# Selection and Over-Crediting in Forest-Based Carbon Offset Projects: A Comparison of Regulated and Voluntary Carbon Markets

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# Rapid Growth in Nature-Based Carbon Offset Trading Come with Depreciated Offset Qualities

- There is **rapid global growth** in carbon offset trading, with significant (over one-fourth by 2022) contributions from nature-based projects, especially **forest-based projects**.
- In the meantime, concern about **low-quality forest carbon credits** (i.e., offset credits **represent much lower actual $CO_2$ sequestrations**) grows.
- The market inefficiency problem stems from **information asymmetry** of credit sellers over buyers, ecological knowledge barriers evaluating quality of forest-based offsets, and **market protocols** allowing project developers to pursue maximized credits with low-quality offsets.

# Our Contributions

- Evaluate forest-based offset projects in the U.S. using **precise, ground-truthed forest carbon measurement**.
- Show that variation in market rules among **regulated and voluntary carbon offset markets** induces entrance selection of U.S. improved forest management (IFM) projects by their **historical forestry practices**.
- Use long-term forest simulations to quantify the significant **over-crediting** for forest-based offsets on both markets due to **lowered baseline settings**.

# Model for Improved Forest Management and Carbon Offsetting

- Long-run average forest carbon storage is determined by geopotential variables ($\mathbf{G}$) of the forestland and human activities ($\mathbf{A}$):

$$\tilde{f}(\mathbf{G}, \mathbf{A})$$

- A representative IFM project developer's expected payoff is dependent on their choice of post-market forest management plan $\mathbf{A}'$ and the carbon market they choose to enter (which differs by offset prices, credit issuance schemes, entry costs, etc.):

$$\pi(\mathbf{G}, \mathbf{A}, \mathbf{A}', m)$$

  Where $m \in \{0, CARB, VCM\}$.
- Given forestland characteristics $\mathbf{G}$ and historical forest management practices $\mathbf{A}$, project developer maximizes payoff by choosing $\mathbf{A}'$ and $m$:

$$\max_{m \in \{0, CARB, VCM\}} \max_{\mathbf{A}'} \pi(\mathbf{G}, \mathbf{A}, \mathbf{A}', m)$$

# Data

- **Forest Offset Project Shapefiles**: Novel dataset of improved forest management (IFM) projects Map.
  - CARB: 34 projects, shapefiles public and obtained from CARB.
  - VCM: 28 projects, shapefiles scraped from maps.
- **Project Documents**: Measurements and illustrations of forest carbon projections submitted by project developers to carbon registries (ACR, CAR, Verra) Summary Statistics.
- **Forest Carbon**: US Forest Inventory and Analysis Dataset (FIA data), with forest observational plots of exact coordinates across 20 states in US Forest Service Region 9.
  - 514 FIA plots overlay our 62 projects: $2,077$ plot-year observations, 1999-2021.
- **Controls**: Climate, soil and land characteristics controls from NOAA, US Forest Service, and USGS.

# Matching Control Construction and Event Study Regression Analysis

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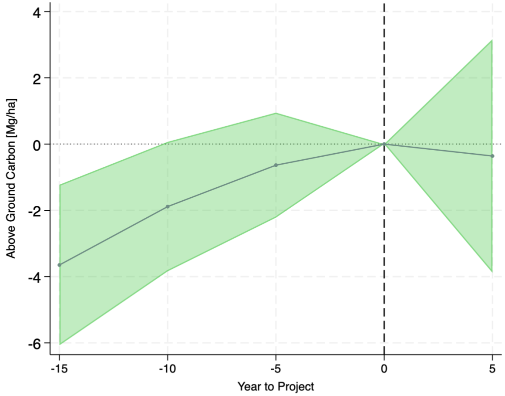
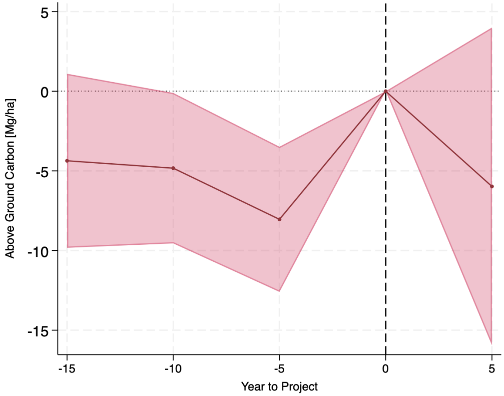
- First, we construct control forestland with **similar capacities to store biomass carbon** comparing with the IFM project sites.
  - We employ **five-nearest-neighbor-matching with replacement**, based on biophysical and socio-economic variables (growing degree days, soil nitrogen, precipitations, land bearing, slope, ownership, and forest types). Box and Scatter.
- We run **event study type analysis** comparing the biomass of project versus control carbon stocks before and after market entrance, separate by the two different markets Full Notations:

$$LiveCarbon_{it} = \alpha + \sum_{k=-15,-10,-5,5} \beta^{ck} Project_i \times B_{it}^k \times CARB$$
$$+ \sum_{k=-15,-10,-5,5} \beta^{vk} Project_i \times B_{it}^k \times VCM + \delta_t + \psi_i + \epsilon_{it}$$

# Differential Pre-Market Forestry Practices




(a) Projects entering the **California regulated market** wit **high (over 80%)** initial issuance scheme exhibit relative **increasing** biomass trends. CARB Issuance




(b) Projects entering the **voluntary market** with **low (below 30%)** initial issuance scheme show **declining** relative biomass trends. VCM Issuance

# Two-Stage Logistic Model on Market Entrance with Pre-Market Live Carbon Trends

- We construct the indicator *gradient* for **pre-market forest management** as the slopes of plot-level time-series regressions of FIA biomass carbon stocks on observation years before any market entrance.
- **Two-Staged Logistic Model** on same set of project and control plots with $gradient^+ = \mathbf{1}_{\{gradient \geq 0\}}$, $|gradient|$ and all other forestland characteristics predicts **positive impacts** of $|gradient|$ on carbon market entrance and $gradient^+$ on CARB versus VCM entrance Full Table.

| | Direct Estimate | | Bootstrap Estimate | |
|---|---|---|---|---|
| | 1st Stage Market Entry | 2nd Stage CARB Entry | 1st Stage Market Entry | 2nd Stage CARB Entry |
| $gradient^+$ | 0.1748 | 0.7284** | 0.2125 | 0.6677* |
| | (0.1458) | (0.2984) | (0.1361) | (0.3228) |
| $\|gradient\|$ | 0.1310*** | 0.0283 | 0.1030** | 0.0202 |
| | (0.0470) | (0.0892) | (0.0474) | (0.1037) |

# Simulation Estimates with Nested Logistic Regression Extrapolate Welfare from Forest Carbon Offsets

- We develop an entry choice model using **Landis II forest simulation model** that replicates the equilibrium entry choice. Full Simulation Parameters
Exp. Issuance Exp. Profit
- Simulation implies **lowered baselines than business-as-usual** are used as counterfactual to maximize credit issuance on both markets.
- Adding simulation estimates to a nested logistic model, **an upper bound of 1059 Million** $tCO2e$ emission removal by IFM projects is implied across the 20 states. Nested Logit Results
- Switching to **business-as-usual** baseline enforcement solve low-quality offsets, but lower emission reduction by 15.4% due to **decreased participation in regulated market**.

# Policy Implications

- **Enforcing baseline standards** using FIA data to **align baseline projections with historical forest management practices** will increases offset market integrity, at the cost of **reducing market entrance incentives and climate benefits**.
- **Introducing credible rating agencies** to inform buyers, investors and customers on forest offset qualities.
- Also need to refine credit issuance schemes to **balance participation incentives for projects with diverse historical management practices**.

# CARB Market Credit Issuance Schemes

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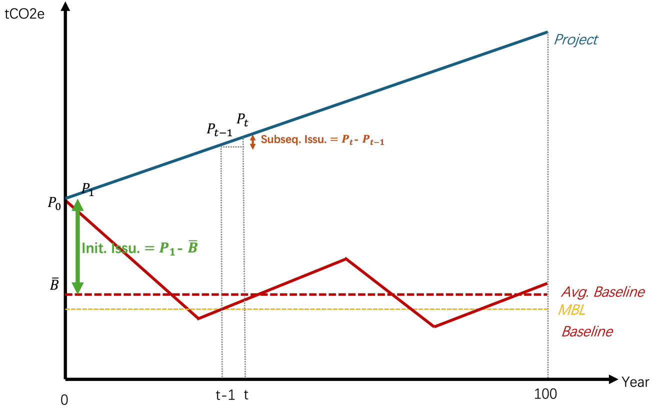
Regulated California carbon market provides initial issuance of over 80% of credits based on long-run average baseline comparisons.



