



VCS Methodology

VM0045

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METHODOLOGY FOR IMPROVED FOREST  
MANAGEMENT USING DYNAMIC  
MATCHED BASELINES FROM NATIONAL  
FOREST INVENTORIES

Version 1.0

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Sectoral Scope 14

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# 1 SOURCES

No sources are referenced within this methodology.

# 2 SUMMARY DESCRIPTION OF THE METHODOLOGY

Additionality and Crediting Method	
Additionality	Performance Method
Crediting Baseline	Performance Method

This methodology is applicable to a wide range of improved forest management (IFM) practices and employs standardized approaches for demonstration of additionality and derivation of project baselines to simplify application of the methodology.

The focus of accounting is on estimation of GHG emissions and/or carbon stock change in permanent plots, not on estimation of stocks per se, therefore improving the precision of reported GHG emission reductions and/or removals.

The methodology employs a broad monitoring and accounting framework that captures the GHG impacts of IFM practices aimed at avoiding emissions (from harvest or natural disturbance) or enhancing sequestration. Projects may apply a combination of practices implemented together in the same area.

Examples of potential activities include enrichment planting, release of natural regeneration via management of competing vegetation, stand irrigation and/or fertilization, reducing timber harvest levels, deferring harvest/extending rotations or cutting cycles, designating reserves, and altering fire severity via fuel load treatments.

For all activities, the methodology uses a matching approach to construct a quasi-experimental design with matched pairs of treatments (project) and controls (baseline), with baseline plots sourced from existing continuously measured national or sub-national forest inventory data. Carbon stock change is directly monitored in permanent sample units representing the project and baseline scenarios. The baseline is represented by a collection of sample plots outside of the project area that match the initial conditions of each paired project plot. Ex post monitoring of the baseline in this way provides a more robust estimation of impacts compared to model- or

default-driven approaches, which reflect the effects of exogenous factors like climate and timber markets on achieved emission reductions.

An important distinguishing feature of this methodology is that no forest growth and yield modeling is required to account GHG emission reductions and/or removals. This methodology uses a dynamic performance benchmark approach, where the baseline scenario is represented by constituent baseline plots that are continuously monitored, paired with sample units representing the project scenario. Most IFM methodologies are dependent on long-term projections using forest growth and yield models.

## 3 DEFINITIONS

### **Composite baseline**

A group of constituent baseline plots representing the baseline scenario, located outside of the project area. A composite baseline is paired to each sample unit used to monitor the project scenario and is updated over time to establish a dynamic performance benchmark for additionality and crediting baselines. Each composite baseline is derived as the optimally weighted k-nearest neighbor combination of plots that matches the initial conditions of its paired project sample unit.

### **Constituent baseline plot**

An individual sample plot representing the baseline scenario, located outside of the project area, that constitutes a component of one or more composite baselines.

### **Donor pool**

A population of potential sample plots located outside of the project area, from which constituent baseline plots are sourced. The donor pool is a representatively sampled, continuously measured national or sub-national forest inventory.

### **Project sample unit**

A permanent forest inventory plot (either fixed area or variable radius plot) used as the primary sample unit selected for measuring and monitoring carbon stock change and emissions in the project scenario. “Plot” and “sample unit” are used interchangeably within this methodology. A sample unit may constitute a collection of plots (e.g., a cluster), provided that the collection of plots is sampled from within a single stand. Sample units are paired with a composite baseline.

### **Stand<sup>1</sup>**

A contiguous, defined area composed of trees sufficiently uniform in age-class distribution, composition, and structure and growing on a site of sufficiently uniform quality, to be a distinguishable unit. Relevant in accounting as the primary building block (i.e., a minimum

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<sup>1</sup> Definition adapted from Helms, J. A. (Ed.). (1998). *Dictionary of forestry*. Society of American Foresters.

mapping unit of variable size) for quantifying project area and identifying areas subject to harvest or disturbance.

## 4 APPLICABILITY CONDITIONS

This methodology applies to all improved forest management activities, including activities representing discrete interventions and activities representing changes in management regime realized over long time horizons.

The methodology is applicable under the following conditions:

- 1) The project area qualifies as forests remaining as forests, and the project activity involves an intervention expected to achieve improved net carbon emission outcomes relative to business-as-usual practices (including but not limited to extended rotations/cutting cycles, designating reserves, fuel load treatments to mitigate fire risk, enrichment planting, release of natural regeneration via management of competing vegetation, stand irrigation and/or fertilization).
- 2) The project is located in a national or sub-national jurisdiction where approved data sources, and matching covariates and procedures applied in which they occur, are specified in an appendix to the methodology.

This methodology is not applicable under the following conditions:

- 1) The project activity involves reducing the frequency and/or intensity of timber harvest and the project area is subject to any pre-existing legal encumbrance specifically restricting timber harvest.
- 2) The project activity involves a change in hydrology and/or soil disturbance exceeding 10 percent of the project area.<sup>2</sup> The methodology is not applicable to Wetland Restoration and Conservation (WRC) activities.
- 3) The project activity involves any deliberate reduction in lying dead wood stocks that is expected to exceed 5 percent of net emission reductions.<sup>3</sup>

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<sup>2</sup> Note that the absence of changes in hydrology and soil disturbance exceeding 10 percent of the project area, resulting from the project activity, must be verified on an ongoing basis.

<sup>3</sup> As determined by applying the CDM *Tool for testing significance of GHG emissions in A/R CDM project activities*. Available at: [https://cdm.unfccc.int/methodologies/ARmethodologies/tools/ar-am-tool-04-v1.pdf/history\\_view](https://cdm.unfccc.int/methodologies/ARmethodologies/tools/ar-am-tool-04-v1.pdf/history_view)

## 5 PROJECT BOUNDARY

### Spatial boundary

The spatial extent of the project boundary encompasses all lands subject to implementation of the project activities.

### GHG boundary

Selected carbon pools and sources included in the project boundary are listed in Tables 1 and 2.

**Table 1: Selected Carbon Pools<sup>4</sup>**

Source	Included?	Justification/Explanation
Aboveground tree biomass	Yes	Required pool. Expected to be subject to significant change due to the project activity.
Aboveground woody non-tree biomass	Conditional on project activity	Where this pool is subject to significant decrease due to the project activity (e.g., due to site preparation), it must be included in the project scenario (and may be included or excluded in the baseline scenario).  Otherwise, this pool may be included only where it is possible to account in both the project and baseline scenarios (i.e., aboveground non-tree woody biomass must be included in the national forest inventory data used for the composite baseline).
Aboveground non-tree herbaceous biomass	No	Not required due to insignificance
Belowground biomass	Yes	Expected to be subject to significant change due to the project activity
Dead wood	Yes	Required pool. Accounting boundary restricted to standing dead wood (lying dead wood not included).
Litter	No	Not required due to insignificance
Soil organic carbon	No	Not expected to be subject to significant change due to the project activity

<sup>4</sup> Significance defined by applying the CDM *Tool for testing significance of GHG emissions in A/R CDM project activities*. Available at: [https://cdm.unfccc.int/methodologies/ARmethodologies/tools/ar-am-tool-04-v1.pdf/history\\_view](https://cdm.unfccc.int/methodologies/ARmethodologies/tools/ar-am-tool-04-v1.pdf/history_view)

Source	Included?	Justification/Explanation
Wood products	No for reduced impact logging (RIL) with no or minimal (<25 percent) effect on total timber extracted  Yes for all other activities	Required pool, except where the project activity involves RIL with no or minimal (<25 percent) effect on total timber extracted, in which case wood products must not be included.

**Table 2: GHG Sources Included in or Excluded from the Project Boundary<sup>5</sup>**

Source	Gas	Included?	Justification/Explanation	
<b>Baseline and Project</b>	CO <sub>2</sub>	N/A	.	
	CH <sub>4</sub>	N/A		
	Emissions from nitrogen-containing soil amendments or from decomposition of plant materials with fixed nitrogen	N <sub>2</sub> O	Conditional on project activity	N <sub>2</sub> O emissions from nitrogen-containing soil amendments are included in the scenario where nitrogen fertilizer is applied as part of the project activity. N <sub>2</sub> O emissions are conservatively set to zero in the baseline.
		Other	N/A	
		Burning of tree biomass (emissions from burning non-tree biomass not included because they are <i>de minimis</i> )	CO <sub>2</sub>	Conditional on project activity
	CH <sub>4</sub>		Conditional on project activity	
	N <sub>2</sub> O		Conditional on project activity	

<sup>5</sup> Significance defined by applying the *CDM Tool for testing significance of GHG emissions in A/R CDM project activities*. Available at: [https://cdm.unfccc.int/methodologies/ARmethodologies/tools/ar-am-tool-04-v1.pdf/history\\_view](https://cdm.unfccc.int/methodologies/ARmethodologies/tools/ar-am-tool-04-v1.pdf/history_view)



Source	Gas	Included?	Justification/Explanation
Burning of fossil fuels			the probability and/or magnitude of emissions from forest fires).
	Other	N/A	
	CO <sub>2</sub>	Excluded	<i>De minimis</i>
	CH <sub>4</sub>	Excluded	<i>De minimis</i>
	N <sub>2</sub> O	Excluded	<i>De minimis</i>
	Other	Excluded	<i>De minimis</i>

## 6 BASELINE SCENARIO

The crediting baseline uses a dynamic performance benchmark approach, where the baseline scenario is represented by designated composite baselines (made up of forest measurement plots located outside of the project area) that are continually monitored, paired with sample units representing the project scenario.

A group of constituent baseline plots sourced from a donor pool of national or sub-national forest inventory plots is collectively matched to project sample units and designated as a “composite baseline.” Matching is achieved using a k-nearest neighbor optimal matching approach, deriving weights for constituent baseline plots to produce a weighted combination (composite baseline) that conforms to the initial conditions of the paired project sample unit. Matching conditions are defined referencing one or more covariates representing biophysical and anthropogenic factors driving carbon stock change.

Initial conditions of composite baselines and project sample units must be matched at  $t=0$  (prior to the initiation of the project activity) and the selection and weighting of constituent baseline plots subsequently held constant throughout the project crediting period (with rare exceptions, see Section 8.1).

Note that it is recommended that a two-stage sample is employed for the project scenario, with primary units (e.g., stands) selected via probability proportional to size (acreage) and secondary units (e.g., plots) selected via simple random sampling (SRS) or systematic sampling with a fixed sample size within each selected primary unit (which is self-weighting and simplifies calculations). In this case, a composite baseline would be matched to each primary unit on the basis of initial covariate values averaged across the secondary units.

Constituent baseline plots may be sourced from new or existing continuously measured national or sub-national forest inventories and must meet the following requirements:

- 1) Sample plots must be located outside of the project area.
- 2) Sample plot populations from which constituent baseline plots are sourced must be from un-biased, representative sampling at a regional scale.
- 3) Sample plots must be subject to continuous, periodic re-measurement throughout the project crediting period. Constituent baseline plots need not be on the same re-measurement schedule, but must be re-measured at least every 10 years.
- 4) Initial conditions must be quantified from measurements collected at time  $t-10$  or more recently.
- 5) Sample plots must be located in the same ecoregion (e.g., referencing ecological sections from Cleland et al. (2007<sup>6</sup>) in the U.S. or Holdridge life zones<sup>7</sup> elsewhere).
- 6) Trees on sample plots must be given unique identification numbers to permit tracking of individual stems.
- 7) Measurement parameters (e.g., minimum diameter at breast height) must be paired with the project sample units.

Projects must use approved data sources, matching covariates, and procedures for the national or sub-national jurisdiction in which they occur, as specified in the methodology appendices (e.g., Appendix A Procedure for developing composite baselines in the United States). Where not specified in the current version of the methodology, approved data sources, matching covariates, and procedures for other national or sub-national jurisdictions may be developed through revisions to the methodology.

## 7 ADDITIONALITY

Additionality must be demonstrated using a performance method, following the steps below.

### **Step 1: Regulatory Surplus**

Project proponents must demonstrate regulatory surplus in accordance with the rules and requirements regarding regulatory surplus set out in the latest version of the *VCS Methodology Requirements*.

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<sup>6</sup> Cleland, D. T., Freeouf, J. A., Keys, J. E., Nowacki, G. J., Carpenter, C. A., & McNab, W. H. (2007). *Ecological subregions: Sections and subsections for the conterminous United States*. Gen. Tech. Report WO-76D. USDA Forest Service. <https://doi.org/10.2737/WO-GTR-76D>

<sup>7</sup> Leemans, R. (1992). *Global Holdridge life zone classifications*. IIASA. Available at: <https://resources.unep-wcmc.org/products/31d5e80482834f6ba6ee51a2813b82e7>

## Step 2: Performance Benchmark

Composite baselines derived per the procedures set out in Section 6 represent the without-project activity, or baseline scenario. Updating the composite baselines periodically throughout the project crediting period produces a dynamic and spatially variable performance benchmark in terms of periodic carbon stock change. At each monitoring event, where equation 1 yields a positive value, the project is deemed additional; note that equation 1 is the same as equation 11 (used to calculate net emission reductions).

$$ER_t = (A_t \times \overline{ER}_t + LK_t) \times (1 - UNC_t) \quad (1)$$

Where:

$ER_t$	Net GHG emission reductions in year $t$ (t CO <sub>2</sub> e)
$A_t$	Project area in year $t$ (unit area)
$\overline{ER}_t$	Mean GHG emission reductions in year $t$ (t CO <sub>2</sub> e per unit area per year)
$LK_t$	Leakage in year $t$ (t CO <sub>2</sub> e)
$UNC_t$	Uncertainty in year $t$ (percent)

# 8 QUANTIFICATION OF GHG EMISSION REDUCTIONS AND REMOVALS

## 8.1 Baseline Emissions

Baseline quantification is focused on measured carbon stock change in the composite baselines, representing the absence of the project activity. Each project sample unit  $i$  has a corresponding paired composite baseline  $i$ , composed of one or more constituent baseline plots  $j$ .

Harvest or disturbance emissions include carbon emitted from live tree above- and below-ground biomass, dead wood, and harvested wood products (i.e., carbon not retained in harvested wood products for 100 years or more after harvest).

