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LETTER

# Achieving high-integrity tree-planting projects in the voluntary carbon market

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Supplementary material for this article is available online

## Abstract

Globally, the voluntary carbon market (VCM) is a popular mechanism for carbon emitters to purchase credits and offset their emissions. Despite criticisms of unclear carbon outcomes, long-term durability of projects, and impacts on local communities, there are few systematic studies that assess their ecological and social outcomes based on ground-level data and robust counterfactuals. This study synthesizes data from the carbon market registry, on-ground surveys, and satellite data to inform VCM standards and policies for land-use related carbon market projects in India. We analyzed satellite imagery to assess changes in tree cover in more than 20 000 plots participating in all VCM afforestation projects registered in the country as of 2022 and surveyed project developers to assess the implementation process and local households to and evaluate economic impacts for 366 households in two of the ongoing projects. We compare these results with comparable plots and households using statistical and machine learning approaches. We find robust evidence of increases in tree cover in both participating and comparable non-participating plots—however there are significantly higher increases in the former (average increase 48 compared to 26%). We also find increases in incomes and asset ownership in both participating and non-participating households in two projects, with significantly higher increases in income in one project and in assets in the other. However, half of the projects are no longer operational, which calls into question the durability of these projects despite positive outcomes for tree cover. Results suggest that VCM standards and policies that foster economic well-being of local stakeholders are more likely to deliver sustained carbon benefits. Successful, long-lasting projects provide examples that evaluation of project implementation plans for continuous engagement, economic incentives, and security of land tenure for local stakeholders at the outset could lead to more viable, long-term VCM projects. Robust counterfactual data on changes in tree cover and economic outcomes are critical for improving the integrity of the VCM.

## 1. Introduction

The voluntary carbon market (VCM) emerged in the early 2000s as a mechanism to help mitigate climate change. The VCM potentially drives finance towards climate mitigation by allowing corporate and other entities who are not legally required to reduce their greenhouse gas emissions to voluntarily offset their emissions. As of 2023, almost half of publicly listed companies had made net-zero commitments, although the extent to which offsets from VCM credits are deployed in implementing these goals is unclear (Haya *et al* 2023). The purchase of VCM credits has increased many fold in the last decade, with 'forestry and land use' projects comprising 46% of the volume of credits in 2021 (So *et al* 2023).

Despite the increase in demand, VCM projects have come under considerable criticism, particularly with regards to nature-based solutions (NBS) such as forestry and land use projects (So *et al* 2023). Such projects include both avoided emissions from deforestation and carbon removal from reforestation and afforestation. Globally, avoided deforestation (REDD+) accounts for one quarter of all VCM credits issued and 46% of 'forestry and land use' credits (So *et al* 2023). Evidence points to cases in which carbon benefits from avoided deforestation have been overstated and suggests that they lack robustness according to the key criteria for integrity: additionality, leakage, and durability (Correa *et al* 2020, West *et al* 2020, 2023, Guizar-Coutiño *et al* 2022), although some studies indicate that land management can effectively sequester carbon (Coffield *et al* 2022, Zheng and Zhang 2023). The private sector has consequently become wary of such projects and associated risks from accusations of green-washing. These concerns have led to a 62% decline in value for REDD+ projects between 2022 and 2023 (Procton 2024).

Tree planting, although a smaller portion of credits issued to date (8% of forestry and land use credits but 28% of all projects) (So *et al* 2023), mitigates climate through carbon removal rather than avoidance. Tree planting efforts are potentially more straightforward to assess than avoided deforestation by providing convincing counterfactuals that can be tracked over time. Value of these projects increased by approximately 30% between 2022 and 2023 (Procton 2024).

Many factors need to be considered and incorporated in VCM standards to achieve high integrity tree-planting projects (Brancalion and Holl 2020). Tree plantations can sequester carbon while benefiting water supplies, biodiversity, and local livelihoods. But they can also create water stress if inappropriately located in grassland ecosystems (Lahiri *et al* 2023), contribute to the loss of biodiversity if non-native and non-diverse species are planted (Wang *et al* 2022), and be implemented in a top-down manner that usurps the rights of local communities and indigenous groups to make decisions about their land use practices (Gerber 2011).

Global studies identify India as a high priority for achieving cost effective climate mitigation and conservation of biodiversity through tree planting efforts and restoration (Griscom *et al* 2020, Strassburg *et al* 2020, Shyamsundar *et al* 2022). Although VCM projects in India are mostly related to renewable energy, afforestation and reforestation make up 75% of credits (87% of projects) in the forestry and land use category (So *et al* 2023). The experience of these projects in India provides an opportunity to synthesize across data sets to determine outcomes across multiple dimensions including carbon sequestration and socio-economic benefits for local communities. Yet there has been limited data to help assess the socio-economic impacts of VCM at the household level.