# VCM Credit Issuance Schemes

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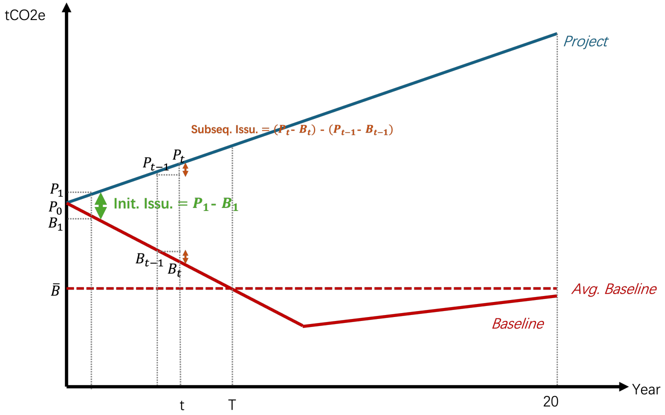
Voluntary market ties gradual credit issuance to future realized biomass storage and baseline projections



# Map of 62 IFM Projects

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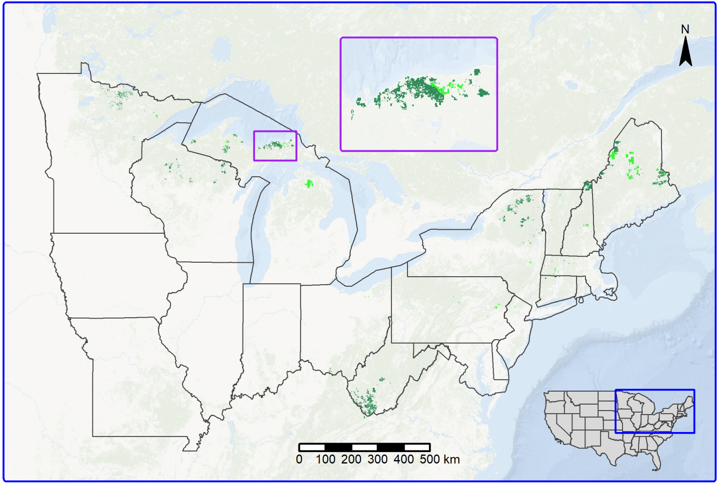


# Regulated VS Voluntary Markets: Project Characteristics

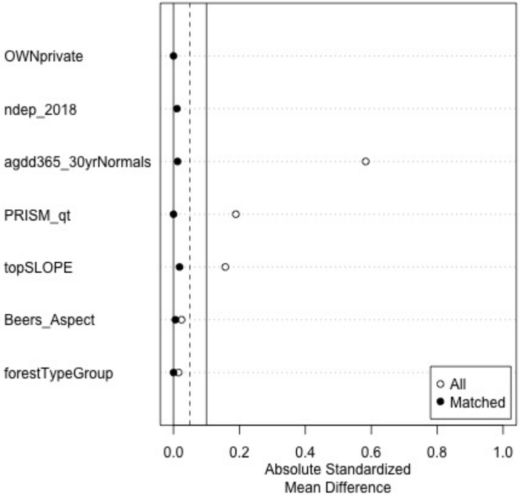
| | CARB | VCM | T-Test P-Value |
|---|---|---|---|
| Area [1000 Hectare] | 34 | 11 | 0.002 |
| Entrance Year | 2017 | 2019 | 0.010 |
| % Private Land | 0.77 | 0.57 | 0.109 |
| % Historical CE | 0.38 | 0.39 | 0.934 |
| % Agent Prep. | 1.00 | 0.82 | 0.010 |
| % Timber Owned | 0.71 | 0.39 | 0.013 |
| Baseline Uncertainty | 0.04 | 0.08 | 0.000 |
| Reversal Risk | 0.18 | 0.17 | 0.004 |