For each constituent baseline plot, carbon stock change is calculated at the re-measurement time,  $mt$ , and annualized as:

$$\Delta LAG_{bsl,i,j,mt} = (LAG_{bsl,i,j,t} - LAG_{bsl,i,j,t-X_{bsl,i,j,t}}) \times (1/X_{bsl,i,j,t}) \quad (2a)$$

$$\Delta LBG_{bsl,i,j,mt} = (LBG_{bsl,i,j,t} - LBG_{bsl,i,j,t-X_{bsl,i,j,t}}) \times (1/X_{bsl,i,j,t}) \quad (2b)$$

$$\Delta DW_{bsl,i,j,mt} = (DW_{bsl,i,j,t} - DW_{bsl,i,j,t-X_{bsl,i,j,t}}) \times (1/X_{bsl,i,j,t}) \quad (2c)$$

Where:

$\Delta LAG_{bsl,i,j,mt}$	Annual change in live aboveground biomass stocks in the baseline scenario at constituent baseline plot $j$ in composite baseline $i$ calculated at re-measurement time $mt$ (t CO <sub>2</sub> e per unit area per year)
$LAG_{bsl,i,j,t}$	Live aboveground biomass stocks in the baseline scenario at constituent baseline plot $j$ in composite baseline $i$ at time $t$ (t CO <sub>2</sub> e per unit area)
$LAG_{bsl,i,j,t-X_{bsl,i,j,t}}$	Live aboveground biomass stocks in the baseline scenario at constituent baseline plot $j$ in composite baseline $i$ at time $t-X_{bsl,i,j,t}$ (t CO <sub>2</sub> e per unit area)
$\Delta LBG_{bsl,i,j,mt}$	Annual change in live belowground biomass stocks in the baseline scenario at constituent baseline plot $j$ in composite baseline $i$ calculated at re-measurement time $mt$ (t CO <sub>2</sub> e per unit area per year)
$LBG_{bsl,i,j,t}$	Live belowground biomass stocks in the baseline scenario at constituent baseline plot $j$ in composite baseline $i$ at time $t$ (t CO <sub>2</sub> e per unit area)
$LBG_{bsl,i,j,t-X_{bsl,i,j,t}}$	Live belowground biomass stocks in the baseline scenario at constituent baseline plot $j$ in composite baseline $i$ at time $t-X_{bsl,i,j,t}$ (t CO <sub>2</sub> e per unit area)
$\Delta DW_{bsl,i,j,mt}$	Annual change in dead wood stocks in the baseline scenario at constituent baseline plot $j$ in composite baseline $i$ calculated at re-measurement time $mt$ (t CO <sub>2</sub> e per unit area per year)
$DW_{bsl,i,j,t}$	Dead wood stocks in the baseline scenario at constituent baseline plot $j$ in composite baseline $i$ at time $t$ (t CO <sub>2</sub> e per unit area)
$DW_{bsl,i,j,t-X_{bsl,i,j,t}}$	Dead wood stocks in the baseline scenario at constituent baseline plot $j$ in composite baseline $i$ at time $t-X_{bsl,i,j,t}$ (t CO <sub>2</sub> e per unit area)
$X_{bsl,i,j,t}$	Length of measurement interval ending at time $t$ for constituent baseline plot $ij$ (years)

Note that the re-measurement time  $mt$  is expected to precede the project start date for the initial measurement intervals.

For each reporting year  $t$ , annual carbon stock change calculated for re-measurement times  $mt$  (calculated in Equations 2a, 2b, and 2c), where  $t-mt$  is less than the length of the measurement interval corresponding to re-measurement time  $mt=X_{bsl,i,j,t}$ , (see Equations 3a, 3b and 3c), is summed for each constituent baseline plot. Then, the composite baseline  $i$  is calculated as the weighted sum of carbon stock change across constituent baseline plots.

$$\Delta LAG_{bsl,i,t} = \sum_{j=1}^n W_{bsl,i,j} \sum_{mt=-10}^t \Delta LAG_{bsl,i,j,mt} [t - mt < X_{bsl,i,j,t}] \quad (3a)$$

$$\Delta LBG_{bsl,i,t} = \sum_{j=1}^n W_{bsl,i,j} \sum_{mt=-10}^t \Delta LBG_{bsl,i,j,mt} [t - mt < X_{bsl,i,j,t}] \quad (3b)$$

$$\Delta DW_{bsl,i,t} = \sum_{j=1}^n W_{bsl,i,j} \sum_{mt=-10}^t \Delta DW_{bsl,i,j,mt} [t - mt < X_{bsl,i,j,t}] \quad (3c)$$

Where:

$\Delta LAG_{bsl,i,t}$	Annual change in live aboveground biomass stocks in the baseline scenario at composite baseline $i$ in year $t$ (t CO <sub>2</sub> e per unit area per year)
$\Delta LAG_{bsl,i,j,mt}$	Annual change in live aboveground biomass stocks in the baseline scenario at constituent baseline plot $j$ in composite baseline $i$ calculated at re-measurement time $mt$ (t CO <sub>2</sub> e per unit area per year)
$\Delta LBG_{bsl,i,t}$	Annual change in live belowground biomass stocks in the baseline scenario at composite baseline $i$ in year $t$ (t CO <sub>2</sub> e per unit area per year)
$\Delta LBG_{bsl,i,j,mt}$	Annual change in live belowground biomass stocks in the baseline scenario at constituent baseline plot $j$ in composite baseline $i$ calculated at re-measurement time $mt$ (t CO <sub>2</sub> e per unit area per year)
$\Delta DW_{bsl,i,t}$	Change in dead wood stocks in the baseline scenario at composite baseline $i$ in year $t$ (t CO <sub>2</sub> e per unit area per year)
$\Delta DW_{bsl,i,j,mt}$	Annual change in dead wood stocks in the baseline scenario at constituent baseline plot $j$ in composite baseline $i$ calculated at re-measurement time $mt$ (t CO <sub>2</sub> e per unit area per year)
$W_{bsl,i,j}$	Weight of constituent baseline plot $j$ in matched composite baseline $i$ ; value between 0 and 1 (dimensionless)

Note that constituent plots within a given composite baseline need not be on the same re-measurement schedule, nor have the same or fixed measurement intervals over a crediting period.

Table 3: Illustrative Derivation of Live Aboveground Biomass Stock Change for a Composite Baseline Applying Equations 2 and 3:

 a) Periodic Measurement of Live Aboveground Biomass in Constituent Baseline Plots ( $LAG_{bsl,i,j,t}$ )

Plot <i>bsl, i, j</i>	Year <i>t</i>												
	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5
1	430.3							325.7				338.7	
2			260.1					284.6					
3		233.7					247.3						238.2
4	335.6					361.7							387.4
5			459.4					474.8					
6				214.2				230.2					
7			195.8					216.2					
8	195.0					145.4					165.3		
9		80.0					91.2					86.7	
10		190.0				152.0					170.0		

b) Calculation of Annual Change in Live Aboveground Biomass Stocks in Constituent Baseline Plots at Re-Measurement Time  $mt$   
 ( $\Delta LAG_{bsl,i,j,mt}$ )

Plot $bsl, i, j$	Time $mt - X_{bsl,i,j,t}$	Time $mt$	$LAG_{bsl,i,j,t} - X_{bsl,i,j,t}$	$LAG_{bsl,i,j,t}$	$X_{bsl,i,j,t}$ (years)	$LAG_{bsl,i,j,t}$ $- LAG_{bsl,i,j,t} - X_{bsl,i,j,t}$	$\Delta LAG_{bsl,i,j,mt}$
1	-7	0	430.3	325.7	7	-104.6	-14.9
1	0	4	325.7	338.7	4	13.0	3.3
2	-5	0	260.1	284.6	5	24.5	4.9
3	-6	-1	233.7	247.3	5	13.6	2.7
3	-1	5	247.3	238.2	6	-9.1	-1.5
4	-7	-2	335.6	361.7	5	26.1	5.2
4	-2	5	361.7	387.4	7	25.7	3.7
5	-5	0	459.4	474.8	5	15.4	3.1
6	-4	0	214.2	230.2	4	16.0	4.0
7	-5	0	195.8	216.2	5	20.4	4.1
8	-7	-2	195.0	145.4	5	-49.6	-9.9
8	-2	3	145.4	165.3	5	19.9	4.0
9	-6	-1	80	91.2	5	11.2	2.2
9	-1	4	91.2	86.7	5	-4.5	-0.9
10	-6	-2	190	152	4	-38.0	-9.5
10	-2	3	152	170	5	18.0	3.6

c) Calculation of Change in Live Aboveground Biomass Stocks in Composite Control  $i$  in Year  $t$  ( $\Delta LAG_{bsl,i,t}$ )

Plot $bsl, i, j$	$W$	Year $t$				
		1	2	3	4	5
1	0.08	-14.9	-14.9	-14.9	-11.7	-11.7
2	0.05	4.9	4.9	4.9	4.9	0.0
3	0.05	2.7	2.7	2.7	0.0	-1.5
4	0.05	5.2	5.2	0.0	0.0	3.7
5	0.17	3.1	3.1	3.1	3.1	0.0
6	0.11	4.0	4.0	4.0	0.0	0.0
7	0.10	4.1	4.1	4.1	4.1	0.0
8	0.17	-9.9	-9.9	4.0	4.0	4.0
9	0.16	2.2	2.2	2.2	-0.9	-0.9
10	0.05	-9.5	0.0	3.6	3.6	3.6
$\Delta LAG_{bsl,i,t}$		-1.0	-0.5	1.7	0.9	-0.2

Note that for Plot 1, years 4 and 5 reference annual stock change from re-measurement times  $mt=0$  and 4 respectively.



Note that weights for constituent baseline plots ( $W_{bsl,i,j}$ ) are determined at  $t=0$  and fixed throughout the project crediting period, except where a constituent baseline plot has become invalid (e.g., where a unit is no longer in a forest condition or has not been re-measured in over 10 years; see Section 6), in which case all weights in the respective composite baseline are recalculated to sum to 1, holding relative weights of the remaining valid constituent plots constant.

Harvested wood product stocks ( $HWP_{bsl,i,j,t}$ ) are calculated using Equation 4.

$$\begin{aligned}
 HWP_{bsl,i,j,t} = & (BBremoved_{saw,wt=sfw,bsl,i,j,t} \times SF_{saw,wt=sfw} + BBremoved_{pulp,wt=sfw,bsl,i,j,t} \times \\
 & SF_{pulp,wt=sfw}) + (BBremoved_{saw,wt=hwd,bsl,i,j,t} \times SF_{saw,wt=hwd} + \\
 & BBremoved_{pulp,wt=hwd,bsl,i,j,t} \times SF_{pulp,wt=hwd})
 \end{aligned} \quad (4)$$

Where:

$HWP_{bsl,i,j,t}$	Harvested wood products remaining stored for 100 years in the baseline scenario at constituent baseline plot $j$ in composite baseline $i$ , harvested in the monitoring interval ending at time $t$ (t CO <sub>2e</sub> per unit area)
$BBremoved_{saw,wt,bsl,i,j,t}$	Saw log bole biomass stocks in wood type $wt$ in commercial species removed in the baseline scenario at constituent baseline plot $j$ in composite baseline $i$ , harvested in the monitoring interval ending at time $t$ (t CO <sub>2e</sub> per unit area)
$BBremoved_{pulp,wt,bsl,i,j,t}$	Pulpwood bole biomass stocks in wood type $wt$ in commercial species removed in the baseline scenario at constituent baseline plot $j$ in composite baseline $i$ , harvested in the monitoring interval ending at time $t$ (t CO <sub>2e</sub> per unit area)
$SF_{saw,wt}$	Saw log 100-year average storage factor (mass remaining stored in use and landfills over 100 years) for wood type $wt$ (dimensionless)
$SF_{pulp,wt}$	Pulpwood 100-year average storage factor (mass remaining stored in use and landfills over 100 years) for wood type $wt$ (dimensionless)
$wt$	Wood type, defined as softwood (sfw) and hardwood (hwd)

Where burning occurs in the monitoring interval ending at time  $t$ , CH<sub>4</sub> and N<sub>2</sub>O emissions from fire are included and calculated using Equation 5, assuming that all stock change is subject to burning. Otherwise,  $Bburn_{bsl,i,j,t}$  is set equal to zero.

$$\begin{aligned}
 Bburn_{bsl,i,j,t} = & \sum_{g=1}^G GWP_g \times ((LAG_{bsl,i,j,t} - LAG_{bsl,i,j,t-X_{bsl,i,j,t}}) + (DW_{bsl,i,j,t} - \\
 & DW_{bsl,i,j,t-X_{bsl,i,j,t}})) \times \frac{12}{44} \times \frac{1}{CF} \times C_f \times EF_g \times 10^{-3}
 \end{aligned} \quad (5)$$

Where:

$Bburn_{bsl,i,j,t}$	Emissions of CH <sub>4</sub> and N <sub>2</sub> O in the baseline scenario from biomass burning at constituent baseline plot $j$ in composite baseline $i$ in monitoring interval ending at time $t$ (t CO <sub>2</sub> e per unit area)
$GWP_g$	Global warming potential of gas $g$
$LAG_{bsl,i,j,t}$	Live aboveground biomass stocks in the baseline scenario at constituent baseline plot $j$ in composite baseline $i$ at time $t$ (t CO <sub>2</sub> e per unit area)
$LAG_{bsl,i,j,t-X_{bsl,i,j,t}}$	Live aboveground biomass stocks in the baseline scenario at constituent baseline plot $j$ in composite baseline $i$ at time $t-X_{bsl,i,j,t}$ (t CO <sub>2</sub> e per unit area)
$DW_{bsl,i,j,t}$	Dead wood stocks in the baseline scenario at constituent baseline plot $j$ in composite baseline $i$ at time $t$ (t CO <sub>2</sub> e per unit area)
$DW_{bsl,i,j,t-X_{bsl,i,j,t}}$	Dead wood stocks in the baseline scenario at constituent baseline plot $j$ in composite baseline $i$ at time $t-X_{bsl,i,j,t}$ (t CO <sub>2</sub> e per unit area)
$CF$	Carbon fraction; 0.5
$C_f$	Combustion factor (dimensionless)
$EF_g$	Emission factor for gas $g$ (g/kg dry matter burnt)

Carbon stock change in the baseline scenario is then estimated for each composite baseline  $i$  at time  $t$  (net sequestration), which serves as the performance benchmark (crediting baseline) for each paired project sample unit  $i$ , as:

$$\Delta CO2_{bsl,i,t} = \Delta LAG_{bsl,i,t} + \Delta LBG_{bsl,i,t} + \Delta DW_{bsl,i,t} + \sum_{j=1}^n (HWP_{bsl,i,j,t} \times W_{bsl,i,j}) - Nfert_{bsl,i,t} - \sum_{j=1}^n (Bburn_{bsl,i,j,t} \times W_{bsl,i,j}) \quad (6)$$

Where:

$\Delta CO2_{bsl,i,t}$	Carbon stock change in the baseline scenario in composite baseline $i$ in year $t$ (t CO <sub>2</sub> e per unit area per year)
$\Delta LAG_{bsl,i,t}$	Change in live aboveground biomass stocks in the baseline scenario in composite baseline $i$ in year $t$ (t CO <sub>2</sub> e per unit area per year)
$\Delta LBG_{bsl,i,t}$	Change in live belowground biomass stocks in the baseline scenario in composite baseline $i$ in year $t$ (t CO <sub>2</sub> e per unit area per year)
$\Delta DW_{bsl,i,t}$	Change in dead wood stocks in the baseline scenario in composite baseline $i$ in year $t$ (t CO <sub>2</sub> e per unit area per year)
$HWP_{bsl,i,j,t}$	Harvested wood products remaining stored over 100 years in the baseline scenario at constituent baseline plot $j$ in composite baseline $i$ , harvested in the monitoring interval ending at time $t$ (t CO <sub>2</sub> e per unit area)

$Nfert_{bsl,i,t}$	Direct and indirect nitrous oxide emissions due to nitrogen fertilizer use in the baseline scenario in composite baseline $i$ in monitoring interval ending at time $t$ (t CO <sub>2</sub> e per unit area)
$Bburn_{bsl,i,j,t}$	Emissions of CH <sub>4</sub> and N <sub>2</sub> O in the baseline scenario from biomass burning at constituent baseline plot $j$ in composite baseline $i$ in monitoring interval ending at time $t$ (t CO <sub>2</sub> e per unit area)
$W_{bsl,i,j}$	Weight of constituent baseline plot $j$ in matched composite baseline $i$ ; value between 0 and 1 (dimensionless)

Nitrous oxide emissions due to nitrogen fertilizer use in the baseline scenario ( $Nfert_{bsl,i,t}$ ) are conservatively set to zero.

