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

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Abstract

We undertake the first systematic analysis comparing and contrasting U.S. improved forest management (IFM) projects participating in the California regulated and global voluntary carbon offset markets. We link a novel geospatial dataset of IFM offset projects located in the U.S. Forest Northern Region to measurements of above-ground live carbon collected through U.S. Forest Service Forest and Inventory Analysis (FIA). Statistical and calibrated simulation analyses both provide evidence for market entrance selections and excessive offset credit issuance. As revealed by event study analysis and two-stage logistic regression with carbon trends, IFM projects on regulated and voluntary markets differ significantly in pre-market forest management relative to their statistical counterfactual forestlands with similar carbon storage capacities. Payoff estimations based on forest simulation modeling replicate 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 market rules. Using the simulation model, we also find that real-world market entrance outcomes match with the generous lower baselines implied in the IFM projects' registry documentation, rather than the more appropriate business-as-usual baselines. Because of that, regulated market projects are non-additional and voluntary market projects also issue about 1.8 times the offset credits of their justified emission reduction. 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. Based on the results from a nested logistic model with simulation approximated project payoffs, switching to stricter business-as-usual baselines would solve the overcrediting problem, but also lower the market participation of forest-based projects, and reduce the potential of carbon offset markets to mitigate emissions through motivating forest conservations.

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1 Introduction

Over the past few years, growth in carbon offset markets has signaled the significant and lasting interests among the private sector in purchasing carbon offset credits that can represent meaningful emission mitigation to fulfill their climate commitments[1]. Within carbon markets, nature-based offset credits offer the promise of low-cost climate mitigation. These credits account for CO_2 reductions through ecosystems that sequestrate atmospheric carbon and store it in biomass with photosynthesis. Today, about one-quarter of all U.S. offset projects on three major carbon registries, American Carbon Registry (ACR), Climate Action Reserve (CAR), and Verra (VCS), implement nature-based climate solutions. These projects exercise improved forest management, sustainable agriculture, grassland and wetland preservation. They account for about 17.0 millions tCO_2e of offset credit sold by mid-2024, in which 13.5 millions tCO_2e are sold on the California regulated compliance market, and 4.5 are sold on the global voluntary carbon market.

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

As both regulated and voluntary markets grow, the credibility about whether actual emission reductions are associated with the carbon offsets being sold has been increasingly questioned (Haya et al. 2023, Calyx Global 2024, Probst et al. 2024). For forest-based carbon offset projects, because of the specialized knowledge required for forest management and tree growth modeling, asymmetric

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

information on credit quality and offsetting credibility has posed a significant barrier for non-project developers to accurately evaluate the true environmental benefits of these trades (Woodall et al. 2025). Both supply-side and demand-side market failures can lead to market inefficiencies. On the supply side, adverse selection may cause project developers to deliberately supply low social value offset projects when markets let them undetected. Demand-side can exacerbate this market failure, as buyers may encourage the provision of low-quality offsets that come with lower prices, effectively performing greenwashing.

This paper leverages statistical analysis, field-based forest inventory data, and advanced forest landscape modeling to estimate the decision model of market entrance for forest-based carbon offset projects in the U.S., and to uncover the entry selection biases and resulting inefficiencies on both regulated and voluntary carbon markets. We focus on improved forest management (IFM) projects, which are the most common class of forest-based projects in the U.S.. Our study region is the U.S. Forest Service's 20-state Northern Region (Region 9) that spans Great Lakes, Mideast, New England, east of Plains and north of Southeast. We have an agreement with the regional forest service to use the exact coordinates of their Forest Inventory and Analysis (FIA) field data, which measures above-ground live carbon inventories on randomized forest plots every 5-6 years through tree type and diameter measurements and allometric equations (Bechtold & Patterson 2005)[2]. We compile a novel dataset of geospatial boundaries for 62 IFM projects in this region, among which 34 are traded on the regulated California carbon offset market with shapefiles obtained from CARB, and 28 are traded on the voluntary global carbon offset market with shapefiles identified through manual map scraping. Merging the geospatial datasets, we obtain a panel data for the above-ground carbon levels of IFM project in the region based on ground-truth FIA measurements that are independent of project developers' reports.

We base our analysis on a theoretical model that relates project developers' offset market entrance decisions to observable geophysical and socioeconomic variables that determine the maximum forestland carbon storage capacities, and unobservables that are reflected through historical forest management practices. First to identify historical forestry practices, which lacks public records, we use event study regressions to find that IFM projects' above-ground carbon trends are different by the markets they enter (regulated versus voluntary) relative to control FIA forest plots with similar capacities to store live carbon constructed using five nearest neighbor matching on selected exogenous ecological and socio-economic forestland characteristics. Projects entering the regulated market on

[2]MOU number: 19-MU-11242305-016, signed between Harvard University and USFS Northern Research Station.

average have increasing pre-market carbon stocks relative to their control plots. Projects entering the voluntary market have approximately historical decreasing carbon stocks relative to their controls before market entrance. These differential trends have lead to higher average carbon levels at market entrance for regulated market projects. Based on these regression results, we construct indicators for historical forest management with the signs and sizes of the estimated slopes of pre-market above-ground carbon in time. We then estimate a two-stage logistic regression decision model for IFM projects' market entrance choices, showing that either pre-market conservation or aggressive harvesting would promote forests to enter offset markets, and historical positive carbon accumulations (e.g. through conservation) would encourage the regulated market entrance.

To further identify the causal relationship between historical forest management and market entrance choices, we adapt the LANDIS/PnET model to simulate representative real IFM projects on both carbon offset markets with similar pre-market carbon trends as what we have found with event study analysis. We explicitly calculate the total credit issuance and total expected payoffs for each representative project scenario, under different baseline settings, on both regulated and voluntary carbon markets, inputting the simulated trajectories of above-ground carbon over decades under the two markets' differential credit issuance schemes. Comparing the simulated economic gains measured by either total credit issuance or total payoffs, we have shown that the different offset credit issuance schemes on regulated versus voluntary market can induce entry selection biases of IFM projects depending on their historical forest management plans. The high initial issuance scheme of the regulated market would encourage projects already accumulating high initial carbon stocks to enter. The more gradual credit issuance scheme of the voluntary market awards on continuing forest carbon sequestrations, therefore motivates projects with low initial carbon stocks to enter so that they can change post-market forest management plans to achieve higher carbon levels to trade for credits.

Our forest simulations also reveal an important source of market inefficiency. To achieve the equilibrium market entrance outcomes we see in real-life, offset markets likely allow baseline projections not representative of IFM projects' business-as-usual forest management. The baselines presented in documents submitted by projects and used for their credit issuance need to be with double the observed harvesting rate in order for the simulated market entry choices to align with real-world observations. The lowered baselines can attract more market entrance from IFM projects, with the cost of generating overcrediting issues on both regulated and voluntary markets. The additionality problem is more pronounced for the regulated market when combined with its high initial issuance scheme, when projects can benefit from their pre-market forest conservations and lowered baseline selections on this market, and earn credits without consolidating any changes in their post-market forest management plans to sequestrate additional carbon in forests. We further build a nested logistic regression model to incorporate the expected payoffs from our simulations matching with slopes of historical carbon trends. Applying to counterfactual analysis, our model shows that when enforcing strict business-as-usual baselines rather than the current market-allowed lower baselines, market efficiency is improved as low quality offset credits exit the markets. However, because of the significant drops in expected offset market payoffs, we also predict less carbon emission reduction due to lowered overall market participation rates.

This paper represents the first empirical research exploring the entry selections of forest-based carbon offset projects in regulatory compliance and voluntary carbon markets using ground-truth forest measurement. By constructing and analyzing the first geospatial dataset for IFM projects on the voluntary carbon market, we complement existing literature focusing on the effectiveness of Californian carbon offsets traded on the state's regulated market, with evidence from remote sensing, forest simulations, or non-exact ground data (Badgley et al. 2022, Coffield et al. 2022, Stapp 2022, Stapp et al. 2023). Our paper also presents one of the first attempts to link market mechanisms to supply-side market entrance incentives using forest simulations and discrete choice modeling, supplementing the existing arguments on carbon offset market policies (Aldy & Halem 2022, Pande 2024) and trading behavior analysis from the demand-side (Kim et al. 2024). The paper also adds to discussions on suppliers' significant surplus on offset markets and potential market inefficiencies (Aronoff & Rafey 2023). Our work also relates to the broader literature on nature-based climate solutions, providing empirical evidence for the effectiveness of forest-based offset credit tradings (Griscom et al. 2017, West et al. 2023). Finally, we offer new evidence on the additionality challenges in the emerging carbon offset markets, providing another insight on the potential gaps between environmental market operations and 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 theoretical model for supply-side market decisions. Section 4 introduces data and summary statistics. Section 5 describes the empirical strategy. Section 6 presents our main results. Section 7 summarizes simulation modeling and analysis. 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 planetary health acting as the major and natural sink of carbon through photosynthesis (Pan et al. 2024, Harris et al. 2021). Preservation, restoration and protection of forests are important classes of Nature-based Climate Solutions (NbCS), which are defined as the deliberate human actions that manipulate ecosystems to improve the planet's greenhouse gas budget. Forests have the greatest climate mitigation potential among ecosystems above grassland and wetlands, where existing forest management and avoided deforestation account for over half of this capacity (Griscom et al. 2017, Buma et al. 2024, Anderegg et al. 2025).

Sales of nature-based carbon offsets are important financing sources for NbCS. Advantaged with lower trading prices compared to regular carbon prices on cap-and-trade markets and additional ecological cobenefits, nature-based carbon credits have been taking increasingly significant market share on offset markets in the U.S.. By the end of July 2024, across a total of 1,175 US carbon offset projects with non-zero credit issuance registered under the three main carbon registries, American Carbon Registry (ACR), Climate Action Reserve (CAR), and Verra (VCS)[3], 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.

Improved forest management (IFM) is by far the most common type of forest offset project (Kaarakka et al. 2021, 2023). IFM projects strategically change forest management activities in order to achieve higher levels of forest carbon storage relative to a defined baseline scenario representing the counterfactual without these improved forestry practices. Most of the additional carbon is stored in the form of above-ground live biomass (e.g., the above-ground portion of living trees). The most common strategy for IFM is to restrict the harvesting of forests, including reducing the number of trees to harvest per cycle (decreasing harvesting rate), and cutting older instead of younger trees so trees grow longer and store more carbon above-ground (extending the rotation period). Other methods include improving the ecological condition of land and soil, forest fire risk management, and forest planning to foster the growth of the existing forests (for example, forest thinning).

In the U.S., IFM projects traded on carbon offset markets are owned and managed by timber companies, recreational clubs, tribes, educational institutions, local and state governments. When

[3] Gold Standard (GS) has one forest carbon project only in the country but outside of the continental U.S..

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 their forestry activities and argue how they can achieve increased carbon stocks relative to credible baseline scenarios. After accounting for potential reversal risks and leakage effects, additional carbon net of the baselines will be classified as the amounts of carbon offsetting from IFM. These amounts then get verified by third parties, and rewarded as tradable carbon credits upon market entrance approval by carbon registries, to project developers of the forestland[4]. Post-market forestry practices and forest carbon measurements need to be reported to carbon registries or market regulators continuously, for the project to remain verified and for subsequent credit issuance. If there is lack of post-market reporting or detected deviation from proposed offsetting pathway, project developers may lose market access, have their existing credits void, and face legal challenges from their credit buyers.

2.2 Californian Regulatory Carbon Offset Market

The only regulated carbon offset market in the U.S. (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[5]. Offset projects supplying on the regulated market are not required to be California-based[6]. They need to first register with a qualified carbon registry (ACR or CAR), get verified, and obtain credits from the registries under CARB protocols, then file additional required documents to CARB[7]. Upon approval, CARB allows the conversion of the issued credits to be ARB credits that can be used on the state's regulated market.

IFM projects on this regulated market (referred as "CARB projects" for this paper) need to outline the persistence of increased forest carbon storage through their actions in a 100-year term period, showing forest carbon projections over the century. Their crediting period (i.e., time range

[4]Note that on carbon offset markets intermediary agencies like Finite Carbon and Blue Source are often called "project developers" as they design and even manage IFM projects besides helping project owners to file documents. However, in this paper, we reserve the term "project developer" for forest owners or direct beneficiary who are the actual decision makers on offset market entrance and forest management plans, and instead call the these agents the intermediary.

[5]8% allowance is for emissions before 2020, for 2021-2025 the allowance decreases to 4%, then after 2026 it will be 6%.

[6]Projects providing direct climate benefit to CA will be flagged as Direct Environmental Benefits, or DEBS. Since 2021, at least half of the carbon offset allowance from the CA cap-and-trade program must be fulfilled by DEBS projects.

[7]CARB provides calculation worksheets, estimation formulas, basic statistics, and parameters for baselines. There are three forest protocols from CARB over time, 2011, 2014 and 2015.

when credits can be issued) on this market is 25 years. For baseline scenarios that projects can compare with, the projected 100-year average above-ground live carbon stocks cannot fall below a measure called "common practice", which is the regional average carbon storage capacities based on locations and areas of the forestland, estimated by FIA statistics. CARB projects have their GHG emission removal plan documents and standardized reporting forms to CARB public on carbon registries' websites. Both registries and CARB publish credit issuance, retirement, cancellation details, and the geospatial files for the CARB projects. CARB monitors participating projects every year, requires their annual reporting, and reserves the right to revoke previous offset credit eligibility on the regulated market.

2.3 Voluntary Carbon Market

Voluntary carbon market, or VCM ("the voluntary market" in this paper) is a global market where carbon offsets can be transferred to buyers of any sort. Like the regulated market, each project traded on VCM must register with a certified carbon registry (ACR, CAR, Verra). Project developers are required to follow the protocols issued by their registries, produce GHG emission removal plans that include details of project evaluations and baseline constructions[8].

IFM projects traded on VCM (referred as "VCM projects") are usually following less strict protocols than CARB projects. Common practice tests are not explicitly required for VCM projects' baselines setting. For persistence of carbon removal, a shorter term period of 40 years (except for a few earlier entrants on Verra that takes 100 years) is specified by carbon registries. The crediting period is also shorter at 20 years. Project developers only need to provide the carbon projections for IFM and baseline scenarios over the next 20 years. After market entrance, projects undergo less monitoring by the registries, required to file updates per 5-year period. From public project documents on registry websites, reporting of VCM projects is much less standardized than CARB projects. Though project geospatial files are submitted to carbon registries, they are not made public. Project locations and geospatial information can only be read from maps with geocoordinates included in their GHG emission removal documents. Registries also publish detailed information on credit issuance, retirement and cancellation for their VCM projects.

[8]Protocols could differ across registries and the timing of registrations.

2.4 Offset Credit Issuance Schemes for IFM Projects

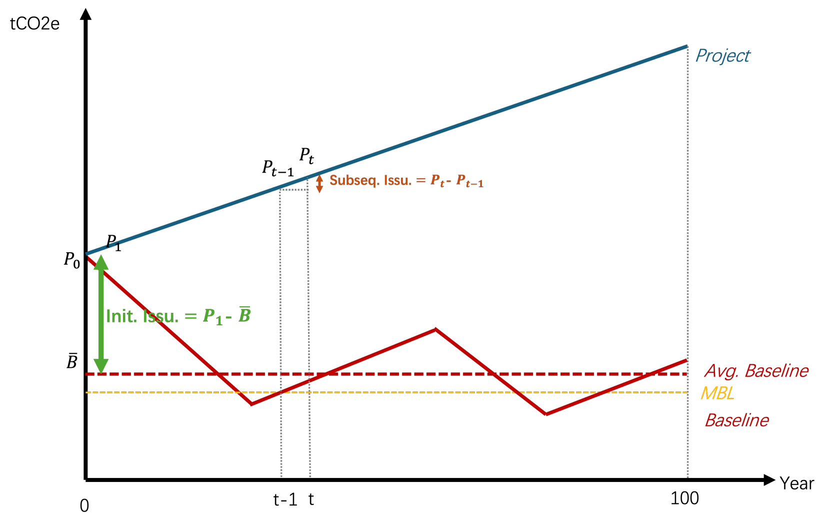
Carbon offset credit issuance schemes determine the amount of credit available for IFM project developers each period post-market. Both regulated and voluntary markets have issuance schemes that theoretically make total credit issuance equal to the amount of additional carbon due to IFM relative to the baseline scenario without IFM. However, the two markets differ significantly in terms of the schedule of issuance. In particular, the regulated market allocates most of the total credit as initial issuance, while the voluntary market distributes most of the total credit in subsequent issuance gradually over time.

Below, we describe the issuance schemes of the two markets with Figure 1, replicating carbon projection diagrams in typical projects' GHG emission removal plan (Appendix Figure A.1)[9].

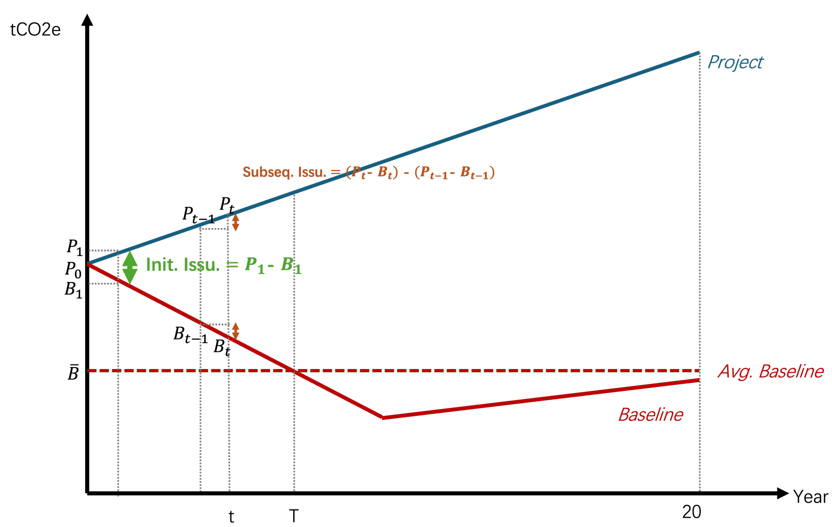
Regulated Market Issuance for CARB Projects On the regulated market, CARB projects submit model-generated baselines and project simulations using peer-reviewed models (usually the Forest Vegetation Simulator (FVS)) for 100 years since project launches, under conditions of legal and financial constraints (Crookston & Dixon 2005). The number of credits being issued is determined by the difference in modeled forest carbon between the IFM project scenario, and the baseline scenario, allegedly contributed by IFM practices such as reduced harvesting. The average above-ground baseline carbon level over the term period of 100 years must be above a minimum baseline level (MBL)[10]. As illustrated with Figure 1 Panel (a), the regulated market has its initial issuance determined as CARB projects' realized carbon stocks by the end of the first reporting period, minus the 100-year average of their baseline projections. For later periods, subsequent offset issuance equals to the changes of realized carbon stocks relative to the previous period (and small changes in baseline average, if there are changes in baseline projections). As a result, this market scheme awards future carbon offsets due to decreasing baseline carbon in the very first (initial) period upon CARB projects entering the regulated market, making the initial credit much greater than any subsequent issuance.

[9]Note that the following descriptions are only accounting for total offset credit issuance related to above-ground live carbon. In calculating total credits, dead and below-ground carbon is also estimated. In our paper, we estimate and illustrate through above-ground live carbon only as it is the major contributors to forest carbon. Also, total credits much account for leakage or secondary effects (e.g. spillovers to increased logging in the other forestland owned by the same timber company) used for buffer pools accounting (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 more detailed mathematical formulas describing the credit issuance schemes including evaluations of present value payoffs from credit sales accounting risks, uncertainties and buffer pools, see Appendix Table B.1.

[10]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 above-ground live carbon stock (ICS). Because CP is normally lower than ICS, MBL=CP for most of the cases.



(a) CARB Project Issuance on Regulated Market



(b) VCM Project Issuance on Voluntary Market

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

Voluntary Market Issuance for VCM Projects On the voluntary offset market, IFM projects registered by American Carbon Registry (ACR)[11] are required to submit simulated project and baseline above-ground carbon trajectories (again usually applying the FVS model) for its crediting period of 20 years. There are no explicit minimum levels required for the long-run average of baseline carbon stocks. As illustrated with Figure 1 Panel (b), on the voluntary market, offset credits are awarded for the continuous changes in realized project versus the baseline carbon stocks. Therefore, the initial issuance represents only the estimated changes in project relative to baseline carbon stocks at the end of the first reporting period. Future carbon offsetting is not rewarded in the initial issuance, instead they are incorporated into subsequent later issuance, which equals to the sum of incremental increase of realized carbon stocks under IFM minus the fluctuation in the baselines carbon[12]. Therefore, the voluntary market issuance scheme provides much smaller initial credit issuance, spreading the shares across subsequent non-initial issuance.

3 Theoretical Framework

3.1 Simplified Model for Forest Management and Carbon Sequestration

Forest carbon inventories are determined by the net difference between carbon dioxide absorption through vegetation' photosynthesis, and emission through respiration. Carbon stored in forests includes mostly above-ground standing live carbon, standing dead carbon, and below-ground carbon of live, dead and soil carbon. In forest literature and modeling (Crookston & Dixon 2005, MacLean et al. 2021), forest carbon stocks are determined by several classes of variables.

The first class is exogenous long-run natural and socioeconomic characteristics of the forestland, including climate variables like average temperature and precipitation, forest types like tree species and composition, geophysical characteristics like soil concentration, land slope and orientation, land ownership status like private versus public, and financial or legal constraints applied to forest managers. This class of factors determines forest carbon storage capacity, or the maximum amount of carbon inventory able to stand and last for decades.