# Regulated VS Voluntary Markets: Credit Issuance and Carbon Storage Back

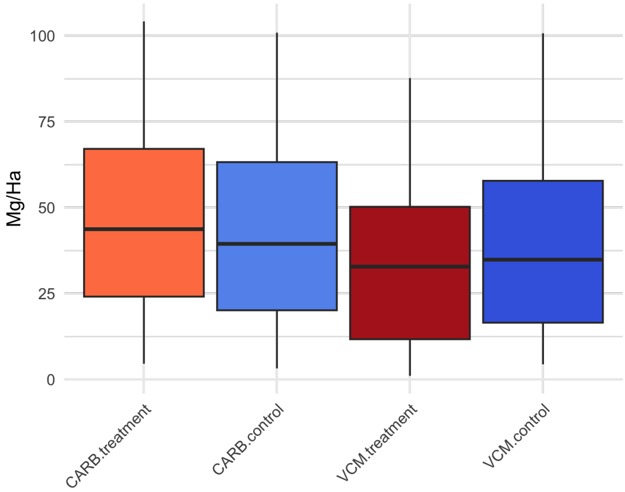
| | CARB | VCM | T-Test P-Value |
|---|---|---|---|
| Initial Credit [$ha^{-1}$] | 62 | 14 | 0.000 |
| Initial/Total Credit | 0.85 | 0.29 | 0.000 |
| Later Credit [$ha^{-1}$] | 8 | 36 | 0.000 |
| Annual Avg. Later Credit [$ha^{-1}$] | 2.7 | 6.9 | 0.000 |
| Initial Carbon Stock [$Mgha^{-1}$] | 66 | 78 | 0.056 |
| Avg. Baseline [$Mgha^{-1}$] | 47 | 47 | 0.991 |
| Pre-Market Carbon Stock (FIA) [$Mgha^{-1}$] | 59 | 49 | 0.158 |

# Matching Results Love Plot

Back

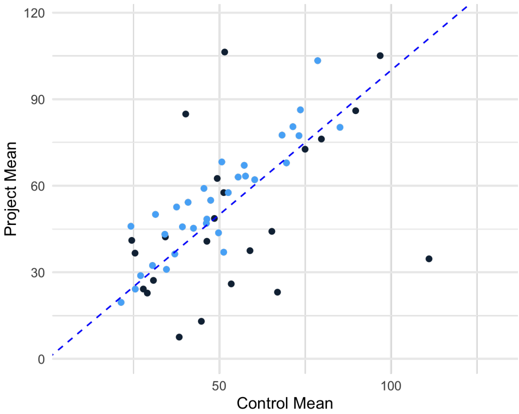


# Project vs. Control Pre-Market Entry Carbon Stocks



# Project vs. Control Pre-Market Carbon Stocks

Back




*Note: Light Blue = CARB projects, Dark Blue = VCM projects.*

# Event Study Type Regression Analysis Back

We run **event study type analysis** comparing the biomass of project versus control carbon stocks before and after market entrance, separate by the two different markets:

$$
\begin{aligned}
LiveCarbon_{it} = \alpha + & \sum_{k=-15,-10,-5,5} \beta^{ck} Project_i \times B_{it}^k \times CARB \\
& + \sum_{k=-15,-10,-5,5} \beta^{vk} Project_i \times B_{it}^k \times VCM + \delta_t + \psi_i + \epsilon_{it}
\end{aligned}
$$

- $B^k$ are bin indicators of FIA survey years $t \in [k, k+4]$ relative to market entrance year 0.
- $Project_i$ indicates if the plot $i$ is within a CARB regulated or VCM IFM project, being 0 if the plot is instead a matched controls.
- Regression is weighted by the matching weights of five neighbors.
- Include observational year ($t$) and plot ($i$) fixed effects.
- Standard errors are clustered at the FIA plot level.