## 8.2 Project Emissions

Stock change in live aboveground biomass in the project scenario in sample unit  $i$  over the monitoring interval ending at time  $t$  is annualized as:

$$\Delta LAG_{wp,i,t} = (LAG_{wp,i,t} - LAG_{wp,i,t-X_{wp,i,t}}) \times (1/X_{wp,i,t}) \quad (7a)$$

$$\Delta LBG_{wp,i,t} = (LBG_{wp,i,t} - LBG_{wp,i,t-X_{wp,i,t}}) \times (1/X_{wp,i,t}) \quad (7b)$$

$$\Delta DW_{wp,i,t} = (DW_{wp,i,t} - DW_{wp,i,t-X_{wp,i,t}}) \times (1/X_{wp,i,t}) \quad (7c)$$

Where:

$\Delta LAG_{wp,i,t}$	Average annual change in live aboveground biomass stocks in the project scenario in sample unit $i$ in the monitoring interval ending at time $t$ (t CO <sub>2</sub> e per unit area per year)
$LAG_{wp,i,t}$	Live aboveground biomass stocks in the project scenario in sample unit $i$ in the monitoring interval ending at time $t$ (t CO <sub>2</sub> e per unit area)
$LAG_{wp,i,t-X_{wp,i,t}}$	Live aboveground biomass stocks in the project scenario in sample unit $i$ in the monitoring interval ending at time $t-X_{wp,i,t}$ (t CO <sub>2</sub> e per unit area)
$\Delta LBG_{wp,i,t}$	Average annual change in live belowground biomass stocks in the project scenario in sample unit $i$ in the monitoring interval ending at time $t$ (t CO <sub>2</sub> e per unit area per year)
$LBG_{wp,i,t}$	Live belowground biomass stocks in the project scenario in sample unit $i$ in the monitoring interval ending at time $t$ (t CO <sub>2</sub> e per unit area)
$LBG_{wp,i,t-X_{wp,i,t}}$	Live belowground biomass stocks in the project scenario in sample unit $i$ in the monitoring interval ending at time $t-X_{wp,i,t}$ (t CO <sub>2</sub> e per unit area)
$\Delta DW_{wp,i,t}$	Average annual change in dead wood stocks in the project scenario in sample unit $i$ in the monitoring interval ending at time $t$ (t CO <sub>2</sub> e per unit area per year)
$DW_{wp,i,t}$	Dead wood stocks in the project scenario in sample unit $i$ in the monitoring interval ending at time $t$ (t CO <sub>2</sub> e per unit area)

$DW_{wp,i,t-X_{wp,i,t}}$	Dead wood stocks in the project scenario in sample unit $i$ in the monitoring interval ending at time $t-X_{wp,i,t}$ (t CO <sub>2</sub> e per unit area)
$X_{wp,i,t}$	Length of measurement interval ending at time $t$ for sample unit $i$ in the project scenario (years)

As with constituent baseline plots, project sample units may be re-measured on a staggered basis (i.e., re-measurements of cohorts of sample units are scheduled in different years within a monitoring cycle) provided that subsets of sample units in the project scenario re-measured in different years are selected systematically or at random from the total sample population.

Harvested wood products remaining stored for 100 years ( $HWP_{wp,i,t}$ ) and emissions of CH<sub>4</sub> and N<sub>2</sub>O from biomass burning ( $Bburn_{wp,i,t}$ ) in the project scenario are estimated using Equations 4 and 5 respectively, substituting the subscript  $bsl$  with  $wp$  to make clear that the relevant values are being quantified for the project scenario. Note that no weighted summing operation is used in these equations in the project scenario.

Where nitrogen fertilizer is applied due to the project activity, nitrous oxide emissions are calculated using Equation 8a.

$$Nfert_{wp,i,t} = Nfert_{wp,direct,i,t} + Nfert_{wp,indirect,i,t} \quad (8a)$$

Where:

$Nfert_{wp,i,t}$	Direct and indirect nitrous oxide emissions due to nitrogen fertilizer use in the project scenario for sample unit $i$ in monitoring interval ending at time $t$ (t CO <sub>2</sub> e per unit area)
$Nfert_{wp,direct,i,t}$	Direct nitrous oxide emissions due to fertilizer use in the project scenario for sample unit $i$ in monitoring interval ending at $t$ (t CO <sub>2</sub> e per unit area)
$Nfert_{wp,indirect,i,t}$	Indirect nitrous oxide emissions due to fertilizer use in the project scenario for sample unit $i$ in monitoring interval ending at time $t$ (t CO <sub>2</sub> e per unit area)

$$Nfert_{wp,direct,i,t} = (F_{wp,SN,i,t} + F_{wp,ON,i,t}) \times EF_{Ndirect} \times 44/28 \times GWP_{N2O} \quad (8b)$$

$$F_{wp,SN,i,t} = M_{wp,SF,i,t} \times NC_{wp,SF,i,t} \quad (8c)$$

$$F_{wp,ON,i,t} = M_{wp,OF,i,t} \times NC_{wp,OF,i,t} \quad (8d)$$

Where:

$Nfert_{wp,direct,i,t}$	Direct nitrous oxide emissions due to nitrogen fertilizer use in the project scenario for sample unit $i$ in monitoring interval ending at $t$ (t CO <sub>2</sub> e per unit area)
-------------------------	------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------

$F_{wp,SN,i,t}$	Project synthetic N fertilizer applied to sample unit $i$ in monitoring interval ending at time $t$ (t N per unit area)
$F_{wp,ON,i,t}$	Project organic N fertilizer applied to sample unit $i$ in monitoring interval ending at time $t$ (t N per unit area)
$M_{wp,SF,i,t}$	Mass of project N-containing synthetic fertilizer applied to sample unit $i$ in monitoring interval ending at time $t$ (t fertilizer per unit area)
$M_{wp,OF,i,t}$	Mass of project N-containing organic fertilizer applied to sample unit $i$ in monitoring interval ending at time $t$ (t fertilizer per unit area)
$NC_{wp,SF,i,t}$	N content of project synthetic fertilizer applied to sample unit $i$ in monitoring interval ending at time $t$ (t N/t fertilizer)
$NC_{wp,OF,i,t}$	N content of project organic fertilizer applied to sample unit $i$ in monitoring interval ending at time $t$ (t N/t fertilizer)
$EF_{Ndirect}$	Emission factor for nitrous oxide emissions from N additions from synthetic fertilizers, organic amendments, and crop residues (t N <sub>2</sub> O-N/t N applied)
$GWP_{N2O}$	Global warming potential for N <sub>2</sub> O; 298

$$Nfert_{wp,indirect,i,t} = Nfert_{wp,volat,i,t} + Nfert_{wp,leach,i,t} \quad (8e)$$

$$Nfert_{wp,volat,i,t} = [(F_{wp,SN,i,t} \times Frac_{GASF}) + (F_{wp,ON,i,t} \times Frac_{GASM})] \times EF_{Nvolat} \times 44/28 \times GWP_{N2O} \quad (8f)$$

$$Nfert_{wp,leach,i,t} = (F_{wp,SN,i,t} + F_{wp,ON,i,t}) \times Frac_{LEACH} \times EF_{Nleach} \times 44/28 \times GWP_{N2O} \quad (8g)$$

Where:

$Nfert_{wp,indirect,i,t}$	Indirect nitrous oxide emissions due to nitrogen fertilizer use in the project scenario for sample unit $i$ in monitoring interval ending at time $t$ (t CO <sub>2</sub> e per unit area)
$Nfert_{wp,volat,i,t}$	Indirect nitrous oxide emissions produced from atmospheric deposition of N volatilized due to nitrogen fertilizer use in sample unit $i$ in monitoring interval ending at time $t$ (t CO <sub>2</sub> e per unit area)
$Nfert_{wp,leach,i,t}$	Indirect nitrous oxide emissions produced from leaching and runoff of N, in regions where leaching and runoff occurs, due to nitrogen fertilizer use in sample unit $i$ in monitoring interval ending at time $t$ (t CO <sub>2</sub> e per unit area). Value = 0 where average annual precipitation is less than potential evapotranspiration, unless subject to irrigation.

$F_{wp,SN,i,t}$	Project synthetic N fertilizer applied to sample unit $i$ in monitoring interval ending at time $t$ (t N per unit area)
$F_{wp,ON,i,t}$	Project organic N fertilizer applied to sample unit $i$ in monitoring interval ending at time $t$ (t N per unit area)
$Frac_{GASF}$	Fraction of all synthetic N added to soils that volatilizes as $NH_3$ and $NO_x$ (dimensionless)
$Frac_{GASM}$	Fraction of all organic N added to soils that volatilizes as $NH_3$ and $NO_x$ (dimensionless)
$Frac_{LEACH}$	Fraction of N (synthetic or organic) added to soils that is lost through leaching and runoff, in regions where leaching and runoff occurs (dimensionless)
$EF_{Nvolat}$	Emission factor for nitrous oxide emissions from atmospheric deposition of N on soils and water surfaces (t $N_2O-N$ /[t $NH_3-N$ + $NO_x-N$ volatilized])
$EF_{Nleach}$	Emission factor for nitrous oxide emissions from leaching and runoff (t $N_2O-N$ /t N leached and runoff)
$GWP_{N_2O}$	Global warming potential for $N_2O$ ; 298

Stock change in the project scenario is then estimated for each sample unit  $i$  in year  $t$  using Equation 9 (net sequestration):

$$\Delta CO2_{wp,i,t} = \Delta LAG_{wp,i,t} + \Delta LBG_{wp,i,t} + \Delta DW_{wp,i,t} + HWP_{wp,i,t} - Nfert_{wp,i,t} - Bburn_{wp,i,t} \quad (9)$$

Where:

$\Delta CO2_{wp,i,t}$	Stock change in the project scenario at sample unit $i$ in year $t$ (t $CO_2e$ per unit area per year)
$\Delta LAG_{wp,i,t}$	Change in live aboveground biomass stocks in the project scenario at sample unit $i$ in year $t$ (t $CO_2e$ per unit area per year)
$\Delta LBG_{wp,i,t}$	Change in live belowground biomass stocks in the project scenario at sample unit $i$ in year $t$ (t $CO_2e$ per unit area per year)
$\Delta DW_{wp,i,t}$	Change in dead wood stocks in the project scenario at sample unit $i$ in year $t$ (t $CO_2e$ per unit area per year)
$HWP_{wp,i,t}$	Harvested wood products remaining stored over 100 years in the project scenario at sample unit $i$ , harvested in the monitoring interval ending at time $t$ (t $CO_2e$ per unit area)

$Nfert_{wp,i,t}$	Direct and indirect nitrous oxide emissions due to nitrogen fertilizer use in the project scenario at sample unit $i$ in the monitoring interval ending at time $t$ (t CO <sub>2</sub> e per unit area)
$Bburn_{wp,i,t}$	Emissions of CH <sub>4</sub> and N <sub>2</sub> O in the project scenario from biomass burning at sample unit $i$ in monitoring interval ending at time $t$ (t CO <sub>2</sub> e per unit area)

Note that any emissions resulting from an initial project treatment (e.g., prescribed burn or thinning) are included in parameter  $\Delta CO2_{wp,i,t}$  because the first monitoring interval begins immediately prior to application of the project activity.

### 8.3 Leakage

Leakage is due to a combination of activity-shifting leakage (outside the project area but within the project proponent's operations) and market leakage (outside both the project area and the project proponent's operations).

Leakage ( $LK_t$ ) is calculated as:

$$LK_t = \text{MIN} \left( 0, A_t \times \frac{1}{n} \sum_{i=1}^n (L\text{Removed}_{wp,i,t} - \sum_{j=1}^n L\text{Removed}_{bsl,i,j,t} \times W_{bsl,i,j}) \times LF_t \right) \quad (10)$$

Where:

$LK_t$	Leakage in year $t$ (t CO <sub>2</sub> e)
$L\text{Removed}_{wp,i,t}$	Live tree biomass stocks removed in the project scenario at sample unit $i$ subject to harvest in the monitoring interval ending at time $t$ (t CO <sub>2</sub> e per unit area)
$L\text{Removed}_{bsl,i,j,t}$	Live tree biomass stocks removed in the baseline scenario (without avoided emissions activity), at constituent baseline plot $j$ in composite baseline $i$ subject to harvest in the monitoring interval ending at time $t$ (t CO <sub>2</sub> e per unit area)
$W_{bsl,i,j}$	Weight of constituent baseline plot $j$ in matched composite baseline $i$ ; value between 0 and 1 (dimensionless)
$LF_t$	Leakage factor (percent)
$A_t$	Project area in year $t$ (unit area)

The leakage factor ( $LF_t$ ) is determined per the following stepwise process:

- 1) Determine whether the project activity involves any permanent reduction in timber supply (i.e., involves any commitments to reduce harvest levels for 100 years or longer), demonstrated at the project start date.
- 2) Where the project activity involves any permanent reduction in timber supply, calculate the national average ratio of merchantable stocking (on a volume or mass basis in commercial species) to total stocking compared to the equivalent ratio in the project area, and apply the corresponding  $LF_t$  parameter value:
  - a) Equal (i.e., national ratio within  $\pm 15$  percent of the project area ratio):  
 $LF_t = 0.4$  (40 percent)
  - b) Less than (i.e., national ratio  $< 85$  percent of the project area ratio):  
 $LF_t = 0.7$  (70 percent)
  - c) More than (i.e., national ratio  $> 115$  percent of the project area ratio):  
 $LF_t = 0.2$  (20 percent)
- 3) Otherwise, where the project activity involves no permanent reduction in timber supply,  $LF_t = 0.1$  (10 percent).