The second class of determining factors is human activities, including harvesting, recreational activities, ecological protection, afforestation, and wildfire management. These activities are en-

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

[12] Per ACR rule, baseline fluctuations when baseline carbon fall below their 20-year averages are not accounted for credits. In the illustration plot, once $t \geq T$, subsequent issuance only counts the increase of realized carbon stocks under project scenario.

dogenously chosen by forestland owners given the first class of exogenous natural and socioeconomic constraints.

The third class of factors is short-run shocks, such as extreme temperature or precipitation, wildfires, storms, timber market price changes or timber demand shocks. These can impact the growth and damages to trees, or instantaneous forest management decision changes, causing fluctuations to forest carbon inventory in the short-run.

We then use a simple model for forest carbon stock at location i and time t:

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

Where $\mathbf{G}$ denotes the exogenous natural and socioeconomic characteristics of the forestland i, consistent in the long-run and invariant in time. $\mathbf{A}$ denotes the long-term human activities related to the forestland i, including forest management activities such as harvesting, preservation, etc.. $\mathbf{S}$ is the class of short-run shocks, time-varying by t.

Here we also assume that $\mathbf{S}$ absorbs temporary shifts in forest management and exogenous physical and economic conditions, plus the terms of function f being separable, we can take the average function across t, then denote the long-run average carbon storage level for forest location i:

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

More generally, we can also summarize other long-run average carbon inventory features such as the trend of carbon storage change in time with averaging functions across t:

$$\mathbf{C}_i = \mathbf{f}(\mathbf{G}_i, \mathbf{A}_i)$$

3.2 Project Developer's Maximization Problem

Though markets and concepts are available since 1980s, forest carbon offset trading has been notably increasing only after the Paris Agreement when demand rises out of the voluntary carbon neutrality commitments of governments and corporations all around the world (Haya et al. 2023, Chandrasekhar 2023). It is not insensible to assume that historically, most forestland owners, private or public, have not taken into consideration the potential benefits of entering their forest as IFM projects and trade on the carbon offset markets.

Therefore, potential IFM project developers have their pre-market forest activities $\mathbf{A}$ chosen to maximize their payoff without any offset markets:

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

Where the average payoff function $\bar{g}$ indicating payoffs from timber markets, recreational activities, etc. depends on exogenous forestland specific characteristics $\mathbf{G}$ and long-run forest management plan $\mathbf{A}$.

Once the option of entering the carbon offset market is available to forestland owners, these potential project developers will consider the option to improve their expected payoffs through offset market participation. In registering as IFM projects, the project developer of forestland i is responsible for guaranteeing GHG removal through changing forest management activities to increase forest carbon storage in the long-run. They gain from sales of the extra carbon stored in forests on carbon markets, but also have lower gains $\bar{g}$ from the traditional activities due to increased costs of forest conservation, and selling less timber because of reduced harvesting.

Assume the post-market forest management plan is denoted as $\mathbf{A}'$, we formulate the payoff entering carbon offset market m relative to non-entrance as:

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

Where in our setting m is one of the two available carbon offset markets in the U.S., *Regulated* or $Voluntary$. Final relative payoff function includes c_m as the entrance transaction cost, which differs between the two markets[13]. Offset credits are sold with an average prices p_m per unit[14].

This maps to a rational, fully-informed project developer's maximization problem of choosing an improved forest management plan $\mathbf{A}'$ on market m:

$$\mathbf{A}'_i = \arg\max_{\mathbf{A}'_i} \pi(\mathbf{G}_i, \mathbf{A}_i, \mathbf{A}'_i, m)$$

We also include the option of m being non-entrance, at which $\pi(\mathbf{G}_i, \mathbf{A}_i, \mathbf{A}'_i, NoEntry) = 0$ at the optimal choice of $\mathbf{A}' = \mathbf{A}$ (continuing the historical forest management practices).

After choosing the new forest management plan $\mathbf{A}'$ to maximize the relative payoffs on $m \in \{NoEntry, Regulated, Voluntary\}$ separately, project developer then selects the market with the

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

[14]In later estimations, market payoffs are more complicated when price also incorporate future discounting, different credit issuance schemes, uncertainties, non-market clearing conditions.

maximized profit to enter. Their final maximized payoff function is:

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

3.3 Identification Strategy

Given the above maximization problem for risk-neutral project developers, we can use discrete choice model to identify parameters of the model function π given full set of $\mathbf{G}$ and the market entry choices of each potential project forestland i. In this case, pre-market historical forestry practices $\mathbf{A}$ is already captured by $\mathbf{G}$. The condition is very ideal.

Scientifically, natural determinants for forestland carbon storage potentials can be identified and measured (e.g. climate, soil, forest type, landscape). Some socio-economic determinants are also identifiable (e.g. land ownership status being private or public). However, it is hard to observe the rest determinants such as financial constraints, legal constraints, and potential economic values in recreation and timber markets access. To capture these unobservables, we will need information on historical forest management $\mathbf{A}$, through which the pre-market optimization problem can capture the unobservables in $\mathbf{G}$.

Meanwhile, human activities $\mathbf{A}$ are also hard to measure systematically. There exist representations such as past harvesting, but data references are scarce with low spatial coverage. Even for IFM projects entering the carbon offset markets, their public documents usually describe historical harvesting non-quantitatively and hardly disclose exact numbers.

However, in this paper, we have data tracking forest carbon inventories up to decades before any IFM project enters a carbon offset market. Therefore, we can use the observed historical forest carbon trends $\mathbf{C}$, to indirectly represent the pre-market forest management plans $\mathbf{A}$. Firstly, we will compare pre-market above-ground carbon trend for participants on either regulated or voluntary carbon offset markets with no-entry controls of similar carbon storage capacities constructed using the observables of $\mathbf{G}$. This analysis will provide grounds linking $\mathbf{C}$ with carbon offset market entrance decisions. Then, we will include $\mathbf{C}$ with the observed $\mathbf{G}$ variables to estimate the discrete choice model for IFM project participation with carbon offset markets.

In reality, the model is likely much more complicated. Market parameters such as offset prices and entry costs are expected to be time-variant as markets and regulations evolve over time. For example, when there is increasing influence from credit rating agencies, greater wildfire risks due to climate change, or reputation shocks due to reports on low-quality forest offsets, market entrance decisions at different timing will change accordingly. To capture those, a dynamic model considering not only entrance choices but also entrance timing need to be used for future studies.

4 Data

4.1 CARB Project Shapefiles and Records

For the IFM projects listed on the regulated Californian carbon market (CARB projects), we collect their official records geospatial shapefiles, panel of credit issuance, retirement and cancellation, directly from California Air Resources Board (CARB). We also download the publicly available documents of each project, including their GHG emission reduction plans and CARB listing and verification forms, from carbon registry websites (ACR and CAR)[15]. From these documents, we manually collect project-level basic information, including ownership status, risk estimates, baseline average, initial carbon stock, etc.. In our study region over 20 states of U.S. Forest Service Region 9, there are 43 IFM projects participating in the regulated market with non-zero credit issuance by July 2024, 28.5% of the total 151 IFM projects listed on the regulated market across the country.

4.2 VCM Project Shapefiles and Records

IFM projects participating in voluntary carbon market (VCM projects) are not required to make their geospatial shapefiles public, though these files are submitted to their registries upon verification for entrance permission[16]. However, registries do require IFM projects to provide maps of project areas with identifiable geocoordinates. Through these maps, we manually digitize the shapefiles for these IFM projects. Among the 37 projects registered under ACR, CAR and Verra located in U.S. Forest Region 9, we are able to construct a novel dataset containing the shapefiles for 29. The remaining 8 projects do not have high resolution maps so scattered polygons are not manually identifiable[17]. Project documentations on basic information and GHG offsetting plans and their credit transaction records are publicly available on registry websites. We downloaded the documents and compile project-level basic information and credit trading records[18].

[15]Registries also provide credit trading records. We have cross-checked 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 on registry websites.

[17]We have tempted machine learning based scraping for these projects, but the results have more errors than manual scraping. For future research, deep learning and AI should be applied to fill in this 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 any FIA plots), document areas are on average $9,668ha$,

4.3 FIA Ground Observational Forest Data

The U.S. Forest Inventory and Analysis (FIA) program collects detailed information regarding forests across the United States over time. 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", which are then scaled to carbon density using tree species specific allometric equations[19]. This measurement represents above-ground live standing carbon stock, which is the majority of total forest carbon inventory (including also standing dead and soil carbon stocks). Plots (parcels of land) are selected randomly by FIA across the country. Each plot is $0.06ha$ in area size, randomly located within each $6,000$-acre hexagon area. Plots are remeasured approximately every $5-6$ years in rolling terms, therefore about 20% of the plots get measured each year (Brand et al. 2003, Bechtold & Scott 2005). Applying an agreement with FIA, we have access to the exact coordinates of the their observational plots in 20 states of U.S. Forest Region 9 (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]. There are $42,124$ FIA plots in total over the region in the period 1999-2021.

To compare FIA plots with similar characteristics for later analysis, we merge the FIA dataset with a series of geophysical variables related to natural carbon storage capacities including precipitation, growing degree days, soil nitrogen concentration, land slope, land aspect sourced from NOAA and USDA (Morreale et al. 2021). Other forest characteristics we take include plot-level private vs public ownership and forest types, both recorded by FIA[21].

Overlapping FIA plots with the IFM project shapefiles (both CARB and VCM projects) we have compiled, limiting to plots with all geophysical and ownership characters non-missing, and restricting to plots with at least two survey years' observations, we have 62 IFM projects overlapping with at least one FIA plot, 34 being CARB projects and 28 being VCM projects. These projects span 13

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 likely draws straight lines to approximate wiggly boundaries of polygons, thus including areas not covered by the project. Our later regression analysis has included a robustness test run on the subsample of VCM projects dropping those with large deviations from documented areas. Our main results have been consistent on this subsample.

[19] More accurate remote-sensing based above-ground carbon measurements by Global Ecosystem Dynamics Investigation (GEDI) Level 4A (L4A) are only available post 2019, when extrapolations to historical measurements are not available yet.

[20] FIA panels publicly available without agreement use plot coordinates that are fuzzed with random noise.

[21] We use the FIA ownership code to define plot land ownership to be private as long as part of the plot has been private in any survey year.

states (DE, IL, IA, IN, MD, MO, RI are the states without any projects), overlay with 514 effective FIA plots, and give a total of 2,077 plot-year observations from 1999-2021[22]. Spatial distribution of these 62 IFM projects is shown in Figure 2. Both CARB and VCM projects are concentrated in forest-rich regions such as Maine, south of West Virginia, and North Michigan.

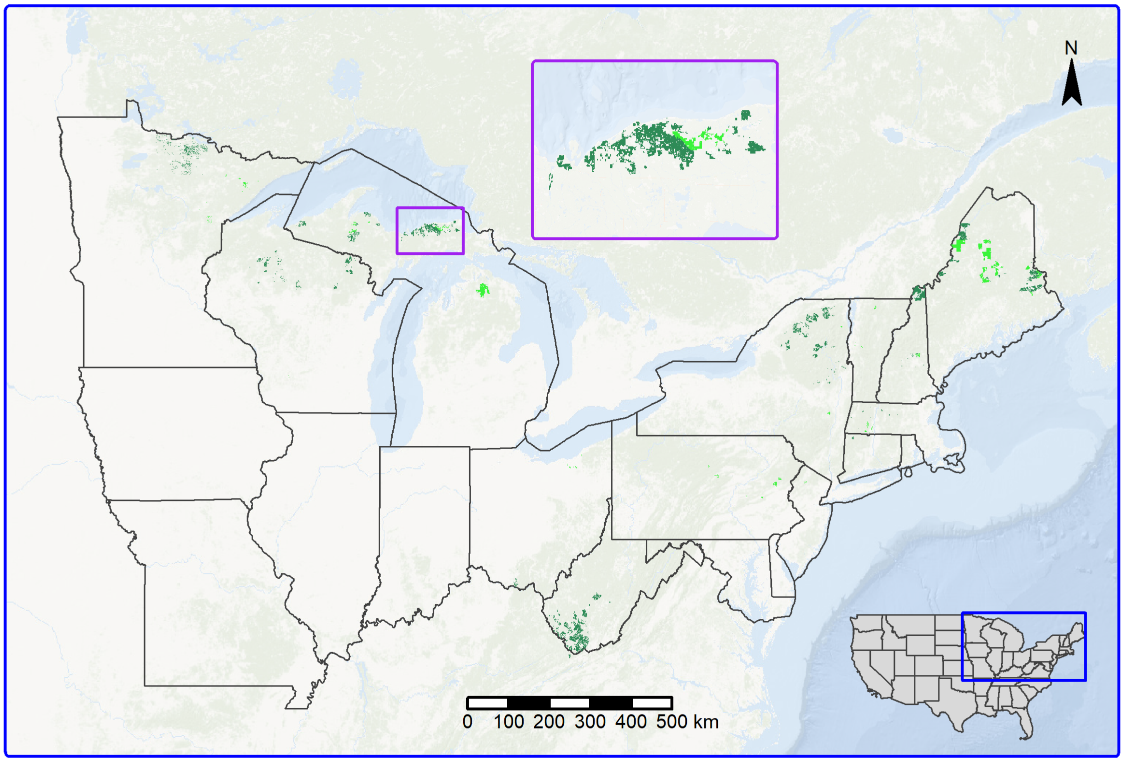


Figure 2: IFM projects in U.S. Forest Region 9

Notes: Map shows 62 IFM projects in Region 9 (20 states). Dark green indicates 34 CARB projects. Light green indicates 28 VCM projects. Zoom in shows 3 Michigan projects, CAFR5003/CAR973 (dark green, CARB project), ACR569, and ACR673 (light green, VCM projects).

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 their differences. On average, CARB projects have larger area, earlier market participation, and greater shares of private land ownership, as compared with VCM projects. Share of historical conservation easement (voluntary legal commitment to perform conservations for ecological protection on private lands) is similar across both CARB and VCM projects at just below 40%. All CARB projects are prepared by intermediary agents such as

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

Blue Source (now Anew Climate) and Finite Carbon, but 17.9% VCM projects are self-prepared. A much higher proportion of CARB projects are owned by timber companies (70.6% versus 39.3%). Comparing with VCM projects, baseline uncertainties estimated by CARB projects are statistically significantly lower by 3.4 percentage points, but their reversal risks are estimated significantly higher by 1 percentage point.

Regarding carbon inventory, VCM projects report to their registries an average 12.0 $Mg\ ha^{-1}$ higher (10% significance) above-ground carbon than CARB projects. Average baseline estimates reported[23] are quite similar at around 47.4 $Mg\ ha^{-1}$. However, VCM projects have lower (but not statistically significant) above-ground live carbon than CARB projects by FIA measurements, up to five years before their market entrance. Both CARB and VCM projects have this FIA carbon measurement much lower than their reported initial carbon stocks to carbon registries upon market entrance[24]. The discrepancies may come from that FIA plots and project sample plots are different, though both are selected with randomization[25]. By protocols for both regulated and voluntary markets, project samples are at least twice the density of FIA plots. Also, FIA plots have been selected years before the IFM projects, so landowners might know where they are and practice different forestry plans there.

By registry records, baselines used for both CARB and VCM projects are lower than their initial carbon stocks by significant margins, signaling predicted effective carbon removals that are essential for offset market entrance. In terms of credit issuance, CARB projects have 4.41 times the initial credit issuance per hectare of VCM projects. On the flip side, VCM projects have on average 4.44 times the non-initial (later) credit issuance per hectare of CARB projects, and the average credit per issue (covering the vintage period of a year) is 2.53 times 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. These observations are consistent with the intuition we derive from the differential crediting schemes on regulated versus voluntary carbon offset markets in the previous background section.

[23] 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.

[24] Market protocols demand projects to use standardized methodology of above-ground carbon measurement the same as FIA's method.

[25] According to CARB protocols, project sample plots used to measure their carbon inventories are selected following stratified randomization, with strata defined by common characteristics affecting carbon stocks. These selected project sample plots are 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 Above-Ground Carbon Stock [$Mg\ ha^{-1}$]	65.807	77.842	-1.947	0.056
Baseline Above-Ground Carbon Stock [$Mg\ ha^{-1}$]	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 [$Mg\,ha^{-1}$]	58.886	48.733	1.430	0.158

Table 1: Summary statistics and statistical t-test results between CARB and VCM projects

Notes: The table presents summary statistics for CARB and VCM projects as well as the t-test results for their difference. Summary statistics and tests are conducted at project level. For FIA pre-market measurements, averages are taken first at project level across plots within the same project measured within five years of project's market entrance, then further summarized at project level. Not all projects have enough FIA observations before market entrance, so one of the VCM projects (CAR 646) is dropped in the FIA observation panel. Above-ground carbon represents above-ground live carbon. Market entrance year is defined as the year of the first (initial credit's) vintage's starting time if its month is before July, or the next year of the year of the first vintage's starting time if its month is July or after. Initial crediting vintage starting date is not recorded for Climate Action Reserve projects, thus we use the first vintage the registry records as the project entrance year. CE stands for conservation easement. Agent stands for intermediary agents on behalf of project proponents (e.g., Blue Source, Finite Carbon). Initial credit indicates the amount of credit issued in the first (earliest) vintage year of the project. Total and non-initial (later) credit issuance are noted from registry records until July 2023. Average later credits is the mean taken across all non-initial issuances.

4.5 Above-Ground 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 contain indications of their historical forestry practices that are only qualitative in project documents. We apply plot-year level time-series regressions on FIA observations within the 62 IMF projects and display the estimated carbon trends in Figure 3[26].

Across all projects, their average above-ground carbon stock has been increasing since over 10 years before offset market entrance. The increasing trend continues after their market entrance. Separately, there are differential carbon trends for CARB and VCM projects. The regression estimated average above-ground carbon for CARB projects increases in early periods to just below $50Mg\ ha^{-1}$, but holds steady from ten years before to five years after their participation into the regulated market. Post-market period after five years of entrance sees some further increasing in CARB carbons above $50Mg\ ha^{-1}$. CARB projects have carbon stock estimates higher than the average and VCM, never falling below $40Mg\ ha^{-1}$. The average carbon level estimates for VCM projects start from below $40Mg\ ha^{-1}$ and decreasing towards about $35Mg\ ha^{-1}$ until five years before entering the voluntary market. Then the VCM projects average carbon inventory sees a sudden jump after they enter the voluntary market, reaching above CARB projects at about $55Mg\,ha^{-1}$. Due to later market entrance and smaller project areas, there remains limited statistical evidence whether this higher carbon level of VCM projects maintain. But from the regression estimation with wide confidence interval, there seems to be slight decrease of average VCM carbons post-market, though still remain high above $50Mg\ ha^{-1}$.

Overall, time series regressions have shown different trends of above-ground carbon stocks for CARB and VCM projects, especially in historical periods long before any offset market entrance. These different trends are correlated with their differential historical (pre-market) forest management strategies, continuing years before the option of offset markets has been considered. As suggested by our theory model in the previous section, it implies that selections into regulated versus voluntary carbon offset markets are correlated with historical forest management activities.

[26]For sample projects' FIA carbon trends consistent with these time series regression estimates, as well as their matched controls' (see the next empirical section) approximately flat pre-market carbon trends, see Appendix Figure C.1.

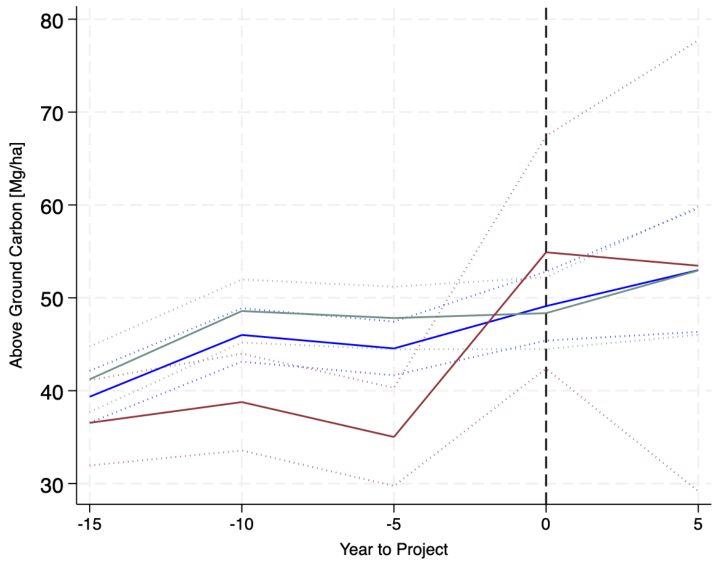


Figure 3: Time series estimations for above-ground carbon storage of Region 9 IFM projects

Notes: Blue=all projects, Green=CARB projects, Red=VCM projects. Average and 95% confidence intervals (marked by dotted lines) are estimated with the regression $AboveGroundCarbon_{it} = \sum_{k=-15,-10,-5,0,5} \beta^k B^k_{it} + \epsilon_{it}$ *and* $AboveGroundCarbon_{it} = \sum_{k=-15,-10,-5,0,5} \beta^{ck} B^k_{it} \times CARB + \sum_{k=-15,-10,-5,0,5} \beta^{vk} B^k_{it} \times VCM + \epsilon_{it}$. *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. *End bins are* $(-\infty, -11]$ *and* $[5, \infty)$. *No constants are controlled in this regression. Standard errors are clustered at FIA plot level. Indicators* $v \in \{CARB, VCM\}$ *denotes whether the FIA plot overlay with CARB or VCM projects. Each point in this plot represents the estimated coefficient* β^{vk}, *which represents the average FIA measured above-ground carbon (unit:* $Mgha^{-1}$*) within five-year bins* k *over plots in* v *projects. 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).*

5 Empirical Strategy

5.1 Constructing Matched Controls by Forestland Carbon Storage Capacities

On the current carbon offset markets, "baselines" are formally defined as the scenario where forest management (mainly regarding tree harvest intensities and rotation lengths) are carried out assuming no entrance of the markets. In both market protocols and project documents, "business-as-usual" is used to describe the forestry practices applied in the counterfactual baseline scenarios[27]. However, forestry practices before entering the carbon offset markets are not discretely reported, making it not very applicable to verify whether simulation parameters for baselines actually reflect historical practices of these IFM projects. For example, drastic drops of baseline above-ground carbon simulations right after offset market entrance (Appendix Figure A.1) can be dubious as deviating from business-as-usual, but implicitly allowed under ambiguous market protocols.