In this paper, we assess tree-planting projects in India which have received credits in terms of the following attributes: changes in tree cover, durability of the project, and outcomes for income and assets for participating households. Using satellite data, interviews with project developers, and household-level surveys of participants and comparable non-participants in the projects, we address the following questions:1) what are the changes in tree cover in plots participating in tree-planting VCM projects in India compared with comparable plots in the surrounding landscape; 2) what are the experiences and perspectives of project developers regarding durability and factors for successful tree-based VCM projects in India; 3) why do farmers participate in VCM projects; and 4) what are the changes in income and assets for households participating in tree-planting projects compared with comparable, non-participating households? Although the number of projects is limited at this time, we draw conclusions from the variety of experiences to inform policies and practices for future VCM tree-planting projects.

## 2. Methods

### 2.1. Project sites

We first selected projects under the forestry and land-use category that have received carbon credits until the end of 2022 (figure 1). In India, VCM projects are registered under two carbon market registries, the gold standard (GS) and the Verified Carbon Standard.

Six projects have received carbon credits in the 'forestry and land use' category out of 71 registered projects in this category in India as of the end of 2022 (figure 1) (So *et al* 2023). Five are tree planting projects under 'afforestation/reforestation' and one is mangrove restoration. The projects collectively involve 21 767 individual farmers' plots and 342 community managed sites (table 1). One project (Project C) was a community managed site without individual plots. We excluded this project from the analysis due to the lack of spatial data and the inability to construct a counterfactual. Plot boundaries for the other five projects were available through the Verra/GS website. The study design is based on the ground realties of these projects. For remote sensing analysis, five out of six projects have availability of the individual plots data and for household interviews, two out of six project are operational on ground at individual household level to conduct household surveys.

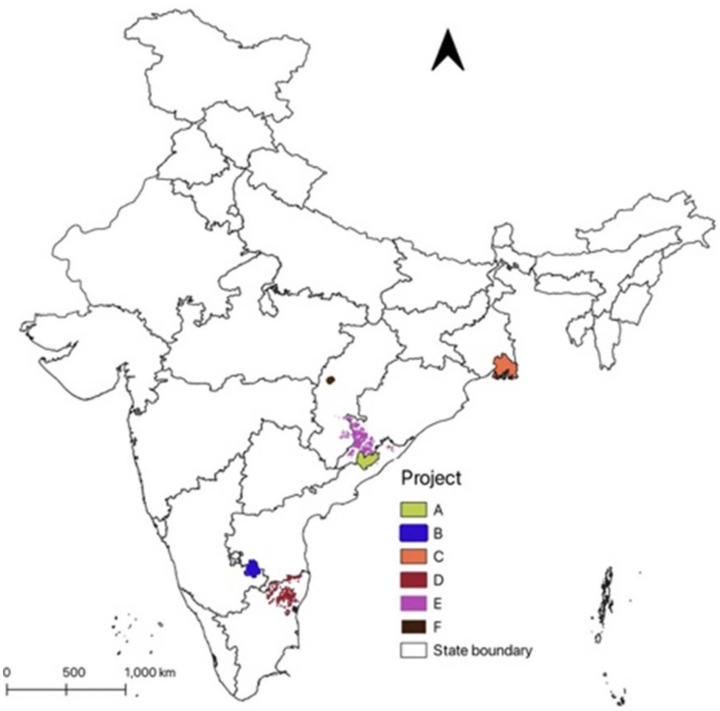


**Figure 1.** Location of selected project intervention from A—F under VCM.

**Table 1.** Projects receiving carbon credits in the voluntary carbon market as of 2022 (So *et al* 2023). Number of plots, area, and carbon credits are from project reports.1 credit = 1 tonne of $CO_2$(eq).

| Project code | Registration | Organization | Year of inception | Number of plots | Area (ha) | Carbon credits |
|---|---|---|---|---|---|---|
| Project A | Verra | NGO | 2010 | 5442 | 6002 | 96 386 |
| Project B | Gold | NGO | 2005 | 1238 | 1177 | 91 092 |
| Project C | Verra | NGO | 2010 | 342 community management sites | 4404 | 194 220 |
| Project D | Verra | International NGO | 2004 | 2647 | 2138 | 207 008 |
| Project E | Verra | Private company | 2001 | 12 437 | 14 970 | 1223 324 |
| Project F | Verra | Private company | 2002 | 3 sites | 248 | 58 122 |

