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

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Updated Version

Abstract

Improved forest management (IFM) project developers in the U.S. can choose to supply emission offset credits to regulated markets, in which the credits are used to demonstrate compliance with a state cap-and-trade program in California, or voluntary markets, in which the credits are used by firms to show progress toward their voluntary emission goals. Emission offset accounting rules, such as the construction of emission baselines and the awarding schemes of offset credits, differ between regulated and voluntary markets. We undertake the first systematic analysis comparing and contrasting IFM projects participating in regulated and voluntary markets in the U.S.. We link a novel geospatial dataset of U.S. IFM offset projects to exact spatial coordinate measurements of above-ground carbon storage collected through U.S. Forest Service Forest and Inventory Analysis (FIA). Statistical and calibrated simulation (LANDIS II) analyses both illustrate market entrance selection as well as excessive offset credits issuance. IFM projects on regulated and voluntary markets differ significantly relative to their statistical counterfactuals with similar forestland capacities prior to market entry. As a result, pre-market forest biomass trends significantly predict the market entrance choices with a multinomial logistic model (MNL). Simulation modeling replicates this entrance outcome, illustrating that regulated market projects realize greater revenues under the regulated market rules than they would under the voluntary market rules, and likewise voluntary market projects realize greater revenues under the voluntary than the regulatory market rules. Then we calibrate in our simulation model the more appropriate business-as-usual baselines than the generous baselines implied in the IFM projects registry documentation. We find that regulated market projects are non-additional and voluntary market projects also issue about three times more offset credits than our business-as-usual baselines can justify. While current offset markets promote forest-based projects as nature-based climate solutions, they also raise serious integrity concerns that may weaken overall incentives for carbon reduction by corporate buyers.

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1 Introduction

On carbon markets, nature-based offset credits, which account for CO_2 reductions through ecosystems that store atmospheric carbon as biomass, offer the promise of low-cost climate mitigation. Today, one-quarter of all US offset projects on three main carbon registries, American Carbon Registry (ACR), Climate Action Reserve (CAR), and Verra (VCS), implement nature-based climate solutions, such as improved forest management, sustainable agriculture, grassland and wetland preservation. These account for about 17.0 millions tCO_2e of offset credit sold by mid-2024, 13.5 millions tCO_2e on the California regulated compliance market, and 4.5 on the global voluntary carbon market. Growth in both regulated and voluntary offset markets has signaled the significant and lasting interests among the private sector, in pursuing meaningful scale of emission mitigation to fulfill their climate commitments[1].

Forest-based offsets take a major market share of nature-based offsets, representing about 80% of all offsets supplied to the California compliance market (Kaarakka et al. 2023). These projects present efforts to increase the amount of biomass carbon stored in forests, applying practices including afforestation, reforestation, avoided forest conversion, and improved forest management. Typically, total carbon emission removals of such projects are determined by comparing their long-run carbon inventories under proposed project managements to the counterfactual no-project scenarios, namely the baselines. Developers of forest-based projects in the US can supply credits to one of the two markets, the regulated compliance market of California, or the global voluntary carbon market. Under the regulated market, project developer operates under the standards established by the regulator (California Air Resources Board, CARB), which specify the eligibility for entry, transparency and reporting standards. Under the voluntary carbon market (VCM), the developer selects among several credit registries that operate as quasi-regulatory entities. Their offset credits are sold on the regulated market to emission sources for up to 8% of their allowances with the California compliance program, or any entities on the non-regulated voluntary carbon market.

As both regulated and voluntary carbon offset markets grow rapidly over recent years, the credibility of the underlined emission reductions associated with the carbon offsets being sold have been increasingly questioned[2]. For forest-based carbon offset projects, because of the specialized

[1]Source: https://www.bloomberg.com/professional/insights/sustainable-finance/long-term-carbon-offsets-outlook-2023/.

[2]Source: Calyx Global Report

knowledge required for forest management and tree growth modeling, asymmetric information on credit quality and offsetting credibility poses a significant barrier to accurately evaluating the true environmental benefits of these trades. Both supply-side and demand-side market failures may lead to market inefficiencies. On the supply side, adverse selection among project developers may cause low social value offset projects to be supplied in the market. Demand-side market failures can exacerbate this inefficiency, as buyers may encourage the provision of low quality offsets that come with lower prices, reflecting as a greenwashing objective.

This paper leverages statistical analysis, field-based forest inventory data, and advanced forest landscape modeling to uncover entry selection biases and resulted inefficiencies in US forest-based carbon offset projects trading on both regulated and voluntary carbon markets. We focus on improved forest management (IFM) projects located the in US Forest Service's 20-state Northern Region (Region 9) that spans from the Midwest to New England. We compile a novel dataset of geospatial boundary shapefiles for 62 IFM projects in the region, among which 34 are traded on the regulated California carbon offset market with data obtained from CARB, and 28 are traded on the voluntary global carbon offset market with data identified through map scraping. Merging our geospatial data with the US Forest Inventory and Analysis (FIA) field data of exact spatial coordinates, we obtain ground-truth estimates of the above-ground carbon stocks for each IFM project based on FIA measurements of the diameters of all trees within each sample plot contained in each project area, at 5.45 survey year intervals from 1999 to 2021.

We base our empirical analysis on a theoretical model that related offset market entrance decisions to forestland carbon storage capacities determined by observable geophysical variables, and unobserved historical forest management practices due to limited public information. To represent historical forestry practices, we use event study type regression analysis to compare projects' above-ground biomass trends with control FIA forest plots constructed with similar capacities to store live carbon using five-nearest neighbor matching on selected geopotential variables (average precipitation level, growing degree days, slope, aspect, nitrogen decomposition, forest type) and land use characteristics (private or non-private ownership). With this analysis, we find that projects with pre-market average increasing and higher carbon stocks than controls enter the regulated market. In contrast, the voluntary market encourages the entry of projects with an average decreasing and lower carbon stocks relative to their matched controls pre-market.

(https://calyxglobal.com/resource-post?q=20&utm_campaign=2024_Resource_VCMQualityTrends).

Analyzing the crediting procedures of both offset markets, we find that their differential offset credit issuance schemes may induce these entry selection biases of IFM projects depending on their historical forest management plans. The over 80% initial issuance of the regulated market in California from comparing starting carbon storage and the long-run baseline average would encourage projects already accumulating high initial carbon stocks to enter. The lower than 30% initial and more gradual subsequent credit issuance scheme of the voluntary market awards on continuing forest carbon accumulations, therefore motivates projects with low initial carbon stocks to enter and change their post-market forest management plans to achieve higher biomass for credits in later years. We use the LANDIS/PnET model to simulate representative forest projects for both regulated and voluntary carbon markets, by establishing the pre-market carbon stock trends we have found with event study analysis. We calculate and compare the simulated total credit issuance and discounted revenues under each market's specific credit issuance scheme for the representative projects, and verify that projects are indeed strategically selecting their markets with the objective to maximize their economic gains.

Comparing FIA field data, project documents, and simulation results, we find two potential sources of inefficiencies on the current offset markets that lead to low-quality carbon offsets representing less actual emission removals than they claim. First, projects may over-report their initial carbon inventories much higher than the ground-truth FIA measurements. Second, projects submitted baseline projections do not represent business-as-usual forest managements when comparing with their historical trends. We find that a doubled implied baseline harvesting rate can be set to produce the lower and fluctuating baseline carbon stocks observed in project documents, leading to the market entry choices seen in the real world. The lowered baselines can attract more market entrance of the IFM projects, making our social welfare estimate based on a multinomial logistic regression model assuming offset market entrance of all eligible forestland in the region the significant contributor as nature-based climate solutions to states' climate goals. However, lowered baselines also effectively cause overcrediting on both markets. Combined with the high initial issuance scheme of the regulated market, additionality issue arises when projects on this market would benefit from their pre-market forest conservation actions and lower baseline selections, without consolidating any changes in their future forest management plans to sequestrate more carbon in forests.

This paper represents the first empirical research exploring the entry selections of forest-based

carbon offset projects in regulatory compliance and voluntary carbon markets. It also serves as the first in the offset literature to employ ground-truth data, in lieu of forest simulation modeling, to estimate the carbon trends and market outcomes of forest-based offset projects under different baseline selections and credit issuance schemes. The paper is also the first to construct and analyze with the geospatial dataset for IFM projects on the voluntary carbon market. In existing literature, empirical studies usually focus on the non-effectiveness of Californian carbon offsets traded on the state's regulated market, with evidence from remote sensing or non-exact ground data matching (Badgley et al. 2022, Coffield et al. 2022, Stapp 2022, Stapp et al. 2023). The paper also presents one of the initial attempts to summarize through documentations of project-level carbon registry records and link market mechanisms to market entrance and outcomes. These supplement the existing literature on carbon offset market policy arguments (Aldy & Halem 2022, Pande 2024) and trading analysis from the buyer's side (Kim et al. 2024). Our work also relates to the broad aspect of nature-based climate solutions, where we provide empirical evidence regarding the effectiveness of motivating improved forest management with market mechanisms (Griscom et al. 2017, West et al. 2023). Finally, we offer new evidence on the additionality challenges of market-based climate mitigation solutions in the emerging carbon offset markets, providing insights on the potential gaps between environmental market operations and the achievement of climate mitigation goals (Aspelund & Russo 2024).

The paper will proceed in the following order. Section 2 provides the background of carbon offset markets. Section 3 discusses a theory model for the market decisions of project developers. Section 4 introduces data and summary statistics. Section 5 describes the main empirical strategy. Section 6 presents the main results. Section 7 summarizes forest simulations. Section 8 concludes.

2 Background

2.1 Improved Forest Management (IFM) Projects on Carbon Offset Markets

Accounting for approximately one-third of land area of the earth, forests are crucial contributors to the planet health, as well as the major and natural sink of carbon through photosynthesis. Preservation, restoration and protection of forests are important classes of Nature-based Climate Solutions (NbCS), which are deliberate human actions that manipulate ecosystems to improve the planet's greenhouse gas budget.

As an important part of the financing for NbCS, nature-based carbon offsets, advantaged with lower trading prices comparing with regular carbon prices on cap-and-trade markets, and additional ecological cobenefits, have been taking increasingly significant market share on carbon offset markets in the US. By the end of July 2024, across a total of 1,175 US carbon offset projects with non-zero credit issuance registered under three main carbon registries, American Carbon Registry (ACR), Climate Action Reserve (CAR), and Verra (VCS), 24.2% are nature-based projects, including forest conservation, agricultural land management, grassland and wetland preservation. Among these, the majority (over 90%) are forest projects, especially improved forest management (IFM) projects.

Improved forest management (IFM) is by far the most common type of forest offset credit (Kaarakka et al. 2021, 2023). IFM projects strategically change forest management activities in order to achieve higher levels of forestland carbon storage relative to a defined baseline scenario representing the counterfactual without these improved forestry practices. Most of the additional carbons are stored in the form of live carbon (e.g., living trees), among which the majority is above ground. The remaining small proportion is stored as underground carbon in the soil. The most common strategy for improved forest management is to restrict the harvesting of forests, including reducing the number of trees to harvest per cycle (decreasing harvesting rate), and extending the rotation period of harvesting so older trees are cut and on average trees grow for longer life terms and store more carbon. Other methods also include improving the ecological condition of land and soil, adapting better forest fire risk management, and planning small scales of tree replanting in order to foster the growth of the existing forests.

In the US, most IFM projects traded on carbon offset markets are owned and managed by private owners, especially timber companies. As a result, the changes in forestland management mainly come from reduced commercial logging activities, giving rise to the economic trade-off with foregone timber sales. Other owners including recreational clubs, tribes, educational institutions, local and state governments. When claiming project credits on the markets, these projects are required to provide discrete plans (usually called the GHG emission reduction, removal or offsetting plans) for improved forest management and argue for their activities in efficiently leading to increased carbon stocks relative to credible baseline scenarios. After accounting for potential reversal risks and leakage effects, additional carbon storage net of the baselines will be verified by third parties, and rewarded as tradable carbon credits upon market entrance approval by their

carbon registries to owners or direct beneficiary of the forestland (referred as project developers in this paper)[3]. To ensure market integrity, post-entrance forest carbon storage and forestry practices are also required to be reported and monitored from time to time by the carbon registries or market regulators. If there are signs of deviation from the projects' proposed carbon offsetting pathway, project developers may face legal suits from their credit buyers.

2.2 Californian Regulatory Carbon Offset Market

The only regulated carbon offset market in the US (referred as the regulated market for the rest of the paper) is the Compliance Offset Program under the Cap-and-Trade Program of California, overseen by California Air Resources Board (CARB). Californian buyers trading on this market are allowed to use up to 8% of their emission allowance as carbon offsets under the CA standard[4]. Offset projects supplying on the regulated market are not required to be California-based[5]. They need to first register with a qualified registry, then file and submit the additional required documents to CARB. After approval, CARB issues credits and the projects can start to trade on the regulated market.

To achieve market entrance on this market, IFM project developers need to follow standard protocols, calculation worksheets, basic statistics and parameters prepared by CARB to produce numbers of their projected carbon offsets[6]. Specifically, IFM projects on the regulated market (referred as CARB projects for rest of the paper) need to outline the persistence of increased forest carbon storage through their actions in a 100-year term period, though the crediting period on this market is 25 years. For the setting of baseline scenarios, the 100-year average above-ground carbon stocks of projects' baseline projections need to be above or comparable with "common practice", the regional average carbon storage capacities based on locations and and areas of the forestland, estimated with codes provided by CARB and data from Forest and Inventory National Program of the US Forest Service. CARB projects already submitting GHG emission removal documents to their registries are additionally required to report those details (numerically and descriptively) in

[3] In some documents, project developers may represent the agencies hired by landowners to manage the activities taken on the forestland. Since in this paper we consider actual decision makers determining the actions taken on forest management, we will merge the representation of landowners and managers in these cases as project developers.

[4] 8% allowance is for emissions before 2020, for 2021-2025 the allowance is 4%, after 2026 it will be 6%.

[5] Projects providing direct climate benefit to CA will be flagged as Direct Environmental Benefits, or DEBS, on the market.

[6] Protocols and parameters are also updated from time to time by CARB. For example, there are three forest protocols, 2011, 2014 and 2015.

the standardized forms prepared by CARB. CARB is also responsible for publishing and updating detailed credit issuance, retirement, concellation, trading price and volume summaries, and the geospatial files for projects they handle on their website. After market entrance is permitted, CARB will monitor the progress of participating projects every year, reserving the rights to reverse previous offset credit issuance if there is evidence that projected emission reduction is not attained.

2.3 Voluntary Carbon Market

Voluntary carbon market (referred as the voluntary market in this paper) is a global market where carbon offsets can be traded to buyers of any sorts. Like projects entering the regulated market, each project traded on VCM must register with a certified carbon registry (ACR, CAR, Verra). To meet the market entrance standards, project developers are required to follow the protocols issued by their target registries, producing GHG emission removal plans including details of project evaluations and baseline constructions. These standards could differ across the choice of registry and the timing of VCM entrance.

IFM projects traded on VCM (referred as VCM projects for the rest of this paper) are usually following less strict protocols. For example unlike CARB, carbon registries normally do not explicitly require common practice tests for baseline scenario setting. For persistence of the carbon removal effects, a shorter term period of 40 years is specified by the registries, with a similar crediting period of 20 years. Meanwhile, project developers only need to provide the carbon storage projections of project and baseline scenarios for the next 20 years. After market entrance, projects will also undergo fewer instances of monitoring by the registries, per 5-year for standard monitoring. Reporting of VCM projects is much less standardized than those on the regulated market, requiring only the GHG emission removal plan but not uniform reporting forms. Though project specific geospatial files and detailed worksheet for credit calculations are required and submitted to carbon registries, they are not made public and only their maps with geocoordinates are included in GHG emission removal documents published on registry websites. Like CARB, registries also publish detailed information on credit issuance, retirement and cancellation by projects registered under them, but price information is rarely reported.

2.4 Offset Credit Issuance for IFM Projects on Carbon Markets

Carbon offset credit issuance directly determines the expected revenues for IFM project developers participating in the markets. Both regulated and voluntary markets issue offset credits with the principle to award additional carbon stored on the project forestland due to adapting improved forest management relative to the baseline scenario of not adapting IFM. The two markets have very different credit issuance schemes. One of the most important differences affecting the entry decisions of project developers is the proportion of initial relative to total carbon credit issuance, where CARB projects has significantly higher initial issuance than VCM ones.

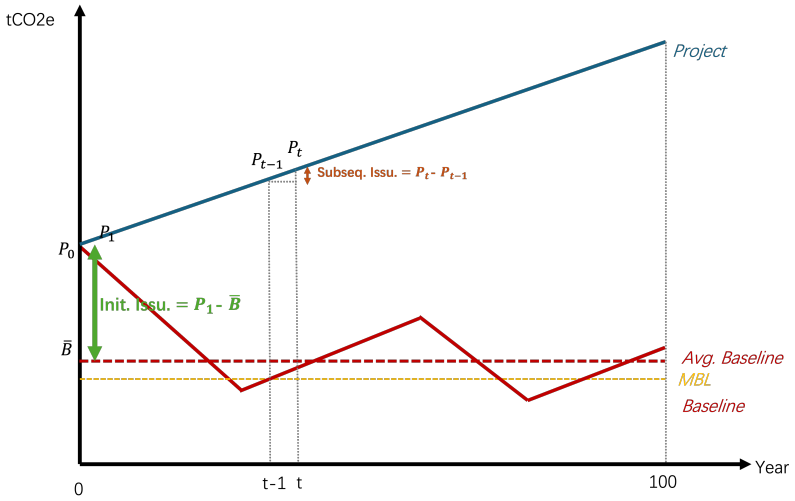
We will further describe the issuance schemes of the two markets to illustrate this crucial difference in initial credits with dipictions of Figure 1, replicating carbon stock projection diagrams (Appendix Figure A.1) in projects' GHG emission removal plans (referred as project documents for the rest of the paper)[7].

Regulated Market Issuance for CARB Projects On the regulated offset market, CARB projects submit model generated baseline and project simulations using academically sounding, peered-reviewed models (usually the Forest Vegetation Simulator (FVS)), with legal constraints setting (e.g. no more than 40% harvesting as bind by state legislation). Comparing baselines with project projections under IFM, such as reduced harvesting or increased rotation periods, the GHG emission reduction is then determined and carbon offset credits are issued accordingly. generally using the Forest Vegetation Simulator (FVS) model) for 100 years. The average above-ground baseline carbon over this term period is required to be no lower than a minimum baseline level (MBL)[8]. The situation is illustrated with Figure 1 Panel (a)[9]. The regulated market credit the initial issuance to this typical CARB project as the difference between its realized carbon stock by the end of the first reporting period, and 100-year average baseline carbon. For later periods

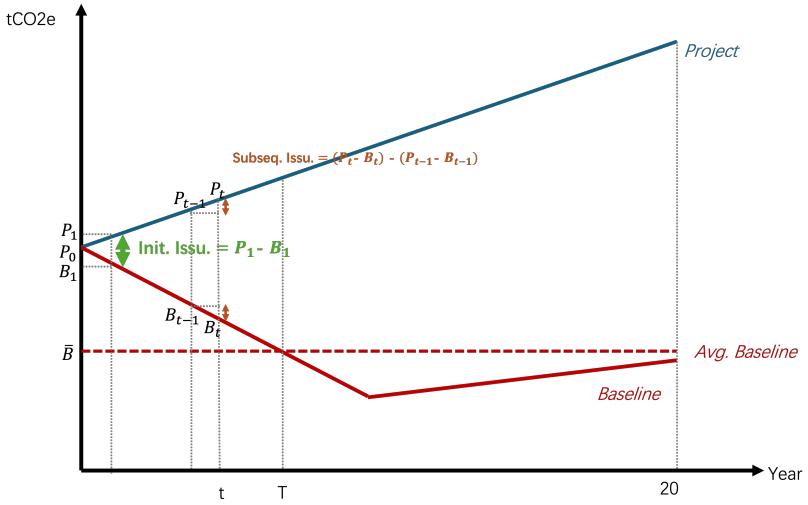
[7]Note that the following descriptions are only accounting for total offset credit issuance, majorly taken by the evaluation of above-ground biomass carbon. In reality, leakage or secondary effects (e.g. spillovers to increased logging in the other forestland owned by the same timber company) used for buffer pools (portion of total credits maintained by the registry in order to counter any reversal events such as forest fires and hurricanes that would destroy live carbon stocks) will also affect the amount of tradable credits for IFM project developers. For detailed mathematical formulas describing the credit issuance schemes including evaluations of present value credit sales accounting risks, uncertainties and buffer pools, see Appendix Table B.1.

[8]Normally taken as the minimum across the common practice (CP) (working with formulas provided by CARB and data provided by FIA) and the project's initial live carbon stock (ICS). Because CP is normally lower than ICS, MBL=CP for most of the times.

[9]Note that the minimum baseline requirement is only for above-ground carbon, and the illustration is assumed to ignore the small portion of dead and below-ground carbon.



(a) CARB Project Issuance on Regulated Market



(b) VCM Project Issuance on Voluntary Market

Figure 1: IFM projects projections, baselines, and initial credit issuance illustrations for both CARB and VCM projects on regulated and voluntary carbon offset markets

subsequent offset issuance, changes of realized carbon storage relative to the previous period (and small changes in baseline average, if there is any) will be counted. As a result, this scheme awards future carbon offsets due to decreasing baseline carbon stocks in the first or initial period. By this scheme, the largest share of offset issuance will occur in the initial period.