As argued by our theoretical model, we will argue that pre-market forest above-ground live carbon trends represents historical forest management plans of IFM projects. Firstly, we 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, we will find control plots with similar carbon storage capacities as project plots.

For each within-project FIA observational plot, we use a list of geophysical variables critical to the capacity of above-ground live forest carbon storage as matching variables[28]. These variables include average precipitation level (over 10 years), average growing degree days (GDD) (over 30 years), soil nitrogen concentration (2018 measurement), average land slope, average land aspect (angle of orientation), forest type (defined by FIA). We also include a socio-economic control indicating private ownership status of the forest plot as a matching variable, to capture the differences in utility functions of private versus public landowners.

We employ nearest neighbor matching with Mahalanobis distance, adapting five neighbors with replacement (NNM-5n) with these seven matching variables. Precipitation is matched exactly by pooled sample quintiles[29]. Forest type and private ownership status are also matched exactly. The

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

[28]In our theory model, these variables do not account for the full list of natural and socio-economic exogenous variables $\mathbf{G}$ affecting equilibrium forest management choice $\mathbf{A}$. But in ecological science, the set of variables used for matching are representative of forestland carbon storage potentials without further legal and financial restrictions (Morreale et al. 2021).

[29]Pooled sample includes 519 treatment plots within IFM project borders, and all $38,101$ potential control plots outside projects.

other continuous variables (GDD, slope, aspect, nitrogen concentration) are matched with calipers set as their standard deviations in the pooled sample. For robustness checks, we will also present results using two alternative matching methods, nearest neighbor matching with Mahalanobis distance, one neighbor with replacement (NNM), and coarsened exact matching (CEM)[30].

Our matching method gives us the sample of 2,407 plots, 514 being IFM project plots, and 1,893 are matched control plots. In Appendix Figure D.1, we show the balance checks for our main NNM-5n matching results. All seven matching variables have their matched control means close (within 0.05 of absolute standardized mean difference) to their treatment (in-project plots) means. Mean of the standardized mean differences over all matching variables is as low as 0.00668. Therefore, we have constructed our control plots comparable in carbon storage potentials to the IFM project plots.

5.2 Event Study Regression

To explore the relationship between offset market entrance and historical forest management plans, we want to identify the trends of IFM project plots' above-ground live carbon relative to matched control plots with similar carbon storage potentials. We employ an event-study regression as our main empirical strategy to examine how above-ground carbon inventories evolve around the timing of market entrance.

The event study regression we run is:

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

Where B^k are bin indicators of FIA survey years $t \in [k, k+4]$ relative to market entrance year of $t = 0$ for plot i[31]. Here, we group the forest inventory observations into 5-year bins in order to increase statistical significance, because FIA's rotating survey frequency (remeasurement gap) is about 5.45 years in our sample. Bin indicators range from 10 years before and 5 years after IFM projects' market entry years. End bins are $k = -15 : t \in (-\infty, -11]$ and $k = 5 : t \in [5, \infty)$. Reference bin $k = 0 : t \in [0, 4]$ is dropped from the regression. $Project_i$ indicates if the plot i is overlapping 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.

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

[31]If plot i is a project plot, $t = 0$ is the project's market entrance year. If plot i is a matched control plot, $t = 0$ is the corresponding project's market entrance year by matching.

The estimated series of β^k are plotted against k to illustrate the pre- and post-market above-ground carbon trends of IFM projects relative to their matched controls. Because market entrance decisions are endogenous, we will interpret these event study estimates descriptively rather than causally.

We also interact this baseline regression with market indicators to identify the differential carbon trends of CARB and VCM projects:

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

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

To explore project-level factors that may be correlated with historical forest management and offset market entrance decisions, we will also use a heterogeneity analysis regression interacting the event study design by markets with factor indicators:

$$\begin{aligned} AboveGroundCarbon_{it} = \alpha &+ \sum_{g \in G} \Big[\sum_{k=-15,-10,-5,5} \beta^{ckg} Project_i \times B_{it}^k \times CARB \times \mathbf{1}_g \\ &+ \sum_{k=-15,-10,-5,5} \beta^{vkg} Project_i \times B_{it}^k \times VCM \times \mathbf{1}_g \Big] + \delta_t + \psi_i + \epsilon_{it} \end{aligned} \tag{3}$$

Where $g \in G$ separate projects by their basic characteristics summarized in the previous section, including history of conservation easement, use of preparing agent, timber company ownership, entrance timing, and project area.

5.3 Maximum Likelihood Discrete Choice Models

In this paper, we will estimate discrete choice models by maximum likelihood to model the IFM project developers' market entrance decisions. These estimated models will also serve our purpose of out-of-sample predictions extending to all forests of U.S. Forest Region 9 using all FIA forest observational plots covering the 20 states. For robustness, we will test different discrete choice models, including multinomial logistic, two-stage logistic, and nested logistic regressions. Our main results will be presented as the two-stage logistic model.

In our theoretical model, IFM projects' decisions of entering regulated, voluntary, or neither market depend on a series of observable exogenous natural and socioeconomic variables, as well as historical forestry practices on the project lands. In our discrete choice models, we will include the set of seven geophysical and socioeconomic variables we have used in the previous subsection for matching (GDD, soil nitrogen concentration, precipitation, land slope, land bearing, forest type, private ownership), which defines carbon storage potentials of the forestland. We will also include indicators for historical forest management plans based on pre-market above-ground carbon trends, as revealed by the event study regressions.

Approximating Pre-Market Carbon Trends We will first estimate a single variable *gradient*, which is the FIA plot-specific slope of above-ground carbon on observation year. In interpretation, it represents how much above-ground carbon are accumulated per year by FIA surveys.

We run the simple linear regression of above-ground carbon on observational year t:

$$AboveGroundCarbon_{it} = a_i + b_i t + \varepsilon_{it} \tag{4}$$

This OLS will be run separately for each project or matched control plot in our sample. The regression period includes all observations if the plot is a matched control, and limit to pre-market periods only for in-project plots. The set of estimated $\hat{b}_i$ will be our *gradient* variable, representing the equilibrium historical forest management plans without offset markets.

To increase precision due to uncertainties accompanying the OLS estimations of *gradient*, we will also represent *gradient* in other ways, such as the indicator of positive carbon accumulations $gradient^{+} = \mathbf{1}_{gradient>=0}$, magnitude of carbon trends $|gradient|$, and bins of *gradient* by unweighted terciles of the sample $gradient^{low}$, $gradient^{med}$, $gradient^{high}$.

Multinomial Logistic Regression Multinomial logistic regression (MNL) models non-binary discrete choices, in our case from no market entrance, regulated market entrance, and voluntary market entrance, with choice (alternative) level plot i utilities specified as:

$$U_i(D_i = m) = \alpha_m + \beta_m' \mathbf{gradient}_i + \lambda_m' \mathbf{X}_i + \epsilon_{mi}$$

Where the decisions D_i have three choices, $m = NoEntry$ (no market entry, base category), $m = Regulated$ (enter regulated market), $m = Voluntary$ (enter voluntary market). Decision factors includes the set of indicators **gradient**, in which we choose the combinations of 1) *gradient* (raw slope estimate) 2) $gradient^{+}$ and $|gradient|$ (sign and size of the slope) 3) $gradient^{low}$, $gradient^{med}$ and $gradient^{high}$ (tercile bins of the slope). We also test a version without any gradient indicators. **X** contains the seven geophysical and socio-economic exogenous variables (forest type as categorical binary indicators).

The MNL model can be readily estimated with maximum likelihood, assuming IIA (independence of irrelevant alternatives) assumption holds and the error term ϵ is i.i.d. Type I extreme value (Gumbel) distributed. Probabilities of choices used for ML estimations are expressed as:

$$Pr(D_i = m) = \frac{\exp(\alpha_m + \beta'_m \mathbf{gradient}_i + \lambda'_m \mathbf{X}_i)}{\sum_m \exp(\alpha_m + \beta'_m \mathbf{gradient}_i + \lambda'_m \mathbf{X}_i)} \tag{5}$$

Regression is weighted by matching weights. Standard errors are clustered at project levels[32]. To address the uncertainties in the OLS *gradient* estimators, we also adapt bootstrapping of 1,000 trials to produce mean, standard error and confidence interval for this model.

Two-Stage Logistic Regression Since IIA assumption can be violated if project developers in reality may first decide on whether to enter any carbon offset market or not, then in the second stage decide on which offset market (regulated or voluntary) to enter, we will fit a two-stage logistic regression model:

$$U_i^1(D_i^1 = 1) = \alpha_1 + \beta'_1 \mathbf{gradient}_i + \lambda'_1 \mathbf{X}_i + \epsilon_{1i}$$
$$U_i^2(D_i^2 = 1) = \alpha_2 + \beta'_2 \mathbf{gradient}_i + \lambda'_2 \mathbf{X}_i + \epsilon_{2i}$$

Where both stages have binary decisions D_i^1, D_i^2. First stage $D_i^1 = 1$ if plot i chooses to enter carbon offset markets, 0 if no entry. Second stage $D_i^2 = 1$ if choice is to enter the regulated market as CARB projects, 0 otherwise entering the voluntary market instead. This stage is only run on the subsample of market entrants, excluding all non-entrance matched control plots. **gradient** include $gradient^{+}$ and $|gradient|$ (sign and size of the slope). **X** contains the seven geophysical and socio-economic exogenous variables.

The two stages of logistic regressions will be separately estimated with maximum likelihood, assuming both error terms ϵ_{1i} and ϵ_{2i} are i.i.d. Type I extreme value (Gumbel) distributed and not correlated with one another. ML probabilities are:

[32]For project plots, cluster at the project level. For matched control plots, cluster at the corresponding matching project level, but do not cluster with the other in-project plots.

$$Pr(D_i^1 = 1) = \frac{\exp(\alpha_1 + \beta_1' \mathbf{gradient}_i + \lambda_1' \mathbf{X}_i)}{1 + \exp(\alpha_1 + \beta_1' \mathbf{gradient}_i + \lambda_1' \mathbf{X}_i)}$$
$$Pr(D_i^2 = 1) = \frac{\exp(\alpha_2 + \beta_2' \mathbf{gradient}_i + \lambda_2' \mathbf{X}_i)}{1 + \exp(\alpha_2 + \beta_2' \mathbf{gradient}_i + \lambda_2' \mathbf{X}_i)} \quad (6)$$

Regression is weighted by matching weights. Standard errors are clustered at project levels, and we will also run bootstrapping to capture standard errors accumulated across gradient estimations, first and second stage logits.

Nested Logistic Regression Nested logistic regression also relax the IIA assumption and allows two-stage estimations with first decision on whether to enter any carbon offset market or not, then on which offset market (regulated or voluntary) to enter. This model allows more flexible correlations within upper layer decisions (enter or not).

The within-nest layer has utilities denoted as:

$$U_i(D_i = m) = \alpha + \beta gradient_{mi}^{exp} + \epsilon_{mi}$$

Decisions D_i again have three choices, $m = NoEntry, Regulated, Voluntary$, where $NoEntry$ is base category. They are further grouped in two nests $n = NoMarket, Market$ where $NoMarket = \{NoEntry\}$, $Market = \{Regulated, Voluntary\}$, where $NoMarket$ is the base category. Gradient decision factor is expanded into a plot-choice specific variable $gradient_{mi}^{exp}$. In definition, $gradient^{exp} = 1$ if sign of $gradient$ for plot i aligns with the sign of the carbon trends estimated in our event study analysis seen for projects listed in market m. $gradient^{exp} = -1$ if $gradient$ for plot i is of the opposite sign of the carbon trend sign estimated by event study in market m (see next section for more details). $gradient^{exp} = 0$ for any plot i when $m = NoEntry$. Error term ϵ is i.i.d. Type I extreme value (Gumbel) distributed. In later section, we will also attempt a model replacing $gradient^{exp}$ with the simulation-approximated offset credit gain for each plot by each market entrance choice.

The upper layer nest level utilities apply to entry versus no entry decision makings:

$$V_i(n) = \delta_n |gradient|_i + \gamma_n' \mathbf{X}_i + \tau_n \ln(\sum_{k \in n} \exp(\frac{\alpha + \beta gradient_{ik}^{exp}}{\tau_n})) + \eta_{ni}$$

Where $\mathbf{X}$ are plot-level controls only applying to the nest stage estimation, again containing the seven geophysical and socio-economic exogenous variables. We also include the size of slope $|gradient|$

with this outer control set. Error term η is i.i.d. Type I extreme value distributed. $\tau_n \in (0,1]$ is nest-level dissimilarity parameter.

The nested logit model is estimated with maximum likelihood, with probabilities of choices used for ML estimations expressed as:

$$\begin{aligned} Pr(D_i = m|n) &= \frac{\exp(\frac{\alpha+\beta gradient_{im}^{exp}}{\tau_n})}{\sum_{k\in n}\exp(\frac{\alpha+\beta gradient_{ik}^{exp}}{\tau_n})} \\ Pr(n) &= \frac{\delta_n|gradient|_i + \gamma_n'\mathbf{X}_i + \tau_n \ln(\sum_{k\in n}\exp(\frac{\alpha+\beta gradient_{ik}^{exp}}{\tau_n}))}{\sum_n \delta_n|gradient|_i + \gamma_n'\mathbf{X}_i + \tau_n \ln(\sum_{k\in n}\exp(\frac{\alpha+\beta gradient_{ik}^{exp}}{\tau_n}))} \end{aligned} \tag{7}$$

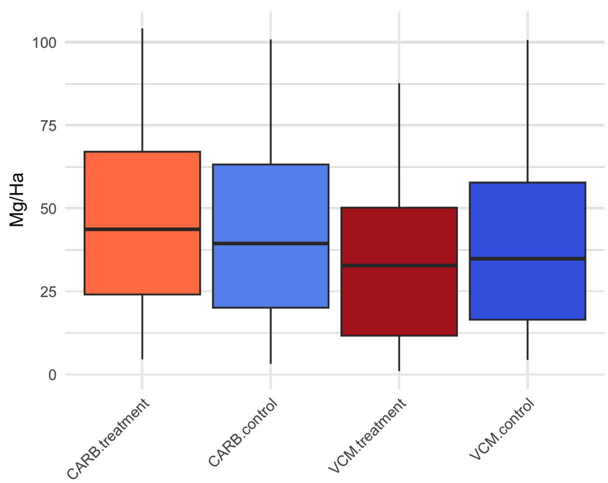
ML model is again estimated with matching weights. Standard errors are clustered at project levels. Due to low rate of convergence, bootstrapping results are not included at this stage.

6 Results

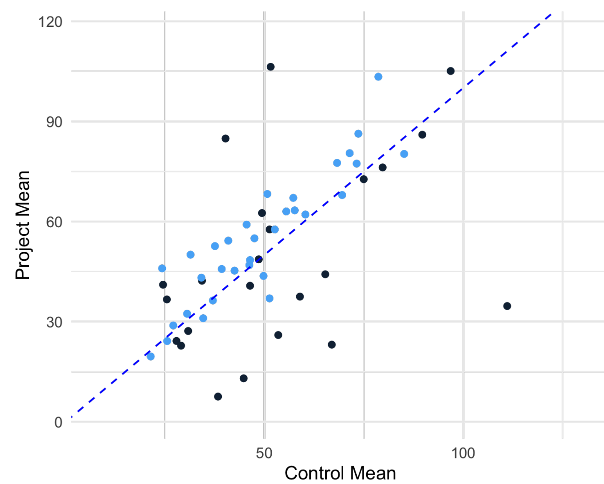
6.1 Pre-Market Above-Ground Carbon Levels for Project and Matched Control Plots

After constructing the matched control plots for IFM project plots based on similar forest carbon storage potentials, we compare their per hectare above-ground carbon levels right before offset market entrance, averaging across FIA measurements taken no more than five years pre-market. In Figure 4 Panel (a), box plot has shown that, on average, CARB projects' pre-market above-ground live carbon level is higher than their matched controls, while VCM projects' average above-ground carbon levels are lower than their controls. Figure 4 Panel (b)'s project-level scatter plot illustrates the same observation, showing CARB projects mostly with pre-market above-ground carbon levels above their controls, while most VCM projects have lower pre-market carbon stocks than their controls. Similar results also persist including all pre-market FIA observations (not just limiting to five years before market entrance) (Appendix Figure E.1).

Summary statistics for selected geophysical matching variables, reported and FIA measured carbon inventories, and t-tests between project, matched control, and reported pre-market above-ground carbon inventories are presented in Table 2. CARB projects have on average greater growing-degree days, higher soil nitrogen concentrations, similar precipitations and aspects as VCM projects. Forestland with more soil nutrition, greater warmth and sunlight is likely with greater carbon storage capacity, but greater land slope may also lead to thinner tree growth. As a result, the actual carbon



(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 matched control average carbon measure, all taken at most five years before the project start trading on the offset markets (five-year pre-market period). The 45-degree dashed line separate projects with above-ground carbon levels above or below their matched controls.

Figure 4: Comparison of five-year pre-market above-ground carbon storage between project and matched control forest observational plots

storage capacities for CARB versus VCM project plots can be ambiguous. This ambiguity is also shown in Table 2 by the greater average pre-market FIA above-ground carbon for CARB versus VCM plots, but the lower average carbon levels for CARB versus VCM matched control plots.

Under plot-level t-tests, CARB projects have statistically significantly higher pre-market carbon inventories than their matched controls as measured by FIA. Pre-market carbon stocks for VCM projects are on average lower than their matched controls, but the difference is not statistically significant (likely due to the much smaller number of VCM plots). These are consistent with Figure 4. Project-level t-tests also show that reported initial carbon stocks (ICS) on both regulated and voluntary markets are significantly higher than the FIA ground-truth pre-market measurements. However, CARB and VCM projects have submitted statistically similar baseline carbon stocks used for credit issuance to our matched controls, though the two are constructed using different principles[33]. But if there is a systematic upward bias on reported carbon stocks, baselines estimated with simulation starting points being the lower FIA measured ICS (instead of the higher reported ICS) would expect a much lower average carbon level than our constructed matched controls.

6.2 Event Study Regression Results

Results of our event study analysis with Eq. 1 and 2 identifying the dynamic of relative above-ground carbon trends of project versus matched control plots with similar carbon storage potentials are presented under Figure 5.

In Panel (a), across all IFM projects (both CARB and VCM projects), FIA measured per hectare above-ground carbon stock has been flat or slightly increasing relative to matched control plots not on any carbon markets and of similar carbon storage capacities, since at least 11 years prior to the IFM projects entering the offset markets. After their market entrance, their above-ground carbon sees a significant jump in the 0-4 years post-market interval. But because of limited post-market FIA surveys, such increase in carbon storage does not have statistically significant evidence to be persistent after five years of the market entrance from the event study regression. In fact, by point estimate, relative carbon level may have decreased, implying inconsistency in improved forest management proposals.

Panel (b) shows the relative above-ground carbon trends for CARB projects listed on the regulated market. With continuously rising carbon inventories relative to controls since more than a decade

[33] Baselines are supposed to quote common practices representing forest conditions on similar lands near the IFM project. Our constructed controls match on land characteristics determining the carbon storage potentials of forestland, instead of by distances to the IFM projects.

	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 [$Mg\ ha^{-1}$]		
Baseline Average	47.407	47.452
Initial Carbon Stock (ICS)	65.807	77.842
Five-Year Pre-Market Period Above Ground Carbon [$Mg\ ha^{-1}$]		
Project	58.886	48.733
Control	50.323	55.795
T-test Statistics		
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 matched control plots

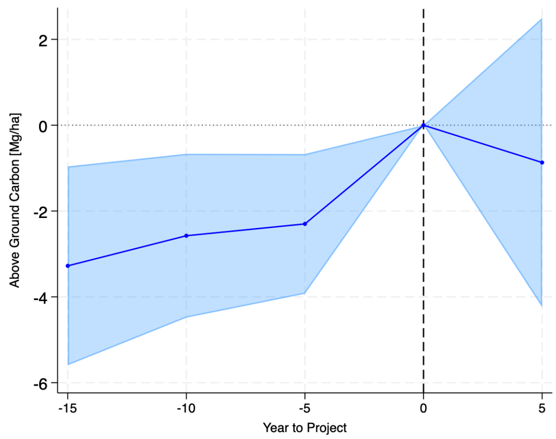
*Notes: The table presents summary statistics for CARB and VCM projects and plots, as well as plot-level (project vs control test) and project-level (all the rest tests with document statistics) t-test results for the difference between above-ground carbon per hectare ($Mgha^{-1}$) between project and matched control FIA plots, FIA measured project five-year pre-market above-ground live carbon stocks versus registry reported ICS (inicial carbon stock), and FIA measured matched control pre-market carbon stocks versus reported baseline average carbon stocks (taken as common practice for CARB projects, or the average over 20-year baseline simulation tables for VCM projects). The t-test panel displays t-statistics of the tests, with p-values indicated by asterisks, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Four VCM projects are dropped from the summary or t-tests because of lack of FIA observations before market entrance (one CAR project), lack of ICS records (two Verra projects), or lack of baseline carbon projection table (one ACR project).*

prior to engaging with the regulated market, the relative project carbon trend remains non-increasing and statistically insignificant from zero since the five-year period before their market entrance, and no further carbon increase is seen after their market entrance. These observations cast doubts on the incentive of CARB projects entering the regulated carbon offset market. If these projects are motivated to trade on their historical forest preservation efforts for the past decade, they will bring additionality problems on the regulated offset market in California.