### 2.2. Analysis of satellite data

For plots in the five VCM projects (treatment plots), we analyzed time series of annual mean Normalized Difference Vegetation Index (NDVI) derived from Landsat images covering the time period from project inception until the end of 2021 and calculated percent change in tree cover due to project inception. Time series analysis was done using 'ShapeSelectForest' package in R, simplified to identify three classes: increase, decrease, and constant green cover. In order to restrict the analysis of NDVI trends to locations with tree cover after the project was implemented rather than NDVI trends in crop, grassland, or barren land, we classified Planet Earth images from 2021 into tree and non-tree classes. NDVI in these non-tree landcovers can occur due to changes in crop type, climate, management, or a variety of reasons, hence we masked out locations with non-tree cover in 2021 in order to avoid confusion with greening in these non-tree landcovers from the Landsat time series. The analysis addressed changes in tree cover since project implementation for locations where trees existed in 2021. We used randomly generated points to check the accuracy of the NDVI trend analysis using Google Earth Images as ground truth information (table S1). We then calculated the percent of pixels within a plot with increasing, decreasing and constant trends. Constant green cover is determined by the 'ShapeSelectForest' algorithm if the best fit to the slope of the NDVI trend, according to BCI values, is not significantly different than zero. Similarly, increasing and decreasing green cover are determined by the best fit being positive or negative (Moisen *et al* 2016, Piffer *et al* 2022).

To compare changes in tree cover in the treatment plots with control plots without VCM projects, we randomly generated an equal number of control plots of approximately the same area as the average area of treatment plots and within a bounding box covering the spatial extent of treatment plots, excluding water bodies, protected areas and treatment plots (table S2). We carried out the same analysis of satellite data for the control plots as we did for the treatment plots.

To ensure comparability between treatment and control plots, we first identified variables that were unbalanced between treatment and control plots (defined as standard mean difference greater than 0.1) (Agarwal *et al* 2022). We eliminated plots that were outside the overlapping range for these variables. We then used optimal method in the MatchIt package in R to further eliminate unmatched control plots to achieve a standard mean difference between treatment and control plots of less than 0.10 for all variables. We matched the data on the following variables that potentially affect tree cover: elevation (SRTM 2024), slope, aspect, terrain position, soil properties (ISRIC 2024), and distance to primary road (see table S3 for sources of data for the variables and for matching statistics) (Schleicher *et al* 2020). We further tested the sensitivity to hidden bias from unidentified confounding variables (Cinelli and Hazlett 2020).

We carried out three independent tests for significant differences in percent increase in tree cover between treatment and control plots for each project: Wilcoxon test, spatial regression models, and causal forests (Biesbroek *et al* 2017, Davis and Heller 2017, DeFries *et al* 2022). See table S4 for collinearity test and supplemental for details of statistical methods.

### 2.3. Interviews of project leaders

To understand the process of VCM project implementation and project proponent perspectives, we conducted semi-structured interviews with the on-ground project implementers for all six projects. We asked them about the motivation to initiate the project, how it is being implemented on the ground, how they convince farmers to join the project, what are the challenges faced during implementation, what is the current status of the project, and what is their opinion on up-scaling the project or long-term durability of the project. We used thematic analysis by coding interview data into various themes, such as motivation to initiate the project, the process followed, especially around convincing farmers to join the project, funding, and challenges to sustain the project on the ground. In order to reduce individual biases, we asked similar question to others who participated as much as possible to triangulate their answers.

### 2.4. Outcomes for households participating in projects

To understand the socio-economic impacts on households participating in the projects, we conducted 366 household surveys (188 with participant farmers and 178 with non-participant farmers), in selected villages for two of the NGO-led projects, Projects A and B. We selected these projects as these are the only two tree plantation projects which were still functioning on the ground as of November, 2022 (community-based Project C was also still functioning but it was not possible to establish control households without any impact from the treatment). We selected 10 participants and 10 non-participants in 20 selected villages for Project A and B. The 10 villages selected were those with maximum household participation under these projects. Based on the availability of farmers, we surveyed 95 participant farmers and 75 non-participants in Project A and 93 participant farmers and 103 non-participants in Project B.

We asked respondents about their land holding, number of household members, number of salaried members, members working in the farms, and annual income. As annual income might not be accurately disclosed, we also asked about assets such as TV, cycle, motor bike, *pucca* (concrete) house, gas, and smart phone in order to construct an asset index score. Participants were asked to respond to the questions for before and after they joined the project. Similarly non-participants were asked the same questions with respect to change since the year of the project intervention. We expect that recall on past assets to be more reliable than income, recognizing caution with interpreting recall data (Mullan *et al* 2014).

We checked comparability and robustness values of participating and non-participating households in terms of head of the household age, family size, number of children, members actively working on farms, primary occupation, and landholding using the same method as matching for the plot data described above (tables S5–S7).