# Two-Stage Logistic Regression Results

Back

| | Direct Estimate | | Bootstrap Estimate | |
|---|---|---|---|---|
| | Entry=CARB | Entry=VCM | Entry=CARB | Entry=VCM |
| | 1st Stage | 2nd Stage | 1st Stage | 2nd Stage |
| | Market Entry | CARB Entry | Market Entry | CARB Entry |
| *gradient*$^+$ | 0.1748 | 0.7284** | 0.2125 | 0.6677* |
| | (0.1458) | (0.2984) | (0.1361) | (0.3228) |
| $\|gradient\|$ | 0.1310*** | 0.0283 | 0.1030** | 0.0202 |
| | (0.0470) | (0.0892) | (0.0474) | (0.1037) |
| Avg. GDD | -0.0001 | 0.0007 | -0.0001 | 0.0008* |
| | (0.0003) | (0.0008) | (0.0001) | (0.0004) |
| Avg. Precip. | -0.0002 | -0.0011 | -0.0002 | -0.0009 |
| | (0.0014) | (0.0025) | (0.0004) | (0.0014) |
| Aspect | -0.0301 | 0.1177 | -0.0291 | 0.1538 |
| | (0.1264) | (0.2199) | (0.0966) | (0.2795) |
| Nitrogen Conc. | -0.0174 | 0.5518 | -0.0159 | 0.6537*** |
| | (0.1551) | (0.3986) | (0.0432) | (0.2253) |
| Slope | 0.0046 | 0.0047 | 0.0049 | 0.0076 |
| | (0.0095) | (0.0186) | (0.0052) | (0.0180) |
| Private Own. | -0.1039 | 8.2557*** | -0.0810 | 4.8968 |
| | (0.9928) | (3.0613) | (0.2504) | (4.0168) |
| Forest Type=100 | 0.1510 | -0.5336 | 0.1516 | -0.5660 |
| | (0.5189) | (0.7726) | (0.2723) | (0.6659) |
| Forest Type=120 | 0.2162 | 0.7030 | 0.2115 | 0.7615 |
| | (0.5098) | (0.6072) | (0.2157) | (0.5436) |
| Forest Type=400 | 0.2417 | -3.1274* | 0.1552 | -2.0810 |
| | (0.9015) | (1.7306) | (0.6277) | (2.3862) |
| Forest Type=500 | 0.2278 | -1.4408 | 0.2540 | -1.7797 |
| | (0.7956) | (2.1668) | (0.3585) | (1.9015) |
| Forest Type=700 | 0.2997 | 0.0070 | 0.2388 | -0.1282 |
| | (0.7069) | (1.2341) | (0.4397) | (0.9734) |
| Forest Type=800 | 0.1064 | 0.7779 | 0.1159 | 0.7707 |
| | (0.7290) | (0.7075) | (0.2046) | (0.5209) |
| Constant | 0.4247 | -13.7943** | 0.4327 | -11.2454*** |
| | (2.2034) | (6.3471) | (0.6789) | (4.5138) |

# Simulation Model Detail Settings

- Simulations performed on a **hypothetical IFM project in Maine** ($5,000ha$) across 150 years, with year 40 market entrance.
- Forestry practices are varied by **changing harvesting rate**, fixing other management plans (e.g., 65% harvesting, rotation period at minimum 20 years).
- **Common practice (CP)** on non-project surrounding land ($45,000ha$) with same capacities to hold biomass fixed at 1.5% harvesting.

# Simulation Model Detail Settings Back

- Project site allowed to have two harvesting scenarios mimicking the regulated and voluntary market project relative biomass trends found with event study regressions, relative to CP:

| Project Scenario | CARB | VCM |
|---|---|---|
| Pre-Market Harvest Rate (40 Years) | 1% | 2% |
| Post-Market Harvest Rate (110 Years) | 1% | 1% |

- Baseline projections allowing two options:

| Baseline | Business-as-Usual | Implied Document Baseline |
|---|---|---|
| Pre-Market Harvest Rate (40 Years) | Same as Project Pre-Market | Same as Project Pre-Market |
| Post-Market Harvest Rate (110 Years) | Same as Project Pre-Market | 5% |