Voluntary Market Issuance for VCM Projects On the voluntary offset market, IFM projects registered by American Carbon Registry (ACR)[10] are required to submit model generated baseline and project simulations (again usually applying the FVS model) for 20 years, which is the crediting period. There are no explicit minimum levels required for long-run average of baseline carbon stocks as illustrated with Figure 1 Panel (b). In this issuance scheme, offset credits are awarded to the continuous changes in realized project carbon stocks relative to the baseline simulations. Therefore, the initial credit issuance represents only the estimated changes in carbon stocks under project IFM plans relative to under baseline scenarios at the end of the first reporting period. As long-run averages of the continuously decreasing baselines are not determinant, future carbon offsetting is not rewarded in the initial issuance. Instead, fluctuations in the baselines are incorporated into later issuance, together with the incremental increase of realized carbon stocks under IFM[11]. Therefore, the voluntary market issuance scheme provides the smaller shares of initial credit issuance.

3 Theoretical Framework

3.1 Simplified Model for Improve Forest Management and Carbon Offsetting

Forest carbon storage, in this case mainly above-ground carbon, is determined by the net difference between carbon dioxide absorption through vegetation' photosynthesis, and emission through respiration. In a simplified setting, the carbon stock in forest could be modeled as determined by four classes of factors. The first class is the location-specific geopotential variables ($\mathbf{G}_i$) of the forestland, including long-run climate variables, forest (tree species) type, geophysical characteristics of the land (e.g. how nutrient is the soil), and certain socioeconomic binding characteristics (e.g. private land ownership). This class of factors determines the maximum biomass carbon to

[10] This registry have 25 over 28 total VCM projects in our sample, so we take its crediting standard for illustration and future simulation purposes.

[11] In addition, per ACR rule, baseline fluctuations at the baseline carbon levels falling below their long-run (20-year) averages are not accounted for during credit counting.

stand permanently (e.g. lasting for couple of decades or more) on a given piece of forestland, representing the net CO_2 sequestration capacity. The second class of factors is human activities ($\mathbf{A}_i$) performed on the forestland, assumed to be constant over the long-run, including harvesting, recreational activities, protection of trees, afforestation, forest fire management. These are the activities chosen by forestland owners to manage their forests. The third class of factors includes exogenous shock variables ($\mathbf{S}_{it}$), such as contemporaneous weather, wildfires, storms, and other shocks (e.g. timber market price or demand shocks), which can impact the growth of trees and the value of live carbon stocks in the short-run. The fourth class of characters are individual-project developer specific determining factors influecing the financial decisions on forestland management (e.g., budget constraints, individual objectives of profit maximization from the forestland), denoted as $\mathbf{E}_i$.

We then assume the relationship function to be f and have forest carbon stock at location i and time t expressed as:

$$C_{it} = f(\mathbf{G}_i, \mathbf{A}_i, \mathbf{S}_{it}, \mathbf{E}_i)$$

In the carbon offset market schemes for IFM projects, a project developer of the land i is responsible for guaranteeing GHG removal through changing the only class of factors it could control, human activities ($\mathbf{A}$), in order to impact the levels of forest carbon storage. In the long run by the terms of carbon offset projects, we further apply the assumption that exogenous shocks ($\mathbf{S}$) can separable in the function and absorbed by risk managements such as the carbon markets' buffer pools.

Then a project developer would plan on moving to improved management plan $\mathbf{A}'$ with the following expected carbon offset credit as award, given that the offset markets are efficient and provide one unit of credit for one unit of emission precisely:

$$\Delta C_i = \mathbb{E}_t[f(\mathbf{G}_i, \mathbf{A}'_i, \mathbf{S}_{it}, \mathbf{E}_i)] - \mathbb{E}_t[f(\mathbf{G}_i, \mathbf{A}_i, \mathbf{S}_{it}, \mathbf{E}_i)] = \bar{f}(\mathbf{G}_i, \mathbf{A}'_i, \mathbf{E}_i) - \bar{f}(\mathbf{G}_i, \mathbf{A}_i, \mathbf{E}_i)$$

Where the average function is $\bar{f}(\mathbf{G}, \mathbf{A}, \mathbf{E}) = \mathbb{E}_t[\mathbf{G}, \mathbf{A}, \mathbf{S}, \mathbf{E}]$.

3.2 Project Developer's Profit Maximization Problem

As mentioned in the background section, project developers endure increased costs when changing from their original forest management plan, including increased costs for better managing the growing forest, and forgone costs selling smaller volume of timbers due to reduced harvesting. Let us assume the average aggregate cost function across time for the project developer is $\bar{g}(\mathbf{G}, \mathbf{A}, \mathbf{E})$.

If we further assume that pre-market forest activities $\mathbf{A}$ is in equilibrium of maximizing project developers' payoff without any offset market, then it can be expressed as the optimization problem of minimizing costs:

$$\mathbf{A}_i = \arg\min_{\mathbf{A}_i} \bar{g}(\mathbf{G}_i, \mathbf{A}_i, \mathbf{E}_i)$$

Therefore, the equilibrium human actions $\mathbf{A}$ before offset credit market availability is determined by land capacity $\mathbf{G}$ and individual project developers' financial constraints $\mathbf{E}$. Note individual financial factors $\mathbf{E}$ is usually unobservable in data, but by this relationship, $\mathbf{E}$ can be inverted from the minimization cost problem from $\mathbf{G}, \mathbf{A}$ before market entrance takes place. Therefore, we can rewrite all functions with $\mathbf{E}$ as $\tilde{f}, \tilde{g}$ all in terms of $(\mathbf{G}, \mathbf{A})$ only.

For a risk-neutral project developer, when putting the forestland i under a new IFM plan and register on one of the carbon offset market $m \in \{Regulated, Voluntary\}$, the person bears c_m as the transaction cost differs between the two markets[12]. Offset credits are sold with average prices p_m per unit[13].

So the project developer's expected payoff from market entrance into m is[14]:

$$\pi(\mathbf{G}_i, \mathbf{A}_i, \mathbf{A}'_i, m) = p_m[\tilde{f}(\mathbf{G}_i, \mathbf{A}'_i) - \tilde{f}(\mathbf{G}_i, \mathbf{A}_i)] - [\tilde{g}(\mathbf{G}_i, \mathbf{A}'_i) - \tilde{g}(\mathbf{G}_i, \mathbf{A}_i)] - c_m$$

Given exogenous climate and land characteristics, market prices, prior forest management

[12] Transaction and entry costs can also be different across carbon registries. For example for account opening and maintenance, the annual fee for ACR and CAR is 500 USD as of 2024, but Verra is higher at 750 USD.

[13] In future models, prices can also incorporate expected market competitions and uncertainty risks. For example, buyers on the regulated market are mostly firms binded by the Californian compliance scheme, while the voluntary market have a wider range of buyers. In statistics, the percentage of retired (sold) over issued NbCS credits is much higher on the voluntary market (32.7% versus 1.5% by mid-2024). If markets do not clear, these percentages may be incorporated into prices of credit sales.

[14] In reality, because of the different carbon issuance schemes, this payoff function further deviates between the two offset markets by q_m portion of total credits being issued initially (in the first reporting period) and the rest $1 - q_m$ is issued subsequently. With a normalized discounting rate δ, the payoff function of the project developer is $\pi(\mathbf{G}_i, \mathbf{A}_i, \mathbf{A}'_i, \mathbf{E}_i, m) = p_m(q_m + (1 - q_m)\delta)[\tilde{f}(\mathbf{G}_i, \mathbf{A}'_i) - \tilde{f}(\mathbf{G}_i, \mathbf{A}_i)] - [\tilde{g}(\mathbf{G}_i, \mathbf{A}'_i) - \tilde{g}(\mathbf{G}_i, \mathbf{A}_i)] - c_m$.

plans, and costs, a rational and idealized project developer with full information will choose the new forest management plan $\mathbf{A'}$ to maximize the payoffs on CARB and VCM markets separately, and then select the market with the maximized profit to enter:

$$U_i = \max_{m \in \{Regulated, Voluntary\}} \{\max_{\mathbf{A}'_i} \pi(\mathbf{G}_i, \mathbf{A}_i, \mathbf{A}'_i, m)\}$$

The project developer will participate in one of the two carbon offset markets for offset trading as long as $U_i \geq 0$.

3.3 Identification Strategy

Given the profit maximization problem for risk-neutral project developers in the model above, with given parameters $\bar{f}$, $\bar{g}$, sets of geopotential factors and pre-market human activities $(\mathbf{G}, \mathbf{A})$ will characterize the entry choices of each IFM project i, as CARB project entering the regulated market, or VCM project entering the voluntary market, or neither (no entry).

Scientifically, determinants for forestland carbon storage potentials $\mathbf{G}$ can be identified and sorted. However, it is hard to observe human actions $\mathbf{A}$. There are some representations such as past harvesting, but it is difficult to trace the complete tracking records affecting the standing biomass stocks extending decades before an IFM project enters a carbon offset market, especially as historical activity reports are usually qualitative by protocols of both regulated and voluntary markets. Therefore, in the following empirical sections, we will use the observed forest biomass, $\tilde{f}(\mathbf{G}, \mathbf{A})$, to indirectly represent the pre-market forest management plans. We will compare market entrants' pre-market standing biomass with no-entry controls of similar carbon storage capacities, or say similar $\mathbf{G}$. Therefore, equilibrium pre-market forest management plan $\mathbf{A}$ can be characterized relative to the non-entrants, and we will identify the differential pre-market forestry practices for CARB and VCM projects and link them to their decisions entering the regulated or voluntary markets.

In reality, the model will be much more complicated. Market parameters such as prices and entry costs are expected to change as market evolves over time, for example when there are increasing participation of credit rating agencies. Exogenous shocks $\mathbf{S}$ may not be separable but instead interact with human activities (e.g. tree thining practices in reducing wildfire risks), which would also shift the functions $\tilde{g}$ and $\tilde{f}$.

4 Data

4.1 CARB Project Shapefiles and Records

For the regulated Californian carbon market, we collect official records of project geospatial shapefiles and panel of credit issuance, retirement and cancellation from CARB. We download the the publicly available emission removal plans (documents) and CARB listing and offset verification statements of each projects from carbon registry websites (ACR, CAR, Verra)[15]. Then we manually record project information and measurements (e.g. ownership, risk estimates, baseline average, initial carbon stock). In the 20 states of Region 9, there are 43 IFM projects participating the regulated market, over the 151 total forest projects registered on CARB across the country (28.5%).

4.2 VCM Project Shapefiles and Records

Projects participating in voluntary carbon market are not required to make their geospatial shapefiles public on registry websites, though they submit the files to their registries[16]. However, each registry does require IFM projects to provide maps with identifiable geocoordinates. Through these maps, we manually scrape the shapefiles in ArcGIS for these VCM projects. Among the 37 IFM projects registered under ACR, CAR and Verra located in Region 9, we are able to construct a novel dataset of the shapefiles for 29 VCM projects. The rest 8 projects do not have high resolution maps and consist of quite scattered polygons, which are not identifiable manually[17]. Project documentations and credit transaction records are again downloaded from registry websites, from which we compile project information and measurements[18].

[15] Registries also provide credit trading records. We cross-check with the records of CARB and see no disparities.

[16] Only projects being removed from the market, or not yet approved with zero current carbon offset issuance, have shapefiles still available online.

[17] We tempted machine learning based scraping for these projects, but the results have more errors than manual scraping. In the future, AI may be used to fill in the gap.

[18] Comparing documented project areas with the areas calculated from map scraped geospatial shapefiles for 28 in-sample VCM projects (one is dropped for not overlapping with FIA plots), document areas are on average $9,668ha$, and shapefile average area is $10,719ha$, about 10% higher, statistically significant by t-test (t-statistic of -2.785, p-value of 0.0097). This is consistent with the fact that manual scraping will likely draw straight lines to approximate polygons and thus include areas not covered. Later analysis will run the subsample dropping VCM projects with large deviations from documented areas for robustness checks.

4.3 FIA Ground Observational Forest Data

The US Forest Inventory and Analysis (FIA) program collects detailed information regarding forests across the United States. Above ground carbon is one of the variables included in the survey, referred as ground-truth carbon measurement (relative to remote-sensing based estimations) calculated based on diameters of all trees measured within each FIA observational "plot". Plots (parcels of land) are selected randomly by FIA across the country and remeasured every 5-6 years. Applying an agreement with FIA to access the exact coordinates of the their observational plots in 20 states of Region 9[19], which includes the regions historically rich in forest resources. There are $42,124$ plots in total with average plot area of $565.3ha$ and remeasurement gap of 5.45 years.

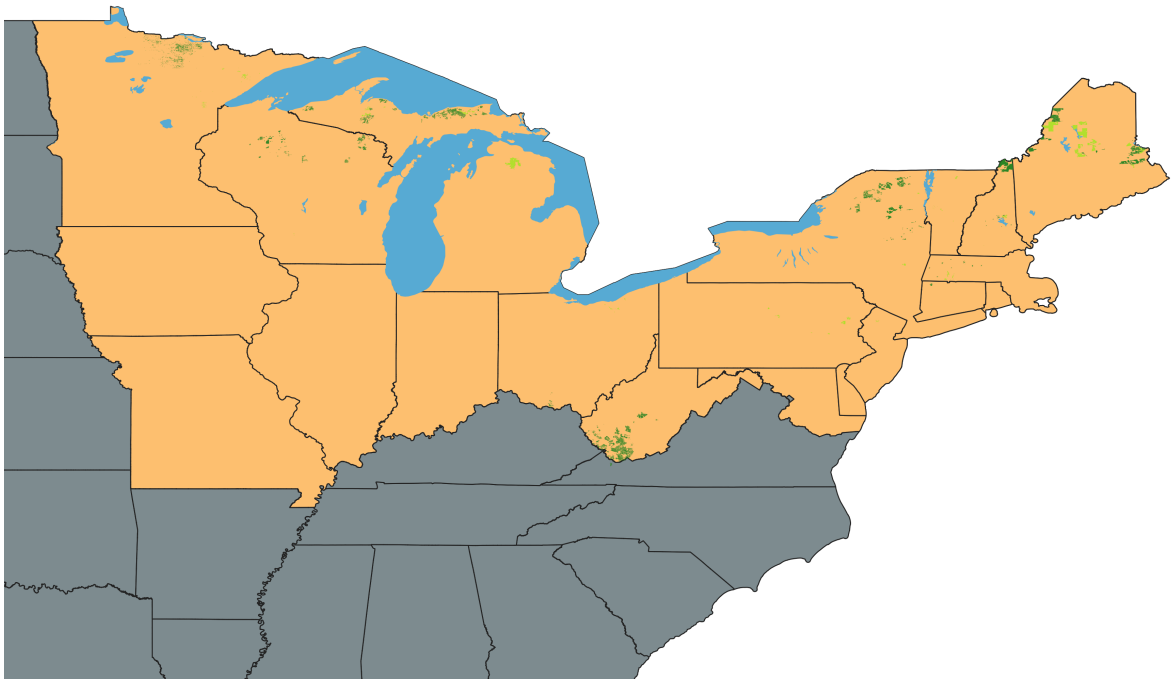
To construct comparable FIA plots with similar carbon storage potentials in later sections, we merge the FIA dataset with a series of geophysical variables including precipitation, growing degree days, soil nitrogen concentration, slope, aspect (Morreale et al. 2021) sourced from NOAA and USDA. Overlapping plots with all these variables non-missing with the IFM project shapefiles we compile for both regulated and voluntary carbon offset markets, we have our dataset with 62 IFM projects overlapping with at least one FIA observational plot with at least two years of survey, including 34 CARB projects and 28 VCM projects. They together span 13 states (except DE, IL, IA, IN, MD, MO, RI), overlaying with 514 effective FIA plots, giving a total of $2,077$ plot-year observations from 1999-2021[20]. The distribution of these 62 projects is in Figure 2. IFM projects on both regulated and voluntary markets are concentrated in forest-rich regions such as Maine, south of West Virginia, and North Michigan.

4.4 Summary Statistics

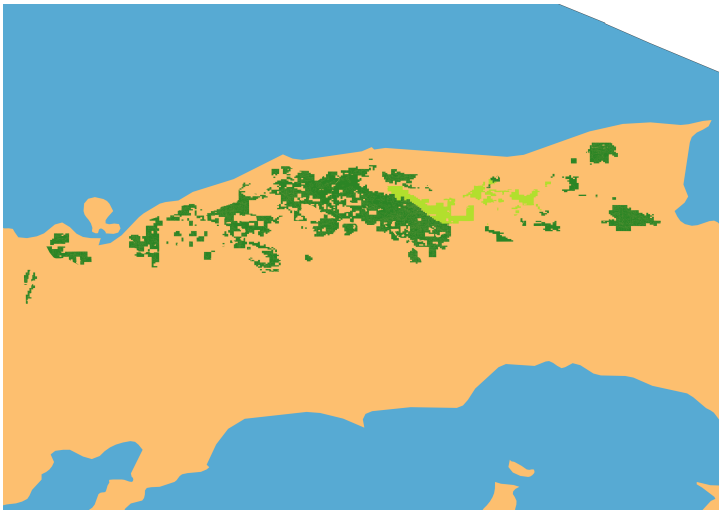
In Table 1, we summarize the basic characteristics, credit issuance, reported and FIA measured carbon inventory of CARB and VCM projects with t-tests on the difference between the two markets. CARB projects have on average the larger area, earlier market participation, and greater share of private land ownership comparing with the VCM projects. Share of historical conservation easement (voluntary legal commitment to perform conservations for ecological protection on private lands) is quite similar across both markets just below 40%. All CARB projects are

[19]Including Connecticut, Delaware, Illinois, Indiana, Iowa, Massachusetts, Maryland, Maine, Michigan, Minnesota, Missouri, New Hampshire, New Jersey, New York, Ohio, Pennsylvania, Rhode Island, Vermont, Wisconsin, West Virginia.

[20]The total number of overlapping plots is slightly higher as 519, 5 are dropped in the matching process described in the next empirical section.



(a) Map of all 62 projects



(b) Map of 3 Michigan projects, CAFR5003/CAR973 (dark green, CARB projects), ACR569, and ACR673 (light green, VCM projects)

Figure 2: Map of 62 IFM projects in Region 9, dark green indicates 34 CARB projects, light green indicates 28 VCM projects.

prepared by agents such as Blue Source (now Anew Climate) and Finite Carbon, but 17.9% VCM projects do not hire agents. A much higher proportion of CARB projects are owned by timber companies (70.6% versus 39.3%). Baseline uncertainties estimated by CARB projects are statistically significantly lower than VCM projects by 3.4 percentage points, but their reversal risks are on average significantly higher by 1 percentage point.

Regarding carbon inventory and credit issuance, VCM projects report to their registries 12.0 $Mgha^{-1}$ higher (10% significance) above ground carbon than CARB projects. Average baseline estimates reported[21] are quite similar at around 47.4 $Mgha^{-1}$. However, VCM projects have lower (but not statistically significant) live carbon storage than CARB projects by FIA measurement up to five years before market entrance, and both markets have FIA carbon much lower than the initial carbon stocks reported to the registries by project developers. The discrepancies are likely due to that FIA plots are different than project sample plots, though both are designed to follow randomized selections[22]. By market protocols, project samples are at least twice the density of FIA plots. Also because FIA plots have been selected years before projects start, there are possibilities that landowners practice different harvesting on them. There are also possibilities that ground measurement of basal areas and conversion to carbon inventories may differ between FIA and market protocols.

By registry reports, baselines used for both markets are lower than initial carbon stocks by significant margins, signaling effective carbon removals as argued by these projects. In terms of credit issuance, due to the differential crediting schemes discussed in the previous section, CARB projects have 4.41 times the initial credit issuance (per hectare) comparing to VCM projects. VCM projects have on average 4.44 times of non-initial (later) credit issuance per hectare comparing to CARB projects, and the average credit per issue (normally covering the vintage of a year) is 2.53 times that of CARB projects. On average, initial credit takes up to 84.6% of total credit issued for CARB projects, comparing with only 28.9% for VCM projects.

[21] For CARB projects, it is taken as the minimum line "common practice" for long-run average. For VCM projects, it is estimated by the 20-year average of projected baseline estimates.

[22] According to CARB, project sample plots used to measure carbon inventories are selected following stratified randomization, with strata defined by common characteristics affecting carbon stocks. These selected project sample plots need to be verified by CARB, but their locations are not made public.