Total asset scores before and after the projects were calculated using principal component analysis using Psych and PsychTools package in R (table S8). Weightings for the PCA were calculated separately for each project for assets at the time of the survey to obtain asset scores relative to other households within the same area. Weightings from the first principal component were applied to each household's assets to obtain an asset score for each household. The same weightings were applied to the reported assets at the onset of the project. We also calculated the increased percentage of individual assets since the project's inception as reported by the households (table S9). To make initial income comparable to income in 2022, we incorporated rate of inflation in India into our analysis using World Bank database (World Bank 2023).

Similar to the analysis of changes in tree cover, we used multiple approaches to test difference in participating and non-participating households before and after project inception: difference in difference models and causal forests (Wing *et al* 2018). In order to estimate treatment effect size from difference in difference model, we used Cohen's d formula (see tables S10–S16 and supplemental for details of statistical methods)

## 3. Results

### 3.1. Tree cover

Analyzes of satellite images with Planet and Landsat data had an accuracy (Kappa value) of 83% for detecting increasing, decreasing, and constant trends in tree cover since project inception (table S1). In the verified polygons available in the carbon project registry for the projects, percent of plots with some increase in tree cover ranged between 70 and 100% across projects (88% for all 20 211 plots in all projects). Median increase in tree cover (based on percentage of pixels within plots with increase in tree cover) ranged between 1 and 53% across projects (table S2).

The matching process to balance treatment and control plots considerably restricted the number of plots that could be compared (table S3) Pooling all five projects together for the matched data, average increase in treatment plots was 48 and 26% for treatment and control plots. Increase in tree cover ranged across projects but in all projects average for treatment plots were higher in treatment than control plots (49 vs 30%, 28 vs 1%, 46 vs 2%, 50 vs 29, and 10 vs 3 for projects A, B, D, E, and F respectively). All three methods to test differences in percent increase in tree cover between treatment and control plots indicate that differences in increase in percent tree cover between treatment and control plots is highly significant in all of the projects (figure 2, tables S11–S13).

### 3.2. Perspectives of project developers

Interviews with developers revealed information about the projects that was less evident from project documents. Semi-structured interviews with all the six project developers revealed considerable heterogeneity among these projects in terms of project conception, process of land acquisition and farmer persuasion, funding sources, distribution of carbon credits benefits, and overall socio-economic impact on farmers upon joining the VCM projects (table 2). For example, the developer of Project B informed us that when he first proposed the idea of a tree planting project and the possibility of earning a steady income from the carbon market to farmers, many farmers signed up to participate on the same day. Similarly, Project A developer discussed labor costs in terms of farmers' willingness to join the project. He also mentioned that developers should not overlook the labor costs that farmers incur when planting trees and that developers often tend to focus more on other monetary costs associated with the projects. The projects were found to be especially heterogeneous in terms of how they convinced farmers to participate. The NGO-led projects already had a presence in the villages and have conducted meetings with farmers to encourage their involvement. The internationally-led NGO was managed by a local NGO to run the project on ground. On the other hand, private companies were initiating projects in the village for the first time, so they approached village leaders and held multiple meetings to convince farmers to participate in their projects. One of the key reasons suggested by the project developers to explain the paucity of afforestation projects compared to renewable projects in India was uncertainty about the success of tree planting.

Projects varied in their longevity. Project F (which was initially proposed to be operational for 65 years) was not operational as of 2022, and Project E and Project D (which were intended to be operational for 30 years) were on the verge of closure. All local NGO led projects A, B, and C with long-term engagement with local communities were functional and were scaling up on ground. The projects led by NGOs were initiated with the intent to economically support local communities whereas private company-initiated projects were focused on the company's profit from carbon credits. Both the private company- based VCM projects were closed due to non-profitability. All the NGO-led projects were initiated in the villages where they had already been working for a long time and had long term associations with the community, whereas private companies had initiated the project in a completely new location. NGOs provided saplings and training to the community to participate in the projects whereas one of the private companies had purchased lands from the farmers and another facilitated bank loans to buy saplings. Only Project B had shared 100% of the carbon credit benefits with the farmers whereas Project A, C, and F intended to support their livelihood but did not plan to directly share the carbon credit with the farmers. Project D and E had proposed but have not yet shared any direct carbon credit benefits with the farmers. All the projects had indirect income support from selling fruits, timber, and land, except for one project which hired farmers as wage labor (table 2).