# Simulated Market Outcomes: Credit Issuance and Emission Reduction

Back

*Unit:* $tCO_2eha^{-1}$

| Baseline: Business-as-Usual | | | | |
|---|---|---|---|---|
| Market | Project Scenario | Initial Issuance | Total Issuance | Emission Reduction |
| Regulated | CARB | -62.4 | -24.4 | 0.0 |
| Regulated | VCM | -41.9 | 25.8 | 50.6 |
| Voluntary | CARB | 0.0 | 12.2 | 0.0 |
| Voluntary | VCM | 9.1 | 49.3 | 44.6 |

| Baseline: Implied | | | | |
|---|---|---|---|---|
| Market | Project Scenario | Initial Issuance | Total Issuance | Emission Reduction |
| Regulated | CARB | 45.5 | 83.4 | 0.0 |
| Regulated | VCM | 12.2 | 79.9 | 50.6 |
| Voluntary | CARB | 38.1 | 57.7 | 0.9 |
| Voluntary | VCM | 34.1 | 82.3 | 44.6 |

# Simulated Market Outcomes: Expected Payoff

Back

*Unit:* $\$ha^{-1}$ Formula and Parameters Sensitivity Checks

| Baseline: Business-as-Usual | | | | | |
|---|---|---|---|---|---|
| Market | Project Scenario | Revenue | Adj. Revenue | Cost | Total |
| Regulated | CARB | -1257 | -126 | 173 | -1209 |
| Regulated | VCM | -768 | -86 | -1 | -854 |
| Voluntary | CARB | 32 | 3 | -4 | 32 |
| Voluntary | VCM | 198 | 13 | -137 | 74 |

| Baseline: Implied | | | | | |
|---|---|---|---|---|---|
| Market | Project Scenario | Revenue | Adj. Revenue | Cost | Total |
| Regulated | CARB | 1008 | 63 | -134 | 938 |
| Regulated | VCM | 369 | 7 | -154 | 222 |
| Voluntary | CARB | 551 | 29 | -60 | 521 |
| Voluntary | VCM | 537 | 33 | -174 | 396 |

# Sample Document Baseline Projection - ACR416

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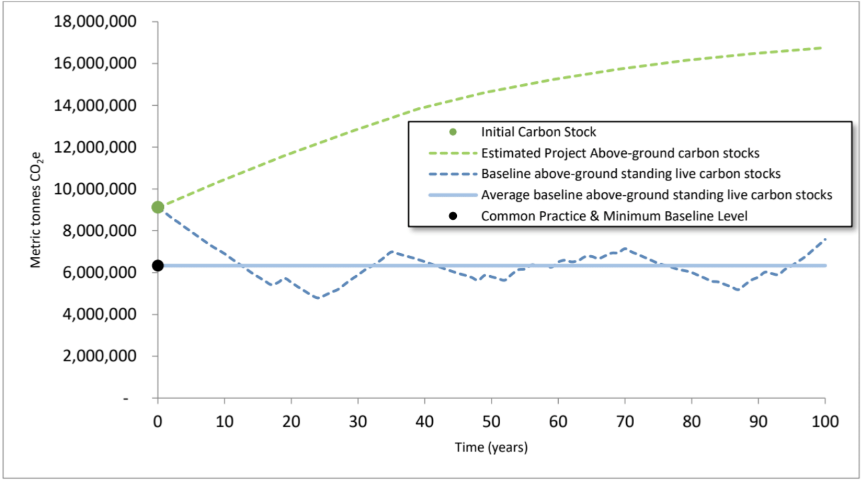


*Figure 2. Baseline and Project Above-Ground Standing Live Carbon Stocks.*

# Simulation Payoff Estimation: Formula

Project developer's payoff:

$$\Pi = \sum_{t=0}^{T_m} \frac{(1-r_m)^t}{(1+\delta)^t} [(1-fa)[(1+u)vp_m C_t + l_m p_m \rho v(P_t \phi_s^P - B_t \phi_s^B)] + \lambda \rho (P_t \phi_s^P - BSU_t \phi_s^{BSU})]$$

*Note: $t$ is years since market entrance, $v = \frac{44}{12}$ is the conversion factor from carbon to carbon dioxide, $m \in \{Regulated, Voluntary\}$ stands for the market, $s \in \{CARB, VCM, Ideal\}$ stands for project scenario. $T$ is the crediting term, 25 years for regulated market and 20 years for voluntary market. $P$ is the biomass projection of project scenarios, $B$ is the biomass projection of baselines, $BSU$ specifically stands for business-as-usual baselines, the actual case without market participation. All estimation of leakage and lumber harvesting is normalized to the next 5 years in accordance to the interval of the simulation.*