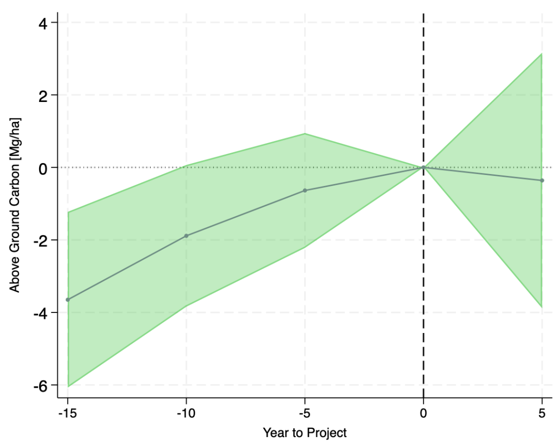
Panel (c) presents the relative above-ground live carbon trend for VCM projects listed on the voluntary offset market. Notably, the pre-market carbon trend is continuously decreasing, reaching about $7.5Mg\ ha^{-1}$ statistically significantly lower carbon inventory level than their matched controls in the 1-5 years bin before market entrance. 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 above-ground carbon stocks, implying the effectiveness of improved forest management plans these projects promise on the voluntary market. However, there is no statistical evidence that this high carbon stock and increasing carbon trend is sustained after five years into the offset market. With the negative but statistically insignificant estimate on the post five years bin, the change of project forestry practices and accumulation of forest carbon seems not to be persistent.

Therefore, using event study analysis, we have recovered the differential pre-market above-ground carbon trends relative to similar carbon storage capacity matched control plots for CARB and VCM projects. Based on our theoretical model, these regressions estimate pre-market relative carbon trends indicative of IFM projects' under-reported historical forest management plans. CARB projects with increasing relative carbon trend imply them practicing forest conservation before ever considering the choice of carbon offset markets. VCM projects with decreasing carbon trend show them historically opting more aggressive harvesting relative to similar forestland. These would also explain the observations of the previous subsection, because historically conserved CARB project forestland has higher carbon levels by the time of market entrance, while historically aggressive harvesting VCM project land sees lower carbon stocks upon market entrance. The event study regressions thus reveal the relationship between historical forestry practices and IFM project developers' market entrance choices between regulated and voluntary offset market, likely due to the two markets' differential credit issuance schemes. High initial issuance on the regulated market would encourage CARB projects with high and increasing carbon inventory to enter. Gradual issuance scheme on the voluntary market would motivate VCM projects with greater gains from the carbon accumulated out of the changes in forestry practices.

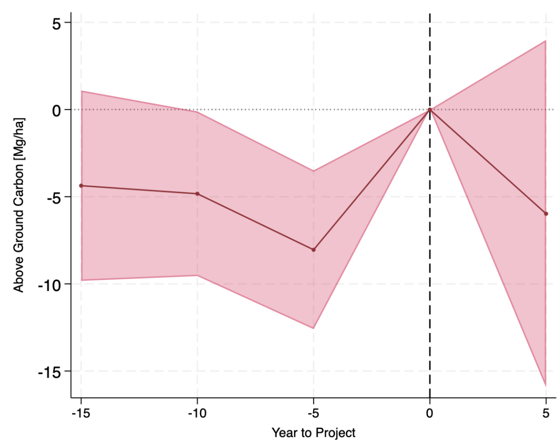
These event study results are robust to using a slightly different definition of market entrance by project claimed starting time in their documents (Appendix Figure F.1), using alternative matching methods for the selection of control plots (Appendix Figure F.2 and F.3), or controlling state-specific linear year trends (Appendix Figure F.4). F-test of the three pre-market five-year bin estimates 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 above-ground carbon trends relative to their matched controls with similar carbon storage capacities.



(a) All



(b) CARB



(c) VCM

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

Notes: Estimates and 95% confidence intervals are estimated with regressions Eq. 1 for Panel (a) and 2 for Panel (b), (c). Each point observation indicates 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 the average carbon levels from nearest-five-neighbor matching control plots with similar carbon storage potentials. 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).

We have also found some limited evidence through event study regressions on two FIA variables related to harvesting, removed basal area per hectare (unit: m^2ha^{-1}) per year, and the ratio of removed basal since last period over the current-period standing basal[34]. In general, CARB projects have lower pre-market harvesting than VCM projects (0.201 versus 0.355 removed basal, 0.010 versus 0.019 removed basal ratio, both rejected at 1% by t-tests), consistent with our previous analysis. Event study results (Appendix Figure G.1) have seen some pre-market decreasing trends in both harvesting variables for CARB projects, and a very slight increasing trend of removed basal for VCM projects, implying pre-market decreasing harvesting for CARB projects and increasing harvesting for VCM projects with no statistical significance. We also look through dead wood management by the measure of per-hectare dead basal area (unit: $Mg\ ha^{-1}$), where on average VCM projects have a 1% significant higher average level of pre-market dead carbon than CARB projects by t-test (2.013 versus 1.609). But event study plots in Appendix Figure G.2 show no statistically significant evidence of changing pre-market dead wood management for either CARB or VCM projects.

6.3 Heterogeneity Analysis

We have conducted a series of heterogeneity analysis with Eq. 3 to observe potential factors influencing the sorting of IFM projects with different pre-market forest management to enter either regulated or voluntary markets.

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[35]. Projects with historical CEs could be more likely to already started with IFM practices such as reduced harvesting. To explore this factor, we identify through documents a total of 24 projects with prior CE records (13 CARB projects and 11 VCM projects). Heterogeneity analysis with event study (Appendix Figure H.1) shows that CE and non-CE projects both have pre-market relative increasing above-ground carbon for CARB projects, meaning prior-conservation efforts regardless of CEs. For VCM projects, CE guarantees a flat but low relative pre-market carbon trend, compared with the non-CE VCM projects with a decreasing pre-market carbon trend. Therefore, CE for VCM projects does signal lower historical harvesting, but the flat carbon trend still represents higher harvesting than CARB

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

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

projects.

Timber Company Ownership Due to significant forgone profits from commercial harvesting, costs of shifting forest management plans for timber companies could be more realized. In our sample, more than half of the IFM projects are owned by timber companies (35 over 62, 24 CARB, 11 VCM). Heterogeneity analysis is run by timber company ownership (Appendix Figure H.2), showing that non-timber company IFM projects have flat and statistically insignificant pre-market carbon trends on both regulated and voluntary markets, and timber company projects have the same carbon trends by CARB and VCM projects as our main event study results (Figure 5). Therefore, timber companies are important players on the offset markets, showing recognition of the payoff differences between the two offset markets and driving the market entrance sorting according to historical forestry practices.

Intermediary Agent Calculations, verifications, measurements and document compilations required for offset market registration are not costless for IFM project developers. In reality, all CARB projects hire an agent to help prepare and manage their project. 23 out of 28 VCM projects also hire intermediary agents[36]. Separating VCM projects with or without using agents, Appendix Figure H.3 provides suggestive evidence that projects not hiring agents have flat instead of decreasing pre-market carbon stocks. Since project developers practicing aggressive harvesting pre-market could expect higher gains on the voluntary market by shifting to less harvesting, they may indeed find hiring agents to be more affordable and beneficial.

Project Area Dividing 62 projects by the median of their reported areas (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 relative above-ground carbon trends (CARB increasing, VCM decreasing). Post-market evidence is again weak with no statistical significance, but smaller area CARB projects see some increasing carbon trends post-market, while larger CARB projects do not. Project sizes seem not to be significantly correlated with market entrance decisions, but there are possibilities that post-market forest managements are correlated.

Entrance Timing As protocols for forest projects change over time, payoff functions of entering projects will also evolve. Furthermore, market structure and consumer preferences also shift over

[36] 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.

time. As a result, early or late offset market entrance may see projects with different historical forestry practices. We divide the 62 projects with the median of their documented starting date (August 2017) and run heterogeneity analysis (Appendix Figure H.5). While CARB projects have similarly increasing above-ground carbon pre-market trends regardless of early or late entrance, the seven early entrance VCM projects show different flat pre-market carbon trends, compared with the late VCM projects with decreasing trends. It is possible that as the voluntary market grows and matures, VCM projects with high historical harvesting realize the opportunities and start to enter. These results thus reflect the importance of future studies to incorporate dynamic market entrance modeling.

6.4 Discrete Choice Model Estimation Results

As shown in our event study analysis, pre-market above-ground live carbon trends can represent historical forest management plans, controlling for forestland with similar exogenous natural and socio-economic characteristics. Therefore, we will use the method describe in the previous empiric section to first construct a *gradient* variable (unit: $Mgha^{-1}yr^{-1}$) by simple OLS of pre-market carbon levels on FIA observational years.

As shown in summary histogram of *gradient* in Figure 6, the distribution of CARB project plots are visually higher than VCM project plots, but the difference with intermediate no entrance matched control plots are less visible. By summary statistics, 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[37]. CARB projects have higher gradients than their no-entrance controls, while VCM projects have lower gradients than their matched controls, though both groups of differences are not statistically significant by t-tests. Overall, we have seen the same observation as the event study analysis.

When we extract indicators of *gradient* for its sign ($gradient^{+}$) and size ($|gradient|$), we gain some statistical significance in t-tests comparing plots by their market entrance outcomes. CARB plots have the highest probability of being non-negative at 0.738 (mean of $gradient^{+}$, followed by no entry plots of 0.676, then VCM plots of 0.605. Average size of *gradient* ($|gradient|$) is greatest for CARB plots at 1.316, followed by VCM plots at 1.174, then non-entry plots at 1.125. Comparing plots of market entrance (CARB or VCM) versus no market entrance, $|gradient|$ is 1% statistically significantly higher by t-test. Within the subsample of plots of market entrance, CARB plots have 1%

[37]Note 54 plots are dropped from the sample due to insufficient pre-market observations for OLS.

significantly greater $gradient^+$ than VCM plots. That supports our choice of the two-stage logistic model including $gradient^+, |gradient|$ as the indicators for historical forest management plans.

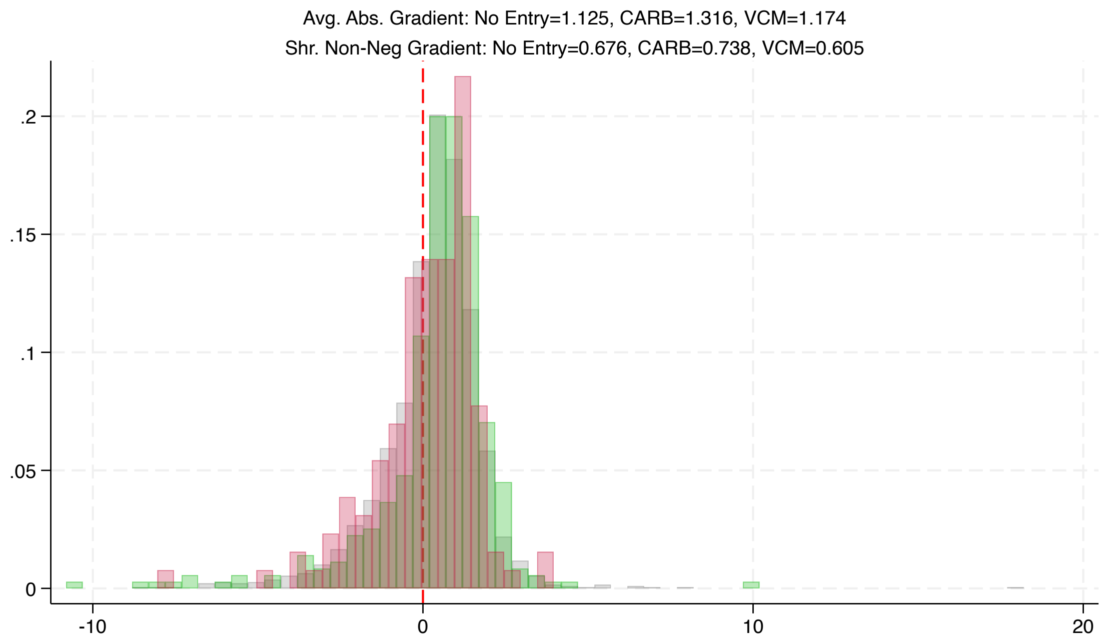


Figure 6: Summary histogram for *gradient* estimates by entry choices

Notes: Estimates of gradient by Eq. 4. No Entry=Gray, CARB Entry=Green, VCM Entry=Red.

Using probability expression of Eq. 6, we estimate two-stage logistic regression model using maximum likelihood and present our results in Table 3. We have found that size of pre-market carbon slope $|gradient|$ positively predict whether a forest plot choose to enter any carbon offset market or not, with statistical significance across both direct and bootstraping estimates. On the other hand, the sign of carbon slope, $gradient^+$, on the second stage positively predicts regulated relative to voluntary offset market entrance. Coefficients are also statistically significant both by direct and by bootstrap estimations. In interpretations, if the historical rate of forest carbon accumulation or depreciation is larger after controlling for geophysical and socio-economic characteristics of the land, the forest plot is likely to enter carbon offset trading as IFM project. If the slope of carbon trend is positive, therefore, already increasing above-ground carbon stocks historically with possible forest conservation efforts, then the market entrant is more likely choosing the regulated market and becoming a CARB project. These discrete choice model estimation results indicate that pre-market forest management practices significantly influence offset market entry decisions, in the way consistent with our observations from the event study analysis. Both historical conservation and aggressive harvesting lead to decisions of offset market entrance, and historical forest conservation leads to the choice of regulated over voluntary market.

Most of the other forestland characteristics in the model do not have statistically significant coefficients, except for private ownership and forest type 400 in direct second stage estimate, and nitrogen concentration in bootstrap second stage estimate. Intuitively, having richer soil by nitrogen concentration may encourage greater incentives to become CARB project because it is easier to achieve high carbon inventories upon market entrance, which will benefit from the high initial issuance scheme of the regulated market. The positive impact from private land ownership is less intuitive, as private land usually have less constraints to conserve historically, thus with more incentives to harvest aggressively before their offset market choices.

We present alternative discrete model estimation results with specifications described in the previous empiric section in Table 4. Overall, our main specification of two-stage logistic model has the lowest Brier score (therefore, smallest in-sample prediction error), and most statistical significance on the estimator of *gradient* indicators. Across all specifications, size of *gradient* contributes significantly to the choice of entering offset markets, especially for the regulated market. Specifically compared with the MNL model without any *gradient* indicators, we see significant decrease in Brier's score of all other model except for the nested logit, implying the improvement of discrete choice model prediction powers after including *gradient* indicators to represent historical forestry practices.

6.5 Out-of-Sample Predictions by Discrete Choice Model

With coefficients estimated from the discrete choice models, we can extrapolate out-of-sample the market entrance probabilities for all FIA forest observational plots with enough observations to estimate *gradient*. We use the direct two-stage logit regression estimates of Table 3 and summarize state-level and all Region 9 average market entrance probabilities weighted by plot areas in Table 5.

In most of the 20 states of Region 9, the most and over 50% forestland would not be predicted to enter any offset market. The predicted proportion to enter the regulated market is the second highest in most states, greater than the proportions predicted to enter the voluntary market. Some forest-rich states with over 50% forest coverage tend to have greater percentage of voluntary market entrants similar or greater than the share of regulated market entrance in prediction, like Massachusetts, Maine, Michigan, New Hampshire and Vermount. Some other states with lower forest coverage also have over 20% voluntary market entrance predictions, including Minnesota and New Jersey. These state-level discrepancies are likely coming from the historical practices of forest conservation versus timber harvesting in each state, which is not entirely dependent on their forest coverage ratio. For

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

Table 3: Two-stage logistic regression maximum likelihood estimation results on carbon offset market entry choices

Notes: First stage logit estimate probability of entering either market (regulated and voluntary), run on full sample. Second stage logit estimate probability of entering regulated market (CARB Entry), run on subsample with only project plots. For direct estimates, standard errors in parentheses are clustered by project, with matched control plots clustered with other controls by the same project they match to, but differently with the corresponding project plots. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. *Omitted forest type being FIA code=900.* $N = 2,353$. *Pseudo R-squared=0.0058 for first stage logit. Pseudo R-squared=0.2999 for second stage logit. Brier's score=0.186. 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* $N = 2,353$. *Mean of bootstrapping estimates and standard errors with Bessel's correction are reported. Bootstrap confidence levels similarly denoted by asterisks are determined by empirical distribution of the bootstrapping estimates.*

Two-Stage Logit (Brier's Score: 0.1855)				
	Direct Estimate		Bootstrap Estimate	
	1st Stage Market Entry	2nd Stage CARB Entry	1st Stage Market Entry	2nd Stage CARB Entry
$gradient^{+}$	0.1748	0.7284**	0.2125	0.6677*
	(0.1458)	(0.2984)	(0.1361)	(0.3228)
$\|gradient\|$	0.1310***	0.0283	0.1030**	0.0202

Multinomial Logit (Brier's Score: 0.1872)				
	CARB Entry	VCM Entry	CARB Entry	VCM Entry
$gradient^{+}$	0.3617**	-0.2771	0.3796**	-0.1910
	(0.1693)	(0.1736)	(0.1555)	(0.2470)
$\|gradient\|$	0.1461***	0.1130	0.1127**	0.0871

Multinomial Logit, *gradient* Tercile Bins (Brier's Score: 0.1870)				
	CARB Entry	VCM Entry	CARB Entry	VCM Entry
$gradient^{low}$	-0.1265	0.6724***	-0.1301	0.4633
	(0.2033)	(0.1939)	(0.1791)	(0.2940)
$gradient^{high}$	0.3744***	0.6142***	0.3511**	0.3947

Multinomial Logit, *gradient* Linear (Brier's Score: 0.1887)				
	CARB Entry	VCM Entry	CARB Entry	VCM Entry
$gradient$	0.0241	-0.0604	0.0250	-0.0473
	(0.0390)	(0.0629)	(0.0397)	(0.0596)

Multinomial Logit, No *gradient* Indicators (Brier's Score: 0.1896)

Nested Logit (Brier's Score: 0.1960)		
	Outer	Inner
$gradient^{exp}$		0.2075
		(0.1592)
$\|gradient\|$	0.1310***	
	(0.0470)	

Table 4: Alternative discrete choice model maximum likelihood regression results

*Notes: Maximum likelihood probability formulas see Eq. 5, 6, 7. For direct estimates, standard errors in parentheses are clustered by project, with matched control plots clustered with other controls by the same project they match to, but differently with the corresponding project plots. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Omitted forest type being FIA code=900. $N = 2,353$. 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 $N = 2,353$. Mean of bootstrapping estimates and standard errors with Bessel's correction are reported. Bootstrap confidence levels similarly denoted by asterisks are determined by empirical distribution of the bootstrapping estimates. For some specifications, some bootstrap trials are dropped out of non-convergence in maximum likelihood estimations. Nested logit do not have bootstrapping results due to too many non-convergence.*

example, Maine and New Hampshire have significant economic contributions from their strong forest product industries.

Averaging across the 20 states, where forest coverage is 42.6%, 52.7% of the forests are predicted by our discrete choice model to stay not entering any carbon offset markets. 27.8% are predicted to enter the regulated market, and the rest 19.5% to enter the voluntary market. Overall, these out-of-sample prediction aligns in magnitudes with in-sample predictions (Appendix Figure I.1). Predicted total forest area to enter either carbon offset market is 33.6 million hectares, more than twenty-times the total area of current IFM projects we study over this region (less than 1.5 million hectares of forest). This is a significant upper bound estimate for potential engagement with the carbon offset markets, assuming (very unlikely) sufficient demand of forest offset credits on both regulated and voluntary markets.

State	Forest Coverage	No Entry	CARB	VCM
Connecticut	0.583	0.532	0.310	0.157
Delaware	0.289	0.588	0.333	0.079
Iowa	0.082	0.547	0.401	0.052
Illinois	0.140	0.572	0.313	0.116
Indiana	0.213	0.568	0.341	0.091
Massachusetts	0.606	0.532	0.255	0.213
Maryland	0.394	0.561	0.304	0.135
Maine	0.891	0.510	0.246	0.244
Michigan	0.561	0.509	0.203	0.289
Minnesota	0.342	0.505	0.203	0.292
Missouri	0.350	0.588	0.301	0.111
New Hampshire	0.830	0.501	0.182	0.317
New Jersey	0.423	0.575	0.207	0.217
New York	0.626	0.520	0.309	0.171
Ohio	0.309	0.536	0.374	0.090
Pennsylvania	0.590	0.529	0.290	0.181
Rhode Island	0.559	0.539	0.270	0.191
Vermont	0.765	0.506	0.266	0.227
Wisconsin	0.493	0.519	0.306	0.175
West Virginia	0.785	0.517	0.338	0.145
Total	0.426	0.527	0.278	0.195

Table 5: Predicted state-level carbon offset market entrance probabilities by two-stage logistic model

Notes: Carbon offset market participation probabilities extrapolated with the two-stage logistic regression direct estimates (Table 3). Total U.S. Forest Region 9 FIA forest observational plots to predict $N = 37,926$, spanning 20 states. Predicted market entrance rates reported are averaged to state level after weighted by area of plots. Forest coverage are calculated as FIA reported 2022 FY forest areas by states over total state areas.