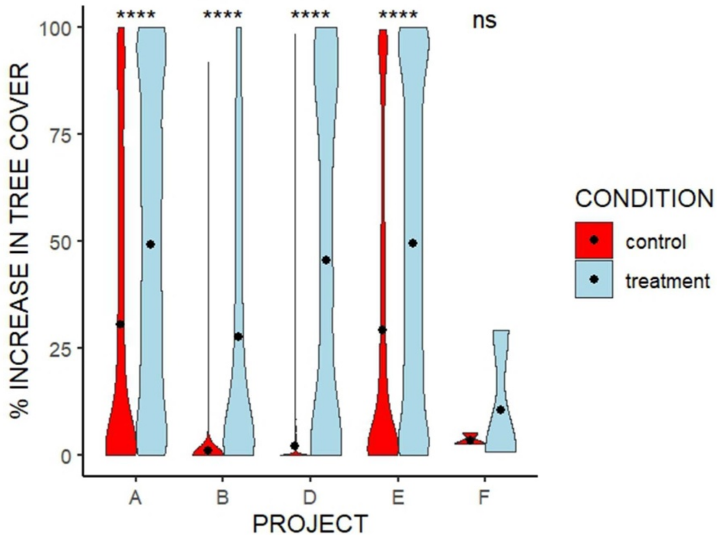


**Figure 2.** Percent change in tree cover with results of Wilcoxon test for change in percent tree cover since project inception between balanced treatment and control plots. Number of plots is 2204 treatment and 2204 control for Project A, 564 treatment and 564 control for Project B, 406 treatment and 405 control for Project D, 5869 treatment and 5872 control for Project E, and 3 treatment and 3 control for Project F. Points are mean values. $^{***} = p < 0.001$. Note that increase in tree cover represents the percent of Landsat pixels with increasing NDVI trend since project inception within pixels with tree cover in 2022. See tables S11–S13 for full results of spatial regression model with Moran's I test and causal forest results.

**Table 2.** Thematic analysis of interview data with project proponent.

| Themes | Project A | Project B | Project C | Project D | Project E | Project F |
|---|---|---|---|---|---|---|
| Project development activities | Voluntary; provide saplings and training | Voluntary; provide saplings and training | Community based mangrove plantations and protection | Saplings to farmers | Encourage farmers to take loan; guarantee purchase of the timber | Purchased farmers land and planted trees |
| Sources of funds for initial project development | International funds | NGO raised funds from philanthropy | International funds | International funds | Bank loan for saplings and fertilizer; company paid for registration and verification | Private company |
| Carbon credit dispersion | Back to International funds/NGO | 100% to local community | Back to International funds/ NGO | International NGO | Did not disperse to local community | Private company |
| Socio-economic benefits | Income from fruit production | Income from fruits production and carbon credits | Income from local NGO initiative for poultry and beekeeping | Income from fruit production | Income from selling timber | Income from selling land and daily wages until project closure |
| Long-term durability | Increase in local participation | Increase in local participation | Increase in local community participation | Conflict between the international NGO and local implementer | The company is attempting to sell or close the project | Project closed and company sold the land. Buyer cut down the trees for solar project |

### 3.3. Farmer participation

Surveys with 356 farmers in Project A and Project B revealed that the main reason farmers participated was to gain additional income. In both Projects A and B, farmers responded that they joined the project because of additional income from selling fruits from the trees, as well as direct payments from carbon market credits (figures 3(a) and (b)). Environmental reasons such as benefit of planting trees on environment, improved water supply, and maintenance of soil

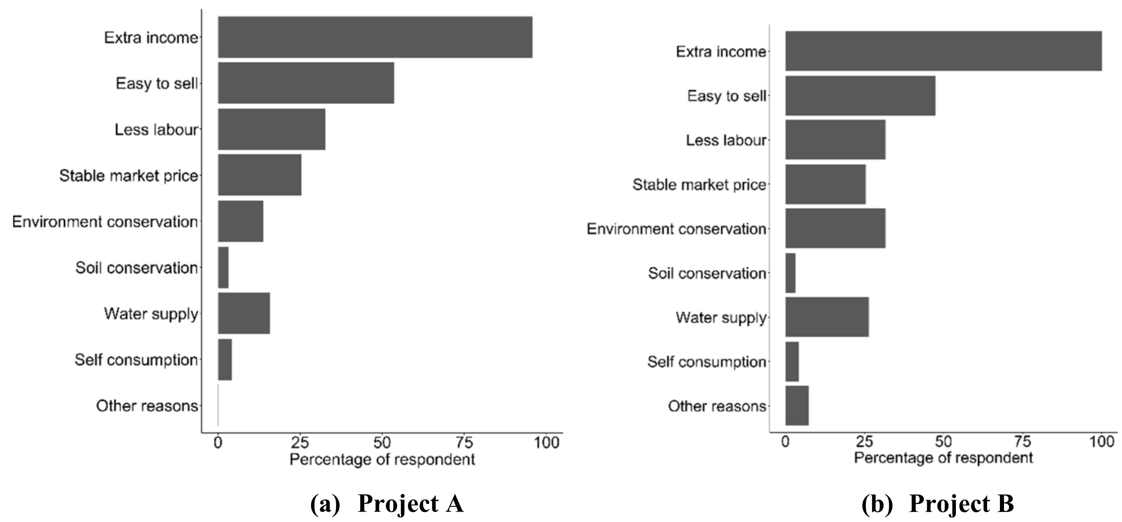


**Figure 3.** Reasons for joining the project (a) Project A and (b) Project B. Other reason for joining was child's future.

quality were mentioned less frequently (figures 3(a) and (b)).