## 8.4 Net GHG Emission Reductions and Removals

Net emission reductions in each year are quantified as:

$$ER_t = (A_t \times \overline{ER}_t + LK_t) \times (1 - UNC_t) \quad (11)$$

Where:

$ER_t$	Net GHG emission reductions in year $t$ (t CO <sub>2</sub> e)
$A_t$	Project area in year $t$ (unit area)
$\overline{ER}_t$	Mean GHG emission reductions in year $t$ (t CO <sub>2</sub> e per unit area per year)
$LK_t$	Leakage in year $t$ (t CO <sub>2</sub> e)
$UNC_t$	Uncertainty in year $t$ (percent)

Mean carbon stock change and emission reductions are calculated using unbiased estimators, such as from Cochran, W. G. (1977). *Sampling techniques* (3rd ed.). John Wiley & Sons or Som, R. K. (1995). *Practical sampling techniques* (2nd ed.). Taylor & Francis.

Equations 12 and 13, used to calculate  $ER_t$  and  $UNC_t$ , assume either:

- 1) A simple random sample (SRS) design, or
- 2) A two-stage sample with primary units (e.g., stands) selected via probability proportional to size (acreage) and secondary units (e.g., plots) selected via SRS or systematic sampling with a fixed sample size within each selected primary unit. In the



latter case, a composite baseline would be matched to each primary unit on the basis of initial conditions averaged across the secondary units (many-to-many matching).

Other statistically robust sample designs (e.g., stratified samples) may be employed and the estimators of the mean and standard error reconfigured to permit unbiased estimation.

Emission reductions are calculated for each sample unit  $i$  in year  $t$ , and the mean emission reduction is quantified as:

$$\overline{ER}_t = \frac{1}{n} \times \sum_{i=1}^n (\Delta CO2_{wp,i,t} - \Delta CO2_{bsl,i,t}) \quad (12)$$

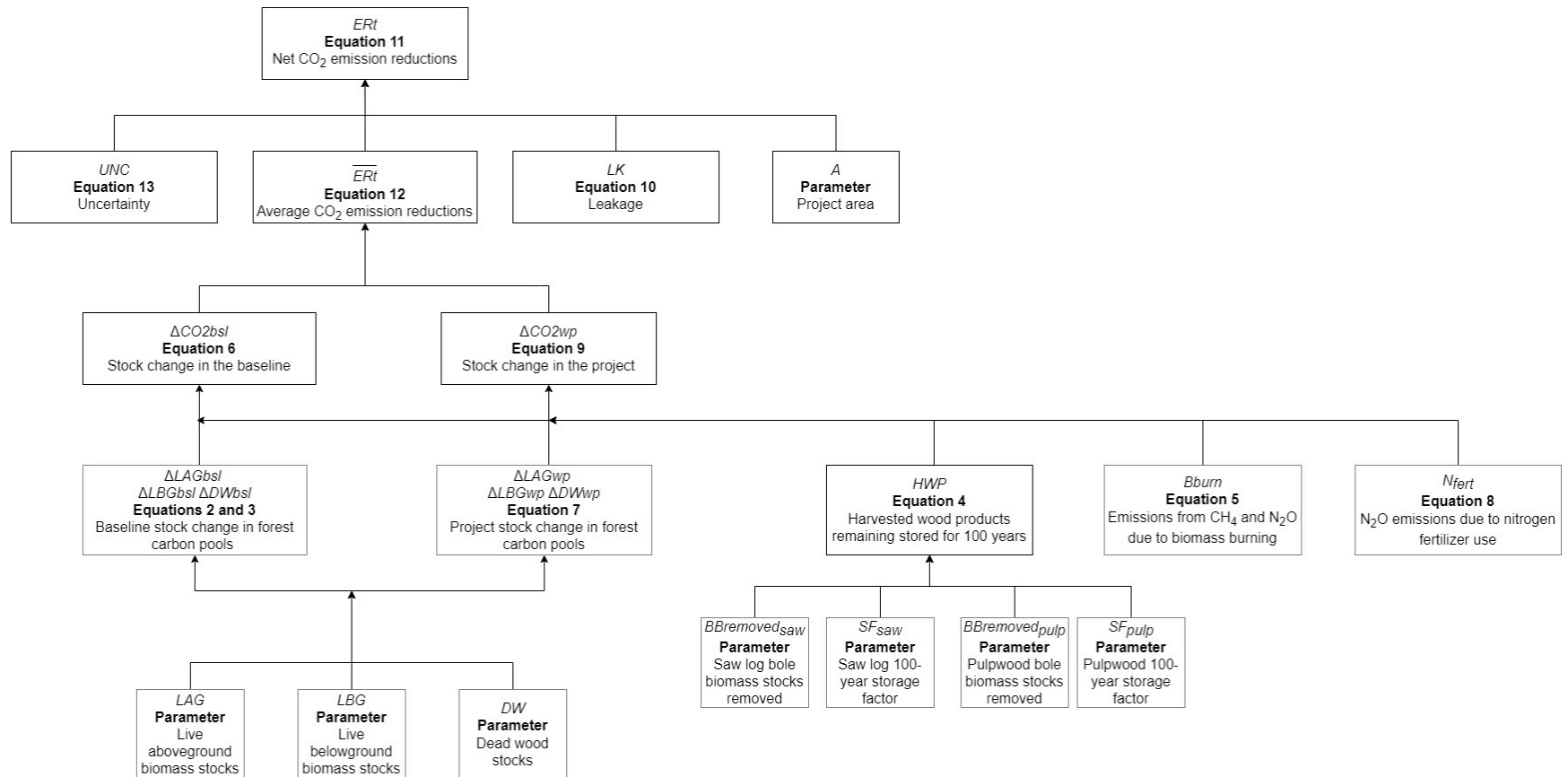
Where:

$\overline{ER}_t$	Mean GHG emission reductions in year $t$ (t CO <sub>2</sub> e per unit area per year)
$\Delta CO2_{wp,i,t}$	Carbon stock change in the project scenario at sample unit $i$ in year $t$ (t CO <sub>2</sub> e per unit area per year)
$\Delta CO2_{bsl,i,t}$	Carbon stock change in the baseline scenario in composite baseline $i$ in year $t$ (t CO <sub>2</sub> e per unit area per year)
$n$	Number of sample units in which stock change values are available for both the project and baseline scenarios

Note that in Equation 12, only sample units  $i$  for which calculated stock change values at time  $t$  are available for both the project and baseline scenarios are included (i.e., two measurement events must have taken place in a sample unit and all of its matched constituent control plots before a paired sample  $i$  is included in the calculation of net emission reductions).

Calculations are summarized in Figure 8.1.

Figure 8.1: Summary of Calculations



## 8.5 Uncertainty

Uncertainty associated with sampling error is quantified and accounted for. Uncertainty in area estimation is assumed to be zero and is addressed via using complete (and accurate) GIS boundaries of the project area, and applying QA/QC procedures specified in the parameter table for  $A_t$ .

Emission reductions are estimated from paired composite baselines and project sample units, and uncertainty ( $UNC_t$ ) is calculated as:

$$UNC_t = MIN(100\%, MAX(0, T \times \left( \frac{1}{n} \times s_{wp,t}^2 + \frac{1}{n^2} \times \sum_{j=1}^c (\sum_{i=1}^n W_{bsl,i,j}^2 \times s_{bsl,t}^2) \right)^{\frac{1}{2}} \times \left( \frac{1}{\overline{ER}_t} \right) - 15\%)) \quad (13)$$

Where:

$UNC_t$	Uncertainty in year $t$ , expressed as the half width of the 95 percent confidence interval as a percentage of the mean (percent)
$s_{wp,t}^2$	Variance of stock change in the project scenario in the monitoring interval ending in year $t$ (dimensionless)
$s_{bsl,t}^2$	Variance of stock change in the baseline scenario in the monitoring interval ending in year $t$ (dimensionless)
$W_{bsl,i,j}$	Weight of constituent baseline plot $j$ in matched composite baseline $i$ ; value between 0 and 1 (dimensionless)
$T$	Critical value of a student's t-distribution for significance level $\alpha = 0.05$ (i.e., $1 - \alpha = 95$ percent confidence interval)
$\overline{ER}_t$	Mean net GHG emission reductions in year $t$ (t CO <sub>2</sub> e per unit area)
$n$	Number of sample units for which stock change values are available in both the project and baseline scenarios
$c$	Total number of unique constituent baseline plots ( $j$ )

Note that in Equation 13, only sample units  $i$  for which calculated stock change values at time  $t$  are available for both the project and baseline scenarios are included (i.e., two measurement events must have taken place in a sample unit and all of its matched constituent control plots before a paired sample  $i$  is included in the calculation of net emission reductions).

## 9 MONITORING

### 9.1 Data and Parameters Available at Validation

<b>Data/Parameter</b>	$SF_{*,wt}$		
<b>Data unit</b>	Dimensionless		
<b>Description</b>	Mass remaining stored in use and landfills over 100 years in wood component * (saw log or pulpwood) in wood type wt (softwood, sfw or hardwood, hwd)		
<b>Equations</b>	4		
<b>Source of data</b>	Table 6-A-5 in Hoover, C., Birdsey, R., Goines, B., Lahm, P., Fan, Y., Nowak, D., Prisley, S., Reinhardt, E., Skog, K., Skole, D., Smith, J., Trettin, C., & Woodall, C. (2014). Quantifying greenhouse gas sources and sinks in managed forest systems. In M. Eve, D. Pape, M. Flugge, R. Steele, D. Man, M. Riley-Gilbert, S. Biggar (Eds.), <i>Quantifying greenhouse gas fluxes in agriculture and forestry: Methods for entity-scale inventory</i> . Technical Bulletin Number 1939 (pp. 6.1–6.114). USDA Office of the Chief Economist. <sup>8</sup>		
<b>Value applied</b>	<b>U.S. region and timber type</b>	<b><math>SF_{saw}</math> Saw log mass remaining stored in use and landfills after 100 years</b>	<b><math>SF_{pulp}</math> Pulpwood mass remaining stored in use and landfills after 100 years</b>
	Northeast softwood	0.402	0.136
	Northeast hardwood	0.437	0.323
	North Central softwood	0.442	0.138
	North Central hardwood	0.411	0.370
	Pacific Northwest (east) softwood	0.415	0.415
	Pacific Northwest (west) softwood	0.511	0.119
	Pacific Northwest (west) hardwood	0.284	0.284
	Pacific Southwest softwood	0.444	0.444

<sup>8</sup> Available at: <https://www.fs.usda.gov/treearch/pubs/46322>

	Rocky Mountain softwood	0.463	0.463
	Southeast softwood	0.423	0.191
	Southeast hardwood	0.417	0.242
	South Central softwood	0.415	0.215
	South Central hardwood	0.393	0.229
	Other West hardwood	0.357	0.357
<b>Justification of choice of data or description of measurement methods and procedures applied</b>	An explanation of the 100-year average method for HWP carbon storage is given in Hoover et al. (2014) in Section 6.5.1 (p. 6-67 “The intent of this measure is to approximate the average annual climate benefit of withholding carbon from the atmosphere by a certain amount each year for 100 years as described by a “decay” curve. This average benefit is one that can be credited in the year of harvest. This estimate of average effect is conceptually similar to the measure of the radiative forcing impact of a current year emission of CO <sub>2</sub> , CH <sub>4</sub> , or other GHG. One ton of CO <sub>2</sub> emissions—in GHG accounting—is equated to the radiative forcing it causes over the 100 years following the emission. The radiative forcing caused in each year is weighted the same over each of the 100 years. We are suggesting the same convention in weighting the carbon storage in wood products equally for each of 100 years.”)		
<b>Purpose of data</b>	Calculation of baseline and project emissions		
<b>Comments</b>	Regions are defined in Hoover et al. (2014). Parameter values above are for application in the United States. Outside of the United States, parameters may be derived from other relevant published sources (e.g., Winjum et al. 1998 <sup>9</sup> ).		

<b>Data/Parameter</b>	$A_t$
<b>Data unit</b>	Unit area
<b>Description</b>	Project area at time $t$
<b>Equations</b>	11
<b>Source of data</b>	Calculated from GIS data, composed of an aggregate of stands individually delineated at $t=0$ (or time of inclusion as an instance of a grouped project)
<b>Value applied</b>	

<sup>9</sup> Winjum, J. K., Brown, S., & Schlamadinger B. (1998). Forest harvests and wood products: Sources and sinks of atmospheric carbon dioxide. *Forest Science*, 44(2), 272–284.

Justification of choice of data or description of measurement methods and procedures applied	Delineation of the project area may use a combination of GIS coverages, ground survey data, remote imagery (satellite or aerial photographs), or other appropriate data. Any imagery or GIS datasets used must be geo-registered referencing corner points, clear landmarks, or other intersection points.
Purpose of data	Reference for other area measures
Comments	

Data/Parameter	$W_{bsl,i,j}$
Data unit	Dimensionless
Description	Weight of constituent baseline plot $j$ in matched composite baseline $i$
Equations	3 and 6
Source of data	Derived following procedures in Appendix A. Weights are derived to produce an optimal match to the paired project sample unit in terms of one or more specified initial condition covariates.
Value applied	Between 0 and 1
Justification of choice of data or description of measurement methods and procedures applied	
Purpose of data	Calculation of baseline emissions
Comments	Weight for each constituent baseline plot is determined at $t=0$ and fixed throughout the crediting period, except where a constituent baseline plot has become invalid (e.g., where a unit is now located within a registered GHG mitigation project area, or where it has not been re-measured in >10 years; see Section 6), in which case all weights in the respective composite baseline are recalculated to sum to 1, retaining the relative weights of the remaining constituent plots.