We also compile the total market entrance outcome predictions for different discrete choice models presented in Table 4. Appendix Figure I.2 has shown that they provide similar magnitudes of no entrance, regulated market entrance, and voluntary market entrance probability estimates, though nested logit provides a higher prediction for regulated market entrance and a lower prediction for voluntary market entrance than the other specifications.

7 Simulations

In the previous section, we have shown that pre-market forest management plans are correlated with market entrance decisions of no entrance, regulated market entrance, or voluntary market entrance. In this section, we will use forest simulation models to further argue for the causal relationship between historical forest management, credit issuance schemes, market entrance outcomes, expected economic and environmental benefits from these markets. We will also attempt discrete choice model estimations with the simulation estimates, to predict the market entrance outcomes under different market rules regarding baselines.

7.1 Simulation Set-Up

The simulation model we adapt is the LANDIS/PnET model (Gustafson et al. 2023). We use it to 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[38]. In this model, forest management is defined through 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 minimum rotation period (the minimum age a tree is allowed to be cut). We will shift forest management only by applying different harvesting rates, keeping the other parameters constant at 1-year harvest interval, minimum rotation period of 20 years, and 65% harvesting scheme[39]. All simulation runs will start with the same initial above-ground live carbon $50 Mg\ ha^{-1}$ uniform across both project and surrounding non-project lands. By running simulations on the same project forestland, we guarantee the same geophysical characteristics and carbon storage capacities within and outside of the project area. The surrounding non-project areas are then equivalent to the matched

[38]Comparing with the tree-based FVS model used by IFM project developers, the LANDIS-II model considers landscape dynamics, with trees growing at different locations interacting with one another. For example, competitions between trees growing at different locations are simulated, so the model can sometimes allow growing trees through pollinate to places where there were previously no trees.

[39]In practice, decreasing harvesting rate, decreasing harvesting scheme, and increasing rotation period are all common IFM practices.

controls in our event study analysis. On these control lands, we apply the uniform 1.5% harvesting rate throughout 150 years, called the common practice[40].

Above-ground carbon trajectory for 150 years will be simulated, with observations generated at five-year intervals. To stabilize model performance and to allow for sufficient impacts of historical forest management, we will set year 40 to be the market entrance time, so that the first 40 years is the pre-market period, and the next 110 years is the post-market period. If the project land enters either regulated or voluntary offset market and changes their harvesting rate, the new practice apply from year 40.

Project Scenarios We want to choose a set of different IFM project scenarios for our simulations representative of CARB and VCM projects. Each scenario is defined by a set of two harvesting rates, pre- and post-market. Due to limited post-market observations in our real-world data, we will make another simplification assumption to fix the post-market harvesting rate for all scenarios at 1%. We test different combinations for each scenario to approximate the relative above-ground carbon trends identified by our event study analysis by the simulated carbon trajectory net of surrounding non-project's simulated carbon levels. We also select on year 35's simulated above-ground carbon inventories, matching to FIA measurements of real IFM projects (Table 1)[41].

In the end, we choose the following representative scenarios for typical CARB and VCM projects. We also add a third scenario called "ideal" that has the same historical forestry practices as the surrounding common practice, but switches to lower harvesting rate post-market (after year 40). Therefore, ideal scenario represents the counterfactual situation of non-entrance control forestland when it instead chooses offset market entrance:

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

Simulated above-ground carbon stock trends for CARB, VCM and Ideal scenarios relative to surrounding controls are shown in Appendix Figure J.1. Comparing with our event study analysis

[40]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 counts not only harvested carbon, but also dead trees removals. This rate is also similar to the harvesting rate in Maine public forests (1.5%), but smaller than that on private forestland (3%) (Thompson et al. 2017). Considering the constraint of the model, we choose the 1.5% harvesting rate at this point which is an advised sustainable harvesting strategy common in the state of Maine.

[41]We also compare the pre-market harvesting rate with pre-market removed basal ratio from our FIA data and our final picks are similar.

with real-world data (Figure 5), the trends are roughly replicated. For the pre-market period before year 40, CARB scenario has an increasing relative trend, and VCM scenario has a decreasing relative trend. At year 35, the difference between CARB and surrounding control is about $5Mg\ ha^{-1}$, similar but lower than the real gap (Table 1). The VCM difference is about $-7Mg\,ha^{-1}$, of similar magnitude to the real data. The Ideal scenario fits a close-zero and flat relative trend by design. After 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 forest management. After 40-50 years in the markets, all three scenarios converge to the same ecological equilibrium with above-ground carbon at about $5Mg\ ha^{-1}$ above surrounding controls.

Baselines Expected payoffs of IFM project on carbon offset markets are dependent on baselines, which dedicate the levels where project scenarios are compared with. If there are no offset credit quality issues (one unit of credit represents no less than one unit of actual CO_2 removal), markets should demand baselines to be simulated with identical, business-as-usual forestry practices as projects' pre-market behaviors throughout 150 years. 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 feature continuously increasing post-market carbon trends, and do not match with the baselines suggested by real-world IFM project documents (Appendix Figure A.1), which show drastic decrease right after market entrance and fluctuate at low carbon levels afterwards[42].

To replicate these documented baseline patterns, we increase the post-market harvesting rate to above 2% and discover that the decrease-then-fluctuate pattern occurs when post-market harvesting rate reaches 4% or higher. We have also tested the upper bound (constrained by local legislation demanding harvesting rate to be lower than 40%) and found similar carbon patterns and levels in the long run when post-market harvesting rate is 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 year 40 (the same pre-market harvesting rate maintains). As illustrated in Figure J.2 Panel (b), these implied baselines approximate the decrease-then-fluctuate documented patterns. Though still having carbon levels rising in the long run (40-50 years into the market), they remain consistently lower than the business-as-usual baselines by about $30Mg\ ha^{-1}$.

[42]For some real-world 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 remain rather below project simulated carbon levels under IFM, and they are much flatter in trends.

Adding a third baseline option reflecting common practice throughout on non-project lands, we will use three types of baselines:

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

7.2 Simulation Results

Offset Credit Issuance Simulated credit issuance and implied emissions under three project scenarios, three baseline settings, and two carbon offset markets with different credit issuance schemes are summarized in Table 6[43].

Under common practice baseline, regulated market results in strictly negative total credit issuance that discourages any market entries from all three project scenarios. On the voluntary market, market entrance is encouraged as all scenarios have positive total credit issuance (though VCM scenario has negative initial credit issuance). Actual emission reductions are much higher than regulated market credit issuance, but much lower than the voluntary market total credit issuance except for VCM scenario. Therefore, implied entrance by total credits under the common practice baseline (all enter voluntary market) will result in low-quality offset credit issuance for all but VCM scenario projects.

For business-as-usual baseline setting, which is the theoretical ideal design of carbon offset markets, regulated market still discourages all projects with negative initial and total credit issuance, except for positive a total credit on VCM scenario, because the 100-year average baseline carbon used to determine crediting on the regulated market is higher than initial carbon stocks from the increasing baselines in the long-run. On the other hand, the voluntary market now encourages all project scenarios to enter with positive initial and total credit issuance. With no changes in post-market forestry practices, the CARB scenario gains the lowest total credit. Though over-crediting still exists comparing with zero actual reduction, the over-issuance amount is much smaller than under the common practice baseline[44]. VCM scenario has enjoyed 3.9 times the total credits of common

[43] For this exercise, we do not take into account any possible over-reporting of measurement errors of initial carbon stocks.

[44] The total credit issuance is not zero for CARB scenario 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 CARB scenario at years 5 and 10 after the market entrance.

practice baseline, correcting the under-crediting issue. Emission reductions are also close to the total issuance, verifying high-quality offset crediting by design.

With implied baselines, all project scenarios on both regulated and voluntary markets see significantly greater positive initial and total credit issuance. CARB scenario enjoys the higher total credits on the regulated compared with the voluntary market. VCM scenario expects greater total credits on voluntary than regulated market. The ideal scenario is similar to the CARB scenario, having greater total credit on the regulated market. Therefore under these baselines mimicking real-world IFM project documents, the real-world market entrance outcomes are replicated, when CARB scenario projects enter the regulated market, and the VCM projects enter the voluntary market. However, because implied baselines deviate from business-as-usual, these high credit issuance come at the cost of significant over-crediting on both markets. Actual emission reductions are magnitudes lower than total credit issuance for all scenarios on both regulated and voluntary markets, implying low-quality forest offsets being issued.

Expected Economic Payoffs Risk-neutral project developers would make market entrance decisions not only based on the amount of total credit issuance, but also accounting for leakage, reversal, discounting, intermediary agent costs, and opportunity costs from forgone timber sales. To approximate the expected payoffs of project developers in dollars, we use the set of parameters in Appendix K and evaluate the payoff breakdowns in Table 7.

Those simulated payoffs show largely consistent equilibrium market entrance outcomes based on above-ground live carbon total revenue (first column) or total payoff net of other costs and adjusted revenues (last column) as the decisions based on total credit issuance. Specifically, the implied baseline panel is the only one replicating the real-world observations of CARB scenario projects entering the regulated market for higher expected payoffs, and VCM scenario projects entering the voluntary market. The other two baselines, by total payoffs, both result in all scenarios entering the voluntary market, or no market entrance for VCM scenario under common practice baselines.

For sensitivity analysis, we also conduct payoff estimations under different value functions and parameter references and present the results for simulated total payoffs under implied baselines in Appendix Table K.2. Overall, variations in parameters have caused changes in the magnitudes of the total payoffs project developers will expect, but they do not alter the market entrance decisions by highest expected total payoffs, except in two situations. The first case is when reversal risk is taken not as a discount rate but as a linearly subtracted buffer pool. This significantly reduces the payoffs

Baseline: Common Practice				
Market	Project Scenario	Initial Issuance	Total Issuance	Emission Reduction
Regulated	CARB	-44.0	-6.1	0.0
Regulated	Ideal	-58.2	-9.0	18.4
Regulated	VCM	-85.5	-17.7	50.6
Voluntary	CARB	19.4	30.4	0.0
Voluntary	Ideal	4.6	24.9	16.3
Voluntary	VCM	-23.4	12.7	44.6

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	0.0
Regulated	Ideal	36.2	85.4	18.4
Regulated	VCM	12.2	79.9	50.6
Voluntary	CARB	38.1	57.7	0.0
Voluntary	Ideal	36.7	63.0	16.3
Voluntary	VCM	34.1	82.3	44.6

Table 6: Simulated carbon offset market credit issuance and actual emission reduction

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

of VCM scenarios and reverts their market entrance from voluntary to regulated market, due to high timber opportunity costs out of reduced harvesting. The second case is when market clearance is not assumed, so not all credit issued are expected to be sold. Quoting real-world percentage of retired credits (regulated market at 1.52%, voluntary market at 32.73%), expected payoffs would dominate on the voluntary market, causing CARB projects to switch away from the regulated market.

Baseline: Common Practice							
Market	Project Scenario	Revenue	Add. Carbon	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	Add. Carbon	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	Add. Carbon	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 7: Simulated carbon offset market project developer payoff estimates

Notes: Payoff total and breakdowns all estimated in dollar ($) per hectare ($ha^{-1}$). Payoff function and parameters summarized in Appendix Table K. Add. carbon stands for additional carbon besides above-ground live carbon, including mainly standing dead, and some underground soil carbon, which is approximated as a percentage of the above-ground live carbon. Agent cost contains any intermediary including brokerage, market entrance preparing, and manager costs by agents such as Blue Source (now Anew Climate) and Finite Carbon.

Discussions Our simulation results have suggested that there are significant baseline setting issues in reality. Since implied baselines achieve the real-world market entrance outcomes, they are likely what has been applied on the current offset markets. But when comparing 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 entrance, 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, at the cost of actual emissions being zero (CARB projects) or only 54.2% of the total issued offset credits (VCM projects).

There may be deliberate efforts in offset market designs to increase the incentives of market entrance. We explore these potential manipulations using machine learning text analysis tools on project documents and market protocols. For each document, we construct indices of sentiment (Vader scores), subjectivity (TextBlob subjectivity), and concreteness (Brysbaert et al. 2014) averaging across words around the keyword "baseline" for each document, exponentially weighted by sentence distance with a decay rate of 0.5. Text analysis histograms in Appendix Figure L.1 and L.2 have shown some but limited evidence on our manipulation hypothesis. All documents are neutral in sentiment, objective, and at medium-level concreteness when describing baselines. Project plans are less positive and more concrete than protocols, because of the inclusion of exact project information. VCM projects are less objective than their protocols, and CARB projects are more objective than their protocols. VCM projects are less positive, less objective, and similarly concrete as CARB projects. Considering that baseline setting is especially important for CARB projects in order to claim credits without shifting post-market forest management plans much, it is possible that this causes the subjectivity drop in their documents we see here.

We also observe the correlation matrix of these text characteristics with FIA measured carbon and our estimated representation of historical forestry practices *gradient* (Appendix Figure L.3). VCM projects have carbon stocks and *gradient* positively correlated with sentiment, objectivity, and concreteness. CARB projects instead have carbon negatively correlated with sentiment (subjectivity and concreteness is mixed). So VCM projects with higher carbon stocks may signal greater confidence with baselines, but CARB projects could not because high carbon levels can instead reduce the credibility of setting lower baselines.

Conclusions from our simulation results have limitations. An important thing is that the ideal scenario projects with same pre-market harvesting choice as the surrounding control forestland obtain both positive total credit issuance, and positive total payoffs under implied baselines that we have determined to be consistent to reality. Since control forestland in real-world sample do not enter any carbon offset markets, ideal projects should not be obtaining these positive incentives to enter either carbon offset market. This essentially mean that our payoff estimations fail to capture some unobserved costs faced by project developers, or do not reflect the accurate parameters in payoff estimations. Another possibility is that ideal projects should have the incentives to enter carbon offset markets like CARB and VCM projects, and our non-entrance matched controls in the real-world sample are yet to realize the opportunities on offset markets. This is actually more consistent with the high out-of-sample predictions of both offset market participation rates from our discrete choice models.

Another limitation comes from leakage estimations. Under all baseline scenarios, VCM projects have 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. This accounts for about 0.03% of the U.S. annual harvest[45]. This could be a greater or smaller leakage effect compared with the 40% leakage estimates we are currently using, depending on the elasticity of demand and availability of imports of the U.S. timber market.

7.3 Discrete Choice Model with Simulated Outcomes

In the previous subsection, we have used simulations to argue that the current offset market mechanisms do not guarantee high-quality forest carbon offsets from IFM projects in the U.S.. However, if we advise switching to strictly following the business-as-usual baselines which has little to no over-crediting issues, we may significantly undermine the motivations for IFM projects to participate in carbon markets. So in this subsection, we will reuse one of our discrete choice models, nested logit, to re-estimate a discrete choice model accounting for expected credit issuance by our simulations, and then use it to assess the counterfactual outcomes of changing baselines from implied to business-as-usual.

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

Simulated Plot-Market Specific Expected Outcomes To integrate simulated offset market outcomes in our discrete choice model on offset market entrance, we will need the nested logit model that allows plot-market specific determinants. To compile a plot-market specific explanatory variable indicating the expected relative payoff of each plot on each market (regulated, voluntary, no entrance normalized to payoff zero), we differentiate plots by terciles of their pre-market *gradient* measures by OLS, which represent their historical forest management.

Then to map to simulation estimates, we run simulations on a continuous scale of pre-market harvesting rate $1\%, 1.2\%, ..., 2.8\%, 3\%$ to approximate the variations in *gradient* fixing all the other harvesting parameters of the LANDIS II model. Total carbon credit issuance, estimated payoff relative to non-entrance, and actual emission reductions are estimated for each harvesting rate scenario on both regulated and voluntary markets under all three baselines (common practice, business-as-usual, implied) are illustrated in Appendix Figure M.1. As it shows in Panel (a), under implied baselines which match most to real-life, pre-market harvesting rate affects all three outcome variables (credit, payoff, emission reduction). The decreasing regulated market credits meet the increasing total credit issuance of voluntary market at about 2.2% pre-market harvesting rate, sorting low pre-market harvesting projects into the regulated market, and high pre-market harvesting projects into the voluntary market[46]. The similar crossing of regulated versus voluntary market payoffs happens at around 1.8% pre-market harvesting rate (Panel (b)), resulting in similar equilibrium entrance sorting by low and high pre-market harvesting rates. Actual emission reductions are increasing in pre-market harvesting rates, and difference between the two offset markets only come from their crediting period lengths (regulated market has 25 years, longer than the 20 years of voluntary market).

With the negative causal correlation between pre-market harvesting rates and *gradient*, we assign simulated credits, payoffs and emission reductions to the average across three bins over the range of simulation pre-market harvesting rates we use around the crossing of regulated versus voluntary market outcomes (wrapping both crossings of total credit and total payoff). We then map them to the terciles of *gradient* in our real-world data sample used in previous empirical analysis. For values of the assigned simulated outcomes for each group on each market under each baseline setting, see Appendix Table M.1[47].

[46]Note that total credits cross at about 2.2% pre-market harvesting rate, different to the table results (Table 6) 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.

[47]They reflects the similar results as our main simulation Table 6 and 7, referencing CARB scenario to Group 3 high *gradient* low pre-market harvesting rate, and VCM scenario to Group 1 low *gradient* high pre-market harvesting rate.

Group	*gradient* Tercile	Simulation Pre-Market Harvesting Rates
1	$gradient < 0.0453$	$HRate > 2.4$
2	$gradient \in [0.0453, 0.9085)$	$HRate \in [1.6, 2.4]$
2	$gradient \geq 0.9085$	$HRate < 2.4$

Nested Logistic Regression Estimations and Predictions We evaluate the original nested logit regression with maximum likelihood based on probabilities Eq. 7, as well as the nested logit replacing $gradient^{exp}$ with $payoff^{exp}$, which equals the expected payoffs at plot-market level based on the groupings matching simulations with *gradient* terciles as described above. Results in Appendix Table M.2 show that both nested logits estimate the similar statistically significant positive estimator on $|gradient|$ on outer level. This indicates that the size of *gradient* contributes to whether or not a forest plot enters any carbon offset market, consistent with our main empirical results using two-stage logit. Both $gradient^{exp}$ and $payoff^{exp}$ contribute positively to inner level market entrance, consistent with intuitions that having signs of slope aligning with market mechanisms or greater simulation estimated payoffs encourages offset market entrance. Using $payoff^{exp}$ instead of $gradient^{exp}$ as predictor gives more statistical significance, and the Brier score slightly decreases.

Predicting market entrance probabilities using the two nested logit models over all FIA forest plots in Region 9, we summarize the entrance outcomes and simulation-based estimates of emission reduction, credit issuance, social benefit of carbon offsetting, and payoff to project developers under implied and business-as-usual baselines in Table 8[48]. Overall, the two logits predict quite similar entrance probabilities of 53% no entrance, 35% regulated market entrance, and 12% voluntary market entrance over Region 9[49]. Simulation-based outcomes have more discrepancies, possibly due to binning and matching *gradient* to simulation pre-market harvesting rates. Only the second nested logit incorporating simulated market payoffs has illustrated the over-crediting issue (emission reduction is below total credit issuance) under current mechanism using implied baselines. Because of the large social cost of carbon estimator, social benefit from emission reductions due to potential IFM projects under the current market mechanism is always magnitudes higher than payoffs received by project developers.

If to improve forest offset credit quality and switch to business-as-usual baselines, our nested logit

[48]For business-as-usual baselines, we plug in $gradient^{exp} = 1$ for voluntary market regardless of *gradient*, $gradient^{exp} = -1$ for regulated market regardless of *gradient* for the first logit extrapolations. This comes from predictions according to Table 6 and 7 that all plots would have motivations to enter voluntary offset market under business-as-usual baselines. We plug in group-specific payoffs for predictions using the second logit, according to Appendix Table M.1.

[49]But these predictions have higher probabilities of regulated market entrance and lower voluntary market entrance comparing with other discrete choice models we adapted in Appendix Figure I.2.

predictions indicate there is up to 10 percentage points more no entrance choice and 3.7 percentage points more voluntary market choice, together with a 13.6 percentage point drop in regulated market choice (second logit). This is because the regulated market sees the most expected payoff drop and flips from positive to negative going from implied to business-as-usual baselines. With over 75% drop in total credit issuance by both specifications, there are no longer over-crediting issues, and the low-quality forest credits will indeed no longer be a problem under business-as-usual baselines. Because only VCM scenario projects contribute to carbon emission reductions on either carbon offset market and some of those convert to no entrance with reduced expected payoffs, emission reduction and social benefit actually drop by up to 15.4%. Project developer payoff flips to negative, contributed by the still-existing regulated market participants.