The main reason that non-participants gave for not joining the project was that they were not present during the registration process. Another major reason was land dispute or unclear land tenure at the time of registration, but currently many have cleared land tenure status and are willing to join the tree planting projects. However, more than 85% of non-participants were willing to join the project given the chance (figures 4(a) and (b)).

### 3.4. Impacts on household income and assets

In Projects A and B, results show some significant differences between comparable participating (treatment) and non-participating (control) households in outcomes since project inception (figure 5). The difference-in-difference variable in the regression models is significant for income in Project A ($p < 0.001$) and assets for Project B ($p < 0.05$), but not significant for asset scores in Project A or income in Project B (table S14), similar results are supported by the treatment effect size (table S15). Despite the significant difference in income in Project B between control and treatment households in 2022, the difference-in-difference variable is not significant when accounting for the already significantly higher income in treatment households in Project B prior to the project. Casual forests confirm these results (table S16).

The most notable difference in assets between participating and non-participating households is fridge and car for Project B (although ownership rates are low) and bicycle for Project A (table S8).

## 4. Discussion and conclusions

Nature-based projects in the VCM have recently undergone considerable criticism, mainly due to overestimation of carbon offset, unreliable third-party verification and validation processes, and lack of additionality, transparency, durability, and benefit sharing with the community (Dev and Krishnamurthy 2023, Haya *et al* 2023). However, a detailed understanding of the ground realities of the outcomes of these projects is lacking especially at farm level, particularly in comparison to counterfactuals to assess outcomes in the absence of these projects (Sills *et al* 2015).

In this study, we analyzed satellite images to compare changes in tree cover relative to comparable locations, interviewed project proponents, and conducted household interviews with comparable participant and non-participant farmers to understand the on-ground realities of these projects, how they are impacting their livelihoods, and whether people wanted to be part of the carbon credit projects. In summary, we find robust evidence that increases in tree cover since project inception are higher for plots of households participating in projects than for comparable non-participating plots. This conclusion holds across all six projects that received credits from the VCM. Outcomes for households were also significant, with higher incomes for participating households in one project located in a hilly remote area (Project A) and more assets for households participating in a project located closer to a large urban area (Project B). This difference in location might explain the income effect in Project A where access to job and

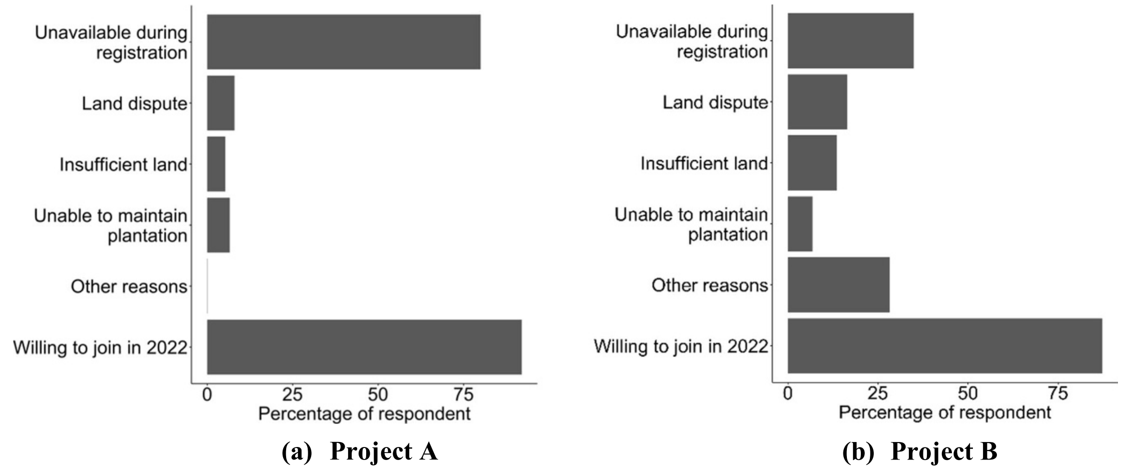


**Figure 4.** Reasons for not joining the project (a) Project A (b) Project B. Other reasons for not joining were: afraid of losing land, interested in traditional farming, insufficient water supply, and unaware of the benefits.