	CARB	VCM	T-Statistic	P-Value
Basic Characteristics				
N	34	28		
Area [Hectare]	33941.027	10718.519	3.176	0.002
Entrance Year	2016.735	2018.714	-2.669	0.010
Shr. Private Land	0.765	0.571	1.629	0.109
Shr. Historical CE	0.382	0.393	-0.083	0.934
Shr. Agent Prep.	1.000	0.821	2.674	0.010
Shr. Timber Owned	0.706	0.393	2.563	0.013
Base. Uncerts.	0.043	0.077	-7.518	0.000
Reversal Risk	0.183	0.174	2.992	0.004
Registry Reported Information				
Initial Carbon Stock $[Mgha^{-1}]$	65.807	77.842	-1.947	0.056
Baseline $[Mgha^{-1}]$	47.407	47.452	-0.012	0.991
Initial Credit $[ha^{-1}]$	61.637	13.979	6.299	0.000
Initial/Total Credit	0.846	0.289	12.243	0.000
Later Credit $[ha^{-1}]$	8.212	36.499	-4.007	0.000
Avg. Later Credit $[ha^{-1}]$	2.728	6.904	-3.892	0.000
FIA Observations				
Five-Year Pre-Market Period Above Ground Carbon $[Mgha^{-1}]$	58.886	48.733	1.430	0.158

Table 1: Summary Statistics and Statistical T-test Results of Difference Between CARB and VCM Projects

Notes: The table presents t-test results for the difference between regulated and voluntary carbon offset market projects. Tests are conducted at project level. Table displays mean across projects and t-statistics plus p-values of the tests. Not all projects available have enough FIA observations before treatment, one of the VCM project (CAR 646) is dropped. Market entrance year is defined as starting year of first vintage if month is before July, or next year of the starting of first vintage if month is July or after. Initial crediting start period is not available for Climate Action Reserve registered projects, thus we use the initial vintage as the starting time of their projects. CE stands for conservation easement. Agent stands for preparing agent on behalf of project proponents (for example, Blue Source, Finite Carbon). Initial credit indicates the credit issued for first vintage year of the project. Total credit and non-initial (later) credit issuance are noted from registry record until July 2023. Average later credits is the mean taken across all later issuance.

4.5 Live Carbon Time Series Trends

With ground-truth FIA measurements tracking back to 1999, we are able to observe the above-ground live carbon trends before and after market entrance for both CARB and VCM projects, which are not reported in CARB and carbon registry documents. We apply time-series regressions on FIA observations within the 62 IMF projects to estimate and display the trends in Figure 3[23].

Combining projects on both markets, their carbon stocks increase since over 10 years before and continue after their market entrance. Separately, there are differential biomass time-series trends for CARB and VCM projects. The regression estimated average above ground carbon for CARB projects increases but holds steady from ten years before to five years after market entrance. Its carbon stock estimate is never below $40 Mgha^{-1}$. The carbon level for VCM projects are lower, estimated to be below $40 Mgha^{-1}$ and decreasing towards about $35 Mgha^{-1}$ five years before entering the voluntary market. It sees a sudden jump after market entrance, reaching higher average carbon inventory than CARB projects (but with no statistical significance). But due to later market entrance and smaller project areas, there are limited statistical evidence post-market whether this higher level of VCM project carbon maintain.

Overall, time series comparison has shown that there are different trends of carbon stocks for CARB and VCM projects especially before offset market entrance, due to their differential forest management strategies lasting years before considering the option of offset markets. It implies that selections into different carbon offset markets are correlated with historical (pre-market) forest management activities, because expected payoffs of these IFM projects in either market are affected by these historical practices, as suggested by our theoretical model.

5 Empirical Strategy

5.1 Constructing Matching Controls by Forestland Carbon Storage Capacities

On the current carbon offset markets, "baselines" are defined as the scenario where forest management (mainly regarding tree harvesting intensities) assume no entrance of the market. In market protocols and project documents, "business-as-usual" is used to described the forestry practices applied in the counterfactual baseline scenarios[24]. However, project practices before entering

[23]For sample projects' FIA biomass trends consistent with these time series regression estimates and their controls' approximately flat pre-market trends, see Appendix Figure C.1.

[24]There may be descriptive word for "business-as-usual" itself, for example, "conservative business-as-usual".

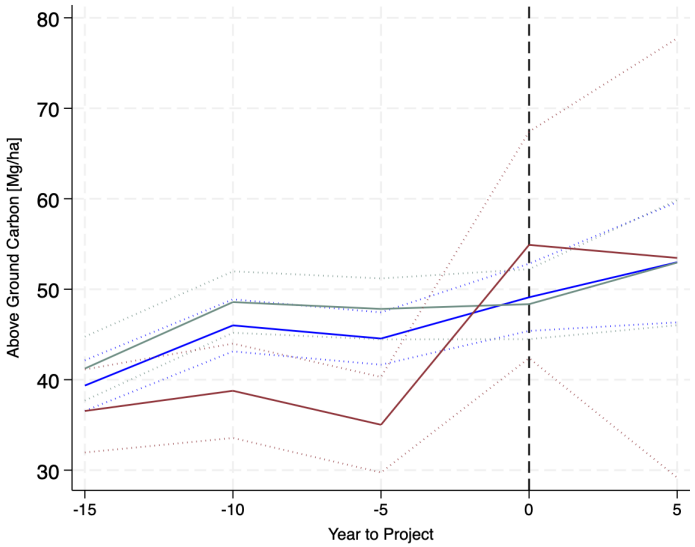


Figure 3: Time series comparison plots for above-ground carbon storage

Notes: Blue=all projects, Green=CARB projects, Red=VCM projects. Average and 95% confidence intervals (marked by dotted lines) are estimated with regressions $LiveCarbon_{it} = \sum_{k=-15,-10,-5,0,5} \beta^k B_{it}^k + \epsilon_{it}$ *and* $LiveCarbon_{it} = \sum_{k=-15,-10,-5,0,5} \beta^{ck} B_{it}^k \times CARB + \sum_{k=-15,-10,-5,0,5} \beta^{vk} B_{it}^k \times VCM + \epsilon_{it}$*. In regressions,* i *is the FIA plot and* t *is observational year.* B^k *are bin indicators of years* $t \in [k, k+4]$*, relative to market entrance year of* 0*. No constants are controlled in this regression. Standard errors are clustered at FIA plot level. Indicators* $CARB$ *and* VCM *denotes whether the FIA plots overlay with projects entering the regulated or voluntary carbon offset markets. Each point observation plots the estimator* β *indicating approximate average FIA measured above-ground carbon (unit:* $Mgha^{-1}$*) within five-year bins (e.g., observation at year* $5n$ *average across the 5-year bin of* $[5n, 5n+4]$*. End bins are* $(-\infty, -11]$ *and* $[5, \infty)$*. Vertical line indicates market entrance year (defined as starting year of first vintage if month is before July, or next year of the starting of first vintage if month is July or after).*

the carbon offset markets are not reported discretely, and checking simulation parameters with business-as-usual practices is not very applicable.

In this paper, we will use market entrance outcomes and forestland potentials to store biomass carbon to identify historical forestry practices. According to our theoretical model, different pre-market forest management plan $\mathbf{A}$ affects market entry decisions for forestland with similar live carbon storage capacities defined by characters $\mathbf{G}$. Therefore, we first need to construct our own reference control FIA plots, different to the baselines used for current offset markets' credit issuance, as the comparable land parcels not engaging with any carbon offset markets, through matching on land characteristics $\mathbf{G}$.

For each within-project FIA observational plot, we use a list of geophysical variables critical to the levels of above-ground carbon storage capacities as matching variables. These variables include average precipitation level (over 10 years), average growing degree days (GDD) (over 30 years), soil nitrogen concentration (measurement 2018), average plot slope, average plot aspect (angle of orientation) from Morreale et al. (2021), and categories of forest type (defined by FIA). Considering that land ownership status is related to forestland owner's payoff function and financial constraints, we also include private versus non-private ownership status (defined as private if at least one year of survey has been recorded as private land by FIA) as a matching variable.

We employ Nearest Neighbor Matching with Mahalanobis distance, five neighbors with replacement (NNM-5n) with the seven matching variables. Precipitation is matched exactly by pooled sample[25] quintiles. Forest type and ownership status are also matched exactly by categories. The other continuous variables (GDD, slope, aspect, nitrogen concentration) are matched with calipers set as the pooled sample's standard deviations. For robustness checks, we also use two alternative matching methods, Nearest Neighbor Matching with Mahalanobis distance, one neighbor with replacement (NNM), and Coarsened Exact Matching (CEM)[26].

In Appendix Figure D.1, we show the balance checks for our main NNM-5n matching results. All matching variables have their matched control average close (within 0.05 of absolute standardized mean difference) to their treatment (in-project plots) means. The average matching error, MSMD (mean of the standardized mean differences over all matching variables), is as low as 0.00668. In this way, we effectively construct forest control plots comparable in terms of carbon

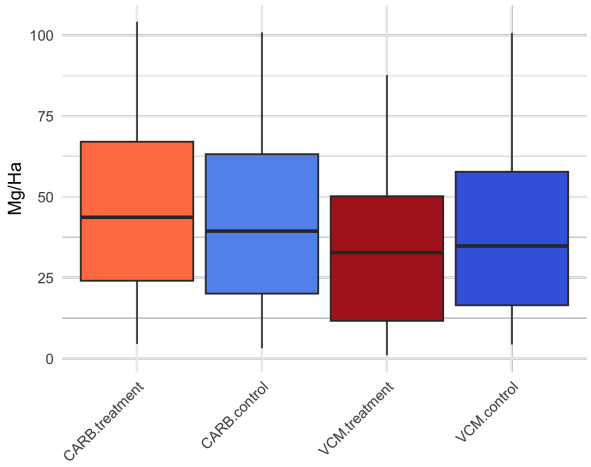
[25] With 519 treatment plots within IFM project borders, and all 38,101 potential control plots outside projects.

[26] Match by exact coarsened groups of each continuous variables' quintiles (precipitation, GDD, nitrogen concentration, slope, aspect), and exact categories by forest type and ownership group.

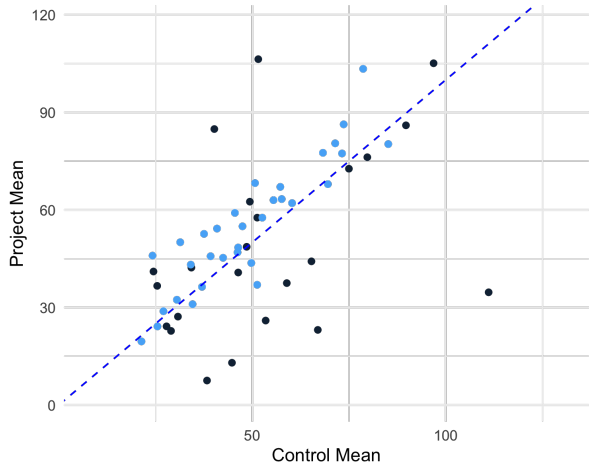
storage potentials to our IFM project plots.

5.2 Comparison of Project Pre-Market Above-Ground Carbon Levels with Matched Controls

We compare per hectare above-ground carbon levels up to five years prior to market entrance between project plots and their no-entry matched control plots with similar live carbon storage capacities in Figure 4. Panel (a) box plot has shown that, on average, CARB projects' pre-market biomass carbon storage is higher than their controls, while VCM projects' above-ground carbon levels are on average lower than their controls. Panel (b) project-level scatter plot further illustrates the same observation, with CARB projects majorly have their pre-market carbon levels above their controls, while most VCM projects have lower pre-market carbon stocks than their controls. Extending beyond five years before market entrance and including all pre-market FIA observations, Appendix Figure E.1 shows the similar results.



(a) Box Plots comparing average above ground carbon ($Mgha^{-1}$) for CARB and VCM project plots and their matched control plots. Blue bars are controls, red bars are treatments. Light color bars are CARB projects, dark color bars are VCM projects.



(b) Scatter comparison of average above ground carbon per hectare ($Mgha^{-1}$) by CARB projects traded on the regulated market (light blue dots) and VCM projects on the voluntary carbon market (dark blue dots). Vertical axis is the project-average carbon measure, horizontal axis is the project's control plots average carbon measure, all taken before the project start trading on the markets (pre-market period). The 45-degree dashed line separate projects that are above or below their controls.

Figure 4: Comparison for Five-Year Pre-Market Above-Ground Carbon Storage Between Project and Matched Control Forest Observational Plots

Summary statistics and statistical t-test for project versus matched control and reported carbon inventories and related matching variables are presented in Table 2. CARB projects have on average the higher growing-degree days, greater soil nitrogen concentrations, similar precipitations and aspects. As a result, CARB projects are likely forestland with greater carbon storage capacities relative to VCM projects. But meanwhile, the greater slope of CARB projects may also lead to thinner tree growth. As a result, the actual carbon storage capacities for CARB and VCM project plots may be ambiguous. By the greater average of pre-market biomass for CARB control plots versus VCM control plots (Figure 4 Panel (a) blue boxes), CARB projects are more likely to have greater carbon storage capacities.

Using t-tests, CARB projects are shown to have statistically significantly higher carbon inventories than their matched controls. Pre-market carbon stocks for VCM projects have been lower than their controls, but the difference is not statistically significant at plot level t-test. Between ground-truth FIA measured live carbon and project submitted measurements of initial carbon stocks and estimated baseline carbon, our t-tests show that initial carbon estimates reported on both markets are significantly higher than the FIA values, consistent with Table 1. However, CARB and VCM projects have submitted statistically similar levels of baseline carbon stocks used for credit issuance to our matched controls constructed with a very different principle. Since baseline projections are supposed to quote common practices representing forest conditions on similar lands, this principle is not violated by our results. If there are suspected reporting issues related to over-crediting on the two carbon offset markets, higher reported initial carbon stocks (used as the starting point of forest simulations) inconsistent with FIA measurement seem to be more of a problem. Otherwise if there are systematic upward bias between reported carbon and FIA measurement, we would expect higher baseline average carbon levels to our constructed matched controls. Then the dubious activities will come from the drastic drops of baseline simulation stocks at the beginning of market entrance (Appendix Figure A.1, which may be deviating from business-as-usual forestry practices under ambiguous forest protocols.

5.3 Event Study Analysis

To observe the trends of above-ground biomass carbon relative to matched control plots and identify pre-market forest management $\mathbf{A}$, our main empirical strategy will be to run event study type regressions. Because FIA's rotating survey frequency (remeasurement gap) is about 5.45

	CARB	VCM
Summary Statistics		
N	34	28
N. of FIA Plots	384	130
Area [hectare]	33941.027	10718.519
Entrance Year	2016.735	2018.714
Geopotential Variables for Matching		
Avg. GDD [degree-day]	5727.666	5156.598
Avg. Precip. [mm]	1048.856	1081.997
Aspect [radian]	0.320	0.364
Nitrogen Conc. [mgL^{-1}]	6.492	5.264
Slope [degree]	16.109	7.676
Report Statistics Summary [$Mgha^{-1}$]		
Baseline Average	47.407	47.452
Initial Carbon Stock (ICS)	65.807	77.842
Five-Year Pre-Market Period Above Ground Carbon [$Mgha^{-1}$]		
Project	58.886	48.733
Control	50.323	55.795
T-tests		
Project vs Control	2.637***	-1.524
Project vs ICS	-2.920***	-8.074***
Control vs Registry Baseline	1.526	1.293

Table 2: Summary and statistical t-tests of pre-market project and control above ground carbon in comparison with one another and registry reported statistics

*Notes: The table presents t-test results for the difference between average above ground carbon per hectare ($Mgha^{-1}$) for treatment versus matched control FIA plots, treatment versus registry reported ICS (inicial carbon stock), and control versus baseline (taken as common practice for CARB, over 20-year baseline average for VCM). Table displays t-statistics of the tests, with p-values indicated by asterisks, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Not all projects available have enough FIA observations before treatment, one of the VCM project (CAR 646) is dropped. Two Verra registered VCM projects are further dropped with lack of ICS data, and one ACR registered VCM project lacks baseline carbon projections.*

years, we group forest inventory observations by 5-year bins to increase statistical significance, ranging from 10 years before and 5 years after IFM projects' market entry years. The event study regression we run is:

$$LiveCarbon_{it} = \alpha + \sum_{k=-15,-10,-5,5} \beta^k Project_i \times B_{it}^k + \delta_t + \psi_i + \epsilon_{it} \tag{1}$$

Where B^k are bin indicators of FIA survey years $t \in [k, k+4]$ relative to market entrance year of $t = 0$. $Project_i$ indicates if the plot i is within a CARB or VCM project, being 0 if the plot is a matched control. Regression is weighted by the matching weights. Linear controls include survey year (t) and plot (i) fixed effects. Standard errors are clustered at the FIA plot level. The estimated series of β^k are plotted against k to illustrate the pre- and post-market trends of IFM project above-ground carbon relative to their matched controls.

Another regression with market indicators interacting with time bins is run to identify the differential live carbon trends of CARB and VCM projects:

$$\begin{aligned} LiveCarbon_{it} = \alpha &+ \sum_{k=-15,-10,-5,5} \beta^{ck} Project_i \times B_{it}^k \times CARB \\ &+ \sum_{k=-15,-10,-5,5} \beta^{vk} Project_i \times B_{it}^k \times VCM + \delta_t + \psi_i + \epsilon_{it} \end{aligned} \tag{2}$$

β^{ck} and β^{vk} will be plotted separately to represent the relative trends of IFM projects on regulated and voluntary carbon markets.

5.4 Multinomial Logistic Regression

Multinomial logistic (MNL) regression is useful for modeling discrete decisions making by rational project developers. In our theoretical model, the decisions of entering regulated, voluntary, or neither market depend on the characteristic set $(\mathbf{G}, \mathbf{A})$. With $\mathbf{G}$ represented by the series of geophysical and socioeconomic matching variables we use (GDD, soil nitrogen concentration, precipitation, slope, bearing, private ownership, forest type), our main event study analysis will further allows pre-market forest management variables $\mathbf{A}$ to be represented by pre-market biomass trends relative to matched controls with similar $\mathbf{G}$. We will then approximate this as a single variable *gradient* estimated as the FIA plot-specific slope of above-ground carbon on observation year

using the simple linear regression:

$$LiveCarbon_{it} = a_i + b_i Year_{it} + \epsilon_{it}$$

This OLS will be run separately for each project or matched control plot, and limiting to pre-market periods only for in-project plots. The set of estimated $\hat{b}_i$ will be the *gradient* variable, representing the forest management plans without offset market participation. To further increase precisions due to the uncertainties accompanying the estimations of *gradient* by OLS, we further bin this indicator for forest management activities and use the variable of $gradient^+ = \mathbf{1}_{gradient>=0}$.

Then MNL will be run as:

$$Pr(D_i = k) = \frac{\exp(\alpha_k + \beta_k gradient_i^+ + \lambda_k' \mathbf{G}_i)}{\sum_k \exp(\alpha_k + \beta_k gradient_i^+ + \lambda_k' \mathbf{G}_i)} \quad k = -1, 0, 1 \tag{3}$$

Where the decisions D_i have three choices, $k = 0$ (no market entry, taken as the base category), $k = -1$ (enter voluntary market), $k = 1$ (enter regulated market). Decision factors $\mathbf{Z}$ includes *gradient*, the seven $\mathbf{G}$ variables (forest type as categorical binary indicators), and a constant term. Regression will be weighted by matching weights. Standard errors are clustered at project or project-grouped control level.

To address the uncertainties in the first stage *gradient* estimates as well as the non-linear second stage logit model, we also use Bootstrapping of $1,000$ trials to produce the Bootstrap confidence intervals for these estimates. The estimated λ coefficients (the direct estimate instead of the Bootstrap ones) will be used for robustness check on our event study analysis, and for state-level welfare analysis later in the simulation extension section.

5.5 Heterogeneity Analysis

In reality, market and individual project level factors can influence the entry decisions of IFM projects. To explore these factors, we will use the heterogeneity analysis design on the previous event study regression Eq. 2:

$$\begin{aligned} LiveCarbon_{it} = \alpha + \sum_{g \epsilon G} [& \sum_{k=-15,-10,-5,5} \beta^{ckg} Project_i \times B_{it}^k \times CARB \times \mathbf{1}_g \\ & + \sum_{k=-15,-10,-5,5} \beta^{vkg} Project_i \times B_{it}^k \times VCM \times \mathbf{1}_g] + \mathbf{X}'\gamma + \delta_t + \psi_i + \epsilon_{it} \end{aligned} \tag{4}$$

Where $g \in G$ separate projects by their characteristics, including history of conservation easement, use of preparing agent, timber company ownership, entrance timing, and project area. Event study plots are then compiled separately for projects with character g on either regulated or voluntary market.

6 Results

6.1 Event Study Analysis

Our event study analysis results with Eq. 1 and 2 are presented under Figure 5.

In Panel (a), across all IFM projects registered on either regulated or voluntary carbon offset markets, FIA measured per hectare above-ground carbon stock has been flat or slightly increasing relative to matched control plots not on the carbon markets and of similar carbon storage capacities, since at least 11 years prior to them participating in the offset markets. After their market entrance, biomass carbon sees a significant jump in the 0-4 years post-market interval. But because of limited post-market FIA surveys, such carbon storage increase does not have statistically significant evidence to be persistent after five years of the market entrance from the regression.

Panel (b) shows the pre-market above-ground carbon trends for CARB projects on the regulated market. With continuously rising carbon inventories relative to controls since more than a decade prior to engaging with the regulated market, the relatively trend remains non-increasing and statistically insignificant from zero since the five-year period before market entrance to after the market entrance. These observations then cast doubts on the incentive of CARB projects entering the regulated carbon offset market. If they are motivated by the opportunity to trade on their historical forest preservation efforts for the past decade, there will be likely additionality problems on the regulated offset market.