Data/Parameter	$GWP_g$
Data unit	Dimensionless
Description	Global warming potential of gas $g$
Equations	5, 8b, 8f, and 8g

Source of data	As set out in the latest version of the <i>VCS Standard</i>
Value applied	A global warming potential of 25 and 298 are applied for CH <sub>4</sub> and N <sub>2</sub> O respectively.
Justification of choice of data or description of measurement methods and procedures applied	Unless otherwise directed by the VCS Program, <i>VCS Standard v4.0</i> requires that CH <sub>4</sub> and N <sub>2</sub> O must be converted to CO <sub>2</sub> e using the 100-year global warming potential derived from the IPCC Fourth Assessment Report.
Purpose of data	Calculation of baseline and project emissions
Comments	

Data/Parameter	$C_f$
Data unit	Proportion of pre-fire fuel biomass consumed
Description	Combustion factor
Equations	5
Source of data	Table 3A.1.12 in IPCC (2003). <i>Good practice guidance for land use, land-use change and forestry</i> <sup>10</sup>
Value applied	The combustion factor is selected based on the forest type.
Justification of choice of data or description of measurement methods and procedures applied	See source of data
Purpose of data	Calculation of baseline and project emissions
Comments	

Data/Parameter	$EF_g$
Data unit	g/kg dry matter burnt
Description	Emission factor for gas <i>g</i>

<sup>10</sup> Available at: [https://www.ipcc.ch/site/assets/uploads/2018/03/GPG\\_LULUCF\\_FULLEN.pdf](https://www.ipcc.ch/site/assets/uploads/2018/03/GPG_LULUCF_FULLEN.pdf)

<b>Equations</b>	5
<b>Source of data</b>	Table 3A.1.16 in IPCC (2003). <i>Good practice guidance for land use, land-use change and forestry</i> <sup>11</sup>
<b>Value applied</b>	The emission factor is selected based on the forest type.
<b>Justification of choice of data or description of measurement methods and procedures applied</b>	See source of data
<b>Purpose of data</b>	Calculation of baseline and project emissions
<b>Comments</b>	

<b>Data/Parameter</b>	$EF_{Ndirect}$
<b>Data unit</b>	t N <sub>2</sub> O-N/t N applied
<b>Description</b>	Emission factor for direct nitrous oxide emissions from N additions from synthetic fertilizers, organic amendments, and crop residues
<b>Equations</b>	8b
<b>Source of data</b>	Table 11.1 in Chapter 11, Volume 4 of the <i>2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories</i> <sup>12</sup>
<b>Value applied</b>	0.01
<b>Justification of choice of data or description of measurement methods and procedures applied</b>	See source of data
<b>Purpose of data</b>	Calculation of baseline and project emissions
<b>Comments</b>	Emission factor applicable to N additions from mineral fertilizers, organic amendments, and crop residues

<b>Data/Parameter</b>	$Frac_{GASF}$
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<sup>11</sup> Available at: [https://www.ipcc.ch/site/assets/uploads/2018/03/GPG\\_LULUCF\\_FULLEN.pdf](https://www.ipcc.ch/site/assets/uploads/2018/03/GPG_LULUCF_FULLEN.pdf)

<sup>12</sup> Available at: <https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol4.html>



<b>Data unit</b>	Dimensionless
<b>Description</b>	Fraction of all synthetic N added to soils that volatilizes as NH <sub>3</sub> and NO <sub>x</sub>
<b>Equations</b>	8f
<b>Source of data</b>	Table 11.3 in Chapter 11, Volume 4 of the <i>2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories</i> <sup>13</sup>
<b>Value applied</b>	0.1
<b>Justification of choice of data or description of measurement methods and procedures applied</b>	See source of data
<b>Purpose of data</b>	Calculation of baseline and project emissions
<b>Comments</b>	

<b>Data/Parameter</b>	<i>Frac<sub>GASM</sub></i>
<b>Data unit</b>	Dimensionless
<b>Description</b>	Fraction of all organic N added to soils that volatilizes as NH <sub>3</sub> and NO <sub>x</sub>
<b>Equations</b>	8f
<b>Source of data</b>	Table 11.3 in Chapter 11, Volume 4 of the <i>2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories</i> <sup>14</sup>
<b>Value applied</b>	0.3
<b>Justification of choice of data or description of measurement methods and procedures applied</b>	See source of data
<b>Purpose of data</b>	Calculation of baseline and project emissions
<b>Comments</b>	

<sup>13</sup> Available at: <https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol4.html>

<sup>14</sup> Ibid.

<b>Data/Parameter</b>	$EF_{Nvolat}$
<b>Data unit</b>	t N <sub>2</sub> O-N/(t NH <sub>3</sub> -N + NO <sub>x</sub> -N volatilized)
<b>Description</b>	Emission factor for nitrous oxide emissions from atmospheric deposition of N on soils and water surfaces
<b>Equations</b>	8f
<b>Source of data</b>	Table 11.3 in Chapter 11, Volume 4 of the <i>2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories</i> <sup>15</sup>
<b>Value applied</b>	0.01
<b>Justification of choice of data or description of measurement methods and procedures applied</b>	See source of data
<b>Purpose of data</b>	Calculation of baseline and project emissions
<b>Comments</b>	

<b>Data/Parameter</b>	$Frac_{LEACH}$
<b>Data unit</b>	Dimensionless
<b>Description</b>	Fraction of N (synthetic or organic) added to soils that is lost through leaching and runoff
<b>Equations</b>	8g
<b>Source of data</b>	Table 11.3 in Chapter 11, Volume 4 of the <i>2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories</i> <sup>16</sup>
<b>Value applied</b>	0.3
<b>Justification of choice of data or description of measurement methods and procedures applied</b>	See source of data
<b>Purpose of data</b>	Calculation of baseline and project emissions

<sup>15</sup> Available at: <https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol4.html>

<sup>16</sup> Ibid.

Comments	
Data/Parameter	$EF_{Nleach}$
Data unit	t N <sub>2</sub> O-N/t N leached and runoff
Description	Emission factor for nitrous oxide emissions from leaching and runoff
Equations	8g
Source of data	Table 11.3 in Chapter 11, Volume 4 of the <i>2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories</i>
Value applied	0.0075
Justification of choice of data or description of measurement methods and procedures applied	See source of data
Purpose of data	Calculation of baseline and project emissions
Comments	

## 9.2 Data and Parameters Monitored

Data/Parameter	$X_{bsl,ij,mt}$ and $X_{wp,i,t}$
Data unit	Years
Description	Length of measurement interval ending at time $mt$ for constituent baseline plot $ij$ , and Length of measurement interval ending at time $t$ for sample unit $i$ in the project scenario
Equations	2 and 7
Source of data	Monitored
Justification of choice of data or description of measurement methods and procedures to be applied	

Purpose of data	
Comments	
Data/Parameter	$LAG_{wp,i,t}$ and $LAG_{bsl,i,j,t}$
Data unit	t CO <sub>2</sub> e per unit area
Description	Live aboveground biomass stocks in the project scenario at sample unit $i$ at time $t$ , and Live aboveground biomass stocks in the baseline scenario at constituent baseline plot $j$ of composite baseline $i$ at time $t$
Equations	2a and 9 Derivation of $BBremoved_{saw}$ and $BBremoved_{pulp}$ parameters
Source of data	Measured in project area
Description of measurement methods and procedures to be applied	<p>Live aboveground biomass will be measured via plot-based sampling. Acknowledging the wide range of valid approaches, and that relative efficiency and robustness are circumstance-specific, procedures for sampling, measurement, and estimation are not specified in the methodology and may be selected by project proponents based on capacity and appropriateness. Stratification may be employed to improve precision but is not required.</p> <p>Sample measurements must:</p> <ul style="list-style-type: none"> <li>• Be demonstrated to be unbiased and derived from representative sampling;</li> <li>• Ensure accuracy of measurements through adherence to best practices and quality assurance/quality control (QA/QC) procedures (to be determined by the project proponent and outlined in standard operating procedures governing field data collection); and</li> <li>• Apply fixed diameter at breast height (dbh) and any other size thresholds.</li> </ul> <p>Aboveground biomass of each sampled tree will be estimated using published allometric equations (in the United States, using Jenkins et al. 2003<sup>17</sup> or stem volume-referenced component ratio methods per Woodall et al. 2011<sup>18</sup>) applied to one or more measured tree attributes,</p>

<sup>17</sup> Jenkins, J. C., Chojnacky, D. C., Heath, L. S., & Birdsey, R. A. (2003). National-scale biomass estimators for United States tree species. *Forest Science*, 49(1), 12–35.

<sup>18</sup> 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*. U.S. Department of Agriculture, Forest Service, Northeastern Research Station. <https://doi.org/10.2737/NRS-GTR-88>

	<p>minimally including dbh. Where using component ratio methods, stem volumes must be estimated by applying published volume equations (in the United States, using equations included in the U.S. Forest Service National Volume Estimator Library (NVEL)<sup>19</sup>) specific to species, genus or family, in descending order of preference, as available.</p> <p>Tree attributes (e.g., dbh, total height) incorporated as independent variables in allometric equations must be directly measured in the field applying established best practices, such as those found in:</p> <p>Kershaw Jr, J. A., Ducey, M. J., Beers, T. W., &amp; Husch, B. (2016). <i>Forest mensuration</i>. John Wiley &amp; Sons.</p> <p>Avery, T. E., &amp; Burkhart, H. E. (2015). <i>Forest measurements</i>. Waveland Press.</p> <p>U.S. Forest Service Department of Agriculture (2019). <i>Field data collection procedures for Phase 2 plots</i>. Forest Inventory and Analysis National Core Field Guide.<sup>20</sup></p> <p>Measurement protocols will be detailed in standard operating procedures. Parameter tables for all tree attributes (e.g., dbh, total height) incorporated as independent variables in allometric equations must be included in the project description under Data and Parameters Monitored.</p> <p>Carbon will be calculated from biomass by applying a carbon fraction of 0.5, and carbon dioxide equivalent (CO<sub>2</sub>e) calculated from carbon applying the factor 44/12.</p>
Frequency	Initial measurement at or preceding time $t=0$ and to be re-measured every 5 years or more frequently in the project and every 10 years or more frequently in the baseline
QA/QC procedures to be applied	
Purpose of data	Calculation of project and baseline emissions
Calculation method	
Comments	
Data/Parameter	$LBG_{wp,i,t}$ and $LBG_{bst,i,j,t}$

<sup>19</sup> Available at: <https://www.fs.fed.us/forestmanagement/products/measurement/volume/nvel/index.php>

<sup>20</sup> Available at: [https://www.fia.fs.fed.us/library/field-guides-methods-proc/docs/2019/core\\_ver9-0\\_10\\_2019\\_final\\_rev\\_2\\_10\\_2020.pdf](https://www.fia.fs.fed.us/library/field-guides-methods-proc/docs/2019/core_ver9-0_10_2019_final_rev_2_10_2020.pdf)

<b>Data unit</b>	t CO <sub>2</sub> e per unit area
<b>Description</b>	Live belowground biomass stocks in the project scenario at sample unit <i>i</i> at time <i>t</i> , and Live belowground biomass stocks in the baseline scenario at constituent baseline plot <i>j</i> of composite baseline <i>i</i> at time <i>t</i>
<b>Equations</b>	2b and 9  Derivation of $BB_{removed_{saw}}$ and $BB_{removed_{pulp}}$ parameters
<b>Source of data</b>	Measured in project area
<b>Description of measurement methods and procedures to be applied</b>	<p>Live belowground biomass will be estimated via component ratio methods (e.g., root to shoot ratios) applied to direct measurements from plot-based sampling. Acknowledging the wide range of valid approaches, and that relative efficiency and robustness are circumstance-specific, procedures for sampling, measurement, and estimation are not specified in the methodology and may be selected by project proponents based on capacity and appropriateness. Stratification may be employed to improve precision but is not required.</p> <p>Sample measurements must:</p> <ul style="list-style-type: none"> <li>● Be demonstrated to be unbiased and derived from representative sampling;</li> <li>● Ensure accuracy of measurements through adherence to best practices and quality assurance/quality control (QA/QC) procedures (to be determined by the project proponent and outlined in standard operating procedures governing field data collection); and</li> <li>● Apply fixed dbh and any other size thresholds.</li> </ul> <p>Belowground biomass of each sampled tree will be estimated using published component ratios (in the United States, using Jenkins et al. 2003<sup>21</sup>).</p> <p>Tree attributes (e.g., dbh, total height) incorporated as independent variables in allometric equations must be directly measured in the field applying established best practices, such as those found in:</p> <p>Kershaw Jr, J. A., Ducey, M. J., Beers, T. W., &amp; Husch, B. (2016). <i>Forest mensuration</i>. John Wiley &amp; Sons.</p> <p>Avery, T. E., &amp; Burkhardt, H. E. (2015). <i>Forest measurements</i>. Waveland Press.</p>

<sup>21</sup> Jenkins, J. C., Chojnacky, D. C., Heath, L. S., & Birdsey, R. A. (2003). National-scale biomass estimators for United States tree species. *Forest Science*, 49(1), 12–35.

	<p>U.S. Forest Service Department of Agriculture (2019). <i>Field data collection procedures for Phase 2 plots</i>. Forest Inventory and Analysis National Core Field Guide.<sup>22</sup></p> <p>Measurement protocols will be detailed in standard operating procedures. Parameter tables for all tree attributes (e.g., dbh, total height) incorporated as independent variables in allometric equations must be included in the project description under Data and Parameters Monitored.</p> <p>Carbon will be calculated from biomass by applying a carbon fraction of 0.5, and carbon dioxide equivalent (CO<sub>2</sub>e) calculated from carbon applying the factor 44/12.</p>
Frequency	Initial measurement at or preceding time $t=0$ and to be re-measured every 5 years or more frequently in the project and every 10 years or more frequently in the baseline
QA/QC procedures to be applied	
Purpose of data	Calculation of project and baseline emissions
Calculation method	
Comments	

Data/Parameter	$LT_{removed_{wp,i,t}}$ and $LT_{removed_{bsl,i,j,t}}$
Data unit	t CO <sub>2</sub> e per unit area
Description	Live tree biomass stocks removed in the project scenario at sample unit $i$ subject to harvest in the monitoring interval ending at time $t$ , and Live tree biomass stocks removed in the baseline scenario at constituent baseline plot $j$ in composite baseline $i$ subject to harvest in the monitoring interval ending at time $t$
Equations	10
Source of data	Measured on permanent sample plots in project area or on without-treatment (baseline) sites respectively
Description of measurement methods and procedures to be applied	<p>Includes pre-existing live tree above- and below-ground biomass that is killed, removed, or emitted on plots subject to harvest.</p> <p>Estimated via pre- and post-harvest cruises as:</p>

<sup>22</sup> Available at: [https://www.fia.fs.fed.us/library/field-guides-methods-proc/docs/2019/core\\_ver9-0\\_10\\_2019\\_final\\_rev\\_2\\_10\\_2020.pdf](https://www.fia.fs.fed.us/library/field-guides-methods-proc/docs/2019/core_ver9-0_10_2019_final_rev_2_10_2020.pdf)