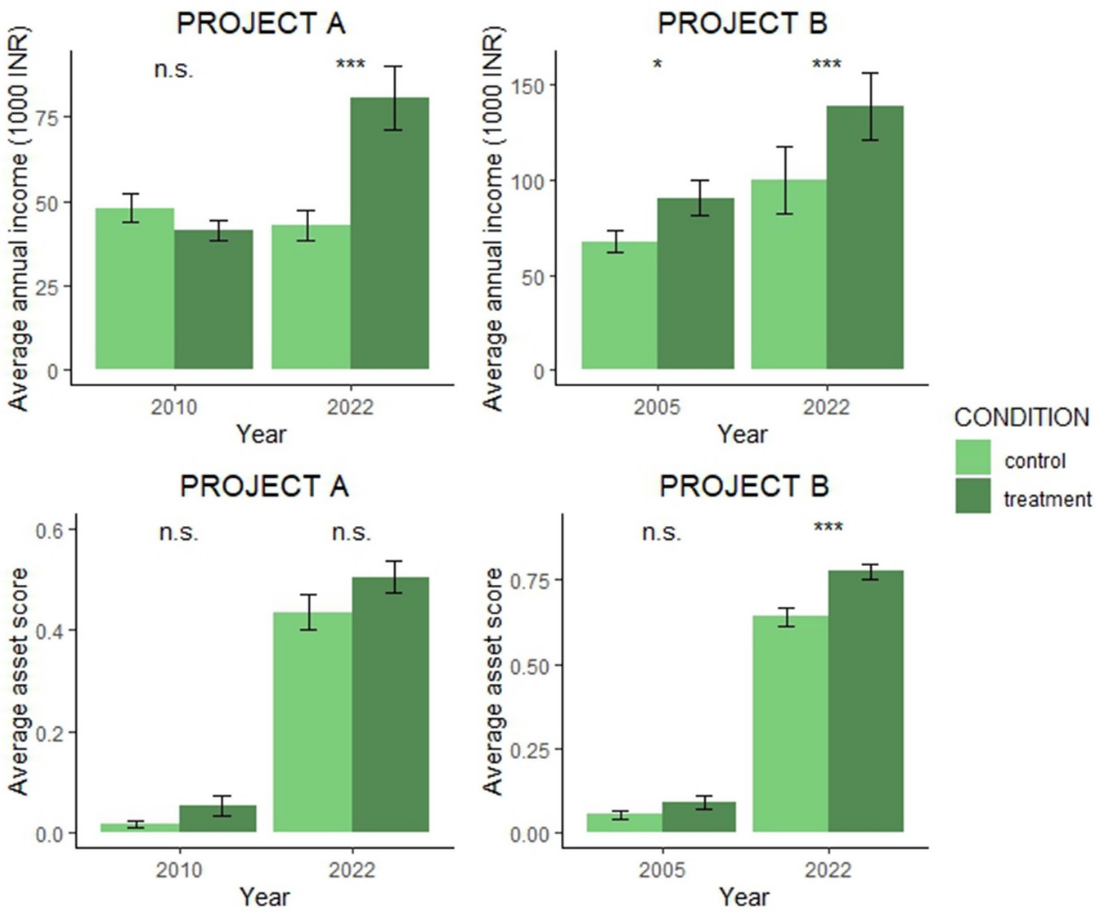


**Figure 5.** Average annual income (inflation-adjusted) and assets score (significance values from Wilcoxon test) since project inception in treatment and control households in Project A and Project B (n.s. = not significant, $^{***}p$ value $<0.001$, $^{*}p$ value $<0.05$). Note difference in scales between Project A and Project B. See tables S14, S15 and S16 for results of difference-in -difference models and causal forests.

other earning opportunities are more limited than in Project B. Consequently, both control and treatment households in Project B have more ready access to employment opportunities and assets, while households in Project A might be less likely to use their income to purchase assets.

Farmers participating in Project A and B are continuing to practice traditional farming system while also adopting fruit tree plantations (Vongvisouk *et al* 2014). The project intervention gave farmers an opportunity to diversify their sources of income, which also supports them during market price fluctuations of the crops. Another important aspect to initiate these projects on the ground is possession of clear land tenure papers. Many farmers were found to have disputed lands and unclear land titles at the time of registration; rendering them ineligible to be part of the VCM initiative. Despite these barriers, most of the non-participants expressed a desire to be part of the VCM projects. Farmers overwhelmingly indicated that the reason for joining the project was for income generation and access to markets.