Panel (c) presents the above-ground carbon storage trend relative to controls for VCM projects listed on the voluntary offset market. Notably, the pre-market biomass trend is decreasing continuously up to the entrance year, reaching about $7.5 Mg ha^{-1}$ statistically significantly lower carbon inventory level than their matched controls in the 1-5 years bin before market engagement. Immediately after market entrance over the 0-4 years bin, the decreasing trend is reverted and there is a sharp relative increase in VCM project biomass, implying the effectiveness of the new improved forest management plans these projects follow due to their market entrance choices. However again

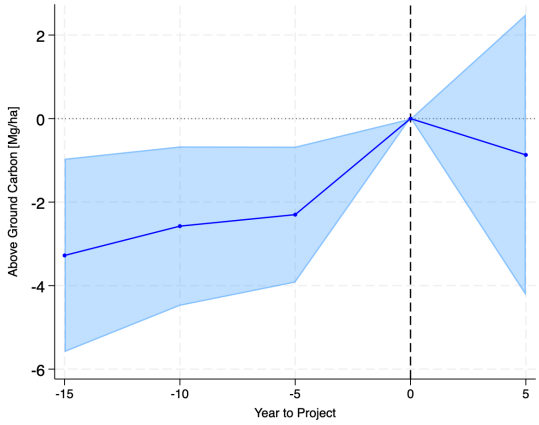
there is no sufficient statistical evidence from this regression after five years of market entrance whether this high carbon stock and increasing carbon trend is maintained. With the negative but statistically insignificant estimate for the post five years bin, the jump in carbon storage at market entrance may not be persistent.

Therefore, using event study analysis, we have recovered the differential pre-market biomass trends relative to similar carbon storage capacity controls for CARB and VCM projects. As argued by the previous theory section, these analysis produce estimates for pre-market relative biomass trends indicative of IFM projects' under-reported historical forest management plans. CARB projects with increasing biomass trend implies them practicing forest conservation before considering the choice of carbon offset markets. VCM projects with decreasing biomass trend shows them opting more aggressive harvesting relative to forestland with similar geophysical characteristics and defined carbon storage capacities until after entering the carbon offset market. These show the effects of historical forestry practices on IFM project developers' market entrance choices between regulated and voluntary offset markets. Reasons for these sorting are likely correlated with the differential credit issuance schemes for the two markets. High initial issuance on the regulated market would encourage CARB projects with high and increasing carbon inventory to enter. Gradual issuance scheme would motivate VCM projects with greater potentials to earn from the change of forestry practices and later accumulations of biomass.

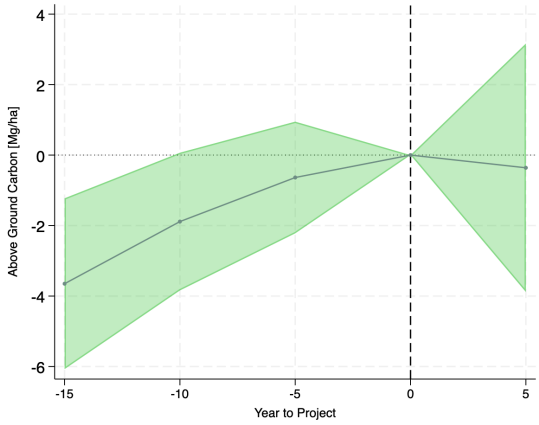
These event study results are robust to using a slightly different definition of market entrance (by project claimed starting time in their documents), or using alternative matching methods for the selection of control plots (Appendix Figure F.1, F.2, F.3). F-test of the three pre-market five-year bin estimates ($(-\infty, -11], [-10, -6], [-5, -1]$ in Eq. 2) being identical between CARB and VCM projects has been rejected at 1% (F-statistic of 4.62, p-value of 0.0032), affirming that CARB and VCM projects have statistically significantly different pre-market biomass trends relative to controls with similar carbon storage capacities.

We also find supportive evidence through other FIA variables related to forestry practices, including harvesting and dead wood management. We inspect two harvesting variables, removed basal area per hectare (unit: $m^2 ha^{-1}$) per year, and the ratio of removed basal since last period over the current-period standing basal[27]. In general, CARB projects have lower harvesting than VCM projects (0.201 versus 0.355 removed basal, and 0.010 versus 0.019 removed basal ratio, both

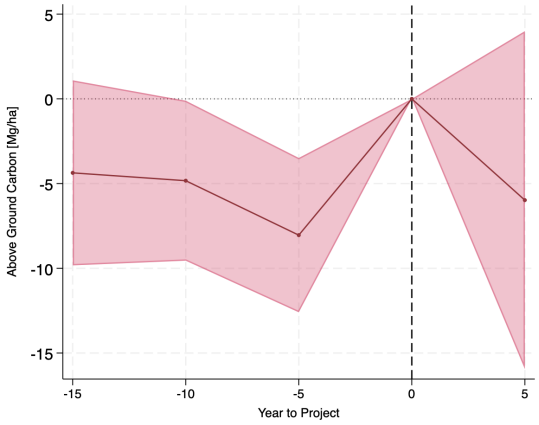
[27]Because removed trees are directly computed from the difference between consequent FIA surveys, the two harvesting variables are correlated with one another as well as with the changes in above-ground carbon.



(a) All



(b) CARB



(c) VCM

Figure 5: Event study plots for FIA measured above-ground carbon storage

Notes: Average and 95% error bars are estimated with regressions Eq. 1 and 2. Each point observation indicates approximate average FIA measured above-ground carbon (unit: $Mgha^{-1}$) within five-year bins (e.g., observation at year $5n$ average across the 5-year bin of $[5n, 5n+4]$), relative to observations from nearest-five-neighbor matching control plots with similar geopotentials. End bins are $(-\infty, -11]$ and $[5, \infty)$. Vertical line indicates market entrance year (defined as starting year of first vintage if month is before July, or next year of the starting of first vintage if month is July or after).

rejected by 1% t-test), leading to the higher and relatively increasing live carbon stocks of CARB projects and the lower and relative decreasing biomass trends of VCM projects. Running event studies for these two variables in Appendix Figure G.1, there are some pre-market decreasing trends in both harvesting variables for CARB projects, and a very slight increasing trend of the removed basal for VCM projects, implying pre-market decreasing harvesting for CARB projects and increasing harvesting for VCM projects but with no statistical significance. For dead wood management, we look at the per-hectare dead basal area (unit: $Mgha^{-1}$). T-test has verified 1% statistically significantly higher dead biomass for VCM projects versus CARB projects (2.013 versus 1.609), suggesting better management for CARB projects. Event study plots in Appendix Figure G.2 show no statistically significant evidence of changing dead biomass management for both CARB and VCM projects pre-market.

6.2 Multinomial Logistic Regression (MNL)

As described in the empirical section previously, firstly we construct the *gradient* variable by simple OLS between non-market or pre-market biomass carbon levels and FIA observational years. The average *gradient* point estimate across 355 plots in CARB projects is 0.362, for 129 VCM plots is 0.062, for 1,869 no entrance control plots is 0.270[28]. These replicate the carbon trends in our event study main analysis, showing that CARB projects have higher gradients than no-entrance controls, while VCM projects have lower gradients than controls, though those differences are not statistically significant by t-tests. In terms of proportion of *gradient* being non-negative, CARB plots have the highest probability of 0.738, followed by no entry plots of 0.676, then VCM plots of 0.605, indicating $gradient^{+}$ correlated with market entrance choices.

Using $gradient^{+}$ as the indicator for historical forest management and fit in the MNL regression model, we produce the estimators in Table 3. $gradient^{+}$ as the indicator for historical biomass trend has just significant positive coefficient on regulated market entry, and negative (with no statistical significance once Bootstrapping) coefficient on voluntary market entry. The signs of these coefficients on $gradient^{+}$ indicate that increasing pre-market carbon stock is positively correlated with the entrance of CARB projects in regulated market, and negatively correlated with the choice of VCM projects to enter the voluntary market. Therefore, MNL results are consistent with the previous event study analysis, indicating that pre-market forest management practices

[28]Note 54 plots are dropped from the sample due to insufficient observations for OLS.

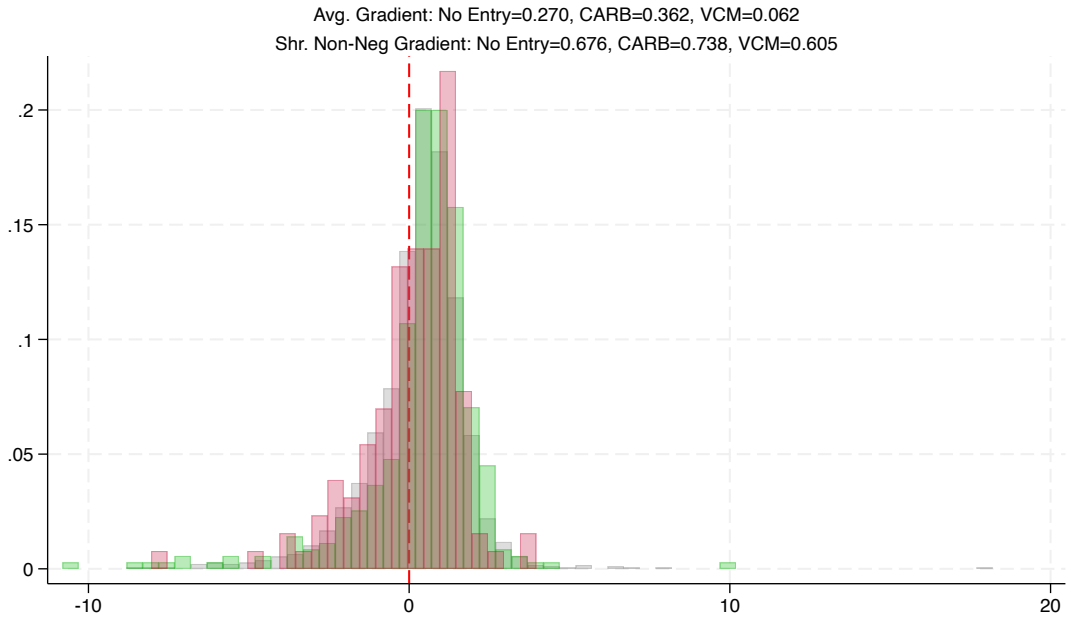


Figure 6: Summary Histogram for *Gradient* Estimates by Entry Choices, No Entry=Gray, CARB Entry=Green, VCM Entry=Red

significantly influence the market entry decisions. Greater biomass accumulations lead to entrance into the regulated market which awards high level of initial carbon stocks. Decreasing biomass practices lead to entrance decisions into the voluntary market, where reverting the decreasing trend is rewarded by offset credits.

Most of the other forest land characteristic factors we include do not have statistically significant coefficients. One of the two exceptions is private ownership, where estimates indicate it encourages regulated market entrance, discourages voluntary market entrance, likely due to private entities seeing greater potentials of profits by the regulated market mechanism. The other exception is nitrogen concentration by Bootstrapping results, which indicates that higher nitrogen concentration in soil (therefore more nutrient land) encourages entrance into regulated market, and discourages entrance into voluntary market. This is likely due to that richer soil means greater biomass capacity of forest and greater biomass levels before market entrance, hence will be more profitable on the regulated offset market.

6.3 Heterogeneity Analysis

In this subsection, we will conduct a series of heterogeneity analysis with Eq. 4 to observe additional factors affecting the sorting of IFM projects with different pre-market forest management

	Direct Estimate		Bootstrap Estimate	
	Entry=CARB	Entry=VCM	Entry=CARB	Entry=VCM
$\mathbf{1}_{\{gradient \geq 0\}}$	0.3005*	-0.3171*	0.3125**	-0.2416
	(0.1656)	(0.1734)	(0.1489)	(0.2356)
Avg. GDD	-0.0000	-0.0004	-0.0000	-0.0004
	(0.0004)	(0.0006)	(0.0001)	(0.0003)
Avg. Precip.	-0.0004	0.0011	-0.0004	0.0011
	(0.0017)	(0.0016)	(0.0004)	(0.0008)
Aspect	-0.0093	-0.0771	-0.0092	-0.0940
	(0.1393)	(0.1649)	(0.1085)	(0.2050)
Nitrogen Conc.	0.1113	-0.2999	0.1153**	-0.3314***
	(0.1591)	(0.3065)	(0.0492)	(0.1223)
Slope	0.0053	-0.0041	0.0056	-0.0052
	(0.0101)	(0.0159)	(0.0057)	(0.0133)
Private Own.	3.2688***	-2.4282**	7.7959***	-2.4708***
	(1.0842)	(1.1425)	(6.4107)	(0.3426)
Forest Type=100	0.0342	0.2895	0.0306	0.3197
	(0.6569)	(0.5438)	(0.3212)	(0.4935)
Forest Type=120	0.3663	-0.2427	0.3772	-0.2271
	(0.6647)	(0.4192)	(0.2406)	(0.4060)
Forest Type=400	-0.3664	0.5947	-2.1947	-0.1475
	(1.3305)	(1.1450)	(4.8666)	(3.3726)
Forest Type=500	0.1588	0.3558	0.1917	0.4733
	(0.9890)	(1.2571)	(0.4001)	(0.9988)
Forest Type=700	0.2552	0.0693	0.2177	-1.8543
	(0.8585)	(0.9245)	(0.4897)	(4.9784)
Forest Type=800	0.3307	-0.3612	0.3395	-0.3181
	(0.9207)	(0.4833)	(0.2234)	(0.3896)
Constant	-4.2627	3.7300	-8.7569***	4.0007***
	(2.8421)	(3.1798)	(6.4889)	(1.6744)

Table 3: Multinomial Logistic Results on Carbon Offset Market Entry Choices with $gradient^{+}$ as Historical Forest Management Activity Indicator

*Notes: Base category being no market entry (matched control plots). Standard errors in parentheses clustered by project or project-grouped controls. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Omitted forest type being FIA code=900. $N = 2,353$, Pseudo R-squared=0.0807, Brier's score=0.188. For Bootstrap, 1000 runs are taken separately on simulating $gradient^{+}$ regressor with first-stage entrant plot-level OLS coefficients and standard errors, and bootstrapping with replacement on second-stage sample of $N = 2,353$. 1 run is dropped for no convergence, so $S = 999$. Mean of estimates and standard errors with Bessel's correction are reported for Bootstrap. Confidence levels for the estimates are determined by empirical distribution of the Bootstrapping results.*

on the regulated and voluntary markets.

By Conservation Easement Conservation easements (CE) are voluntary agreements with legal bindings entered by private land owners in order to protect lands through reducing industrial, commercial and agricultural practices. As a trade-off, CE participants enjoy certain tax benefits[29]. Projects with historical CEs could have already started with IFM practices such as reduced harvesting, and have higher and relatively increasing biomass before any market entrance. Projects with CEs may also have more experience in forest conservation, therefore having reduced project management costs post-market, which motivates them to enter the markets. Meanwhile, historical conservation practices could make it harder for project developers to argue for low carbon level baselines, discouraging them from offset market entrance.

To explore this question, we identify through documents a total of 24 projects with prior CE records, 13 CARB projects on the regulated market, and 11 VCM projects on the voluntary market. Heterogeneity analysis displays the event study results in Appendix Figure H.1. For CARB projects, CE and non-CE projects both have pre-market relative increasing above-ground carbon, signaling prior-conservation forestry practices regardless historical CEs. Post-market estimates, though statistically insignificant, are more different between the two subgroups. Those with CE seem to reduce the carbon stocks after entering the market, while those without CE continue to increase their carbon stocks. For VCM projects, CE guarantees flat but low relative carbon trend before market entrance, comparing with the non-CE VCM projects with decreasing carbon stocks. These are consistent with that CE signals lower harvesting historically, and also show that among those CE projects, still those with lower harvesting eventually enter the regulated market, while those with heavier harvesting enter the voluntary market.

By Timber Company Ownership Due to forgone commercial harvesting profits, costs of shifting forest management plans for timber companies could be higher than other landowners. In our sample, more than half of the 62 projects are owned by timber companies (35), most CARB projects (24). Heterogeneity analysis is run by timber company ownership (Appendix Figure H.2), showing that non-timber company owned IFM projects have flat and statistically insignificant pre-market biomass trends on both regulated and voluntary markets, and timber company owned projects have the same trends by CARB and VCM projects in Figure 5. Therefore,

[29]Source: https://www.conservationeasement.us/what-is-a-conservation-easement/.

timber companies are important players on the offset market, featuring the market entrance sorting according to historical forestry practices we see in the main results, and showing recognition of the cost and benefit differences between the two markets upon their entrance.

By Preparing Agent With higher latent costs of market entrance on additional calculations, measurements and document compilations, all CARB projects hire an agent to prepare and manage their market participation. 23 out of 28 VCM projects also hire agents, since submissions to carbon registries also require much efforts[30]. Separating VCM projects with or without agents, Appendix Figure H.3 provides suggestive evidence that projects not hiring agents have flat instead of decreasing pre-market carbon stocks. Considering that project developers practicing aggressive harvesting pre-market could have lower carbon levels to start with but expect higher gains on the voluntary market shifting to less harvesting, they may indeed find hiring agents to be affordable and beneficial in arguing for their projects.

By Area Dividing 62 projects by their the median area reported to registries (20,936 acres), heterogeneity analysis (Appendix Figure H.4) shows that both small and large area projects on either market have the same overall pre-market biomass relative trends (CARB increasing, VCM decreasing). Post-market evidence is again weak with no statistical significance, but CARB projects with smaller areas see some increasing in carbon stocks post-market, while larger ones do not. As a result, project sizes seem to be not significantly correlated with market entrance decisions, but there are possibilities that post-market forest managements are correlated.

By Entrance Timing As protocols for forest projects changes over time, entrance costs will also evolve. Furthermore, market structure and consumer preference also shift over time. As a results, early or late entrance into offset markets may be important for the decision makers. To explore this, we divide the 62 projects with the median of their documented starting date (August 2017) and run heterogeneity analysis in Appendix Figure H.5. While CARB projects have similar increasing above-ground carbon pre-market trends regardless of early or late entrance, early entrance VCM projects (7) show different flat trends before market participation, comparing with late projects with decreasing carbon stocks. It is possible that as the voluntary market matures, VCM projects

[30]This choice of using agents are not necessarily related to whether the owner is a timber company. Among the 5 VCM projects instead prepare documents by themselves, 2 are owned by timber companies.

with low carbon stocks and high harvesting rates realize the difference between the two offset markets and begin to enter the voluntary one allowing them more to gain from switching their harvesting plans.

7 Simulations

In the previous section, we have shown that pre-market forest management plans are correlated with market entrance decisions into regulated versus voluntary carbon offset markets. In this section, we will use forest simulation models to argue for the causality relationship between historical forest management, credit issuance schemes, market entrance outcomes, expected economic and environmental benefits from these markets.

7.1 Set-Up

The simulation model we adapt is the LANDIS/PnET model, which will simulate forest cover trajectories on a typical hypothetical Maine landscape of $50,000$ hectares, within which $5,000$ hectares are designated as the IFM project land. Comparing with the tree-based FVS model used in most forest projections by IFM project developers, the LANDIS II model considers landscape dynamics, with trees growing at different locations interacting with one another. For example, LANDIS II accounts for competitions between trees growing at different locations, and it can sometimes allow growing trees through pollenate to places where there were previously no trees.

In this model, forest management can be defined by harvesting interval (frequency of harvesting), harvesting rate (percentage of area being harvested), harvesting scheme (percentage of biomass to be removed on the harvest area), and the minimum rotation period (the minimum age a tree is allowed to be cut). In practice, decreasing harvesting rate and increasing rotation period are two major IFM options chosen on the carbon offset markets. In our simulation, we will make the simplification that forest management is shifted only by applying different harvesting rates. We set the model at 1-year harvest interval, minimum rotation period of 20 years, and 65% harvesting scheme[31][32]. All simulation runs will start with the same initial landscape biomass $50 Mgha^{-1}$ across the whole field including both project and non-project lands, and generate biomass trajectory for 150 years with above-ground biomass estimates produced every five

[31] This avoids the controversial practice of clearcut (100% removal of all basal areas on the harvesting site).

[32] In future analysis, changing forest management through increasing rotation period or decreasing the harvesting cut will also be studied.

years.

By running simulations on the same forestland, we guarantee the same geophysical characteristics and forestland carbon storage capacities within and outside of the project area every run. These surrounding non-project areas are then equivalent to the matched controls in our previous empirical analysis. Then on these control lands, we apply the uniform 1.5% harvesting rate throughout the 150 years of simulations, called the common practice[33].

Choosing Project Scenarios To stabilize model performance and to allow for sufficient impacts from historical pre-market forest management, for each run of project simulations, we will set year 40 to be market entrance time, so the first 40 years are pre-market, and the next 110 years are post-market. If the project land enters either regulated or voluntary offset market and changes the harvesting rate, the new practice will be applied since year 40.

We want to choose the IFM project scenarios, defined by pre- and post-market harvesting rates, that are representative of CARB and VCM projects observed in our data. We do so by approximating the relative above-ground carbon trends identified by event study analysis, running test simulations and select the settings showing increasing and decreasing above-ground carbon stocks relative to the surrounding non-project controls. We also select on year 35's carbon inventories, matching to FIA measurements of real world IFM projects in Table 1. With limited observed data post-market, we will further make the simplification assumption that all scenarios will have the same post-market harvesting rate at 1%[34].

In the end, we choose the following scenarios to represent typical CARB and VCM projects, plus a third scenario reflecting the identical pre-market harvesting rate as the common practice:

Project Scenario	CARB	Ideal	VCM
Pre-Market Harvest Rate (40 Years)	1%	1.5%	2%
Post-Market Harvest Rate (110 Years)	1%	1%	1%

[33]This rate multiplying by 65% basal removal is similar to the removed basal ratio (around 1% annually) observed in our FIA data among matched control plots. Note there are measurement errors and the FIA measured removed biomass counts not only harvested carbon, but also removals from ground (for example, dead trees) for forestry. This rate is also similar to the harvesting rate in Maine public forests (1.5%) and smaller than that on private forestland (3%) (Thompson et al. 2017). Considering the constraint of the model and the intervals of output, we choose the 1.5% harvesting rate at this point that reflects a sustainable harvesting strategy common in the state of Maine, but a higher common practice may be chosen for robustness checks in future analysis.