	$LTremoved_{\bullet,i,t} = (LAG_{\bullet,i,t} - LAG_{\bullet,i,t-x}) + (LBG_{\bullet,i,t} - LBG_{\bullet,i,t-x})$ <p>Where:</p> <p><math>LTremoved_{\bullet,i,t}</math> Live tree biomass stocks removed in scenario • (with or without avoided emissions activity) at sample unit <math>i</math> (or constituent sample <math>j</math> in composite baseline <math>i</math>) subject to harvest in the monitoring interval ending at time <math>t</math> (t CO<sub>2</sub>e per unit area)</p> <p><math>LAG_{\bullet,i,t}</math> Live aboveground biomass stocks in scenario • (with or without avoided emissions activity) at sample unit <math>i</math> (or constituent sample <math>j</math> in composite baseline <math>i</math>), subject to harvest in the monitoring interval ending at time <math>t</math>, measured at time <math>t</math> (t CO<sub>2</sub>e per unit area)</p> <p><math>LAG_{\bullet,i,t-x}</math> Live aboveground biomass stocks in scenario • (with or without avoided emissions activity) at sample unit <math>i</math> (or constituent sample <math>j</math> in composite baseline <math>i</math>) subject to harvest in the monitoring interval ending at time <math>t</math>, measured at time <math>t-x</math> where <math>t-x</math> is the time of the most recent measurement preceding the harvest (t CO<sub>2</sub>e per unit area)</p> <p><math>LBG_{\bullet,i,t}</math> Live belowground biomass stocks in scenario • (with or without avoided emissions activity) at sample unit <math>i</math> (or constituent sample <math>j</math> in composite baseline <math>i</math>) subject to harvest in the monitoring interval ending at time <math>t</math>, measured at time <math>t</math> (t CO<sub>2</sub>e per unit area)</p> <p><math>LBG_{\bullet,i,t-x}</math> Live belowground biomass stocks in scenario • (with or without avoided emissions activity) at sample unit <math>i</math> (or constituent sample <math>j</math> in composite baseline <math>i</math>) subject to harvest in the monitoring interval ending at time <math>t</math>, measured at time <math>t-x</math>, where <math>t-x</math> is the time of the most recent measurement preceding the harvest (t CO<sub>2</sub>e per unit area)</p> <p>Where harvest does not occur in a given sample unit <math>i</math> or <math>j</math> in the monitoring interval ending at time <math>t</math>, <math>LTremoved_{wp,i,t}</math> and <math>LTremoved_{bst,i,j,t}</math> are set to zero.</p>
Frequency	Initial measurement at or preceding time $t=0$ and to be re-measured every 5 years or more frequently in the project and every 10 years or more frequently in the baseline
QA/QC procedures to be applied	
Purpose of data	Determination of leakage
Calculation method	
Comments	



<b>Data/Parameter</b>	$DW_{wp,i,t}$ and $DW_{bsl,i,j,t}$
<b>Data unit</b>	t CO <sub>2</sub> e per unit area
<b>Description</b>	Dead wood biomass stocks in the project scenario in sample unit <i>i</i> at time <i>t</i> , and Dead wood biomass stocks in the baseline scenario in constituent baseline plot <i>j</i> of composite baseline <i>i</i> at time <i>t</i>
<b>Equations</b>	2c and 9
<b>Source of data</b>	Field measurements
<b>Description of measurement methods and procedures to be applied</b>	<p>Standing dead wood will be sampled via plot-based forest inventory methods, and lying dead wood via line intersect sampling,<sup>23</sup> perpendicular distance sampling,<sup>24</sup> or other un-biased approaches. Specific sample designs/intensities, and measurement and estimation procedures may be selected by project proponents based on capacity and appropriateness. Stratification may be employed to improve precision but is not required.</p> <p>Sample measurements must:</p> <ul style="list-style-type: none"> <li>• Be demonstrated to be unbiased and derived from representative sampling;</li> <li>• Ensure accuracy of measurements through adherence to best practices and quality assurance/quality control (QA/QC) procedures (to be determined by the project proponent and outlined in standard operating procedures governing field data collection); and</li> <li>• Apply fixed size thresholds.</li> </ul> <p>For each standing dead tree, stem volume must be estimated using published volume equations (in the United States, using equations included in the U.S. Forest Service National Volume Estimator Library (NVEL)<sup>25</sup>) specific to species, genus or family, in descending order of</p>

<sup>23</sup> Warren, W. G., & Olsen, P. F. (1964). A line intersect technique for assessing logging waste. *Forest Science*, 10(3), 267–276.

Van Wagner, C. E. (1968). The line intersect method in forest fuel sampling. *Forest Science*, 14(1), 20–26.

<sup>24</sup> Williams, M. S., & Gove J. H. (2003). Perpendicular distance sampling: An alternative method for sampling downed coarse woody debris. *Canadian Journal of Forest Research*, 33(8), 1564–1579. <https://doi.org/10.1139/x03-056>

Williams, M. S., Valentine, H. T., Gove, J. H., & Ducey M. J. (2005). Additional results for perpendicular distance sampling. *Canadian Journal of Forest Research*, 35(4), 961–966. <https://doi.org/10.1139/x05-023>

Ducey, M. J., Williams, M. S., Gove, J. H., Roberge, S., & Kenning R. S. (2013). Distance-limited perpendicular distance sampling for coarse woody debris: Theory and field results. *Forestry*, 86(1), 119–128. <https://doi.org/10.1093/forestry/cps059>

<sup>25</sup> Available at: <https://www.fs.fed.us/forestmanagement/products/measurement/volume/nvel/index.php>

	<p>preference, as available. The equations must be applied to one or more measured tree attributes, minimally including dbh and remaining stem height. Note that standing dead wood is restricted here to aboveground stem (bole) biomass.</p> <p>Tree attributes (e.g., dbh, total height) incorporated as independent variables in allometric equations must be directly measured in the field, applying established best practices such as those found in:</p> <p>Kershaw Jr, J. A., Ducey, M. J., Beers, T. W., &amp; Husch, B. (2016). <i>Forest mensuration</i>. John Wiley &amp; Sons.</p> <p>Avery, T. E., &amp; Burkhardt, H.E. (2015). <i>Forest measurements</i>. Waveland Press.</p> <p>U.S. Forest Service Department of Agriculture (2019). <i>Field data collection procedures for Phase 2 plots</i>. Forest Inventory and Analysis National Core Field Guide.<sup>26</sup></p> <p>Measurement protocols will be detailed in standard operating procedures. Parameter tables for all tree attributes (e.g., dbh, total height) incorporated as independent variables in allometric equations must be included in the project description under Data and Parameters Monitored.</p> <p>Biomass of standing and lying dead wood must be estimated from sampled volumes using published wood densities specific to species, genus or family, in descending order of preference, as available and density reduction factors referencing decomposition states (e.g., procedures per Harmon et al. 2011<sup>27</sup>).</p> <p>Carbon will be calculated from biomass by applying a carbon fraction of 0.5, and carbon dioxide equivalent (CO<sub>2e</sub>) calculated from carbon applying the factor 44/12.</p>
<b>Frequency</b>	Initial measurement at or preceding time $t=0$ and to be re-measured every 5 years or more frequently in the project and every 10 years or more frequently in the baseline
<b>QA/QC procedures to be applied</b>	
<b>Purpose of data</b>	Calculation of project and baseline emissions

<sup>26</sup> Available at: [https://www.fia.fs.fed.us/library/field-guides-methods-proc/docs/2019/core\\_ver9-0\\_10\\_2019\\_final\\_rev\\_2\\_10\\_2020.pdf](https://www.fia.fs.fed.us/library/field-guides-methods-proc/docs/2019/core_ver9-0_10_2019_final_rev_2_10_2020.pdf)

<sup>27</sup> 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. U.S. Department of Agriculture, Forest Service, Northern Research Station. <https://doi.org/10.2737/NRS-RP-15>

Calculation method	
Comments	
Data/Parameter	$BB_{removed_{saw,wt,bsl,i,j,t}}$ and $BB_{removed_{saw,wt,wp,i,t}}$
Data unit	t CO <sub>2</sub> e per unit area
Description	<p>Saw log bole biomass stocks in wood type <math>wt</math> (<math>wt</math> = softwood [sfw] or hardwood [hwd]) in commercial species removed in the baseline scenario in constituent baseline plot <math>j</math> of composite baseline <math>i</math> in the monitoring interval ending at time <math>t</math>, and</p> <p>Saw log bole biomass stocks in wood type <math>wt</math> (<math>wt</math> = softwood [sfw] or hardwood [hwd]) in commercial species removed in the project scenario at sample unit <math>i</math> in the monitoring interval ending at time <math>t</math></p>
Equations	4
Source of data	Field measurements from permanent plots subject to harvest in the monitoring interval ending at time $t$
Description of measurement methods and procedures to be applied	<p>Saw logs will be distinguished from pulpwood on the basis of dbh:</p> <ul style="list-style-type: none"> <li>i) Softwood saw logs are from trees with at least 22.9 cm (9 in) dbh.</li> <li>ii) Hardwood saw logs are from trees with at least 27.9 cm (11 in) dbh.</li> </ul> <p>Saw log bole biomass is estimated for saw log-sized stems cut and removed in the monitoring interval ending at time <math>t</math>, from the most recent pre-harvest measurements preceding time <math>t</math> (i.e., <math>LAG_{i,t-x}</math>), via either of the following two approaches:</p> <p><b>Approach 1 – Estimate bole volume and apply wood density</b>                  Bole biomass is estimated by applying published volume equations (e.g., those included in the U.S. Forest Service National Volume Estimator Library (NVEL)<sup>28</sup>) and wood densities (specific to species, genus or family, in descending order of preference, as available).</p> <p>Tree attributes (e.g., dbh, total height) incorporated as independent variables in allometric equations must be directly measured in the field applying established best practices, such as those found in:</p> <p>Kershaw Jr, J. A., Ducey, M. J., Beers, T. W., &amp; Husch, B. (2016). <i>Forest mensuration</i>. John Wiley &amp; Sons.</p>

<sup>28</sup> Available at: <https://www.fs.fed.us/forestmanagement/products/measurement/volume/nvel/index.php>

	<p>Avery, T. E., &amp; Burkhardt, H. E. (2015). <i>Forest measurements</i>. Waveland Press.</p> <p>U.S. Forest Service Department of Agriculture (2019). <i>Field data collection procedures for Phase 2 plots</i>. Forest Inventory and Analysis National Core Field Guide.<sup>29</sup></p> <p>Measurement protocols will be detailed in standard operating procedures. Parameter tables for all tree attributes (e.g., dbh, total height) incorporated as independent variables in allometric equations must be included in the project description under Data and Parameters Monitored.</p> <p><b>Approach 2 – Estimate aboveground biomass and apply stem component ratio</b></p> <p>Bole biomass is estimated by applying a published stem component ratio to total aboveground biomass estimated using a published allometric equation (e.g., in the United States, using Jenkins et al. 2003<sup>30</sup> for stem component ratios and total aboveground biomass equations).</p> <p>Carbon will be calculated from biomass by applying a carbon fraction of 0.5, and carbon dioxide equivalent (CO<sub>2</sub>e) calculated from carbon applying the factor 44/12.</p> <p>Note that these parameters are restricted to commercial species. In the United States, commercial species are defined as those not from species groups 23, 43, and 48 (see FIA Database User Guide Appendix E<sup>31</sup>).</p>
Frequency	Initial measurement at or preceding time t=0 and to be re-measured every 5 years or more frequently in the project and every 10 years or more frequently in the baseline
QA/QC procedures to be applied	
Purpose of data	Calculation of project and baseline emissions
Calculation method	
Comments	

<sup>29</sup> Available at: [https://www.fia.fs.fed.us/library/field-guides-methods-proc/docs/2019/core\\_ver9-0\\_10\\_2019\\_final\\_rev\\_2\\_10\\_2020.pdf](https://www.fia.fs.fed.us/library/field-guides-methods-proc/docs/2019/core_ver9-0_10_2019_final_rev_2_10_2020.pdf)

<sup>30</sup> Jenkins, J. C., Chojnacky, D. C., Heath, L. S., & Birdsey, R. A. (2003). National-scale biomass estimators for United States tree species. *Forest Science*, 49(1), 12–35.

<sup>31</sup> Available at: [https://www.fia.fs.fed.us/library/database-documentation/current/ver80/FIADB%20User%20Guide%20P2\\_8-0.pdf](https://www.fia.fs.fed.us/library/database-documentation/current/ver80/FIADB%20User%20Guide%20P2_8-0.pdf)

Data/Parameter	$BBremoved_{pulp,wt,bsl,i,j,t}$ and $BBremoved_{pulp,wt,wp,i,t}$
Data unit	t CO <sub>2</sub> e per unit area
Description	<p>Pulpwood bole biomass stocks in wood type <i>wt</i> (<i>wt</i> = softwood [sfw] or hardwood [hwd]) in commercial species removed in the baseline scenario at constituent baseline plot <i>j</i> of composite baseline <i>i</i> in the monitoring interval ending at time <i>t</i>, and</p> <p>Pulpwood bole biomass stocks in wood type <i>wt</i> (<i>wt</i> = softwood [sfw] or hardwood [hwd]) in commercial species removed in the project scenario at sample unit <i>i</i> in the monitoring interval ending at time <i>t</i></p>
Equations	4
Source of data	Field measurements from permanent plots subject to harvest in the monitoring interval ending at time <i>t</i>
Description of measurement methods and procedures to be applied	<p>Pulpwood logs will be distinguished from saw logs on the basis of diameter at breast height:</p> <ul style="list-style-type: none"> <li>i) Softwood pulpwood is from trees with 12.7 to 22.8 cm (5.0 to 8.9 in) dbh.</li> <li>ii) Hardwood pulpwood is from trees with 12.7 to 27.8 cm (5.0 to 10.9 in) dbh.</li> </ul> <p>Pulpwood bole biomass is estimated for pulpwood-sized stems cut and removed in the monitoring interval ending at time <i>t</i>, from the most recent pre-harvest measurements (i.e., <math>LAG_{i,t-x}</math>), via either of the following two approaches:</p> <p><b>Approach 1 – Estimate bole volume and apply wood density</b></p> <p>Bole biomass is estimated by applying published volume equations (e.g., equations included in the U.S. Forest Service National Volume Estimator Library (NVEL)<sup>32</sup>) and wood densities (specific to species, genus or family, in descending order of preference, as available).</p> <p>Tree attributes (e.g., dbh, total height) incorporated as independent variables in allometric equations must be directly measured in the field applying established best practices, such as those found in:</p> <p>Kershaw Jr, J. A., Ducey, M. J., Beers, T. W., &amp; Husch, B. (2016). <i>Forest mensuration</i>. John Wiley &amp; Sons.</p> <p>Avery, T. E., &amp; Burkhart, H. E. (2015). <i>Forest measurements</i>. Waveland Press.</p>

