

Forest project that has conducted fire risk assessment and reduction work on the project area that contributed to lowering the fire risk for the entire project area as confirmed in the form of written communication from the Maryland Department of Natural Resources or other qualified independent resource, recognized as expert by academic, private and government organizations.	2%
Forest project that has not assessed or conducted fire risk reduction work on the project area.	4%

(ix) Natural Disturbance Risk II - Disease or Insect Outbreak: A disease or insect outbreak has the potential to cause a reversal, especially in certain carbon pools

Table D.8. Natural Disturbance Risk II - Disease or Insect Outbreak

Project Specific Circumstances	Contribution to Reversal Risk Rating
Forest project within the United States	3%

(x) Natural Disturbance Risk III - Other Episodic Catastrophic Events: A major wind-throw event (hurricane, tornado, high wind event) has the potential to cause a reversal, especially in certain carbon pools.

Table D.9. Natural Disturbance Risk III – Other Episodic Catastrophic Events

Project Specific Circumstances	Contribution to Reversal Risk Rating
Forest project within the United States	3%

(e) Use table D.10 to summarize the forest project's reversal risk rating. As indicated above, projects that employ a qualified conservation easement, or that occur on public lands, are exempt from certain risk categories. Such qualified conservation easements must clearly identify the goals and objectives of the forest project according to the terms of this protocol.

Table D.10. Project Contribution to the Buffer Account Based on Risk.

Risk Type	Risk Category	Contribution to Reversal Risk Rating from Tables E.2 to E.9
Financial	Financial Failure	
Management	Illegal Forest Biomass Removal	
	Conversion	
	Over Harvesting	
Social	Social	
Natural Disturbance	Wildfire	
	Disease or Insect Outbreak	
	Other Catastrophic Events	

(f) The forest project's reversal risk rating is calculated using equation D.1:

Equation D.1. Reversal Risk Rating
100% - [(100%-FinancialFailure%) * (100%-IllegalForestBiomassRemoval%) * (100%-Conversion%) * (100%-OverHarvesting%) * (100%-SocialRisk%) * (100%-Wildfire%) * (100%-Disease/InsectOutbreak) * (100%-OtherCatastrophicEvents%)]

Appendix E. References

Cairns M.A., S. Brown, E.H. Helmer, and G.A. Baumgardner. (1997). Root biomass allocation in the world's upland forest. Oecologia, 111, 1-11. https://doi.org/10.1007/s004420050201.

Domke, G. M., Woodall, C. W., & Smith, J. E. (2011). Accounting for density reduction and structural loss in standing dead trees: Implications for forest biomass and carbon stock estimates in the United States. *Carbon Balance and Management*, *6*(1), 1-11. https://doi.org/10.1186/1750-0680-6-14

Dubayah, R., Sheldon, S., Clark, D., Hofton, M., Blair, J., Hurtt, G., Chazdon, R. (2010). Estimation of tropical forest height and biomass dynamics using lidar remote sensing at La Selva, Costa Rica. https://doi.org/10.1029/2009JG000933

Fisher, R. A., Koven, C. D., Anderegg, W. R., Christoffersen, B. O., Dietze, M. C., Farrior, C. E., ... & Moorcroft, P. R. (2018). Vegetation demographics in Earth System Models: A review of progress and priorities. *Global change biology*, *24*(1), 35-54.Vegetation demographics in Earth System Models: a review of progress and priorities. https://doi.org/10.1111/gcb.13910

Fisk, J. P., Hurtt, G. C., Chambers, J. Q., Zeng, H., Dolan, K. A., & Negrón-Juárez, R. I. (2013). The impacts of tropical cyclones on the net carbon balance of eastern US forests (1851–2000). *Environmental Research Letters*, *8*(4), 045017. https://doi.org/10.1088/1748-9326/8/4/045017

Goward, S.N., C. Huang, F. Zhao, K. Schleeweis, K. Rishmawi, M. Lindsey, J.L. Dungan, and A. Michaelis. 2015. NACP NAFD Project: Forest Disturbance History from Landsat, 1986-2010. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1290

Harmon, M. E., Woodall, C. W., Fasth, B., Sexton, J., & Yatkov, M. (2011). Differences between standing and downed dead tree wood density reduction factors: a comparison across decay classes and tree species. *Res. Pap. NRS-15. Newtown Square, PA: US Department of Agriculture, Forest Service, Northern Research Station. 40 p.*, *15*, 1-40. https://doi.org/10.2737/NRS-RP-15