[34]In this assumption, the post-market optimal IFM plan is independent of pre-market forest management and whether the market is regulated or voluntary. In reality this is unlikely to be true, so for future analysis, sensitivity checks will be needed testing different post-market harvesting rates.

Model simulated above-ground carbon stock trends for CARB, VCM and Ideal scenarios relative to the surrounding controls are shown in Appendix Figure J.1. Comparing with event study analysis with real data in Figure 5, the trends are roughly replicates. CARB scenario has an increasing trend, and VCM scenario has an decreasing trend pre-market. At year 35, the difference between CARB and control is about $5Mgha^{-1}$, similar but lower than the gap in Table 1. The VCM difference is about $-7Mgha^{-1}$, of similar magnitude to the real data. The Ideal scenario fits a close-zero biomass difference at market entrance by design. Comparing with the pre-market removed basal ratio from our FIA data, the CARB and VCM scenario pre-market harvesting rate is also similar.

Note that after the assumed market entrance at year 40, Ideal and VCM scenarios see jumps in above-ground carbon due to lowered harvesting rates, while CARB sees relative flat trends because of no change in its harvesting rate. After 40-50 years in the markets, all three scenarios have the same level of carbon stocks ($5Mgha^{-1}$ above controls), implying the same ecological equilibrium under 1% harvesting rate.

Choosing Baselines IFM project payoffs and decisions on carbon offset markets are dependent on not only project scenarios, but also on the selection of baselines. Ideally if there are no quality issues of forest carbon offset credits (one unit of credit represents no less than one unit of actual carbon removal), markets should demand baselines to be set with identical, business-as-usual forestry practices as projects' pre-market historical behaviors extended to post-market periods. However, if we compare these Business-as-Usual baseline projections following the pre-market harvesting rates of the three project scenarios we choose (Appendix Figure J.2 Panel (a)), they are continuously increasing post-market and do not match the baselines illustrated by real world IFM project documents (Appendix Figure A.1), which drastically decrease right after market entrance and stay fluctuating at low carbon levels[35].

To replicate these decreasing and fluctuating biomass baseline patterns with our LANDIS II model, we increase the post-market harvesting rate to above 2% and discover that the patterns occur only after post-market harvesting rate reaches to 4% or higher. Constrained by local legislation demanding harvesting rate to be lower than 40%, we have also tested the upper bound and

[35]For some projects, the overall long-run above ground carbon trends for baselines are slightly decreasing, while for others trends are slightly increasing. But overall, the baseline carbon levels never reach close to the project carbon levels.

found similar patterns and similar levels of long-run carbon stocks when harvesting rate reaches 5% or above. Therefore, we approximate the baselines used for credit issuance in the real word as the "Implied" baselines assuming 5% harvesting rate after market entrance (maintaining the same pre-market harvesting rate). As illustrated in Figure J.2 Panel (b), though these baselines still have their carbon levels increase in the long run after 40-50 years in the market, they are consistently lower than the Business-as-Usual baselines by about $30 Mgha^{-1}$.

Adding a third baseline option reflecting the common practice of non-project lands, we will use three types of baselines as summarized below:

Baseline	Common Practice	Business-as-Usual	Implied
Pre-Market Harvest Rate (40 Years)	1.5%	Same as Project Pre-Market	Same as Project Pre-Market
Post-Market Harvest Rate (110 Years)	1.5%	Same as Project Pre-Market	5%

7.2 Simulated Offset Market Performance

Simulated market outcomes including credit issuance and implied emissions under three project scenarios, three baseline settings, and two carbon offset markets (with different credit issuance schemes described in the background section) are summarized in Table 4[36].

Under Common Practice baseline setting, regulated market results in strictly negative credit issuance that discourage any market entries from all three project scenarios. Meanwhile on the voluntary market, all project scenarios will have positive total credit issuance (though VCM scenario still has negative initial issuance). Therefore, if entrance decisions are made according to positive total credit issuance, we would see all scenarios of projects entering only the voluntary market. Meanwhile, because the post-market harvesting rate (1%) is lower than common practice (1.5%) for all scenarios, the implied emission reductions are all positive or clost-to-zero. However, these reductions are always much higher than total credit issuance on the regulated market (which are negative), but much lower than the total credit issued on the voluntary market. Therefore, neither market issues the fair amount of offset credits to projects under their issuance schemes with respect to common practice baselines.

For Business-as-Usual baseline setting, which is the target design of carbon offset markets in theory, regulated market still discourages all projects with negative initial and total credit issuance

[36]For this exercise, we do not take into account possible over-reporting of initial carbon stocks seen in Table 1.

except for positive total credit on VCM scenario projects, because of the aggregated credit gains in non-initial periods. These are majorly because that the 100-year average baseline carbon measures used to determine crediting is higher than initial carbon stocks at market entrance with increasing baselines in the long-run. As implied carbon emission reductions are non-zero, under-crediting in this market is still significant. On the other hand, the voluntary market now encourages all project scenarios to enter with positive initial and total credit issuance. Reflecting no changes in post-market forestry practices, the CARB scenario gains the lowest total credit and implied reduction, magnitudes lower than under the common practice baseline because CARB scenario could not benefit from the lower baseline setting of 1.5%[37]. Ideal scenario sees little changes having the same baseline as common practice. VCM scenario has enjoyed 3.9 times the total credits of common practice baseline, additional gains from using the business-as-usual baseline with a 0.5% higher harvesting rate. Emission reductions under business-as-usual baselines, which are the true climate benefits by definition, are also close to the total issuance on the voluntary market, signaling efficient and high-quality offset crediting, especially for VCM scenario.

With Implied baseline setting, all project scenarios on both regulated and voluntary markets see significantly greater positive initial and total credit issuance. CARB scenario enjoys the greater initial issuance and highest total credits on the regulated market, comparing with the voluntary market. VCM scenario expects greater total credits on voluntary market relative to the regulated market. The Ideal scenario is more similar to the CARB scenario, having greater issuance on the regulated market. Then in this baseline setting, the real world market outcomes are replicated, when CARB scenario enters the regulated market and the VCM scenario enters the voluntary market. This is at the cost of using Implied baselines deviating from business-as-usual, which causes significant over-crediting on both markets. It is also misleading that implied emission reductions (much greater than the true climate benefits indicated by the emission amounts under business-as-usual baselines) under these baselines are uniformly greater than the total credit issuance on both markets for every project scenario, instead signaling conservative credit issuance. However, also note that Ideal scenario, which in real world maps to controls of no-entry, would enter the CARB market by total economic payoff being positive and greatest on this market. This could imply the possibility of under-entry of eligible IFM projects on the current market,

[37]The total credit issuance is not zero for CARB scenario though harvesting plan is not changed post-market, because the voluntary market (ACR standard) allows credit gains from increasing realized stocks alone when baseline stocks falls below their 20-year average. In this case, it happens at the start of the post-market period, gaining some credits for this scenario at years 5 and 10 after the market entrance.

consistent with the results of MNL.

Baseline: Common Practice				
Market	Project Scenario	Initial Issuance	Total Issuance	Emission Reduction
Regulated	CARB	-44.0	-6.1	15.7
Regulated	Ideal	-58.2	-9.0	13.1
Regulated	VCM	-85.5	-17.7	3.9
Voluntary	CARB	19.4	30.4	15.9
Voluntary	Ideal	4.6	24.9	10.8
Voluntary	VCM	-23.4	12.7	-1.4

Baseline: Business-as-Usual				
Market	Project Scenario	Initial Issuance	Total Issuance	Emission Reduction
Regulated	CARB	-62.4	-24.4	0.0
Regulated	Ideal	-53.5	-4.3	18.4
Regulated	VCM	-41.9	25.8	50.6
Voluntary	CARB	0.0	12.2	0.0
Voluntary	Ideal	2.4	26.5	16.3
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	123.9
Regulated	Ideal	36.2	85.4	126.5
Regulated	VCM	12.2	79.9	119.6
Voluntary	CARB	38.1	57.7	101.9
Voluntary	Ideal	36.7	63.0	100.7
Voluntary	VCM	34.1	82.3	95.9

Table 4: Simulated Carbon Offset Market Issuance and Actual Emission Reduction Outcomes

Notes: Credit issuance and emission reduction unit is tCO_2e per hectare based (ha^{-1}), converted from above-ground carbon to CO_2 with atomic weight factor 12/44. *Emission reduction taken as the difference between projected biomass and baseline biomass at the end of the crediting period (25 years for regulated market, 20 years for voluntary market).*

7.3 Simulated Economic Payoffs for Project Developers

In the real world, risk-neutral project developers would make market entrance decisions not only based on the amount of total credit issuance, but also accounting leakage, reversal, discounting, agent costs, and opportunity costs of timber sales. To approximate the payoffs of project developers in dollars, we compile the estimation using the set of parameters in Appendix K and summarize the payoff breakdown results in Table 5.

Those estimation results have shown that market entrance decisions based on biomass-total revenue (first column) or total payoff considering other cost and revenue components (last column) are largely consistent with the decisions made based on total credit issuance in the previous subsection. Specifically, the Implied baseline panel replicates the real world equilibrium outcome that CARB scenario projects enter regulated market for higher expected payoffs, while VCM scenario projects enter the voluntary market[38]. Under the other two baselines, Common Practice and Business-as-Usual, total payoffs considering costs decrease to negative suggesting more disadvantaged situations for voluntary offset market entrance, because of the considerable opportunity costs of giving up alternative timber sales under reduced harvesting. Under all baseline scenarios, the VCM project has an average 1.61 thousand broad feet per hectare decrease in timber harvesting (estimated as timber volume of White Oak) per year during its term (20 years), relating to about 17.2 million broad feet timber harvest per year across all existing VCM projects in Region 9 and accounting for 0.03% of the US annual harvest[39]. This creates a potentially greater leakage effect not captured by the 40% leakage estimates due to the relative inelastic demand of US timber market.

To check for sensitivity, we conduct payoff estimations under different value function and parameter assumptions in Appendix Table K.2. Overall, variations in parameters cause changes in magnitudes of the total payoffs for project developers under Implied baseline setting, but does not alter the market entrance decisions in accordance to reality except in two cases. The first case is when reversal risk is taken not as a discount rate but as a buffer pool, accounting linearly instead of by powers. This significantly reduces the payoffs of VCM scenario and reverts market entrance from voluntary to regulated market, due to the high timber opportunity costs. The second case is when market clearance is not assumed, or say not all credit issued are expected to be sold. Because in real world, regulated market sees a much lower percentage of forest credit retirement (1.52%) comparing with voluntary market (32.73%), quoting these percentages in expected payoff calculations would

[38]Note that, however, the assumption that Ideal scenario projects (same pre-market harvesting choice as the surrounding control forestland) would not enter either market in equilibrium essentially fails by these simulations. To achieve that outcome, different discount rates, updated market expectations (e.g. insufficient demand), and unobserved latent costs would need to apply so all scenarios have significantly smaller expected revenues, or significantly greater costs. For this and later analysis in this stage, we will make the simplified assumption that Ideal scenario should in equilibrium enter the market, but in reality they are not but instead selected as our no-entry matched controls because potential project developers of those forestland have not yet realized the possibility of offset market entrance.

[39]US annual forest harvest of timber estimated at around 400 Million m^3 or 170 billion broad feet (Butler & Sass 2023).

make performance on the voluntary market dominates, causing CARB scenario projects to switch from the regulated market. Also due to the low percentage of credit retirement, VCM scenario projects have negative payoffs on either market due to high timber opportunity costs, suggesting no offset market entrance at all. Therefore, though our sensitivity analysis generally suggests robustness of the payoff estimations, we have shown that discounting and demand-side expectations can significantly affect the equilibrium offset market outcomes.

Baseline: Common Practice							
Market	Project Scenario	Revenue	Standing Dead Add.	Leakage	Agent Cost	Timber Opp. Cost	Total
Regulated	CARB	-871	-87	-5	120	0	-843
Regulated	Ideal	-1151	-115	-6	159	-68	-1180
Regulated	VCM	-1682	-168	-7	232	-107	-1733
Voluntary	CARB	296	30	-3	-33	0	289
Voluntary	Ideal	107	11	-4	-12	-73	29
Voluntary	VCM	-246	-25	-5	28	-116	-363

Baseline: Business-as-Usual							
Market	Project Scenario	Revenue	Standing Dead Add.	Leakage	Agent Cost	Timber Opp. Cost	Total
Regulated	CARB	-1257	-126	0	173	0	-1209
Regulated	Ideal	-1052	-105	-6	145	-68	-1086
Regulated	VCM	-768	-77	-9	107	-107	-854
Voluntary	CARB	32	3	0	-4	0	32
Voluntary	Ideal	79	8	-4	-9	-73	1
Voluntary	VCM	198	20	-6	-22	-116	74

Baseline: Implied							
Market	Project Scenario	Revenue	Standing Dead Add.	Leakage	Agent Cost	Timber Opp. Cost	Total
Regulated	CARB	1008	101	-37	-134	0	938
Regulated	Ideal	832	83	-35	-110	-68	703
Regulated	VCM	369	37	-30	-47	-107	222
Voluntary	CARB	551	55	-26	-60	0	521
Voluntary	Ideal	544	54	-24	-59	-73	442
Voluntary	VCM	537	54	-21	-59	-116	396

Table 5: Simulated Carbon Offset Market Project Developer Payoff Estimates

Notes: Payoff total and breakdowns all estimated in dollar ($) per hectare ($ha^{-1}$). Payoff function and parameter summary see Appendix K. Standing dead indicates estimated contribution from standing dead (and possibly including soil carbon underground) carbon as a percentage of the living biomass. Agent cost contains brokerage, market entrance preparing and manager costs by agents such as Blue Source (now Anew Climate) and Finite Carbon.

7.4 Extension Analysis

In this subsection, several extension analysis following the simulation are presented.

Continuous Pre-Market Harvesting Rate Relationship with Entrance According to our theoretical model, pre-market (historical) forest management plans are determinants to the entry decisions of IFM projects. In our empirical analysis, we have found correlations between different pre-market forest management plans, as reflected by different relative trends of above-ground carbon stocks, and the entering CARB versus VCM projects. We can use simulations further explore this relationship. We run simulations with a continuous set of pre-market harvesting rates $[1\%, 1.2\%, ..., 2.8\%, 3\%]$. Total carbon credit issuance are estimated for for both regulated and voluntary market entrance, and results with Implied baselines (the setting fitting the real world observations) are illustrated in Appendix Figure L.1[40].

As it shows, under a uniform post-market harvesting rate (1%), pre-market harvesting rate affect expected offset credit gains for project developers. Regulated market credits have decreased with higher pre-market harvesting rates, because initial credit issuance is lowered due to lower carbon levels at market entrance from heavier pre-market harvesting, and slower live carbon accumulations post-market. In the meantime, voluntary market has mostly increasing total credit issuance as pre-market harvesting rate increases. This is because that higher pre-market harvesting rate is awarded for the greater changes made towards a low-harvesting plan of 1% post-market, per credit issuance scheme of the voluntary market. As a result, regulated and voluntary market credit outcomes cross one another at about 2.2% pre-period harvesting, sorting low pre-market harvesting projects into the regulated market, and high pre-market harvesting projects into the voluntary market[41]. In principle, markets should award more credits to projects with greater decrease of tree harvesting. However from our simulations, the regulated market, defined by its credit issuance scheme which provides high initial credit issuance, are systematically biasing towards projects with lower harvesting rate to start with, though their future IFM actions may

[40]Simulation outcomes with Business-as-Usual and Common Practice baselines are also generated in Appendix Figure L.2. As they suggested, Common Practice as baselines suggest minimal market entrance into the voluntary market only at low pre-market harvesting rate, and Business-as-Usual baselines always favor the voluntary market entrance over the regulated market regardless of the pre-period harvesting rate.

[41]Note that total credits cross at about 2.2% pre-market harvesting rate, different to the table results (Table 4) that shows total credit on voluntary market already increases above that on regulated market at the 2% pre-market harvesting VCM scenario. This is due to the noises over separate simulation runs, even with the same parameter settings. Future work will be done to produce confidence intervals for these simulation estimates.

not change.

Text Analysis for Baseline Reporting Overall, our simulation results have illustrated that there are significant baseline setting issues in reality. Comparing the outcomes of Business-as-Usual and Implied baselines, the regulated market allows 4-5 times the harvesting rate to be set as baseline comparing to historical average, essentially rewarding CARB projects with pre- instead of post-market forest conservation efforts. The voluntary market does rewards VCM projects for the increase in carbon stocks due to improved forest management after their market entry, but it also allows 2-2.5 times the historical harvesting rate to be set as baselines. Total credit issuance and discounted revenues can be up to 200% and flip signs using Implied instead of Business-as-Usual baselines, creating significant over-crediting issue. However, if switching to Business-as-Usual baselines to prevent low-quality offsets, motivations for carbon market participation will be significantly undermined.

With these analysis, we argue there may be deliberate efforts in market designs to balance the incentives of market entrance and the needs for quality offset credits. To explore the possible manipulations with baseline setting, we use machine learning text analysis tools to study whether these behaviors have traces in project documents and market protocols. For all these documents, we construct measurements of sentiment (Vader scores), subjectivity (TextBlob subjectivity), and concreteness (Brysbaert et al. 2014) of words around the keyword "baseline", exponentially weighted by sentence distance with a decay rate of 0.5.

Text analysis results histogramed in Appendix Figure M.1 and M.2 has indicates that all documents are neutral in sentiment, objective, and medium-level concrete when describing baselines. Project plans are less positive and more concrete than protocols, because of the use of exact project information. VCM projects are less objective than their protocols, and CARB projects are more objective than their protocols. Overall, VCM projects by their documents are less positive, less objective, and similarly concrete than CARB projects. Considering that baseline setting is especially important for CARB projects in order to claim credits without shifting post-market forest management plans, it is possible that this causes the subjectivity to drop in their documents.

We also observe the correlation matrix of these text characteristics with FIA measured initial carbon stocks, initial stocks relative to their matched controls, and the estimated *gradient* variable representing non-market carbon trends. Though correlation coefficients are small in magnitudes,

we do see that VCM projects are having carbon stocks and *gradient* positively correlated with sentiment, objectivity, and concreteness. CARB projects instead have negative correlations with sentiment (subjectivity and concreteness is mixed by carbon stock or *gradient* measures). So VCM projects with higher carbon stocks may signal greater confidence with baselines in market entrance, but CARB projects could not because high carbon levels can instead reduce the credibility of future emission removal plans, and then baseline setting would need to be more negative in order to persuade their market monitors.

State-Level Full Market Entrance Extrapolation With the multinomial logistic regression, we can extrapolate the out-of-sample market entrance decisions for all FIA forest observational plots. We use the direct MNL regression estimates of Table 3 and summarize state-level market entrance probabilities weighted by plot areas in Appendix Table N.1. In most 20 states of Region 9, the most forestland would not enter any offset market, second by the proportion entering the regulated market, and the least would enter the voluntary market. Maine, Vermont and New Hampshire, the three forest-rich northeastern states, plus Michigan and Minnesota, the north Midwestern forest-rich states, are the only five states estimated to see more voluntary instead of regulated market entrance, suggesting notable forest management changes in those states under the predicted voluntary market entrance.

Applying these state-level predictions to forest area coverage and simulation predicted project developers' economic gains and actual emission reductions in Table 4 and 5, we summarize the state-level and Region 9 total project benefits and the social benefits of resulting CO_2 reduction under the current Implied baselines. We also evaluate the counterfactual when both markets switch under the Business-as-Usual baselines, causing all CARB projects to switch and instead enter the voluntary market. Our results in Appendix Table N.2 have shown that overall the social benefits of full offset market entrance are magnitudes higher than the private economic gains transferred to project developers by the offset markets, under either Implied or Bussiness-as-Usual baselines. These are all contributed by the entrance of VCM projects entering the voluntary market, as CARB projects do not produce actual emission reductions. However, shifting from Implied to Business-as-Usual baseline would reduce project developers' benefits by more than 10 times.

To summarize, the MNL model-based extrapolation exercise has implied significant environmental gains of extending carbon offset market entry choices to all eligible forestland owners across

Midwest and Northeast. Resulting emission reduction is quite significant, proving the potential of carbon offset markets to enhance nature-based climate solutions. For example in Massachusetts, where it plans to reduce the 1990 emission of 93.2 Million tCO_2e by 75% in 2040[42], 15% of the reduction are planned to be taken by nature-based climate solutions, which amounts to 10.5 Million tCO_2e by 2040. The extrapolated contribution from IFM project developers entering the carbon offset markets will be about 9.8 Million tCO_2e by 2040 (assuming 2023 year of entrance and 20 years of terms for typical VCM projects), largely contributes to meeting the commonwealth's plan by itself alone.