Nested Logit with $gradient^{exp}$							
Baseline	Shr. No Entrance	Shr. Regulated	Shr. Voluntary	Emission Reduc. $[MtCO_2e]$	Total Credit $[MtCO_2e]$	Social Benefit Emission Reduc. $[M\$]$	Proj. Dev. Payoff $[M\$]$
Implied	0.527	0.349	0.123	1091	716	152764	13570
Business-as-Usual	0.559	0.285	0.156	1039	161	145524	-19340
Change	0.032	-0.064	0.033	-0.047	-0.775	-0.047	-2.425
Nested Logit with $payoff^{exp}$							
Baseline	Shr. No Entrance	Shr. Regulated	Shr. Voluntary	Emission Reduc. $[MtCO_2e]$	Total Credit $[MtCO_2e]$	Social Benefit Emission Reduc. $[M\$]$	Proj. Dev. Payoff $[M\$]$
Implied	0.529	0.348	0.123	1059	2599	148233	13962
Business-as-Usual	0.628	0.212	0.160	896	635	125441	-14030
Change	0.099	-0.136	0.037	-0.154	-0.756	-0.154	-2.005

Table 8: Welfare analysis under implied versus business-as-usual baselines using simulation incorporated nested logit predictions

Notes: Table reports carbon offset market participation probabilities and estimated emission reduction, offset credit issuance, payoffs of project developers, and social benefit from CO_2 *emission reduction over all 20 states of U.S. Region 9. Plot-level entrance probabilities are extrapolated with the nested logistic regression direct estimates (Appendix Table M.2), over all FIA forest observational plots* $N = 37,926$. *State-level market entrance rates reported are averaged across plots after weighted by plot areas. Total Region 9 average probabilities are calculated weighting states' forest areas by FIA reports FY 2022. Plot-level emission reduction, credit, payoff and social benefit are estimated with extrapolated entrance probabilities and gradient-based tercile group mapping to simulation values per hectare of Appendix Table M.1. State-level averages are taken averaged across plots after weighted by plot areas. Then all are aggregated across 20 states by state forest areas. Social benefit of carbon reduction is estimated with emission reduction converted 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). Change row indicates changes in predicted entrance probabilities, or percentage of changes in emission reduction, credit, social benefit and payoff, going from implied to business-as-usual baselines.*

To summarize, our nested logit discrete choice model predicts significant environmental gains of extensive carbon offset market participation by all eligible forestland across Region 9. Resulting emission reduction remains above one billion tCO_2e over the region (or about 0.9 billion tCO_2e switching to business-as-usual baselines), proving the potential of nature-based climate solutions through IFM and carbon offset markets. In Massachusetts, 10.5 million tCO_2e are planned to be removed by 2040[50]. The extrapolated contribution by our models under either implied or business-as-usual will be all above this amount. Our welfare analysis has also shows that restricting baselines to business-as-usual standards will resolve the over-crediting issues on both offset markets, but at the cost of also reducing the environmental benefits and individual project developer payoffs from carbon offsets trading.

However, these estimates come from strong assumptions that make 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 rate of retirement for nature-based solution projects well below 100% (1.52% on regulated market, 32.73% on voluntary market) and the projected instability corporate climate commitments, our estimated welfare gains will be much over-optimistic. Secondly, extending the entrance prediction model to all forestland implies a reduction of timber harvesting of at least 6 billion broad feet annually just from the 20 states of Region 9, accounting for about 3.5% of the U.S. annual timber removal[51]. Considering the steady U.S. timber demand of the U.S. timber market, the significant rate of offset market participation is either not achievable, or the implied oversea leakage can be non-trivial.

8 Conclusion

This paper compiles a novel dataset of 62 improved forest management (IFM) projects in 20 U.S. states traded on either the California regulated or the global voluntary carbon markets. Applying ground-truth forest carbon measurement from FIA, we empirically analyze and model the entry selections of these forest-based projects using event study regressions, discrete choice modeling and forest simulations. We identify differing pre-market forest management practices as key determinants for project developers' entry choices and selections between the two available carbon offset markets due to the two markets' significantly different credit issuance schemes. The California regulated market adapts high initial credit issuance to attract projects with increasing, high above-ground

[50]The Commonwealth plans to reduce from its 1990 emission of 93.2 Million tCO_2e by 75% in 2040, 15% of the which are planned to be taken by nature-based climate solutions, mainly through forestry. Source: March 2024 Massachusetts Priority Climate Action Plan.

[51]Prediction using second nested logit model with $payoff^{exp}$. U.S. forest product market supply and demand source: UNECE Report (source).

carbon storage. Meanwhile, the global voluntary market's gradual credit issuance scheme attracts projects with decreasing, below-control carbon stocks.

However, IFM projects on both regulated and voluntary markets are motivated to submit lower baselines than their business-as-usual practices, enhancing greater economic gains as well as greenwashing. To prevent these 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 baselines are set in accordance to the business-as-usual principle. Additionally, the regulated market could lower the share of initial credit issuance, which will help avoiding entrants who benefit from pre-market forest conservations and practice no meaningful post-market improved forest management. Policy makers and market regulators should also note that, from our counterfactual analysis using discrete choice models, engaging all eligible forestland in carbon offset markets can contribute significantly to states' and country's carbon neutrality goals as a nature-based climate solution, but ensuring market integrity with stricter baselines could also undermine market entrance, private market gains and overall carbon emission reductions through the market mechanism.

This project has several important limitations that future studies should address. First, we use FIA measurements of above-ground carbon for our analysis, which is shown to differ from project reported carbon measurement. Whether systematic upwards bias exists in the carbon reporting on the offset markets is still to be verified, and how that potential bias may affect market efficiency remains unknown. Second, the low temporal frequency of FIA data and uncertainties around project boundaries (especially for VCM projects from manual map scraping) would introduce errors into our empirical results and final conclusions. Third, our simulation analysis requires more robustness runs, and further validations from varying forest management practices (e.g. varying post-market harvesting rates, changing rotation periods, altering harvesting schemes) and market parameters (e.g. adding inflation, financial risks, incomplete market competitions) to be representative of the real-world situations. Forth, for more realistic and accurate predictions of future offset market evolution, more dynamic and more complete models incorporating variations in carbon credit prices, timber market perspectives, reputation costs from current issuance of low quality forest offsets, and future U.S. and global climate policy changes should be used in future studies.

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Appendix

A Sample Project and Baseline Projection Plots

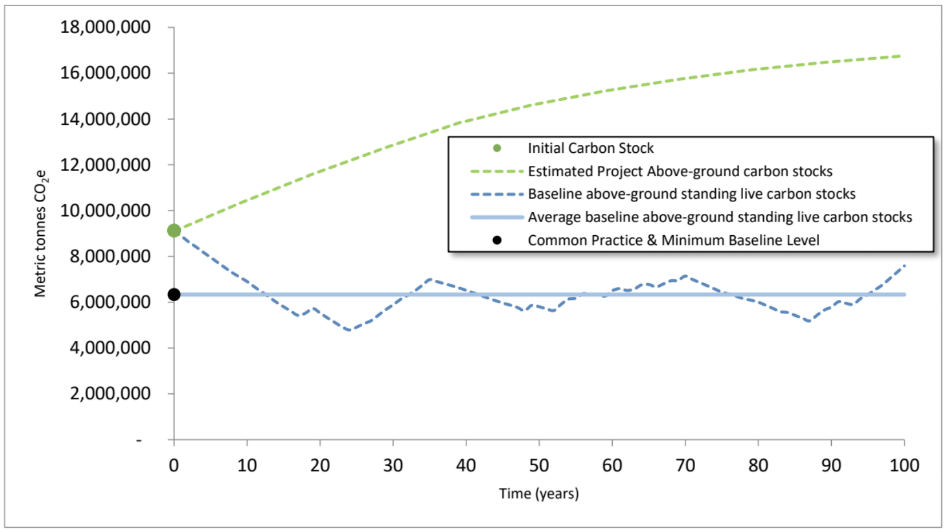


Figure 2. Baseline and Project Above-Ground Standing Live Carbon Stocks.

(a) CAFR5416 (ACR416)

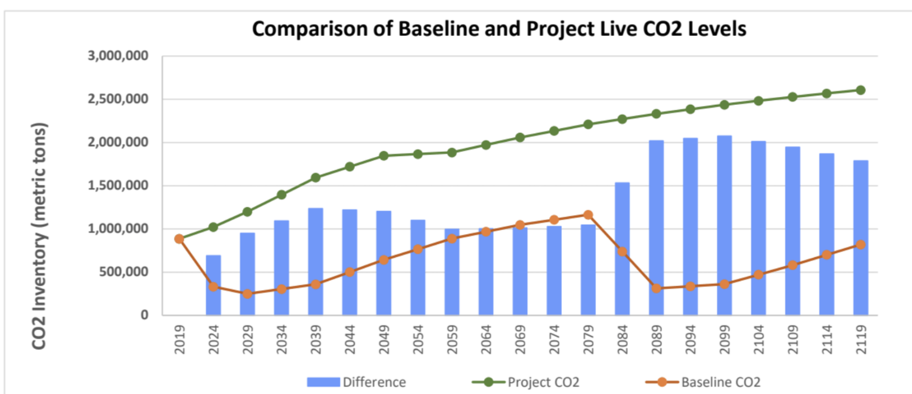


Figure A7.1. – Graph showing the CO_2 relationship between the Baseline scenario (with an objective to maximize net present value), versus the Project's conservation management scenario (with an objective to conserve CO_2), and the difference (in metric tonnes) therein (from 2024 to 2119).

(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

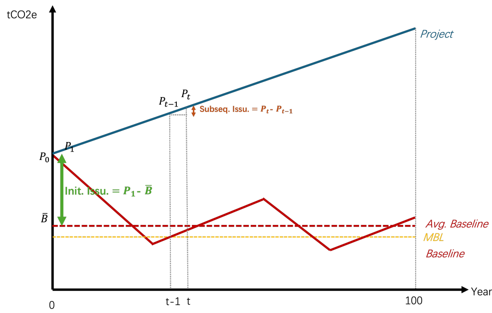
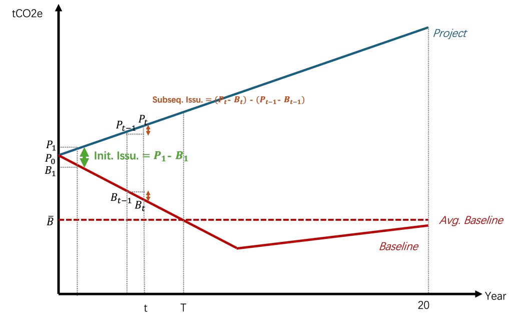
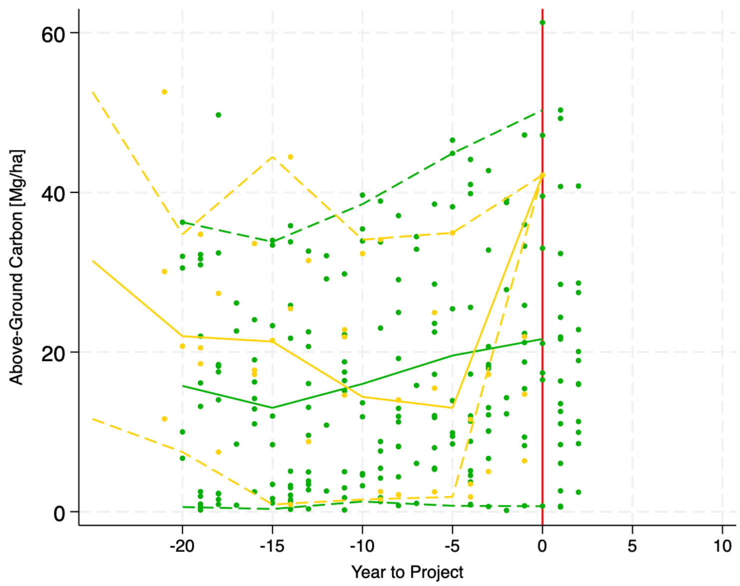
<table>
<tr><th></th><th>Regulated (CARB)</th><th>Voluntary (VCM)</th></tr>
<tr><td>Illustration</td><td>
</td><td>
</td></tr>
<tr><td>Initial Issuance</td><td>$P_1 - \bar{B}$</td><td>$P_1 - B_1$</td></tr>
<tr><td>Subsequent Issuance</td><td>$P_t - P_{t-1}$</td><td>$(P_t - B_t) - (P_{t-1} - B_{t-1})$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

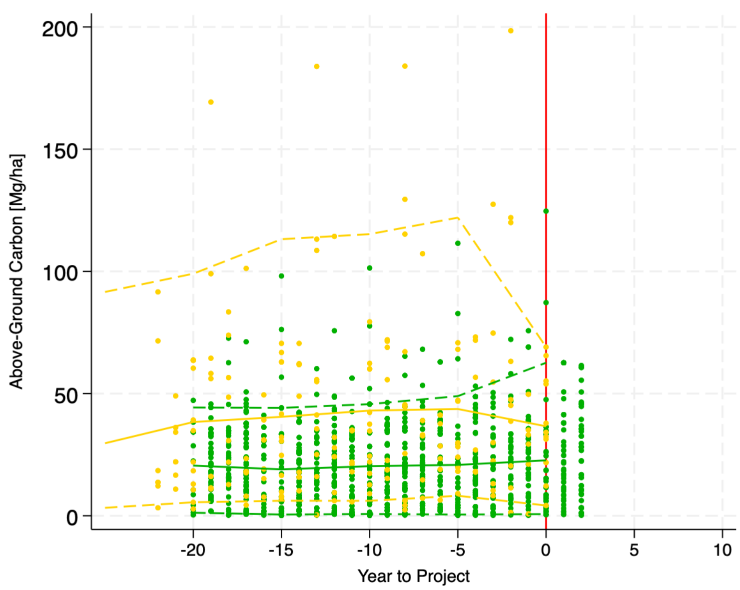
Table B.1: Formulas for carbon credit issuance (initial, subsequent and total), and present value of expected total revenues from offset sales on regulated and voluntary markets

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 in biomass for the project after adapting the improved forest management plan post market entrance year t. B_t indicates simulated baseline tCO2e stored in 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

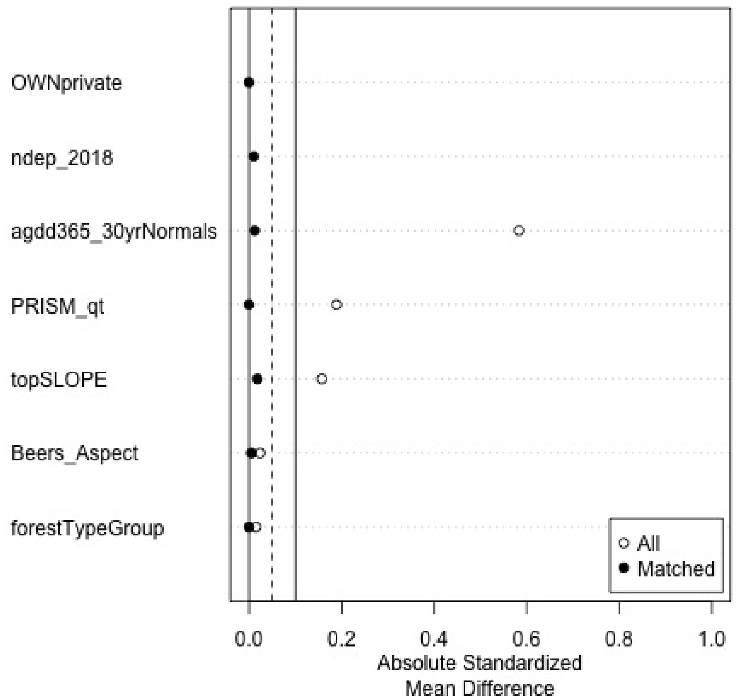
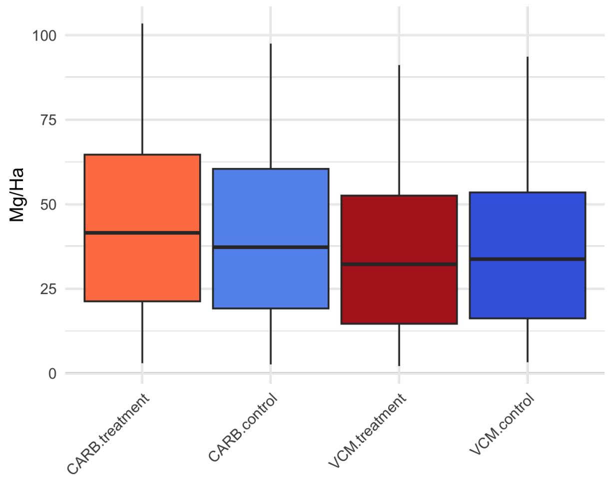


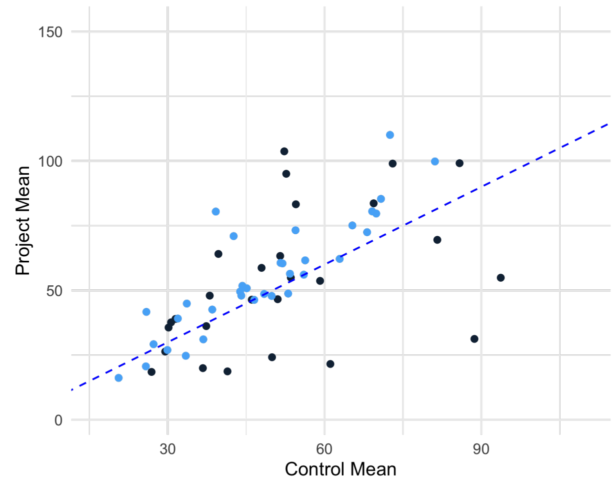
Figure D.1: Balance plot for matching, five nearest-neighbor with replacement

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



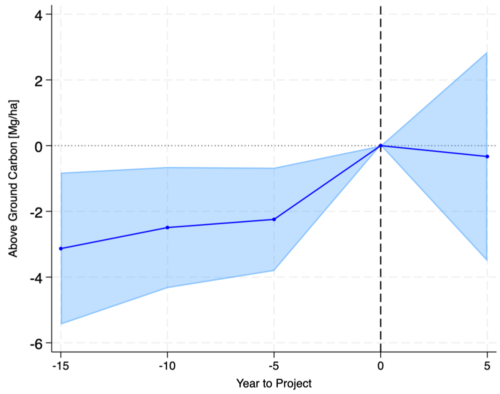
(a) Box plots comparing average above ground carbon ($Mgha^{-1}$) for CARB and VCM project plots and their matched control plots. Blue bars are controls, red bars are treatments. Light color bars are CARB projects, dark color bars are VCM projects.



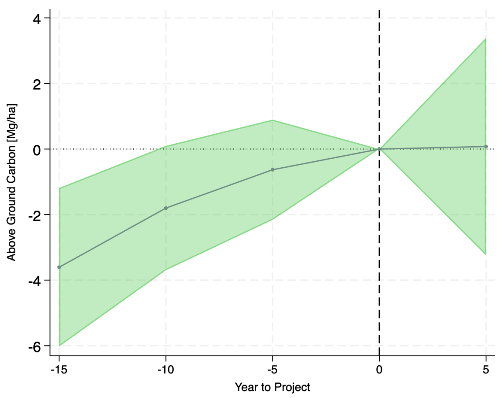
(b) Scatter comparison of average above-ground carbon per hectare ($Mgha^{-1}$) by CARB projects traded on the regulated market (light blue dots) and VCM projects on the voluntary carbon market (dark blue dots). Vertical axis is the project-average carbon measure, horizontal axis is the project's matched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

Figure E.1: Comparison of pre-market above-ground carbon storage between project and matched control forest observational plots

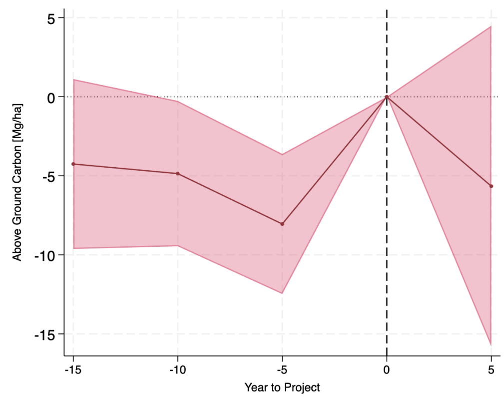
F Event Study Robustness



(a) All



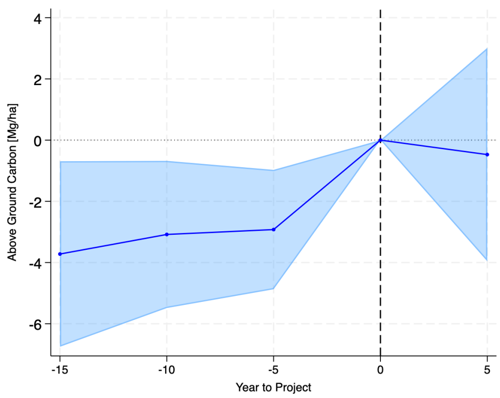
(b) CARB



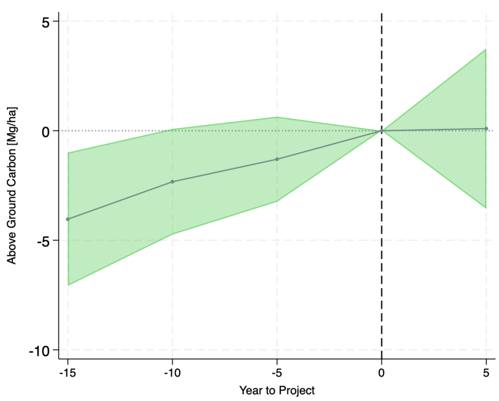
(c) VCM

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

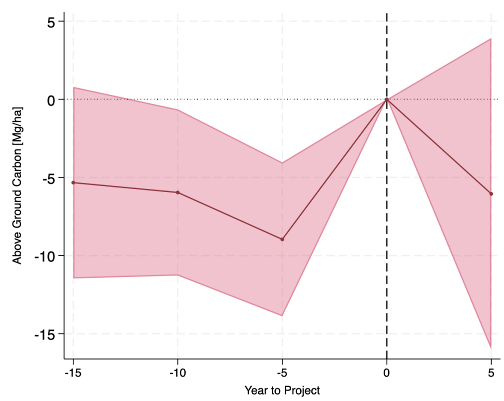
Notes: Notes: Estimates and 95% confidence intervals are estimated with regressions Eq. 1 for Panel (a) and 2 for Panel (b), (c). Each point observation indicates average FIA measured above-ground carbon (unit: $Mgha^{-1}$) within five-year bins (e.g., observation at year $5n$ average across the 5-year bin of $[5n, 5n+4]$), relative to the average carbon levels from nearest-five-neighbor matching control plots with similar carbon storage potentials. 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