# Simulation Payoff Estimation: Parameters

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| Name | Symbol | Value | Source |
|---|---|---|---|
| Discount Rate | $\delta$ | 4% | Historical U.S. interest rate and inflation rate |
| Reversal Risk | $r$ | 18.30% (Regulated)<br>17.36% (Voluntary) | Summary statistics on project documentations |
| Offset Price | $p$ | 21.00 (Regulated)<br>13.61 (Voluntary)<br>$\$/tCO_2e$ | Regulated: CARB Summary of Market Transfers Report<br>Voluntary: AlliedOffsets Price Estimate, US IFM Projects<br>(Taken the average of four weighted quarterly average 2023) |
| Leakage | $l$ | 20% (Regulated)<br>40% (Voluntary) | Project documentations |
| Agent Fee | $f$ | 12.5% | Carbon Credits.com |
| Prob. Use Agent | $a$ | 1 (Regulated)<br>0.8214 (Voluntary) | Summary statistics on project documentations |
| Harvest Density | $\rho$ | 65% | Simulation setting |
| Harvest Rate | $\phi$ | 1%, 1.5%<br>2%, 5% | Scenario and baseline specific |
| Standing Dead | $u$ | 10% | Estimation from project documentations |
| Lumber Price | $\lambda$ | 150 $\$/MBF$<br>180.96 $\$/MgC$ | NH suggested stumpage values for southern state, oak, lower bound. Conversion factor from USDA Wood Handbook, white oak with green wood moisture average 71%, specific gravity 0.72, density 75 $lb/ft^3$ |

# Simulation Sensitivity: Expected Payoff

Back

| | | Baseline: Implied | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Market | Project Scenario | Original | Alt. Buffer Treatment | Same Offset Price | Offset Price Growth | VCM No Agent | High Agent Cost | High Standing Dead | High Lumber Price | Market Not Clear |
| Regulated | CARB | 938 | 937 | 773 | 945 | 938 | 857 | 1114 | 1114 | 14 |
| Regulated | VCM | 222 | 137 | 164 | 238 | 222 | 193 | 286 | 122 | -102 |
| Voluntary | CARB | 521 | 460 | 662 | 524 | 580 | 485 | 619 | 619 | 170 |
| Voluntary | VCM | 396 | 122 | 535 | 406 | 455 | 361 | 493 | 315 | 52 |

*Notes: Payoff total is estimated in dollar ($) per hectare ($ha^{-1}$). All estimation under Implied baseline (same harvesting rate as project pre-market, 5% harvesting post-market). Original is the main estimation. Alt. Buffer Treatment do not use reversal risk as discount rate but instead takes away the portion each issuance as buffer pool mechanism. Same Offset Price assume same unit offset price of 17.31 dollars per $tCO_2$ for both regulated and voluntary markets. Offset Price Growth assume annual nominal price growth rate of 2% on both regulated and voluntary markets. VCM No Agent assume no use of agents for all voluntary market participants. High Agent Cost assumes 20% agent cost. High Standing Dead assumes 30% standing dead. High Lumber Price take the upper bound of oak NH stumpage price at 380 dollars per MBF. No Market Clearance considers partial instead of 100% offset sales based on the percentage of retired credits on the two markets summarized from registry record data, 1.52% for regulated market and 32.73% for voluntary market.*

# Nested-Logistic Estimation Results with Simulation Payoff Approximations

Back

| Nested Logit with $payoff^{exp}$ | | | | | | | |
|---|---|---|---|---|---|---|---|
| Baseline | Shr. No Entrance | Shr. Regulated | Shr. Voluntary | Emission Reduc. $[MtCO_2e]$ | Total Credit $[MtCO_2e]$ | Social Benefit Emission Reduc. $[M\$]$ | Proj. Dev. Payoff $[M\$]$ |
| Implied | 0.529 | 0.348 | 0.123 | 1059 | 2599 | 148233 | 13962 |
| Business-as-Usual | 0.628 | 0.212 | 0.160 | 896 | 635 | 125441 | -14030 |
| Change | 0.099 | -0.136 | 0.037 | -0.154 | -0.756 | -0.154 | -2.005 |