However, note that there are strong assumptions for these estimates, making them generous upper bounds for the possible outcomes of full carbon offset market participation. Firstly, there needs to be sufficient market demand now and into the future so all issued forest offsets will be purchased. With the current rate of retirement on this market for nature-based solution projects (32.73%) and the projected instability of carbon market demands, it is very likely that our estimated welfare gains are over-optimistic. Secondly, extrapolated entrance rate should not change when project developers' expected economic benefits drop significantly when switching to business-as-usual baselines, which is unlikely in reality when project developers are continuum instead of discrete of the two simulation scenarios. However, if protocols for baselines do not ensure business-as-usual but instead keep the implied, the increasing availability of low-quality forest carbon offsets on the markets would lower the incentives for more direct emission reductions (e.g. cutting the use of fossil fuels) and could eventually derail the climate goals of offset buyers. Thirdly, extending to all forestlands implies a reduction of timber harvesting through VCM project participation of 22 billion broad feet annually just from the 20 states of Region 9, accounting for about 13% of the US annual timber removal. Considering the relative steady demand on the US timber market[43], implied leakage could be significantly discounting the social benefit of total carbon reduction.

8 Conclusion

This paper compiles a novel dataset of 62 improved forest management (IFM) projects in 20 US states traded on either the regulated or the voluntary carbon markets. Applying ground-truth forest carbon measurement from FIA, we empirically analyze the entry selection problems of these

[42]Source: March 2024 Massachusetts Priority Climate Action Plan.
[43]Source: UNECE Report (source).

forestry-based projects using regressions and simulations, and identify differing pre-market forest management strategies as key determinants for project developers' entry choice decisions and selections between the two available carbon offset markets in the US with significantly different credit issuance schemes through profit maximization. In the California regulated market, high initial credit issuance attracts projects with increasing, high above-ground carbon storage compared to control forestland with similar capacities. These projects may have the problem of reporting lower baselines in order to secure their eligibility of market entrance and to maximize credit gains. In contrast, the global voluntary market's gradual credit issuance scheme attracts projects with decreasing, below-control carbon stocks that are motivated to implement improved forest management and raise their future carbon inventories. However, without checks based on historical trends, these projects are also motivated to submit lower baselines than their business-as-usual practices, enhancing greater economic gains on the market. In the end, both markets are trading low-quality forest carbon offsets. To prevent overcrediting and additionality issues, the monitoring agents, CARB or carbon registries, should be responsible for comparing historical carbon trends with project developers' simulated baselines to ensure that the business-as-usual criterion is met for baseline settings. Additionally, the regulated market's credit issuance scheme could be adjusted to lower the share of initial credit, which may help to avoid entrants with no meaningful post-market forest conservations. Using the estimates of a multinomial logistic model, we extrapolate that engaging all eligible forestland in the voluntary carbon market will significantly contribute to states and national goal of carbon neutrality as a nature-based climate solution, even when enforcing business-as-usual baselines significantly undermines the private economic gains for project developers.

This project has several limitations that future studies should address. First, we use FIA measurements of above-ground carbon, which may differ from project-reported data to the registries by the selections of observational plots and by biomass carbon estimation methods. Systematic bias relative to actual carbon stocks representative of project areas may persist using FIA data, for instance if landowners practice different harvesting on FIA plots. Second, the low temporal frequency of our data, along with uncertainties around project locations and areas (particularly for VCM projects where we rely on manual map scraping), introduces additional uncertainties into our empirical results, and affects the following simulation analysis. Third, our simulation analysis requires more validations from varying forest management practices (e.g. different post-market

harvesting practices, changing rotation periods, changing harvesting schemes) and market parameters (e.g. inflation, financial risks, incomplete market competitions). More robustness runs are also needed to construct the confidence intervals for our current estimates, due to the inherent variability of the simulation model.

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Appendix

A Sample Project and Baseline Projection Plots

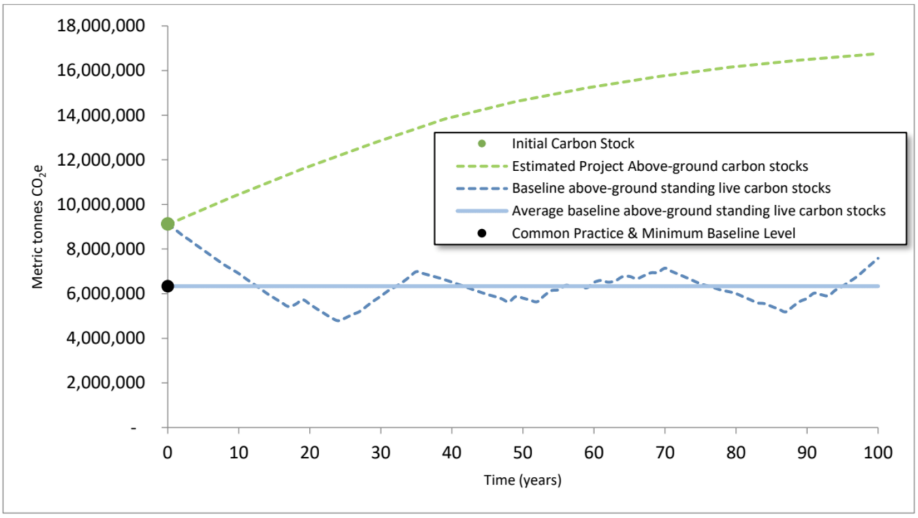


Figure 2. Baseline and Project Above-Ground Standing Live Carbon Stocks.

(a) CAFR5416 (ACR416)

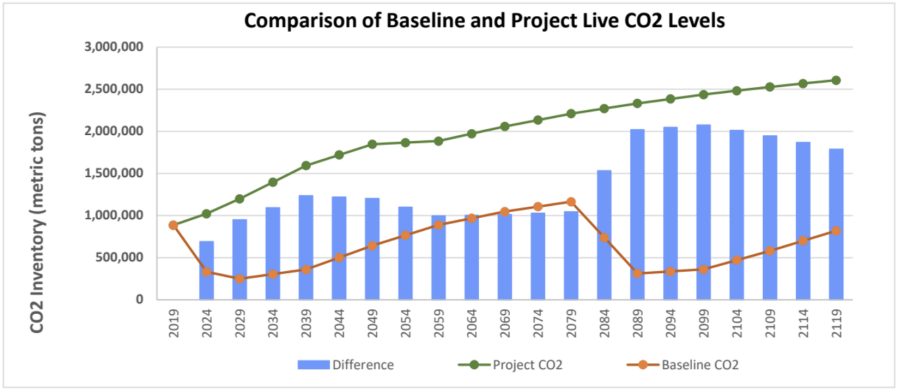


Figure A7.1. – Graph showing the CO_2 relationship between the Baseline scenario (with an objective to maximize net present value), versus the Project's conservation management scenario (with an objective to conserve CO_2), and the difference (in metric tonnes) therein (from 2024 to 2119).

(b) ACR634

Figure A.1: Sample project and baseline projection plots for two projects (ACR416, ACR634) submitted to American Carbon Registry.

Notes: CAFR5416 (ACR416) - Meriwether IFM, CARB project entering August 31st 2018, located in PA, owned by Timber Company. ACR634 - ILTF/NICC SIG Fond Du Lac Band Forest Carbon Project, VCM project entering January 9th 2019, located in MN, owned by tribe. Projection lines taken for greenhouse-gas-emission reduction plan submitted to American Carbon Registry (ACR).

B Mathematical Expressions of Credit Issuance and Expected Revenue

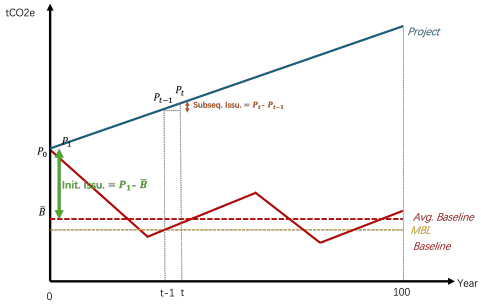
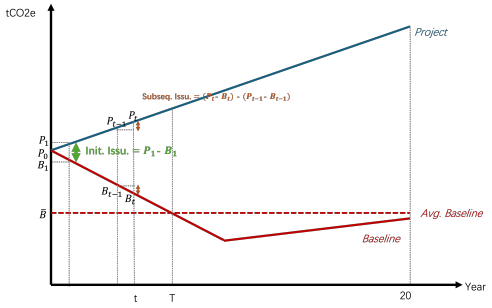
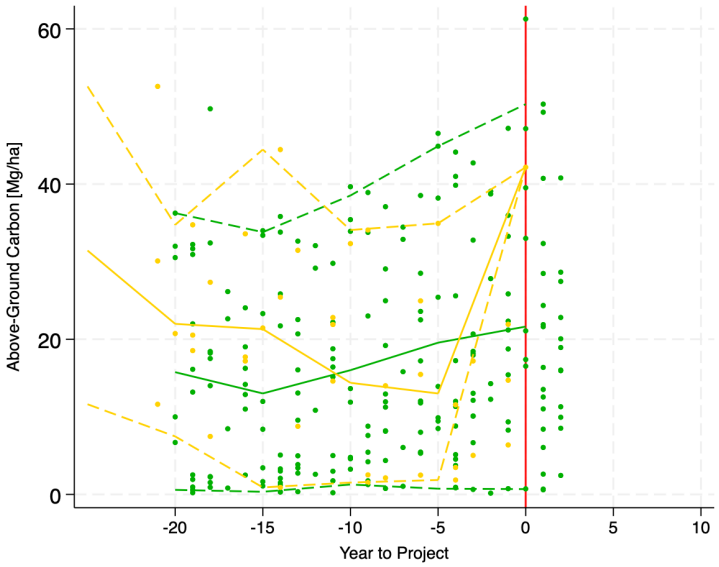
	Regulated (CARB)	Voluntary (VCM)
Illustration		
Initial Issuance	$P_1 - \bar{B}$	$P_1 - B_1$
Subsequent Issuance	$P_t - P_{t-1}$	$(P_t - B_t) - (P_{t-1} - B_{t-1})$ or when $B_t < \bar{B}$, $P_t - P_{t-1}$
Total Issuance	$P_{25} - \bar{B}$	$P_{20} - \bar{B}$
Total Revenue PV	$(1-s)qp\delta^{\bar{v}}((1-\delta)\sum_{t=0}^{24}\delta^t P_t + \delta^{25}P_{25} - \bar{B})$	$(1-s)qp\delta^{\bar{v}}((1-\delta)\sum_{t=1}^{19}\delta^t P_t$ $-(1-\delta)\sum_{t=1}^{T-1}\delta^t B_t + \delta^{20}P_{20} - \delta^T\bar{B})$

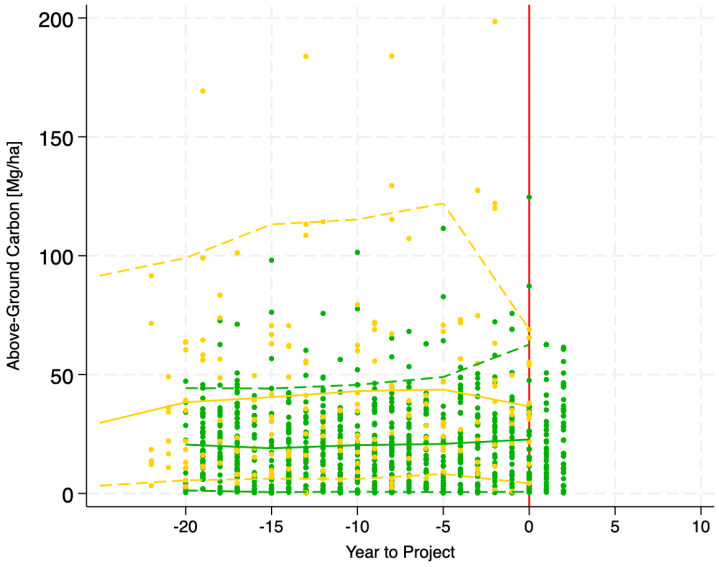
Table B.1: Formulas for carbon credit issuance (initial, subsequent and total), and present value of expected total revenues from offset sales on regulated and voluntary markets

Notes: The table present the mathematical formulas for carbon offset credit issuance of IFM projects with projections and baselines illustrated by Figure 1. P_t indicates projected tCO2e stored as biomass for the project after adapting the improved forest management plan post market entrance year t. B_t indicates simulated baseline tCO2e stored as biomass for the counterfactual assuming original forest management plan post market entrance year t. $\bar{B}$ is the average of baseline carbon projections, over 100 years for CARB projects and over 20 years for VCM. VCM projects credit issuance typically adapt the ACR standard (American Carbon Registry), which takes 25 over 28 VCM projects in our sample. In this case, assume a single cut-off year is T in the diagram (assuming no second-crossing of the baseline with its average). Crediting period for a typical CARB project is 25 years, and 20 years for VCM projects. For PV (present value) calculations, denote the combination of "leakage factor" (proportion of GHG emission reduction countered by leakage or secondary effects) and buffer pool contribution as s, then the offset credit issuance would be $(1-s)I_t$. Assume that the price per unit credit is fixed in time p, the average portion of credits being sold is q, future discounting rate is δ and credits are sold on average $\bar{v}$ years after their issuance.

C Sample Project Above Ground Carbon Plots



(a) In-Project Plots



(b) NNM-5n Matched Control Plots

Figure C.1: Sample plots for FIA above ground carbon (unit: $Mgha^{-1}$) observations in two projects, CAFR5416 (ACR416) and ACR634, and their NNM-5n matched control plots

Notes: Green for CAFR5416 (ACR416) - Meriwether IFM, CARB project entering August 31st 2018, located in PA, owned by Timber Company. Gold for ACR634 - ILTF/NICC SIG Fond Du Lac Band Forest Carbon Project, VCM project entering January 9th 2019, located in MN, owned by tribe. Red vertical line indicates market entrance year (defined as starting year of first vintage if month is before July, or next year of the starting of first vintage if month is July or after). Solid lines are average across all observations within 5-year bins (e.g. bin of 5n *summarize FIA observations in years* $[5n, 5n+4]$*). End bins are* $(-\infty, -16]$ *and* $[10, \infty)$*. Dashed lines are 5% and 95% percentiles across all observations in the 5-year bins.*

D Matching Love Plot

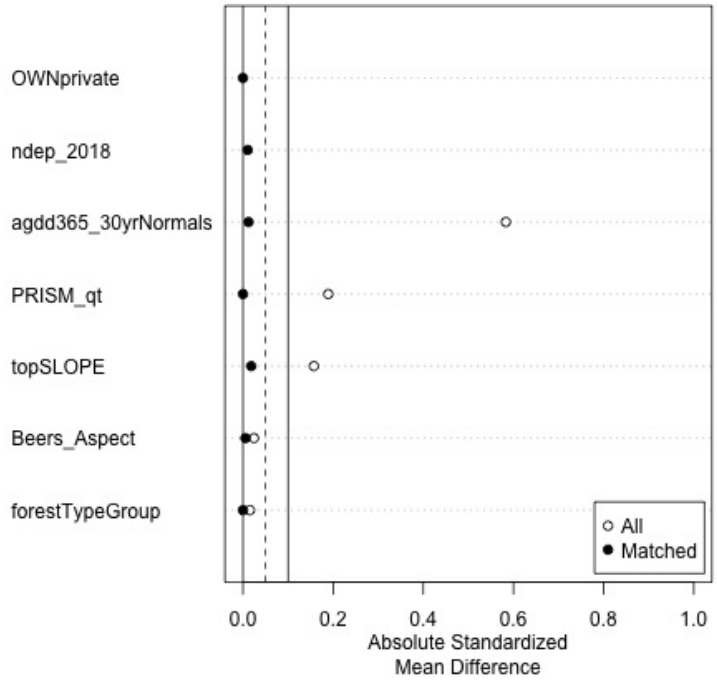
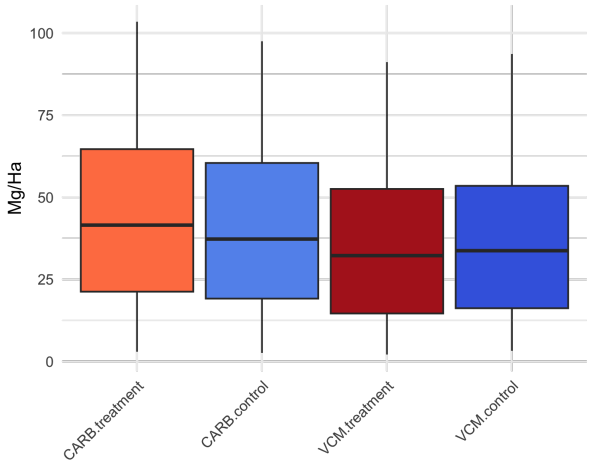


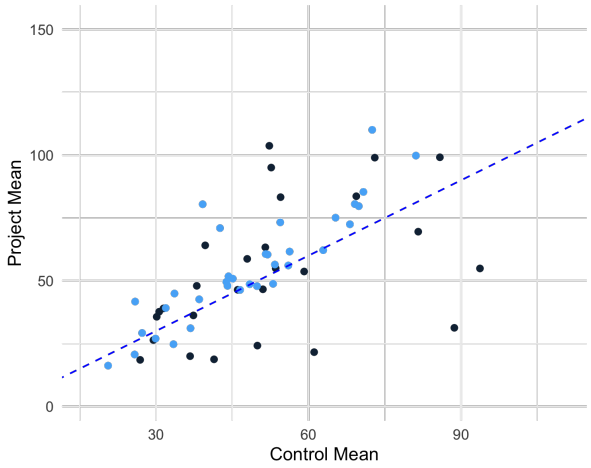
Figure D.1: Balance Plot for Matching, Five Nearest-Neighbor with Replacement

Note: For matching variables, PRISM_ qt = average precipitation quantiles; agdd365_ 30yrNormals=average growing degree days (GDD); ndep_ 2018=soil nitrogen concentration; topSLOPE=average plot slope; Beers_ Aspect=average plot aspect; forestTypeGroup=FIA main categories of forest type; OWNprivate=land ownership status being private or non-private.

E Summary Statistics Box and Scatter Plots, All Pre-Market Observations



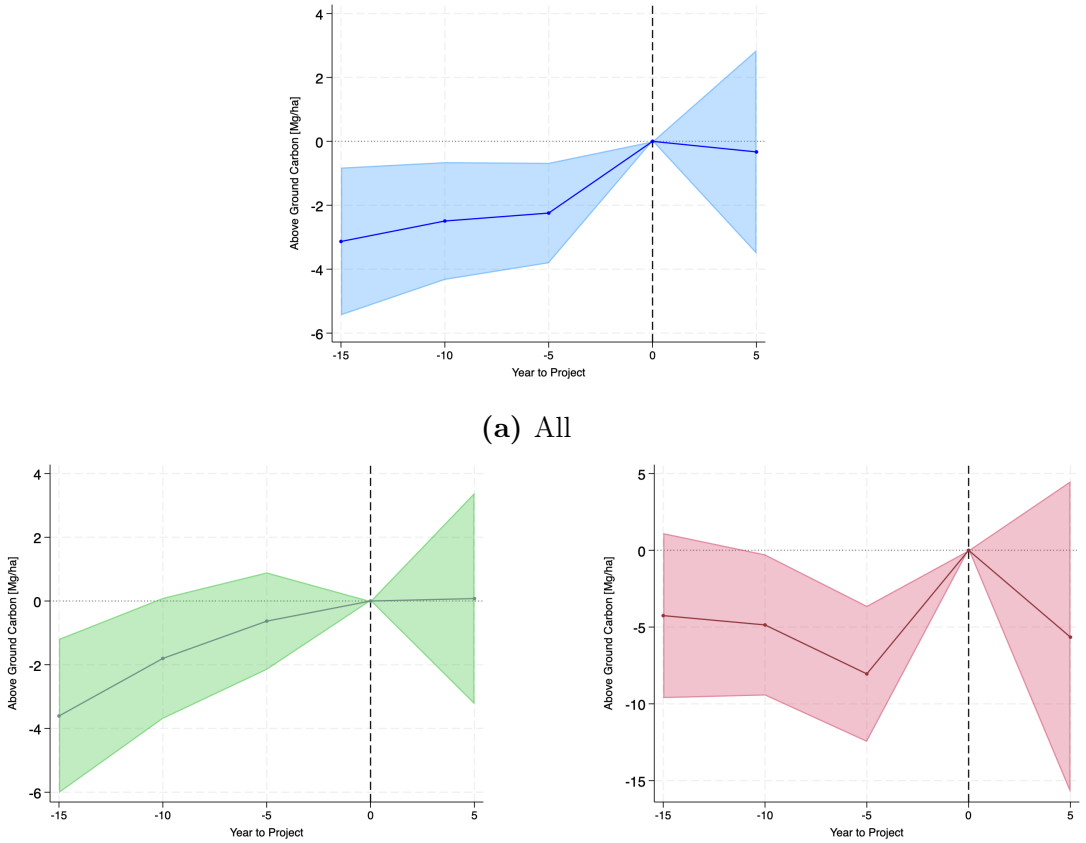
(a) Box Plots comparing average above ground carbon ($Mgha^{-1}$) for CARB and VCM project plots and their matched control plots. Blue bars are controls, red bars are treatments. Light color bars are CARB projects, dark color bars are VCM projects.



(b) Scatter comparison of average above ground carbon per hectare ($Mgha^{-1}$) by CARB projects traded on the regulated market (light blue dots) and VCM projects on the voluntary carbon market (dark blue dots). Vertical axis is the project-average carbon measure, horizontal axis is the project's control plots average carbon measure, all taken before the project start trading on the markets (pre-market period). The 45-degree dashed line separate projects that are above or below their controls.