<sup>32</sup> Available at: <https://www.fs.fed.us/forestmanagement/products/measurement/volume/nvel/index.php>

	<p>U.S. Forest Service Department of Agriculture (2019). <i>Field data collection procedures for Phase 2 plots</i>. Forest Inventory and Analysis National Core Field Guide.<sup>33</sup></p> <p>Measurement protocols will be detailed in standard operating procedures. Parameter tables for all tree attributes (e.g., dbh, total height) incorporated as independent variables in allometric equations must be included in the project description under Data and Parameters Monitored.</p> <p><b>Approach 2 – Estimate aboveground biomass and apply stem component ratio</b></p> <p>Bole biomass is estimated by applying a published stem component ratio to total aboveground biomass estimated using a published allometric equation (e.g., in the United States using Jenkins et al. 2003<sup>34</sup> for stem component ratios and total aboveground biomass equations).</p> <p>Carbon will be calculated from biomass by applying a carbon fraction of 0.5, and carbon dioxide equivalent (CO<sub>2</sub>e) calculated from carbon applying the factor 44/12.</p> <p>Note that these parameters are restricted to commercial species. In the United States, commercial species are defined as those not from species groups 23, 43, and 48 (see FIA Database User Guide Appendix E<sup>35</sup>).</p>
Frequency	Initial measurement at or preceding time t=0 and to be re-measured every 5 years or more frequently in the project and every 10 years or more frequently in the baseline
QA/QC procedures to be applied	
Purpose of data	Calculation of project and baseline emissions
Calculation method	
Comments	
Data/Parameter	$M_{wp,SF,i,t}$

<sup>33</sup> Available at: [https://www.fia.fs.fed.us/library/field-guides-methods-proc/docs/2019/core\\_ver9-0\\_10\\_2019\\_final\\_rev\\_2\\_10\\_2020.pdf](https://www.fia.fs.fed.us/library/field-guides-methods-proc/docs/2019/core_ver9-0_10_2019_final_rev_2_10_2020.pdf)

<sup>34</sup> Jenkins, J. C., Chojnacky, D. C., Heath, L. S., & Birdsey, R. A. (2003). National-scale biomass estimators for United States tree species. *Forest Science*, 49(1), 12–35.

<sup>35</sup> Available at: [https://www.fia.fs.fed.us/library/database-documentation/current/ver80/FIADB%20User%20Guide%20P2\\_8-0.pdf](https://www.fia.fs.fed.us/library/database-documentation/current/ver80/FIADB%20User%20Guide%20P2_8-0.pdf)

Data unit	t fertilizer per unit area
Description	Mass of project N-containing synthetic fertilizer applied to sample unit <i>i</i> in year <i>t</i>
Equations	8c
Source of data	Application records, substantiated with one or more forms of documented evidence pertaining to the selected sample unit and relevant monitoring period (e.g., management logs, receipts, or invoices)
Description of measurement methods and procedures to be applied	
Frequency	
QA/QC procedures to be applied	
Purpose of data	Calculation of project emissions
Calculation method	
Comments	

Data/Parameter	$NC_{wp,SF,i,t}$
Data unit	t N/t fertilizer
Description	N content of project synthetic fertilizer applied
Equations	8c
Source of data	N content is determined following fertilizer manufacturer's specifications.
Description of measurement methods and procedures to be applied	
Frequency	

QA/QC procedures to be applied	
Purpose of data	Calculation of project emissions
Calculation method	
Comments	

Data/Parameter	$M_{wp,OF,i,t}$
Data unit	t fertilizer per unit area
Description	Mass of project N-containing organic fertilizer applied to sample unit <i>i</i> in year <i>t</i>
Equations	8d
Source of data	Application records, substantiated with one or more forms of documented evidence pertaining to the selected sample unit and relevant monitoring period (e.g., management logs, receipts, or invoices)
Description of measurement methods and procedures to be applied	
Frequency	
QA/QC procedures to be applied	
Purpose of data	Calculation of project emissions
Calculation method	
Comments	

Data/Parameter	$NC_{wp,OF,i,t}$
Data unit	t N/t fertilizer
Description	N content of project organic fertilizer applied



Equations	8d
Source of data	Peer-reviewed published data may be used. For example, default manure N content may be selected from Edmonds et al. (2003) cited in U.S. Environmental Protection Agency (2011). <i>Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2009. EPA 430-R-11-005.</i>
Description of measurement methods and procedures to be applied	See source of data
Frequency	
QA/QC procedures to be applied	
Purpose of data	Calculation of project emissions
Calculation method	
Comments	

### 9.3 Description of the Monitoring Plan

Monitoring is conducted for both the baseline and project scenarios. Monitoring employs a quasi-experimental design where carbon stock change is directly monitored in paired permanent project sample units and constituent baseline plots (located outside of the project area). Monitored stock parameters are collected and recorded at the sample unit scale, and emission reductions are estimated independently for each sample unit.

Project proponents must detail the procedures for collecting and reporting all data and parameters listed in Section 9.2. The monitoring plan must contain at least the following information:

- 1) A description of each monitoring task to be undertaken, and the technical requirements therein
- 2) Definition of the accounting boundary
- 3) Parameters to be measured, including parameter tables for all directly measured tree attributes (e.g., diameter at breast height, total height) incorporated as independent variables in allometric equations
- 4) Data to be collected and data collection techniques, documented in a standard operating procedure for field data collection. Sample designs will be specified (clearly delineate spatially the sample population, and justify sampling intensities, selection of

sample units and sampling stages, where applicable) and un-biased estimators of population parameters identified, which will be applied in calculations.

- 5) Anticipated frequency of monitoring
- 6) Quality assurance and quality control (QA/QC) procedures to ensure accurate data collection and screen for, and where necessary, correct anomalous values, ensure completeness, perform independent checks on analysis results, and other safeguards as appropriate
- 7) Data archiving procedures, including procedures for any anticipated updates to electronic file formats. All data collected as a part of the monitoring process, including QA/QC data, must be archived electronically and kept for at least two years after the end of the last project crediting period.
- 8) Roles, responsibilities and capacity of monitoring team and management

#### **Permanent sample plots (constituting project sample units)**

Permanent plot measurements must be archived, and all trees assigned unique identification numbers. Individual trees on permanent plots must be marked in the field (e.g., painted or tagged) and stems mapped with azimuth and distance from plot center recorded.

#### **Composite baseline**

A database must be maintained detailing constituent baseline plots and their respective weights (derived at  $t=0$ ), with unique identifiers ascribed to each composite baseline, its constituent baseline plots, and all trees in those plots. The monitoring plan must specify the schedule and procedures for periodically acquiring, archiving, and processing re-measurement data from the constituent plots.

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# APPENDIX 1: PERFORMANCE METHOD – UNITED STATES

## Introduction

This appendix must be used in tandem with the main methodology body for all projects in the United States. The appendix focuses on a step-by-step process for developing a composite baseline using USDA Forest Service Forest Inventory & Analysis data. All steps included in this appendix must be considered a requirement of the methodology unless explicitly labeled as optional. Similar appendices may be required for additional geographies based on available national or regional forest inventory data that meet all requirements within the main methodology body.

## Applicability Conditions

This appendix is applicable under the following conditions:

- 1) The project activity meets all applicability conditions set out in Section 4 of the methodology; and
- 2) The project area is located within the conterminous United States.

Note that the application of the performance benchmark, as explained below, effectively excludes, based on comparative outcomes, crediting of project activities that may be expected to be implemented without carbon incentives, and ensures that credited projects produce performance improvements relative to the business-as-usual case (represented by the crediting baseline). The most plausible baseline scenario is defined by the level of carbon stock change observed in the matched control (without carbon finance) plots. For example:

- **IFM activity implementing constraints on timber harvest:** Matched control plots may be expected to witness business-as-usual timber harvests of greater magnitude and/or higher frequency than the project activity that imposes constraints on timber harvest.
- **IFM activity implementing management of competing vegetation to release natural regeneration:** Matched control plots, subject to business-as-usual minimal or no treatment of competing invasive shrubs may be expected to witness continued suppression of natural regeneration and lower tree growth than the project activity that reduces the extent of competing vegetation and releases the regenerating trees.

## Baseline Scenario

The baseline scenario is represented by business-as-usual practice on U.S. Forest Service (USFS) Forest Inventory and Analysis (FIA) inventory plots matched to specific project sample units. FIA inventory plots are an appropriate source for establishing business-as-usual practices in the U.S., selected via representative sampling at a national scale and meeting all other requirements specified in Section 6 of the methodology. Selection of appropriately matched FIA inventory plots is ensured through requirements regarding donor pool selection (see Procedure for Developing Composite Baselines in the United States).

## Performance Benchmark

The performance benchmark is set equal to weighted average stock change as measured on FIA plots matched to specific project sample units (with weighting proportional to the closeness of the match), representing business-as-usual practice. Equation 1 in the methodology derives and applies the performance benchmark for demonstration of additionality. Equation 6 derives the performance benchmark for the crediting baseline. The performance benchmarks essentially represent expected business-as-usual practice in forest stands similar to the project area. Equations 1 and 6 are dependent on periodic measurement of matched FIA plots. Procedures to match FIA plots to project sample units are provided below. Nearest-neighbor matching is an established impact evaluation approach in the environmental field<sup>36</sup> and has been previously applied to evaluate the impacts of incentive programs on forest management using U.S. Forest Service National Woodland Owner Survey data.<sup>37</sup>

## Procedure for Developing Composite Baselines in the United States

In the United States, composite baselines (used to derive performance benchmarks for additionality and crediting baselines) must be developed using data derived from the USFS FIA database. The following steps must be followed to develop matches for the population of sample units:

- 1) **Donor pool selection:** The donor pool for each sample unit is set by a process that involves the application of both exact matching criteria and calipers (maximum permitted difference between sample unit and individual control plots).
  - a) Subset the FIA database to select eligible FIA plots. Begin with the most recent measurement of potential donor plots (i.e., exclude plots whose PLT\_CN is listed as another plot's PREV\_PLT\_CN in the FIA PLOT table). Then, exclude plots that meet any of the following criteria (plots may not be excluded on the basis of any criteria other than those provided below):
    - i) Lacking at least two completed measurement cycles (i.e., KINDCD in FIA PLOT table is equal to 2);

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<sup>36</sup> Ferraro, P. J., & Hanauer, M. M. (2014). Advances in measuring the environmental and social impacts of environmental programs. *Annual Review of Environment and Resources*, 39(1), 495–517. <https://doi.org/10.1146/annurev-environ-101813-013230>

<sup>37</sup> Song, N., Aguilar, F. X., & Butler, B. J. (2014). Cost-share program participation and family forest owners' past and intended future management practices. *Forest Policy and Economics*, 46, 39–46. <https://doi.org/10.1016/j.forpol.2014.06.003>

- ii) Plot measurements (MEASYEAR) are more than 2 years older than the standard re-measurement period (standard re-measurement period is 5 years for eastern and 10 years for western FIA regions);
  - iii) Spanning more than one condition code (i.e., FIA COND table variable CONDPROP\_UNADJ is equal to 1);
  - iv) Located inside of the project area (to assess the location of any FIA plot, the nearest project area boundary will be buffered externally by 1.6 kilometers);
  - v) Located within a registered GHG mitigation project area (if this may be determined;<sup>38</sup> to assess the location of any FIA plot, the nearest project area boundary will be buffered externally by 1.6 kilometers);
  - vi) Not of the same stand origin category as the project sample unit (i.e., STDORGCD from FIA COND table);
  - vii) Not of the same forest type group<sup>39</sup> as the project sample unit;
  - viii) Not within the same land ownership class (public, private) as the project sample unit; and
  - ix) Not within the same U.S. Forest Service ecological section<sup>40</sup> in which the project sample unit is located.
  - x) Optional – calipers: FIA plots may be excluded where they exceed a user-specified caliper value (an absolute value of the difference between the sample unit and FIA plot value) for one or more of the included continuous covariates (see Table A1.1). The magnitude of any calipers applied may be set by the project proponent, justified based on expected relationship between the covariate and stock change (in the context of the IFM project activity) and number of available FIA plots (see Part b).
- b) If after donor pool selection there are fewer than 50 plots available for matching, redefine the donor pool in a stepwise fashion following the criteria below. After each step, assess the size of the donor pool; when it exceeds 50 plots, proceed to matching in Step 2 below.
- i) Remove any calipers applied in Step (x) above.
  - ii) Remove the restriction to ecological section, incorporating all FIA plots within the ecological province where that ecological section is found;
  - iii) Remove the restriction to ecological province, incorporating all FIA plots within the states where that ecological province is found.
- 2) **Matching:** Matching applies a k-nearest neighbor optimal matching approach with replacement,<sup>41</sup> with k equal to 10. For each FIA plot in the donor pool, calculate initial condition covariates from

<sup>38</sup> Note that (v) is optional and it is conservative to include plots located within a registered GHG mitigation project area.

<sup>39</sup> Forest type groups are listed in Appendix D in Burrill, E. A., Wilson, A. M., Turner, J. A., Pugh, S. A., Menlove, J., & Christiansen, G. (2018). *The Forest Inventory and Analysis Database: Database description and user guide version 8.0 for Phase 2*. U.S. Department of Agriculture, Forest Service. Available at: <https://www.fia.fs.fed.us/library/database-documentation/>

<sup>40</sup> Cleland, D. T., Freeouf, J. A., Keys, J. E., Nowacki, G. J., Carpenter, C. A., & McNab, W. H. (2007). *Ecological subregions: Sections and subsections for the conterminous United States*. Gen. Tech. Report WO-76D. USDA Forest Service. <https://doi.org/10.2737/WO-GTR-76D>

<sup>41</sup> See Stuart, E. A. (2010). Matching methods for causal inference: A review and a look forward. *Statistical Science*, 25(1), 1–21. <https://doi.org/10.1214/09-STS313>

the most recent plot measurements collected prior to project start, then calculate Mahalanobis distances relative to each project sample unit. For each project sample unit, select the 10 FIA plots with the lowest Mahalanobis distances and derive relative weights proportional to the inverse of the Mahalanobis distance, that sum to 1 (Equation A1 below). The vector of initial condition covariates must include the covariates specified in Table A1.1. Additional covariates may be incorporated provided that: (1) there is a theoretically sound or empirically demonstrated basis for including them (e.g., peer-reviewed study), (2) they are derived from direct measurements or published sources (e.g., U.S. Census Bureau data), and (3) minimum match quality may be obtained (see below).

$$W_{bsl,i,j} = \frac{1/MD_{ij} \times 100}{\sum_{j=1}^{10} 1/MD_{ij} \times 100} \quad (A1)$$

Where:

$W_{bsl,i,j}$	Weight of constituent baseline plot $j$ in matched composite baseline $i$ ; value between 0 and 1 (dimensionless)
$MD_{ij}$	Mahalanobis distance of constituent baseline plot $ij$ relative to project sample unit $i$ (dimensionless)

Mahalanobis distance is a multivariate measure defining the “nearness” or similarity of two individuals, here a project sample unit and a FIA plot in the donor pool. The R package `optmatch`<sup>42</sup> may be used to calculate Mahalanobis distances and implement the matching approach outlined above. Calculation of Mahalanobis distance is further explained in Rosenbaum (2010<sup>43</sup>) and Stuart (2010<sup>44</sup>).