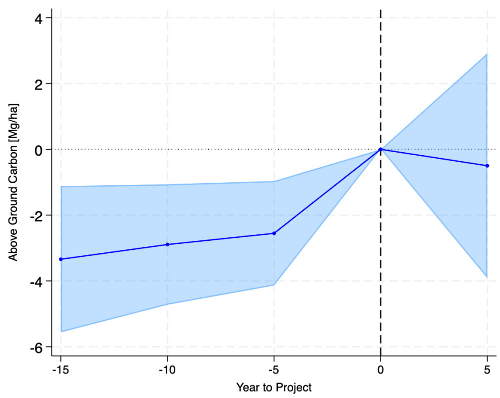
(b) CARB



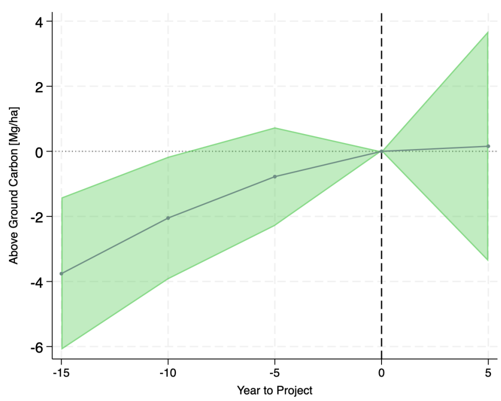
(c) VCM

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

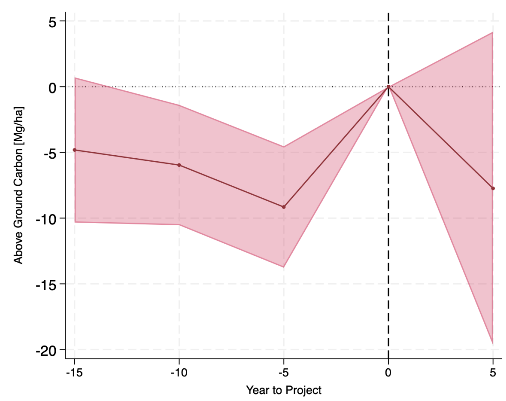
Notes: Estimates and 95% confidence intervals are estimated with regressions Eq. 1 for Panel (a) and 2 for Panel (b), (c). Each point observation indicates average FIA measured above-ground carbon (unit: $Mgha^{-1}$) within five-year bins (e.g., observation at year $5n$ average across the 5-year bin of $[5n, 5n+4]$), relative to the average carbon levels from nearest-neighbor matching control plots with similar carbon storage potentials. 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



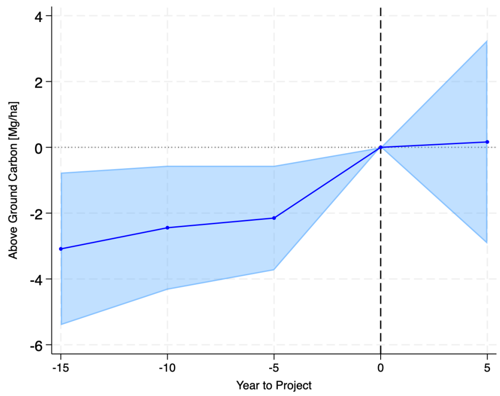
(b) CARB



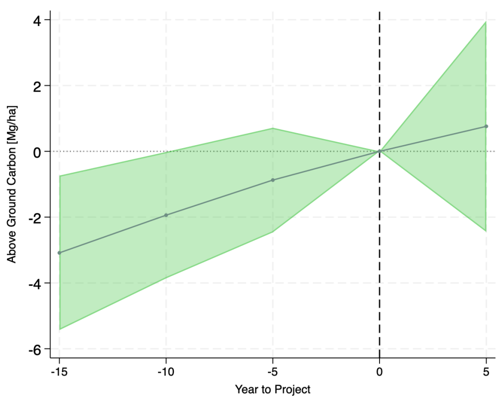
(c) VCM

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

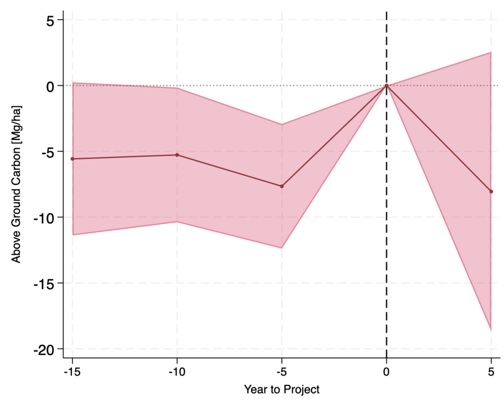
Notes: Estimates and 95% confidence intervals are estimated with regressions Eq. 1 for Panel (a) and 2 for Panel (b), (c). Each point observation indicates average FIA measured above-ground carbon (unit: $Mgha^{-1}$) within five-year bins (e.g., observation at year $5n$ average across the 5-year bin of $[5n, 5n+4]$), relative to the average carbon levels from coarsened exact matching (CEM) control plots with similar carbon storage potentials. 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

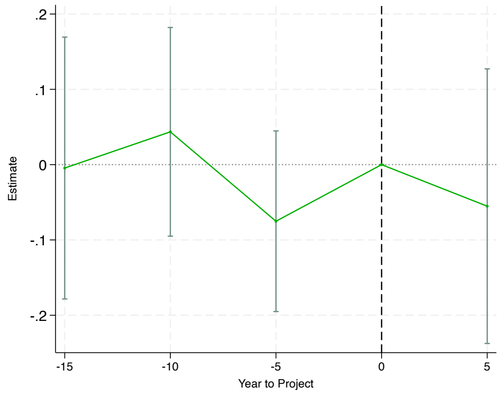


(c) VCM

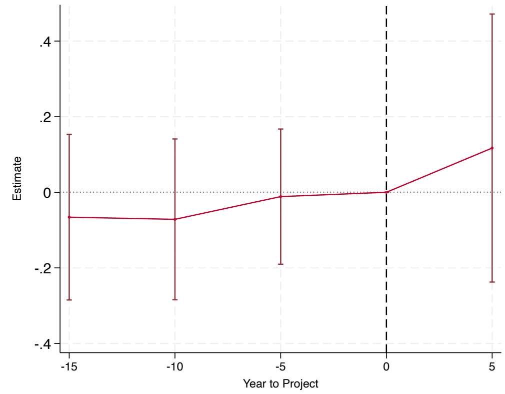
Figure F.4: Event study plots for FIA measured above-ground carbon storage, alternative coarsened exact matching (CEM)

Notes: Event study regression includes additional controls of state-specific linear year trends. Estimates and 95% confidence intervals are estimated with regressions Eq. 1 for Panel (a) and 2 for Panel (b), (c). Each point observation indicates 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 the average carbon levels from five-nearest-neighbor matching control plots with similar carbon storage potentials. 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).

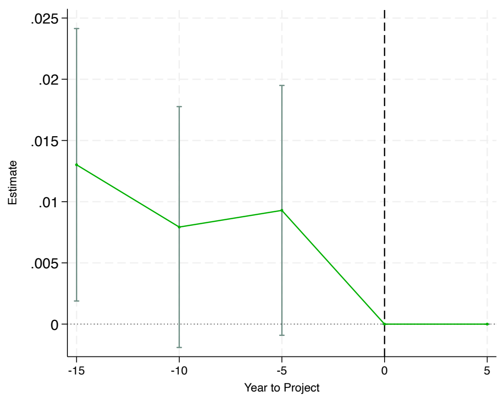
G Harvest Indicators Event Study Plots



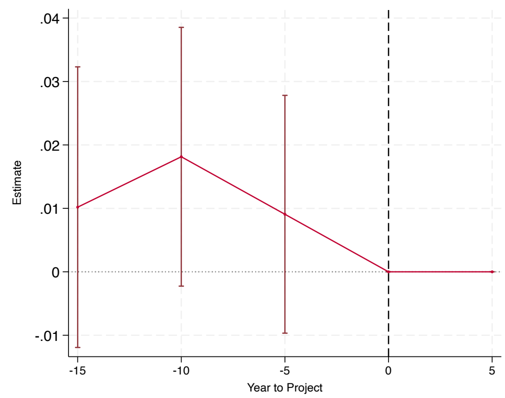
(a) Removed Basal Area Per Hectare Per Year-CARB



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

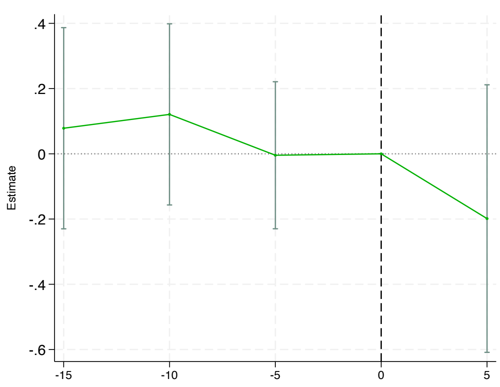


(c) Ratio of Removed over Standing Basal Area Per Year-CARB

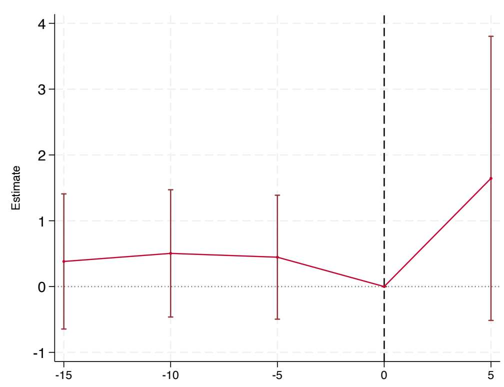


(d) Ratio of Removed over Standing Basal Area Per Year-VCM

Figure G.1: Harvest Event Study Plots



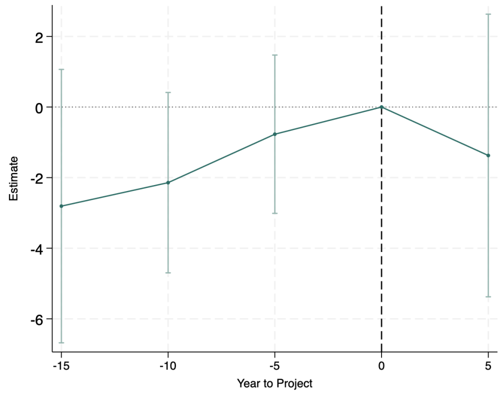
(a) Dead Basal Areas Per Hectare-CARB



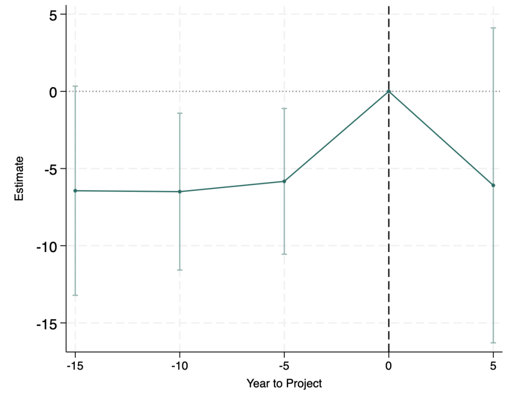
(b) Dead Basal Areas Per Hectare-VCM

Figure G.2: Dead Biomass Event Study Plots

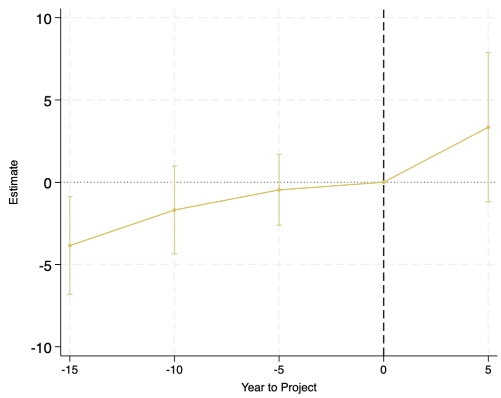
H Event Studies for Heterogeneity Analysis



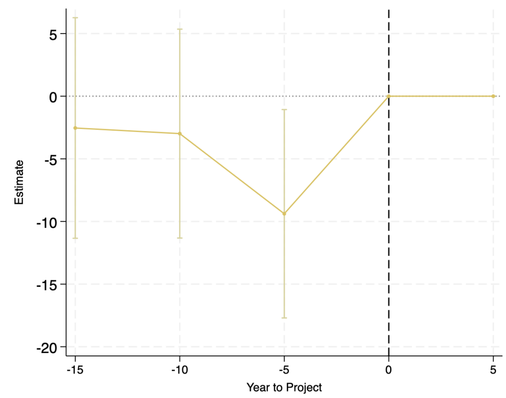
(a) CARB-with CE



(b) VCM-with CE

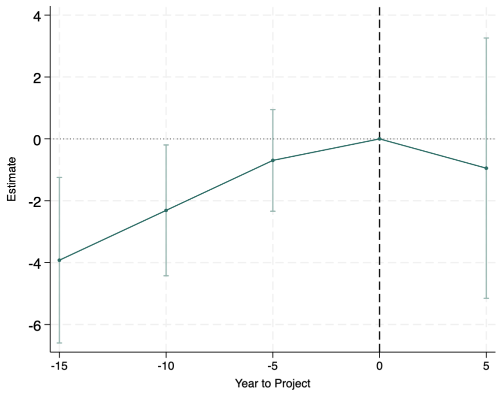


(c) CARB-without CE

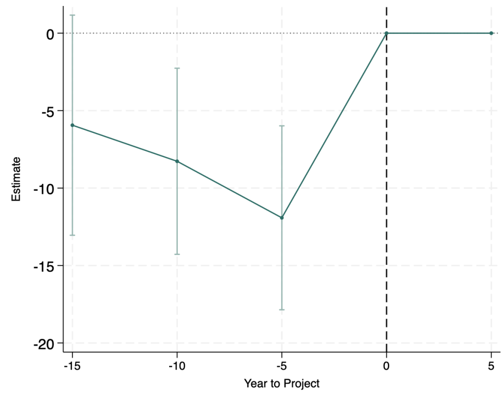


(d) VCM-without CE

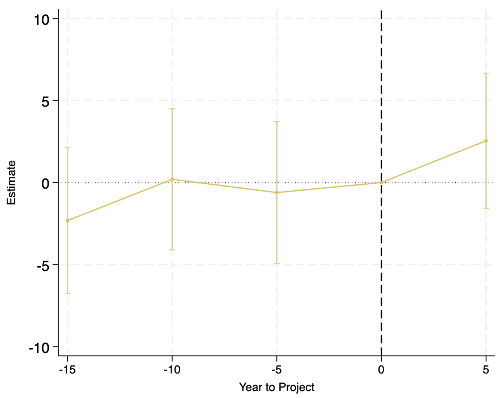
Figure H.1: Event study plots for projects separated by with or without historical conservation easement commitments (CE)



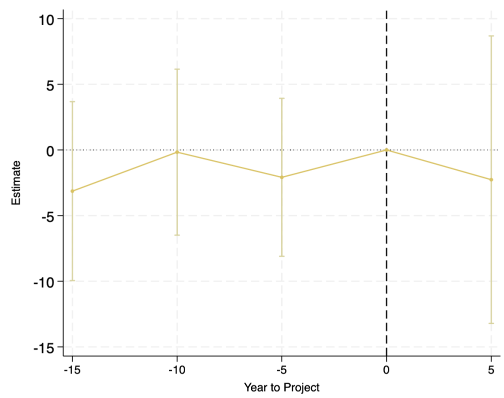
(a) CARB-Timber Company



(b) VCM-Timber Company

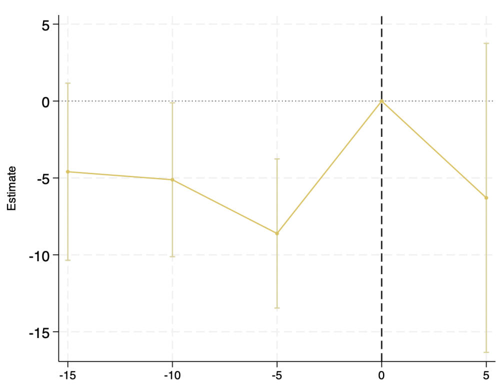


(c) CARB-Non Timber Company

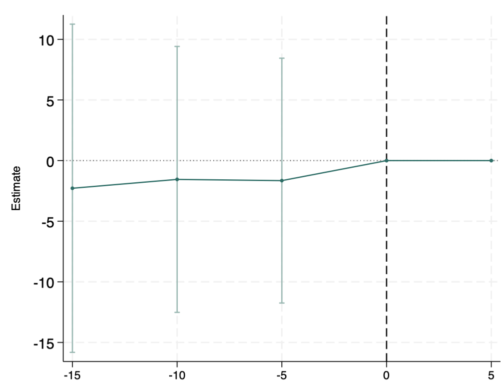


(d) VCM-Non Timber Company

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

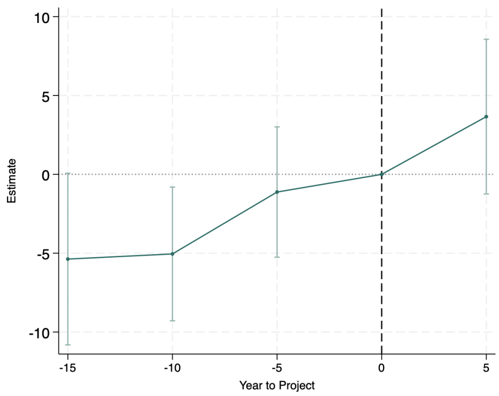


(a) VCM-With Preparing Agents

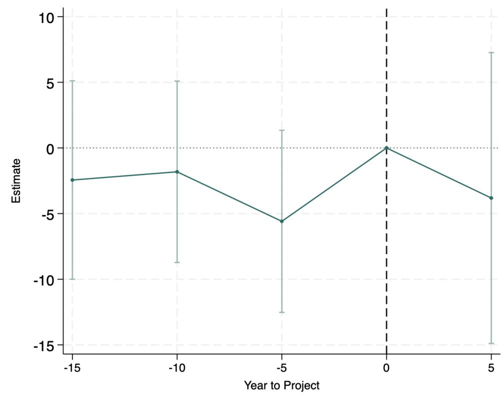


(b) VCM-No Preparing Agents

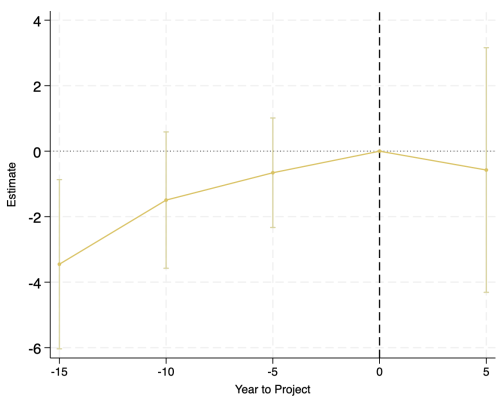
Figure H.3: Event study plots for VCM projects separated by agent preparation or self preparation status



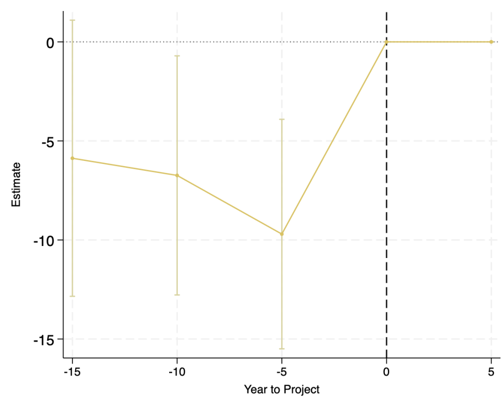
(a) CARB-Small Area



(b) VCM-Small Area

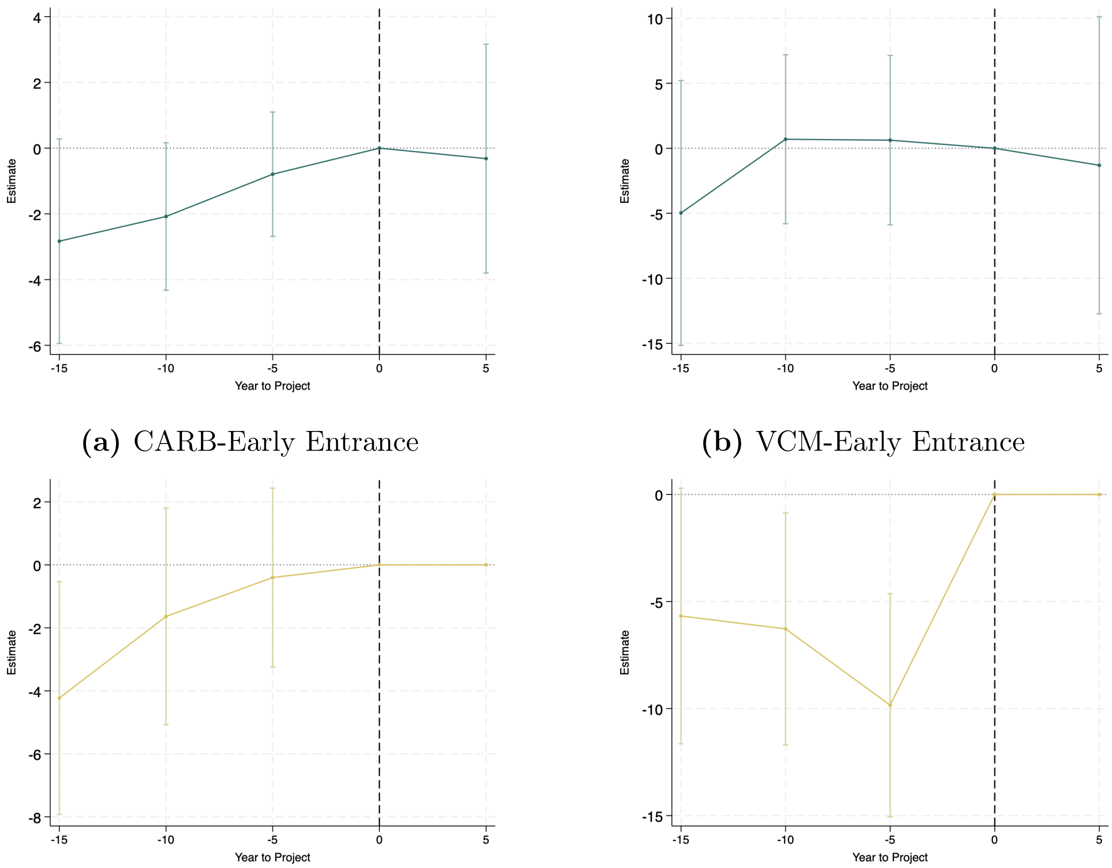


(c) CARB-Large Area



(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 Discrete Choice Model Additional Tables and Figures