Figure E.1: Comparison for Pre-Market Above-Ground Carbon Storage Between Project and Matched Control Forest Observational Plots

F Event Study Robustness



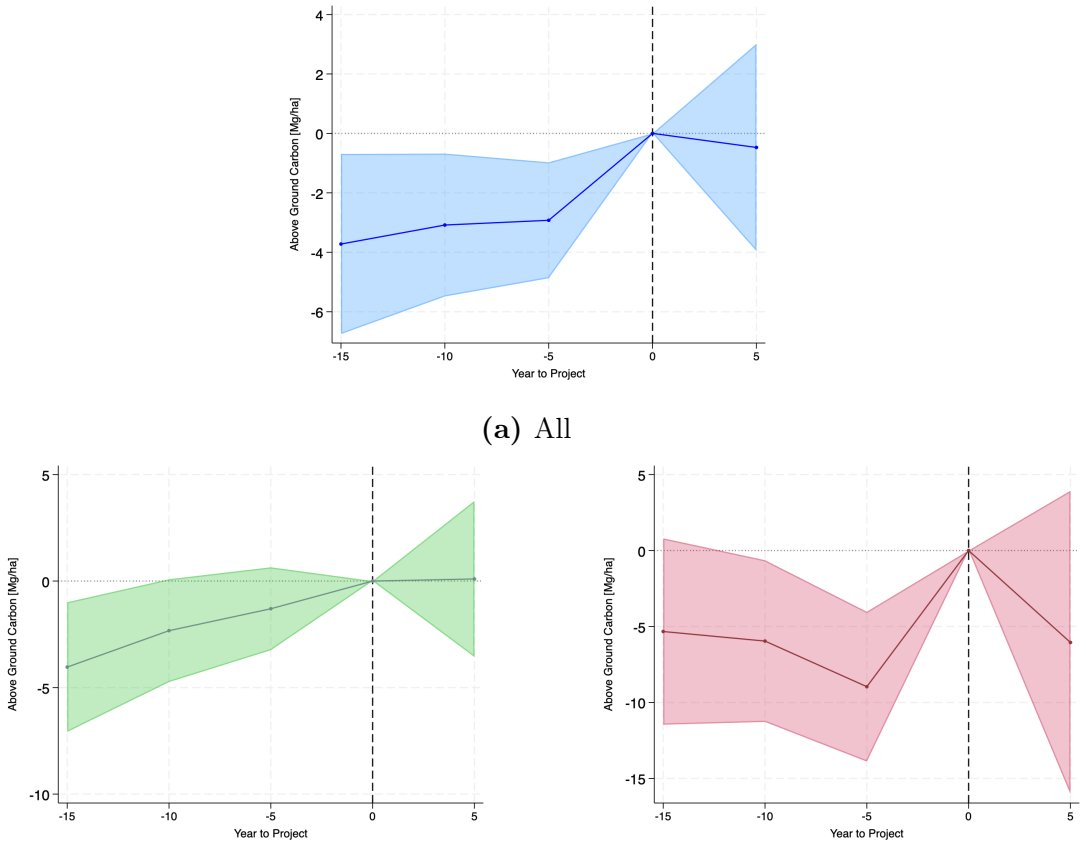
(a) All

(b) CARB

(c) VCM

Figure F.1: Event study plots for FIA measured above-ground carbon storage, different starting year definition

Notes: Average and 95% error bars are estimated with regressions Eq. 1 and 2. Each point observation indicates approximate average FIA measured above-ground carbon (unit: $Mgha^{-1}$) within five-year bins (e.g., observation at year $5n$ average across the 5-year bin of $[5n, 5n+4]$), relative to observations from nearest-five-neighbor matching control plots with similar geopotentials. End bins are $(-\infty, -11]$ and $[5, \infty)$. Vertical line indicates market entrance year (defined as starting year recorded in registry documents if month is before July, or next year of the starting year if month is July or after).



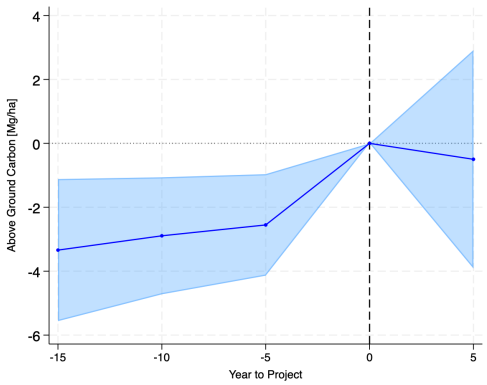
(a) All

(b) CARB

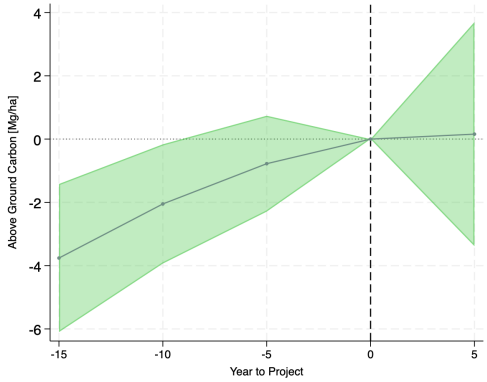
(c) VCM

Figure F.2: Event study plots for FIA measured above-ground carbon storage, alternative NNM one-neighbor matching

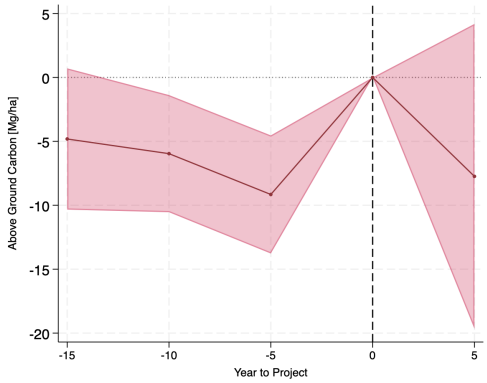
Notes: Average and 95% error bars are estimated with regressions Eq. 1 and 2. Each point observation indicates approximate average FIA measured above-ground carbon (unit: $Mgha^{-1}$) within five-year bins (e.g., observation at year $5n$ average across the 5-year bin of $[5n, 5n+4]$), relative to observations from nearest-one-neighbor matching control plots with similar geopotentials. End bins are $(-\infty, -11]$ and $[5, \infty)$. Vertical line indicates market entrance year (defined as starting year of first vintage if month is before July, or next year of the starting of first vintage if month is July or after).



(a) All



(b) CARB

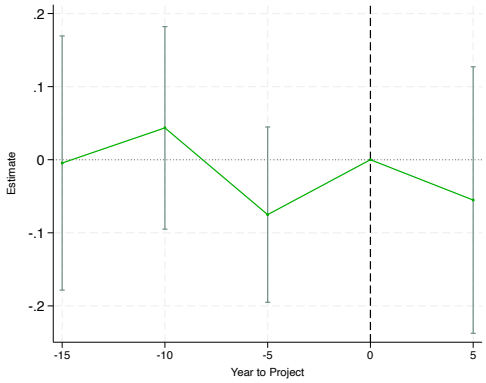


(c) VCM

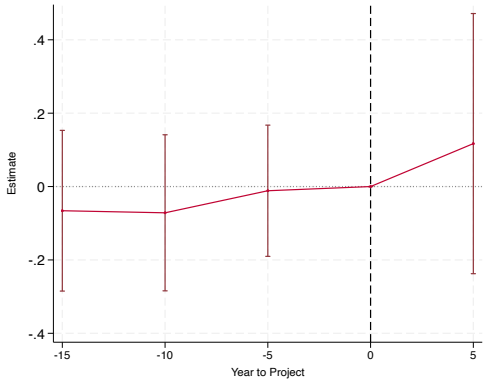
Figure F.3: Event study plots for FIA measured above-ground carbon storage, alternative coarsened exact matching (CEM)

Notes: Average and 95% error bars are estimated with regressions Eq. 1 and 2. Each point observation indicates approximate average FIA measured above-ground carbon (unit: $Mgha^{-1}$) within five-year bins (e.g., observation at year $5n$ average across the 5-year bin of $[5n, 5n+4]$), relative to observations from coarsened exact matching (CEM) control plots with similar geopotentials (matched by quintiles of precipitation, GDD, nitrogen concentration, slope, aspect, and exact categories by forest type and ownership group). End bins are $(-\infty, -11]$ and $[5, \infty)$. Vertical line indicates market entrance year (defined as starting year of first vintage if month is before July, or next year of the starting of first vintage if month is July or after).

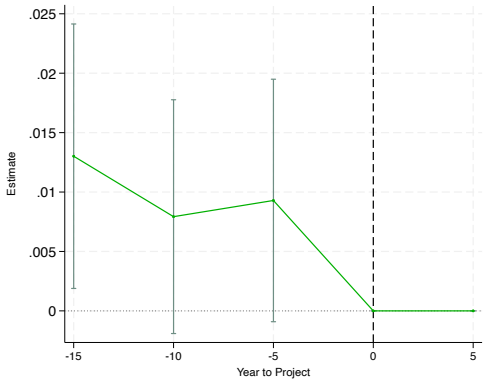
G Harvest Indicators Event Study Plots



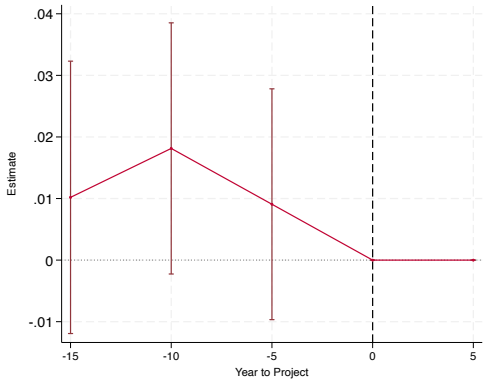
(a) Removed Basal Area Per Hectare Per Year-CARB



(b) Removed Basal Area Per Hectare Per Year-VCM

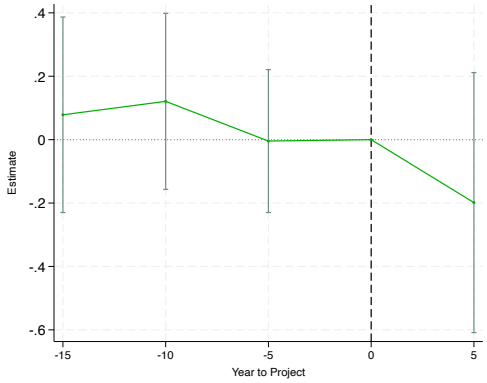


(c) Ratio of Removed over Standing Basal Area Per Year-CARB

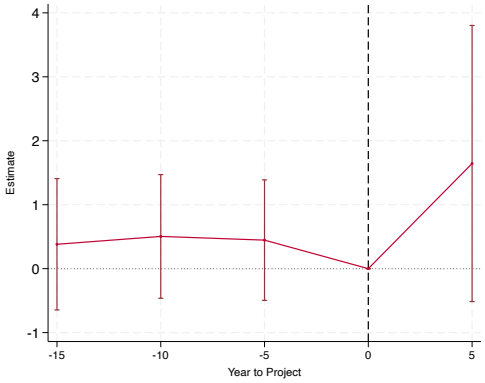


(d) Ratio of Removed over Standing Basal Area Per Year-VCM

Figure G.1: Harvest Event Study Plots



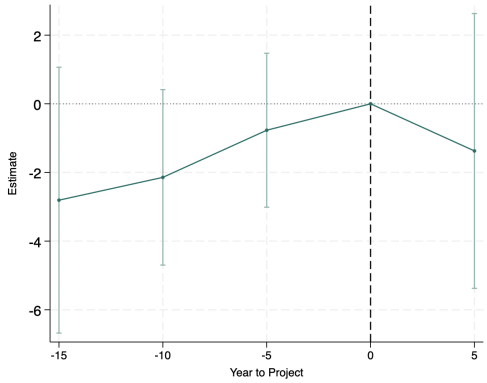
(a) Dead Basal Areas Per Hectare-CARB



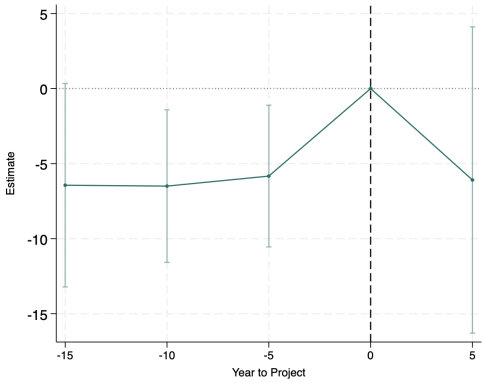
(b) Dead Basal Areas Per Hectare-VCM

Figure G.2: Dead Biomass Event Study Plots

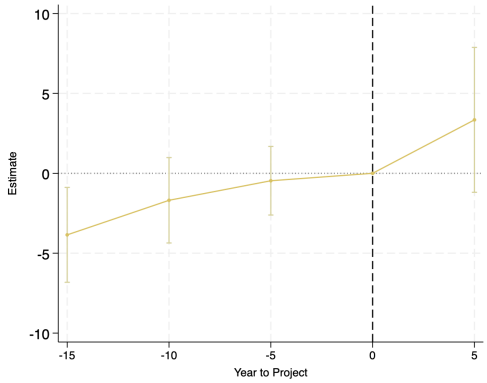
H Event Studies for Heterogeneity Analysis



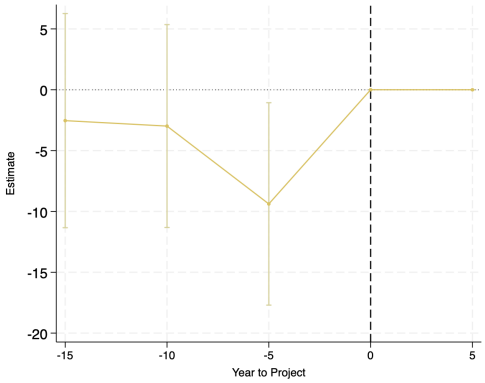
(a) CARB-with CE



(b) VCM-with CE

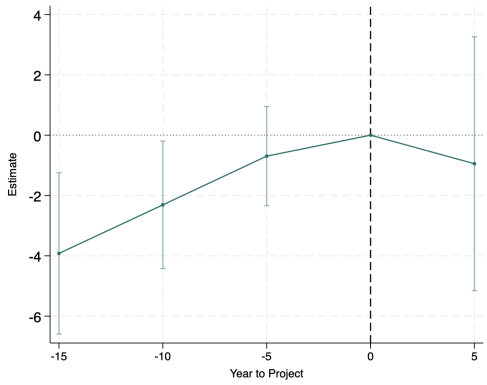


(c) CARB-without CE

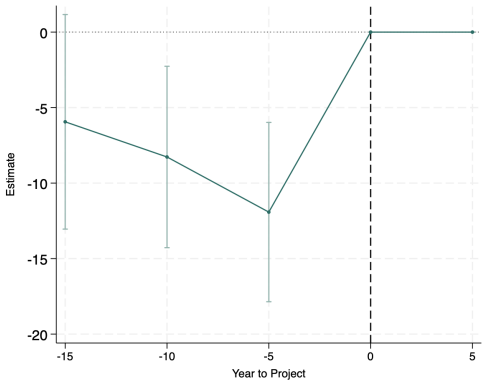


(d) VCM-without CE

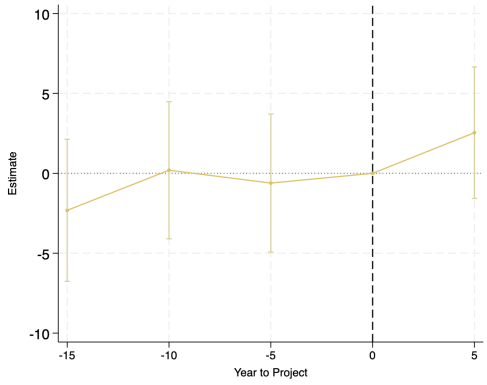
Figure H.1: Event study plots for projects separated by with or without historical conservation easement commitments (CE)



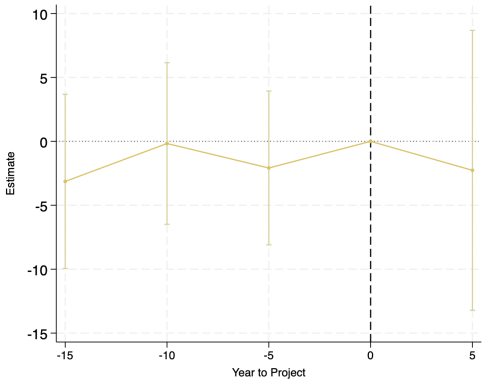
(a) CARB-Timber Company



(b) VCM-Timber Company

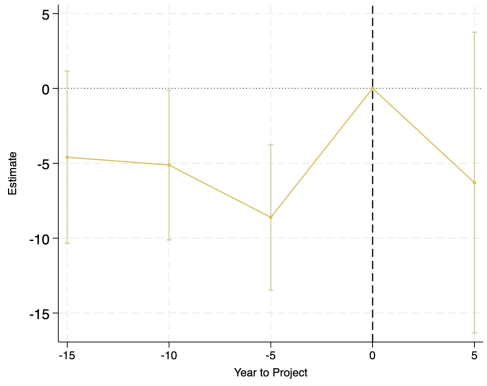


(c) CARB-Non Timber Company

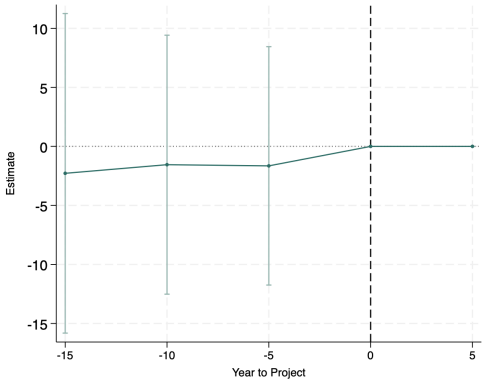


(d) VCM-Non Timber Company

Figure H.2: Event study plots for projects separated by timber company or otherwise ownership

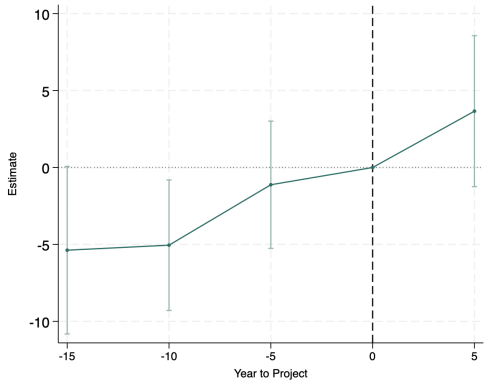


(a) VCM-With Preparing Agents

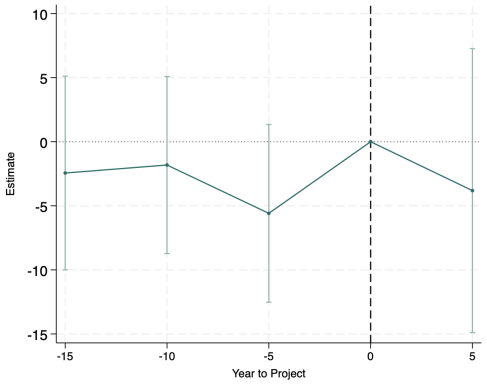


(b) VCM-No Preparing Agents

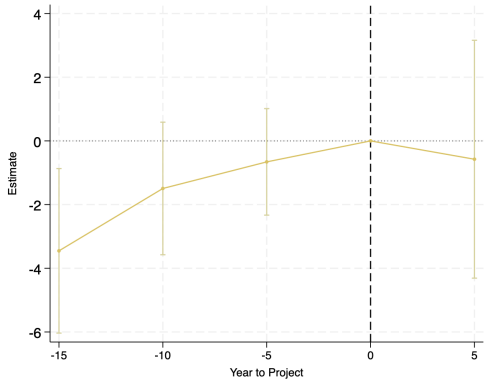
Figure H.3: Event study plots for VCM projects separated by agent preparation or self preparation status



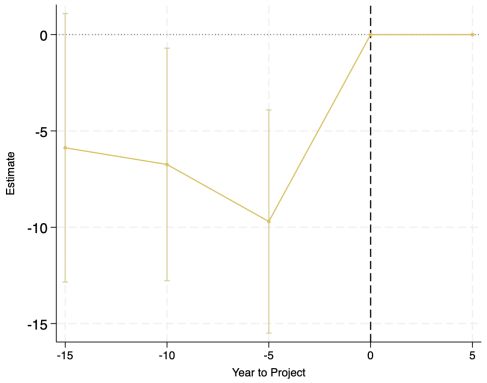
(a) CARB-Small Area



(b) VCM-Small Area

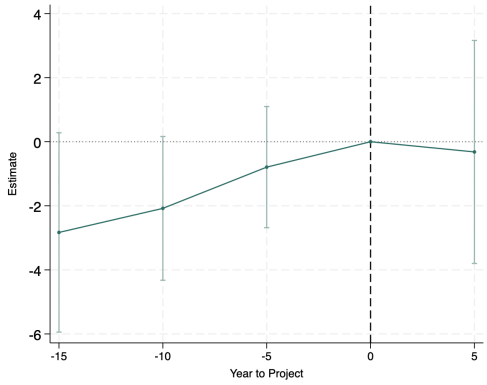


(c) CARB-Large Area

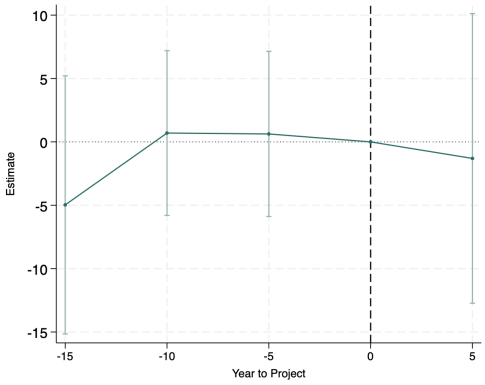


(d) VCM-Large Area

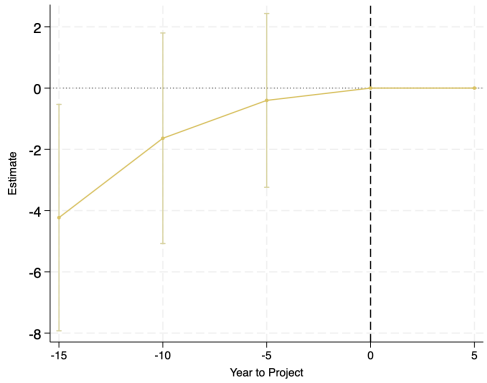
Figure H.4: Event study plots for projects separated into small or large areas