Huang, W., Swatantran, A., Johnson, K., Duncanson, L., Tang, H., Dunne, J. O. N., ... & Dubayah, R. (2015). Local discrepancies in continental scale biomass maps: a case study over forested and non-forested landscapes in Maryland, USA. Carbon balance and management, 10(1), 1-16. https://doi.org/10.1186/s13021-015-0030-9

Hurtt, G., Moorcroft, P., Pacala, S., Levin, S. (1998). Terrestrial models and global change: challenges for the future. https://doi.org/10.1073/pnas.012249999

Hurtt, G., Pacala, S., Moorcroft, P., Caspersen, J., Shevliakova, E., Houghton, R., Moore, B. (2002). Protecting the future of the U.S. Carbon Sink. https://doi.org/10.1073/pnas.012249999

Hurtt, G., Dubayah, R., Drake, J., Moorcroft, P., Pacala, W., Blair, J., Fearon, M (2004). Beyond Potential Vegetation: Combining Lidar Data and a Height-Structured Model for Carbon Studies. https://doi.org/10.1890/02-5317

Hurtt, G., Wickland, D., Jucks, K., Bowman, K., Brown, M. E., Duren, R. M., ... & Verdy, A. (2014). NASA carbon monitoring system: prototype monitoring, reporting, and verification.

Hurtt, G., Thomas, R., Fisk, J., Dubayah, R., Sheldon, S. (2016). The impact of fine-scale disturbances on the predictability of vegetation dynamics and carbon flux. https://doi.org/10.1371/journal.pone.0152883

Hurtt, G., Zhao, M., Sahajpal, R., Armstrong, A., Birdsey, R., Campbell, E., ... & Tang, H. (2019). Beyond MRV: high-resolution forest carbon modeling for climate mitigation planning over Maryland, USA. *Environmental Research Letters*, *14*(4), 045013. https://doi.org/10.1088/1748-9326/ab0bbe

Hurtt, G., Silva, C., Lamb, R., Ma, L., Shen, Q. (2020). High-resolution Monitoring of Forest Carbon Sequestration to Meet Climate Goals. https://doi.org/10.1002/essoar.10505479.1

Hurtt, G., Ma L., Lamb, R., Campbell, E., Leslie-Bole, H., Huang, C., Silva, C., Shen, Q., Lu, J. Rudee, A., Lister, A., O'Neil-Dunne, J., Dubayah, R. (2022). Beyond Forest Carbon Monitoring: Integrating High-Resolution Remote Sensing and Ecosystem Modeling for Geospatial Assessment and Attribution of Changes in Forest Carbon Stocks Over Maryland, USA. (in prep)

Ma, L., Hurtt, G., Tang, H., Lamb, R., Campbell, E., Dubayah, R., ... & Silva, C. (2021). High-resolution forest carbon modelling for climate mitigation planning over the RGGI region, USA. *Environmental Research Letters*, *16*(4), 045014. https://doi.org/10.1088/1748-9326/abe4f4

Ma, L., Hurtt, G., Ott, L., Sahajpal, R., Fisk, J., Lamb, R., Tang, H., Flanagan, S., Chini, L.,

Chatterjee, A., Sullivan, J. (2022). Global evaluation of the Ecosystem Demography model (ED v3.0). https://doi.org/10.5194/gmd-15-1971-2022

Miles, Patrick D; Smith, W. Brad.(2009). Specific gravity and other properties of wood and bark for 156 tree species found in North America. Res. Note NRS-38. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 35 p.

Moorcroft, P., Hurtt, G., Pacala, S. (2001). A method for scaling vegetation dynamics: the ecosystem demography model (ED). https://doi.org/10.1890/0012-9615(2001)071[0557:AMFSVD]2.0.CO;2

Silva, J. A., Sedano, F., Flanagan, S., Ombe, Z. A., Machoco, R., Meque, C. H., ... & Hurtt, G. (2019). Charcoal-related forest degradation dynamics in dry African woodlands: Evidence from Mozambique. *Appl. Geogr*, *107*, 72-81.https://doi.org/10.1016/j.apgeog.2019.04.006

Smith, James E.; Heath, Linda S.; Skog, Kenneth E.; Birdsey, Richard A. (2006). Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-343.

Technical Guidelines, Voluntary Reporting of Greenhouse Gasses (1605(b)) Program. January 2007. Office of Policy and International Affairs. United States Department of Energy.

Woodall, C. W., Heath, L. S., Domke, G. M., & Nichols, M. C. (2011). Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the US forest inventory, 2010. *Gen. Tech. Rep. NRS-88. Newtown Square, PA: US Department of Agriculture, Forest Service, Northern Research Station. 30 p.*, *88*, 1-30. https://doi.org/10.2737/NRS-GTR-88