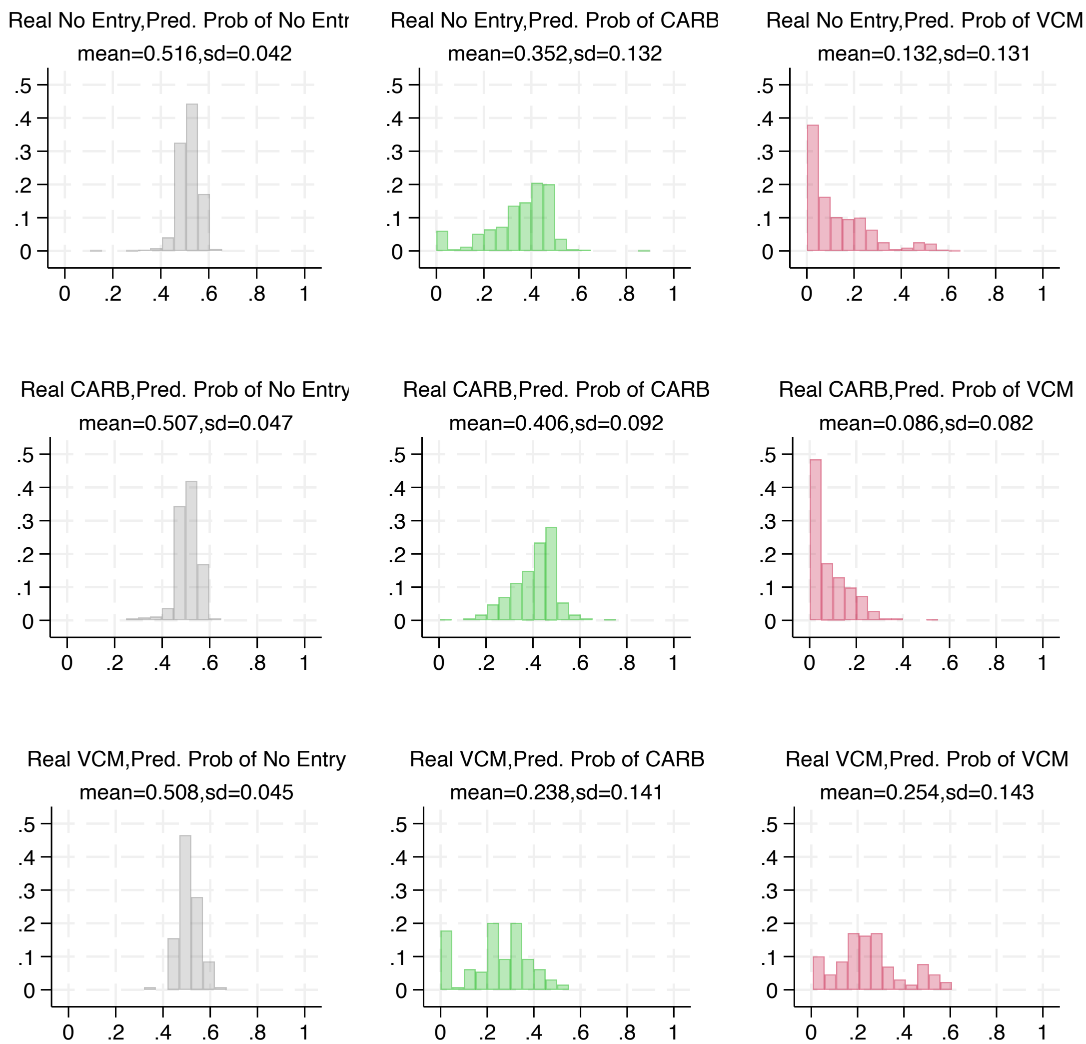


Figure I.1: Summary histogram for in-sample predictions of two-stage logit model

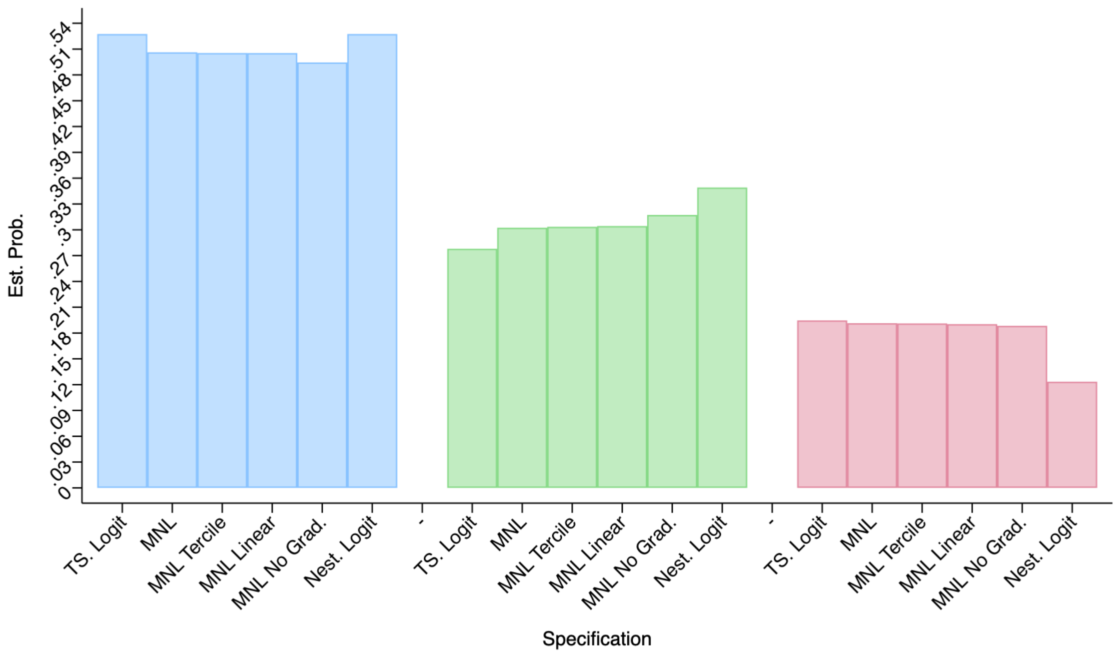


Figure I.2: Bar chart comparison of average Region 9 predicted market entrance outcomes by different discrete choice models

Notes: Blue=No Entrance, Green=CARB, Red=VCM.

J Simulation Set-Up Trend Tests

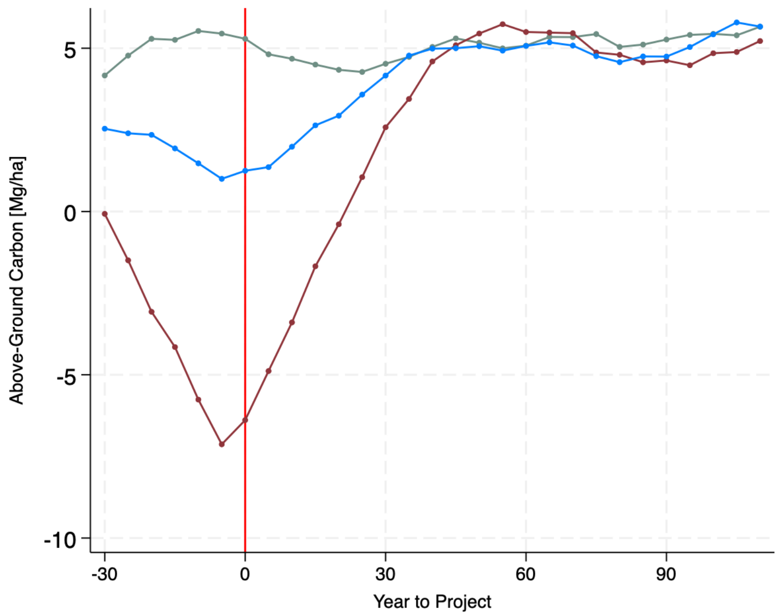
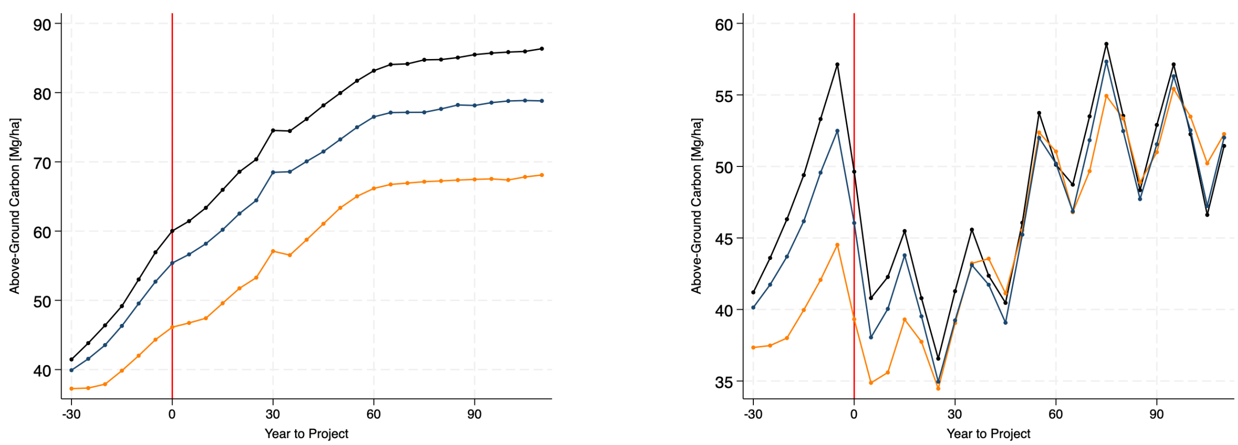


Figure J.1: Simulation plot: Green=CARB Scenario, Red=VCM Scenario, Blue=Ideal Scenario

Notes: Plots indicate the simulated project above ground carbon relative to (subtracting) the natural baseline, which is the average carbon levels 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 formula:

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

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 carbon projection of project scenarios, B is the carbon 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
Additional Carbon	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.

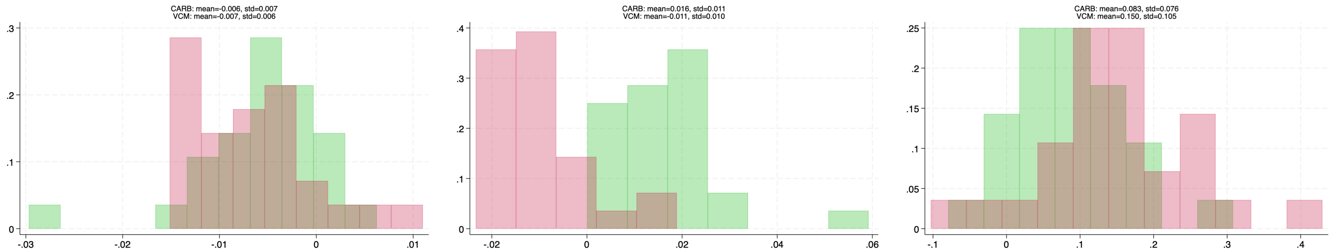
Table K.1: Payoff parameter sources and summary

					Baseline: Implied					
Market	Project Scenario	Original	Alt. Buffer Treatment	Same Offset Price	Offset Price Growth	VCM No Agent	High Agent Cost	High Standing Dead	High Timber Price	Market Not Clear
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 baselines

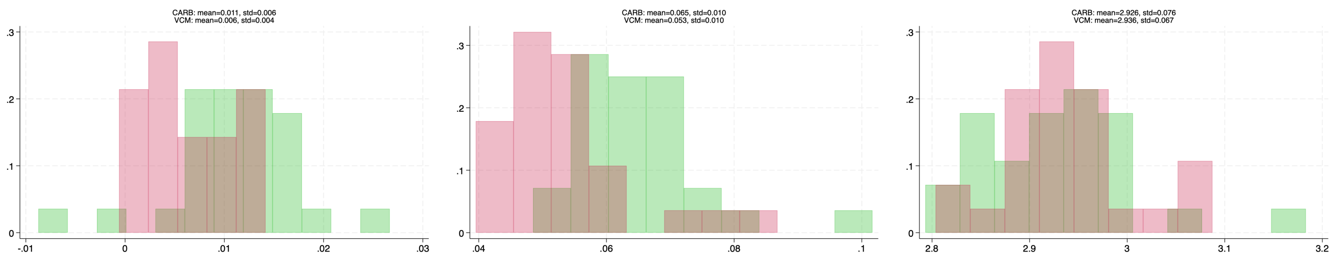
Notes: Payoff total is estimated in dollar ($) per hectare ($ha^{-1}$). Payoff function and parameter summary see Appendix K. All estimation under Implied baseline (same harvesting rate as project pre-market, 5% harvesting post-market). Original is the main estimation same as Table 7. Alt. Buffer Treatment 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 Text Analysis Results



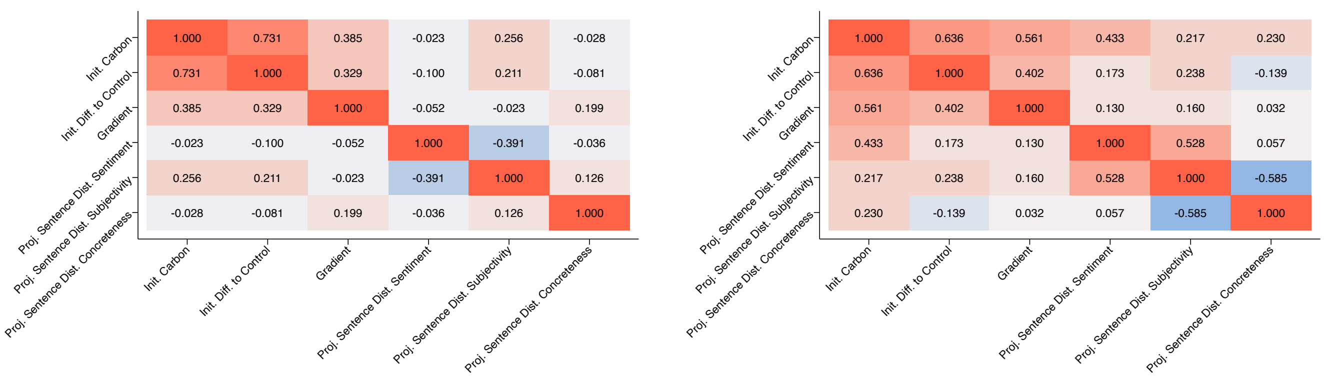
(a) Sentiment **(b)** Subjectivity **(c)** Concreteness

Figure L.1: Distribution histograms for text analysis, difference of project plans and protocols



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

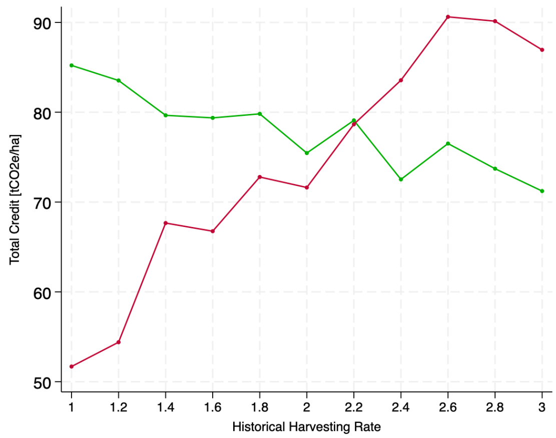
Figure L.2: Distribution histograms for text analysis, project plans scores



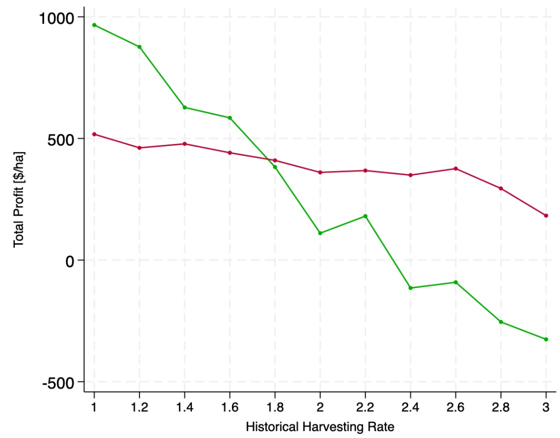
(a) CARB **(b)** VCM

Figure L.3: Correlation matrix between project document text representation and FIA carbon measurements

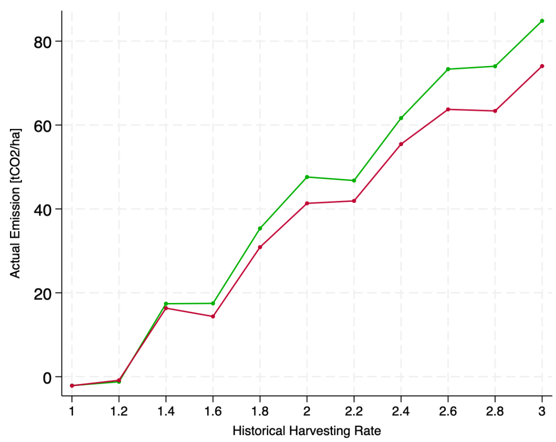
M Simulation-Based Nested Logit Estimations



(a) Total Credit



(b) Total Payoff



(c) Total Emission Reduction

Figure M.1: Simulation estimated market and environmental outcomes of total credit issuance, total payoff under implied baselines: Green=enter regulated market, Red=enter voluntary market.

Baseline: Common Practice				
Market	Group	Total Issuance $[tCO_2e\ ha^{-1}]$	Total Payoff $[\$\ ha^{-1}]$	Emission Reduction $[tCO_2e\ ha^{-1}]$
Regulated	1	48.4	-690.4	73.5
Regulated	2	13.4	-978.3	36.8
Regulated	3	-17.6	-1176.0	4.7
Voluntary	1	66.6	79.2	64.2
Voluntary	2	40.5	24.7	32.1
Voluntary	3	16.3	11.2	4.4

Baseline: Business-as-Usual				
Market	Group	Total Issuance $[tCO_2e\ ha^{-1}]$	Total Payoff $[\$\ ha^{-1}]$	Emission Reduction $[tCO_2e\ ha^{-1}]$
Regulated	1	-26.0	-2191.5	73.5
Regulated	2	-15.0	-1551.9	36.8
Regulated	3	-6.6	-956.8	4.7
Voluntary	1	2.4	-679.3	64.2
Voluntary	2	17.0	-235.4	32.1
Voluntary	3	29.0	193.1	4.4

Baseline: Implied				
Market	Group	Total Issuance $[tCO_2e\ ha^{-1}]$	Total Payoff $[\$\ ha^{-1}]$	Emission Reduction $[tCO_2e\ ha^{-1}]$
Regulated	1	73.5	-196.5	73.5
Regulated	2	78.4	314.7	36.8
Regulated	3	82.8	823.5	4.7
Voluntary	1	87.8	300.7	64.2
Voluntary	2	72.5	394.9	32.1
Voluntary	3	57.9	485.6	4.4

Table M.1: Group level average simulated estimates for credit, payoff and actual emission reduction

Credit and emission estimated similarly as Table 6. Total payoff estimated similarly as Table 7. Simulations run on pre-market harvesting rate varying at $1\%, 1.2\%, ..., 2.8\%, 3\%$. *Pre-market harvesting rat range mapping to groups: Group 1-*$[2.6\%, 3.0\%]$, *Group 2-*$[1.6\%, 2.4\%]$, *Group 1-*$[1.0\%, 1.4\%]$. *Group averages map to terciles of real-sample gradient from low to high, reflecting greater to smaller harvesting rate.*

Nested Logit with $gradient^{exp}$ (Brier's Score: 0.1960)		
	Outer	Inner
$gradient^{exp}$		0.2075
		(0.1592)
$\|gradient\|$	0.1310***	
	(0.0470)	
Nested Logit with $payoff^{exp}$ (Brier's Score: 0.1957)		
	Outer	Inner
$payoff^{exp}$		0.0004**
		(0.0002)
$\|gradient\|$	0.1119***	
	(0.0468)	

Table M.2: Nested logistic regression maximum likelihood estimators

*Notes: Maximum likelihood probability formulas see Eq. 7. Standard errors in parentheses are clustered by project, with matched control plots clustered with other controls by the same project they match to, but differently with the corresponding project plots. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Omitted forest type being FIA code=900. $N = 2,353$. Outer estimation considers whether or not to enter carbon offset markets, inner estimation considers whether to enter the regulated or voluntary offset market. The seven geophysical and socio-economic factors are included in regressions but not reported by this table.*