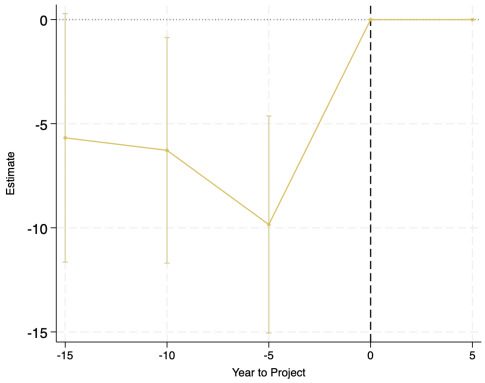
(a) CARB-Early Entrance



(b) VCM-Early Entrance



(c) CARB-Late Entrance



(d) VCM-Late Entrance

Figure H.5: Event study plots for projects separated by early and late entrance

I Multinomial Logistic Regression Results with *gradient* as Historical Forest Management Activity Indicator

	Direct Estimate		Bootstrap Estimate	
	Entry=CARB	Entry=VCM	Entry=CARB	Entry=VCM
Gradient	0.0246	-0.0602	0.0240	-0.0484
	(0.0390)	(0.0630)	(0.0399)	(0.0588)
Avg. GDD	-0.0000	-0.0004	-0.0000	-0.0004
	(0.0004)	(0.0005)	(0.0001)	(0.0003)
Avg. Precip.	-0.0005	0.0011	-0.0005	0.0010
	(0.0017)	(0.0016)	(0.0004)	(0.0008)
Aspect	-0.0059	-0.0668	-0.0031	-0.0814
	(0.1394)	(0.1661)	(0.1103)	(0.1930)
Nitrogen Conc.	0.1152	-0.3114	0.1148**	-0.3378***
	(0.1591)	(0.3115)	(0.0482)	(0.1220)
Slope	0.0055	-0.0050	0.0054	-0.0057
	(0.0102)	(0.0159)	(0.0055)	(0.0134)
Private Own.	3.2391***	-2.3956**	7.8803***	-2.4429***
	(1.0846)	(1.1414)	(6.4453)	(0.3194)
Forest Type=100	0.0547	0.3071	0.0586	0.3247
	(0.6519)	(0.5413)	(0.3255)	(0.4793)
Forest Type=120	0.3908	-0.2665	0.4019*	-0.2306
	(0.6616)	(0.4219)	(0.2388)	(0.3931)
Forest Type=400	-0.3386	0.6009	-2.1517	-0.2190
	(1.3187)	(1.1410)	(4.9027)	(3.5480)
Forest Type=500	0.1736	0.3532	0.2195	0.5044
	(0.9902)	(1.2678)	(0.4028)	(1.0272)
Forest Type=700	0.2811	0.0532	0.2541	-1.6876
	(0.8567)	(0.9238)	(0.5181)	(4.7831)
Forest Type=800	0.3308	-0.3478	0.3478*	-0.3153
	(0.9218)	(0.4772)	(0.2185)	(0.3754)
Constant	-4.0172	3.4354	-8.6414***	3.8702***
	(2.9211)	(3.2146)	(6.4692)	(1.7480)

Table I.1: Multinomial Logistic Results on Carbon Offset Market Entry Choices with *gradient* as Historical Forest Management Activity Indicator

Notes: Base category being no market entry (matched control plots). Standard errors in parentheses clustered by project or project-grouped controls. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. *Omitted forest type being FIA code=900.* $N = 2,353$, *Pseudo R-squared=0.0776, Brier's score=0.189. For Bootstrap, 1000 runs are taken separately on simulating gradient regressor with first-stage entrant plot-level OLS coefficients and standard errors, and bootstrapping with replacement on second-stage sample of* $N = 2,353$. *1 run is dropped for no convergence, so* $S = 999$. *Mean of estimates and standard errors with Bessel's correction are reported for Bootstrap. Confidence levels for the estimates are determined by empirical distribution of the Bootstrapping results.*

J Simulation Set-Up Trend Tests

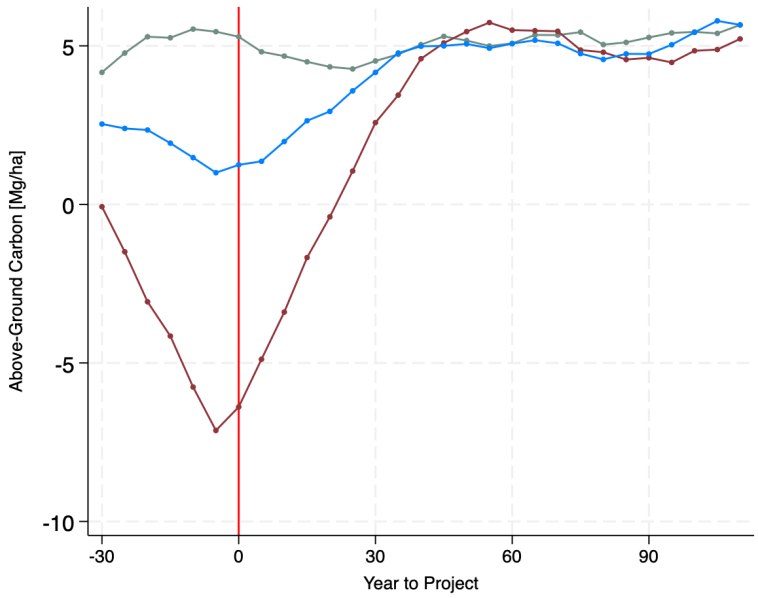
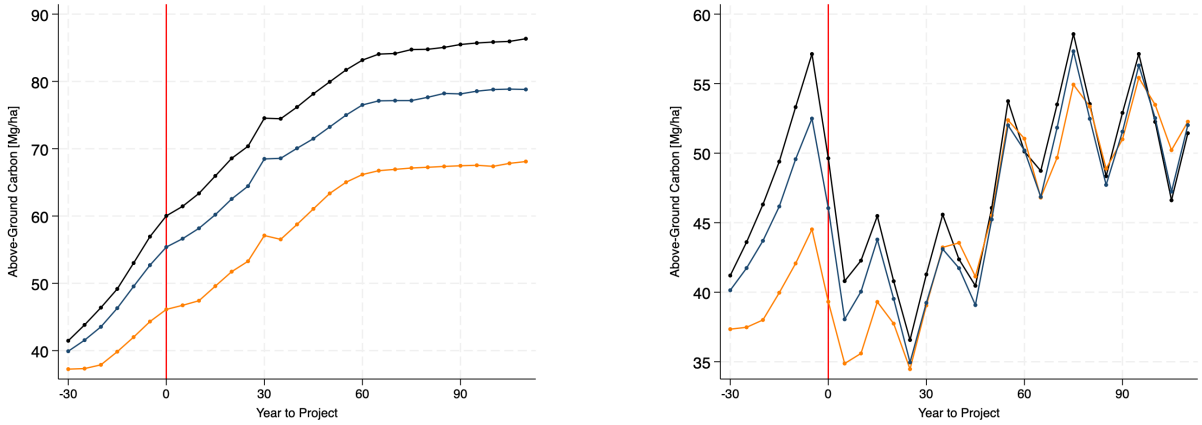


Figure J.1: Simulation Plot: Green=CARB Scenario, Red=VCM Scenario, Blue=Ideal Scenario

Notes: Plots indicate the simulated project above ground carbon relative to (subtracting) the natural baseline, which is the average biomass for surrounding non-project areas with same geopotentials, practicing 1.5% rate harvesting. First 10 years of simulations are dropped as the stabilization period of the model.



(a) Business-as-Usual Baseline **(b)** Implied Baseline

Figure J.2: Simulation plots for project "Business-as-Usual" (after market harvesting same as pre-period) and "Implied" (after market harvesting rate 5%) baselines: Green=Pre-Market 1%, Orange=Pre-Market 2%, Blue=Pre-Market 1.5% Harvesting

Notes: First 10 years of simulations are dropped as the stabilization period of the model.

K Project Developer Payoff Simulations Parameters and Sensitivity Checks

Project developer's payoff:

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

Where 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.

All other parameters are summarized below in table.

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

Table K.1: Payoff Parameter Sources and Summary

Market	Project Scenario	Original	Alt. Buffer Treatment	Same Offset Price	Offset Price Growth	VCM No Agent	High Agent Cost	High Standing Dead	High Timber Price	Market Not Clear
					Baseline: Implied					
Regulated	CARB	938	937	773	945	938	857	1114	1114	14
Regulated	Ideal	703	530	567	714	703	637	849	745	-56
Regulated	VCM	222	137	164	238	222	193	286	122	-102
Voluntary	CARB	521	460	662	524	580	485	619	619	170
Voluntary	Ideal	442	173	582	448	501	407	540	428	96
Voluntary	VCM	396	122	535	406	455	361	493	315	52

Table K.2: Sensitivity Analysis for Simulated Carbon Offset Market Project Developer Total Payoff Estimates under Implied Baseline

Notes: Payoff total is estimated in dollar ($) per hectare ($ha^{-1}$). Payoff function and parameter summary see Appendix K. All estimation under Implied baseline (same harvesting rate as project pre-market, 5% harvesting post-market). Original is the main estimation same as Table 5. 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 (average of the two market prices). 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 Timber 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.

L Market Outcome Simulations with Continuous Pre-Market Harvesting Rate

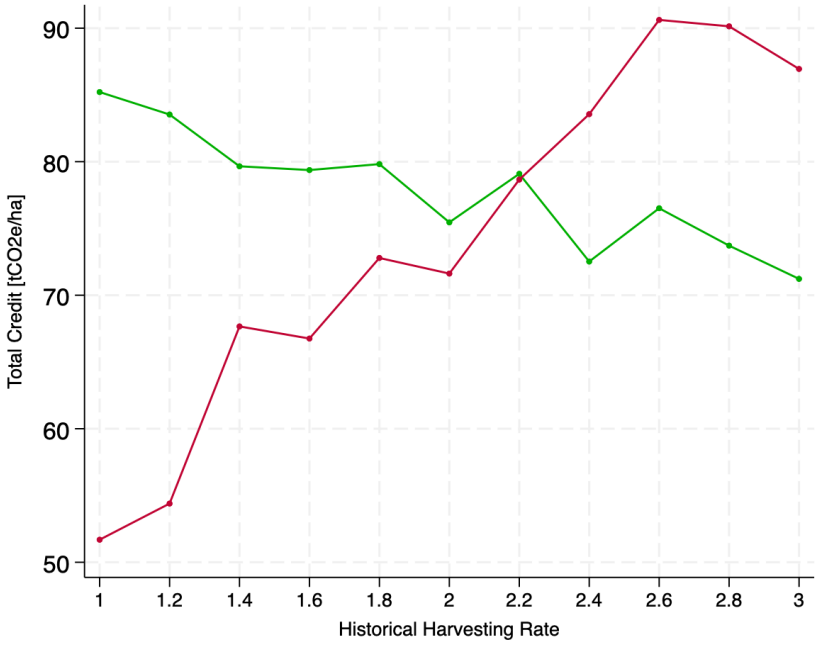
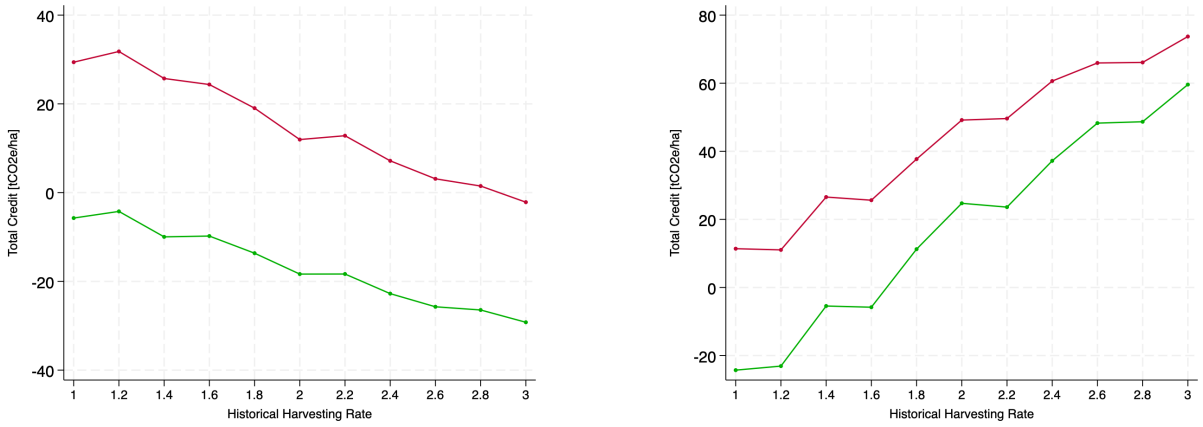


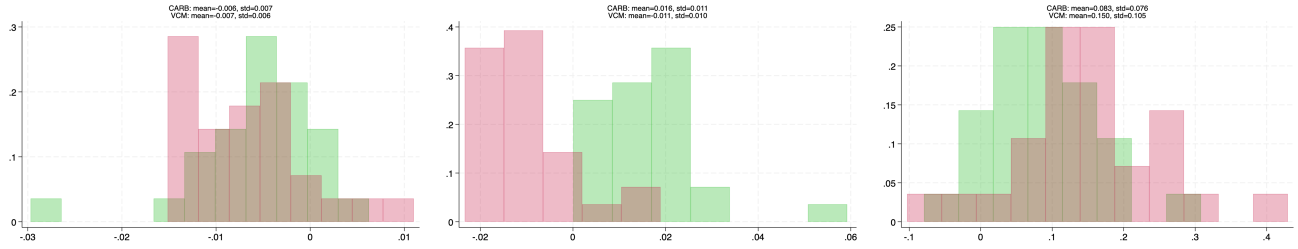
Figure L.1: Simulation estimated market outcomes of total credit issuance with different pre-market harvesting rates 1%-3% and "Implied" (after market harvesting rate 5%) baselines: Green=enter regulated market, Red=enter voluntary market



(a) Common Practice **(b)** Business-as-Usual

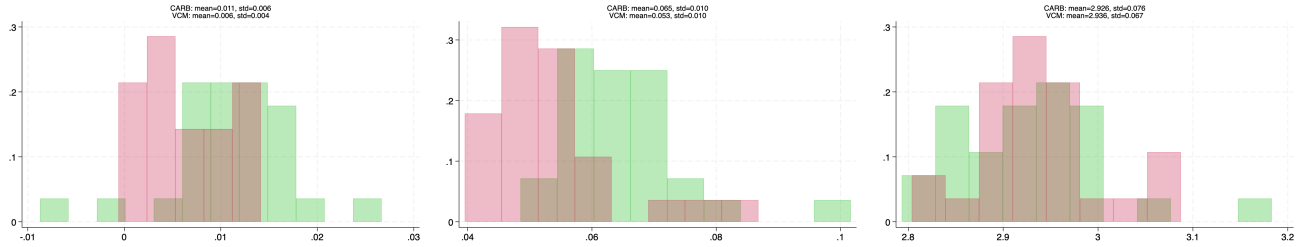
Figure L.2: Simulation estimated market outcomes of total credit issuance under Common Practice and Business-as-Usual baselines: Green=enter regulated market, Red=enter voluntary market.

M Text Analysis Results



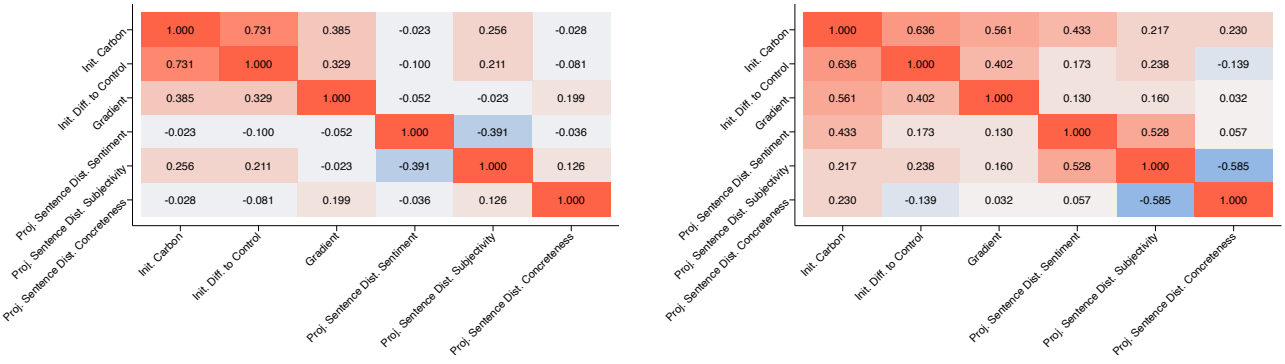
(a) Sentiment **(b)** Subjectivity **(c)** Concreteness

Figure M.1: Distribution Histogram for Text Analysis, Difference of Project Plans and Protocols



(a) Sentiment **(b)** Subjectivity **(c)** Concreteness

Figure M.2: Distribution Histogram for Text Analysis, Project Plans Scores



(a) CARB **(b)** VCM

Figure M.3: Correlation Matrix Between Project Document Text Representation and FIA Carbon Measurements

N State-Level Full Market Entrance Extrapolation

State	No Entry	CARB	VCM
CT	0.531	0.311	0.158
DE	0.584	0.372	0.044
IA	0.441	0.543	0.016
IL	0.577	0.377	0.046
IN	0.545	0.411	0.044
MA	0.522	0.253	0.225
MD	0.596	0.319	0.085
ME	0.494	0.251	0.255
MI	0.476	0.217	0.307
MN	0.465	0.222	0.313
MO	0.578	0.358	0.064
NH	0.404	0.183	0.413
NJ	0.630	0.226	0.144
NY	0.487	0.311	0.202
OH	0.524	0.426	0.050
PA	0.522	0.324	0.154
RI	0.534	0.261	0.206
VT	0.461	0.254	0.285
WI	0.496	0.348	0.155
WV	0.512	0.342	0.145

Table N.1: Predicted State-Level Carbon Offset Market Entrance Probabilities

Notes: Carbon offset market participation probabilities estimated with multinomial logistic regression for all FIA sample plots with all predictors of coefficients in Table 3 (Direct Estimates). Total FIA plots to predict $N = 37,926$ *spanning 20 states of Region 9. Participation rates reported are averaged to state level weighted by area of plots.*

State	Forest Coverage	Project Benefit Business-as-Usual Base. [Million USD]	Project Benefit Implied Base. [Million USD]	Social Benefit of Carbon Reduction [Million USD]
Connecticut	0.58	16	259	576
Delaware	0.29	2	53	32
Iowa	0.08	22	610	93
Illinois	0.14	31	749	461
Indiana	0.21	32	795	432
Massachusetts	0.61	30	400	1377
Maryland	0.39	16	332	423
Maine	0.89	191	2391	9066
Michigan	0.56	244	2674	12590
Minnesota	0.34	213	2341	11003
Missouri	0.35	101	2252	1981
New Hampshire	0.83	70	646	3968
New Jersey	0.42	14	217	581
New York	0.63	190	2841	7704
Ohio	0.31	57	1370	819
Pennsylvania	0.59	149	2495	5265
Rhode Island	0.56	4	49	154
Vermont	0.76	53	642	2601
Wisconsin	0.49	156	2682	5365
West Virginia	0.79	106	1851	3549
Total	0.43	1699	25648	68039

Table N.2: Economic and Environmental Values of State-Level Full Participation into Carbon Offset Markets

Notes: Carbon offset market participation estimation according to MNL estimates and all FIA sample plots with all predictors of Table N.1. Forest area and state-level forest coverage summarized from 2022 Forest Inventory and Analysis Business Report. Project benefit at Business-as-Usual baseline supports both CARB and VCM predicted entrance into voluntary market. Both project benefits under Business-as-Usual and Implied baselines quoted from simulation result Table 5. Social benefit of carbon reduction estimated from emission reduction under the Business-as-Usual baseline quoted from Table 4. Adjustment is made by adding 10% standing dead carbon and reducing 30% leakage. Conversion to USD using EPA estimate of social cost of carbon at 2030 and 2.5% discount rate, Table ES.1, at 140 USD/tCO_2e (2020 currency).