**Table A1.1: Required Covariates for Obtaining Matches of Composite Baselines from USFS FIA plots (see also Data and parameters available at validation for project sample unit, below)**

Covariate	FIA Database Code <sup>45</sup>	Unit
Distance to sample (treatment/project case) unit		Kilometers

<sup>42</sup> Hansen, B. B., & Klopfer, S. O. (2006). Optimal full matching and related designs via network flows. *Journal of Computational and Graphical Statistics*, 15(3), 609–627. <https://doi.org/10.1198/106186006X137047>

<sup>43</sup> Rosenbaum, P. R. (2010). *Design of observational studies* (1st ed.). Springer. <https://doi.org/10.1007/978-1-4419-1213-8>

<sup>44</sup> Stuart, E. A. (2010). Matching methods for causal inference: A review and a look forward. *Statistical Science*, 25(1), 1–29. <https://doi.org/10.1214/09-STS313>

<sup>45</sup> Burrill, E. A., Wilson, A. M., Turner, J. A., Pugh, S. A., Menlove, J., & Christiansen, G. (2018). *The Forest Inventory and Analysis Database: Database description and user guide version 8.0 for Phase 2*. U.S. Department of Agriculture, Forest Service. Available at: [https://www.fia.fs.fed.us/library/database-documentation/current/ver80/FIADB%20User%20Guide%20P2\\_8-0.pdf](https://www.fia.fs.fed.us/library/database-documentation/current/ver80/FIADB%20User%20Guide%20P2_8-0.pdf)

Covariate	FIA Database Code <sup>45</sup>	Unit
Stand age	STDAGE	Years
Site productivity class code	SITECLCD	FIA Classes 1–7 (in cubic feet/acre/year)
<p><b>Regeneration Stocking</b> – Total relative density per acre (Ducey &amp; Knapp 2010<sup>46</sup>) of all live trees <math>\geq 1</math>" and <math>&lt; 5</math>" dbh, of commercial species from FIA's SEEDLING and TREE tables. Commercial species are defined as those not from species groups 23, 43, and 48 (see FIA Database User Guide Appendix E). Relative density (RD) per acre is calculated for each individual as</p> $RD_{per\ acre} = 2.47 \times (0.00015 + (0.00218 \times Specific\ Gravity_{species})) \times \left(\frac{dbh}{10}\right)^{1.6}$	Derived from FIA database (FIADB) data regeneration microplot and tree subplot	Dimensionless (0 to 1)
Elevation	ELEV	Feet (in 10 or 100 foot categories)
Slope	SLOPE	Percent
<p><b>Commercial Stocking</b> – Total relative density per acre (Ducey &amp; Knapp 2010) of live trees of commercial species <math>\geq 5</math>" dbh, with at least one sound, straight 8-foot section. Commercial species are defined as above.</p>	Derived from FIADB data, uses TREECLCD to identify trees with requisite form characteristics	Dimensionless (0 to 1)
Quadratic mean diameter = diameter of tree with average basal area (considering only live trees $\geq 5$ " dbh)	Derived from FIADB data	Inches
Horizontal distance to improved road	RDDISTCD	Code (0 to 9)

<sup>46</sup> Ducey, M. J., & Knapp R. A. (2010). A stand density index for complex mixed species forests in the northeastern United States. *Forest Ecology and Management*, 260(9), 1613–1622. <https://doi.org/10.1016/j.foreco.2010.08.014>



- 3) **Match quality:** Match quality is assessed across the sample population of matched pairs (project sample units and matched composite baselines). For each included covariate  $x$ , calculate the standardized difference of means (SDM) as:

$$SDM = ABS(\bar{x}_{wp,x} - \bar{x}_{bsl,x})/\sigma_{wp,x} \quad (A2)$$

Where:

$\bar{x}_{wp,x}$  Mean value of covariate  $x$  in the population of sample units representing the project scenario

$\bar{x}_{bsl,x}$  Mean value of weighted sum of covariate  $x$  in the population of matched composite baselines representing the baseline scenario

$\sigma_{wp,x}$  Standard deviation of covariate  $x$  in the population of sample units representing the project scenario

The mean value of the weighted sum of covariate  $x$  in the population of matched composite baselines representing the baseline scenario is calculated as:

$$\bar{x}_{bsl,x} = \left(\frac{1}{n}\right) \times \sum_{i=1}^n \sum_{j=1}^{10} Covariate_{x,i,j} \times W_{bsl,i,j} \quad (A3)$$

Where:

$Covariate_{x,i,j}$  Value of covariate  $x$  for constituent baseline plot  $j$  in matched composite baseline  $i$

$W_{bsl,i,j}$  Weight of constituent baseline plot  $j$  in matched composite baseline  $i$ ; value between 0 and 1, derived in Equation A1 (dimensionless)

$n$  Number of matched composite baselines

*Note – Distance to sample unit (a required covariate) will necessarily be equal to 0 for all sample units. As a result, distance to sample unit must be replaced with latitude and longitude for calculation of SDMs and matching quality assessment.*

Overall match results are deemed valid where  $SDM$  for each covariate is less than or equal to 0.25. Where the overall match is deemed valid, component plots and their respective weights across the population of composite baselines are fixed for the duration of the crediting period. If the overall match is not deemed valid, the donor pool selection and matching steps above are repeated with progressively smaller  $k$  values until a valid overall match is achieved.

**Data and parameters available at validation for project sample units (sources of covariate values for project sample units)**

<b>Data/Parameter</b>	Distance to sample (treatment/project case) unit
<b>Data unit</b>	Kilometers
<b>Description</b>	Distance to sample (treatment/project case) unit
<b>Equations</b>	N/A
<b>Source of data</b>	Calculated from GIS analysis of geo-referenced locations
<b>Value applied</b>	
<b>Justification of choice of data or description of measurement methods and procedures applied</b>	<p>Sample unit centers must be geo-referenced in the field with GPS using latitude/longitude. Where a two-stage sample is used (e.g., with a stand as the primary unit and plots as the secondary unit), the relevant location is the centroid of the primary unit.</p> <p>“Fuzzed” (uncorrected) locations of FIA plots recorded in the FIADB will be used for the analysis.</p>
<b>Purpose of data</b>	Matching
<b>Comments</b>	

<b>Data/Parameter</b>	STDAGE
<b>Data unit</b>	Years
<b>Description</b>	Stand age
<b>Equations</b>	N/A
<b>Source of data</b>	Increment cores taken at breast height from sampled trees, obtained via plot-based sampling (see description of measurement methods for live aboveground biomass, <i>LAG</i> )
<b>Value applied</b>	
<b>Justification of choice of data or description of measurement methods and procedures applied</b>	<p>Stand age calculated as average total age (age at breast height + the number of years that passed from germination until the tree reached the point of core extraction).</p> <p>Stand age is estimated from increment cores from three or more representatively sampled live trees <math>\geq 5</math>” dbh, and not over-topped, from within the project sample unit.</p>

	Core each tree at the point of diameter measurement and count the rings between the outside edge and the core to the pith. Add in the number of years that passed from germination until the tree reached the point of core extraction to determine the total age of the tree: 5 years for all eastern species, 5 years for western hardwoods, and 10 years for western softwoods. Compute the average age across all cored trees in the project sample unit. <sup>47</sup>
<b>Purpose of data</b>	Matching
<b>Comments</b>	

<b>Data/Parameter</b>	SITECLCD
<b>Data unit</b>	FIA Classes 1–7 (in cubic feet/acre/year). See definitions in the FIADB User Guide <sup>48</sup>
<b>Description</b>	Site productivity class code
<b>Equations</b>	N/A
<b>Source of data</b>	NRCS Web Soil Survey Database <sup>49</sup>
<b>Value applied</b>	
<b>Justification of choice of data or description of measurement methods and procedures applied</b>	<p>SITECLCD is determined for the sample unit location (center), or where a two-stage sample is used (e.g., with a stand as the primary unit and plots as the secondary unit), SITECLCD is determined as the area-weighted average value for the primary unit.</p> <p>For each map unit, the relevant reference tree species in the NRCS Web Soil Survey is identified as the available tree species with the highest relative basal area, determined from plot-based sampling (see description of measurement methods for live aboveground biomass, LAG).</p>

<sup>47</sup> Taken from USFS FIA Regional Field Guides for Standard (Phase 2) Measurements. Available at: <https://www.fia.fs.fed.us/library/field-guides-methods-proc/>

<sup>48</sup> Burrill, E. A., Wilson, A. M., Turner, J. A., Pugh, S. A., Menlove, J., & Christiansen, G. (2018). *The Forest Inventory and Analysis Database: Database description and user guide version 8.0 for Phase 2*. U.S. Department of Agriculture, Forest Service. Available at: [https://www.fia.fs.fed.us/library/database-documentation/current/ver80/FIADB%20User%20Guide%20P2\\_8-0.pdf](https://www.fia.fs.fed.us/library/database-documentation/current/ver80/FIADB%20User%20Guide%20P2_8-0.pdf)

<sup>49</sup> Available at: <https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm>

	Where a map unit has <NULL> site productivity values, SITECLCD is sourced from the map unit nearest to the project sample unit for which site productivity values are available.
Purpose of data	Matching
Comments	

Data/Parameter	Regeneration stocking
Data unit	Dimensionless
Description	Total relative density per acre (Ducey & Knapp 2010 <sup>50</sup> ) of all live trees $\geq 1$ " and $< 5$ " dbh, of commercial species. Commercial species are defined as those not from species groups 23, 43, and 48 (see FIA Database User Guide Appendix E).
Equations	N/A
Source of data	Plot-based sampling (see description of measurement methods for live aboveground biomass, LAG)
Value applied	Between 0 and 1
Justification of choice of data or description of measurement methods and procedures applied	Relative density (RD) per acre is calculated for each individual tree as $RD_{per\ acre} = 2.47 \times (0.00015 + (0.00218 \times Specific\ Gravity_{Species})) \times (\frac{dbh}{10})^{1.6}$ and then summed for the sample unit.
Purpose of data	Matching
Comments	

Data/Parameter	Commercial stocking
Data unit	Dimensionless
Description	Total relative density per acre (Ducey & Knapp 2010) of live trees of commercial species, $\geq 5$ " dbh, with at least one sound, straight 8-foot section. Commercial species are defined as those not from species groups 23, 43, and 48 (see FIA Database User Guide Appendix E).
Equations	N/A

<sup>50</sup> Ducey, M. J., & Knapp, R. A. (2010). A stand density index for complex mixed species forests in the northeastern United States. *Forest Ecology and Management*, 260(9), 1613–1622. <https://doi.org/10.1016/j.foreco.2010.08.014>

Source of data	Plot-based sampling (see description of measurement methods for live aboveground biomass, LAG)
Value applied	Between 0 and 1
Justification of choice of data or description of measurement methods and procedures applied	Relative density (RD) per acre is calculated for each individual tree as $RD_{per\ acre} = 2.47 \times (0.00015 + (0.00218 \times Specific\ Gravity_{Species})) \times (\frac{dbh}{10})^{1.6}$ and then summed for the sample unit.
Purpose of data	Matching
Comments	

Data/Parameter	ELEV
Data unit	Feet (in 10 or 100 foot categories)
Description	Elevation
Equations	N/A
Source of data	GPS or digital elevation model
Value applied	
Justification of choice of data or description of measurement methods and procedures applied	ELEV is determined for the sample unit location (center), or where a two-stage sample is used (e.g., with a stand as the primary unit and plots as the secondary unit), ELEV is determined as the average value for the secondary units.
Purpose of data	Matching
Comments	

Data/Parameter	SLOPE
Data unit	Percent
Description	Slope
Equations	N/A

<b>Source of data</b>	Digital elevation model or plot-based sampling with hypsometer or clinometer (sample unit average slope)
<b>Value applied</b>	
<b>Justification of choice of data or description of measurement methods and procedures applied</b>	Where determined referencing a digital elevation model, SLOPE is determined for the sample unit location, or where a two-stage sample is used (e.g., with a stand as the primary unit and plots as the secondary unit), SLOPE is determined as the area-weighted average value for the primary unit.
<b>Purpose of data</b>	Matching
<b>Comments</b>	

<b>Data/Parameter</b>	Quadratic mean diameter
<b>Data unit</b>	Inches (to the nearest 0.1 inch)
<b>Description</b>	Diameter of tree with average basal area
<b>Equations</b>	N/A
<b>Source of data</b>	Plot-based sampling (see description of measurement methods for live aboveground biomass, LAG)
<b>Value applied</b>	
<b>Justification of choice of data or description of measurement methods and procedures applied</b>	Based on live trees $\geq 5$ " dbh only
<b>Purpose of data</b>	Matching
<b>Comments</b>	

<b>Data/Parameter</b>	RDDISTCD
<b>Data unit</b>	Code (0 to 9). See definitions in the FIADB User Guide <sup>51</sup>

<sup>51</sup> Burrill, E. A., Wilson, A. M., Turner, J. A., Pugh, S. A., Menlove, J., & Christiansen, G. (2018). *The Forest Inventory and Analysis Database: Database description and user guide version 8.0 for Phase 2*. U.S. Department of Agriculture, Forest Service. Available at: [https://www.fia.fs.fed.us/library/database-documentation/current/ver80/FIADB%20User%20Guide%20P2\\_8-0.pdf](https://www.fia.fs.fed.us/library/database-documentation/current/ver80/FIADB%20User%20Guide%20P2_8-0.pdf)

<b>Description</b>	Horizontal distance to improved road
<b>Equations</b>	N/A
<b>Source of data</b>	GIS analysis
<b>Value applied</b>	
<b>Justification of choice of data or description of measurement methods and procedures applied</b>	<p>Calculated as the shortest straight line, over-land distance from the sample unit center to the nearest improved road. An improved road is a road of any width that is maintained as evidenced by pavement, gravel, grading, ditching, and/or other improvements.</p> <p>Where a two-stage sample is used (e.g., with a stand as the primary unit and plots as the secondary unit), the relevant location is the centroid of the primary unit.</p>
<b>Purpose of data</b>	Matching
<b>Comments</b>	