All the projects had indirect income support from selling fruits, timber, and land, except for one Project F which hired farmers as wage laborer. Most projects focused on fruit trees, as they could provide financial support for the farmers, except for Project E where the farmers were planting eucalyptus plants. Project C was the only project where the community was planting local mangrove plant species and building a nursery from the degraded patches of the mangroves. In order to financially support the community, the NGO initiated poultry and beekeeping as incentives to participate in the mangrove plantation and protection project. These varying approaches to support farmers did not uniformly lead to durable projects. Three of the six projects are no longer functioning as of 2022.

The role of leadership and long-term involvement with the local community were found to be essential for the long term durability of the projects (Agarwal and Lambin 2024, Surattee *et al* 2024). Studies have shown that a positive impact on the local community's economies could lead to sustainable outcomes in the long term (Agarwal *et al* 2017, DeFries *et al* 2022). Both Project A and B were found to have worked on the landscapes for more than 10 years before they initiated the project under VCM. During our interviews, the project developers reported that the intention of the project was to support the community so that the farmers could have secure livelihoods, and they believed that the VCM could bring financial security and stability to farmers' lives.

The motivations driving the initiation of VCM projects significantly differ for NGOs and private companies. For instance, Project E initiated the eucalyptus plantation project to secure raw materials for their company and did not support the farmers even in purchasing the saplings. Despite encountering difficulties in selling the carbon credits and being on the verge of closure under VCM, the company continued to buy raw materials from the farmers. The project developer said: 'As obtaining raw materials for the timber factory was the primary motive, the VCM project served as the secondary objective for the company. The investment in the validation process was expensive, as there were fewer buyers for eucalyptus plantation projects, therefore the company decided not to participate in the VCM'. On the other hand, Project F purchased land from the farmers. When the land price was found to be higher than the profit from the carbon market, the company sold the land to a solar project. However, we cannot generalize, as our sample size for comparing motivations to initiate VCM projects between private companies and NGOs is small. During the interviews, implementers of Projects D and E acknowledged that the projects are not functioning on the ground because they were not financially beneficial for the company. Meanwhile, Project D was, at the time of the interview, considering how to better manage the international project by teaming up with different on-ground partners.

The outcome of higher income due NGO led carbon projects cannot be generalized due to small sample size. However,the satellite analysis found an increase in tree cover in the treatment plots compared to the control plots. This result is consistent with a general greening trend for India (Chen *et al* 2019) and highlights that the projects have generally been successful in promoting tree planting. However, the reported greening trends as well as our study do not consider the species diversity and biodiversity aspects of these plantation projects. Most projects focused on fruit trees, as they could provide financial support for the farmers, except for Project E where the farmers were planting eucalyptus plants which provide timber and have limited biodiversity or additional livelihood value.

Overall, results indicate that positive outcomes from tree-planting projects are achievable in settings with small-scale farmers such as those in India. Outcomes for participating households are possible, but we did not find overwhelming evidence of positive outcomes in all projects. Half of the six projects were no longer in operation, notably those that were initiated more recently by private companies that cited lack of profits. The two projects which were durable and for which we were able to carry out households surveys were initiated to improve livelihoods, with carbon credits as only one component for the overall project. The empirical, ground-based evidence indicates that tree-planting projects can increase tree cover, benefit participating households, and maintain durability if these households receive benefits and project proponents are committed to long-term engagement.

Despite the limited number of VCM projects in India that have been registered to date, this synthesis across projects indicates that learnings can inform future VCM projects. One learning is that if local participants in the projects do not receive tangible benefits, the project is not likely to be durable and will not deliver either carbon or socio-economic benefits over the long term. Another learning is that robust analysis of counterfactual changes in tree cover and economic outcomes is needed to assess additionality. Tree cover increased in both VCM and non-VCM plots. If all increase in tree cover is attributed to the project, there will be an overestimate of the carbon benefit. Additionally, participating households had higher income in 2022 than non-participating households in Project B. But the difference cannot be attributed to the project because incomes were already higher in participating households prior to project inception. Finally, ground data from participating and comparable non-participating households, while expensive and time consuming to acquire, is needed to assess socio-economic changes attributable to projects. Without a system to reliably collect such data, narratives about VCM projects will remain unvalidated. As the VCM matures, these learnings need to be incorporated for the VCM to mature and improve its integrity.

This study has a number of limitations. Given the lack of high resolution data in India on land tenure, we were unable to utilize land tenure details for the control plots used to compare changes in tree cover, unlike household surveys where non-participants were asked about land tenure. We compared the control and treatment plots only on the basis of the biophysical properties. Second, the satellite analysis quantifies changes in tree cover at the resolution of a Landsat pixel (30 m). Changes in carbon stock cannot be quantified from this resolution, particularly without data on tree species and structure. Nor did we assess impacts on biodiversity, soil health, and other important ecological parameters. For the household analysis, data on income and assets before the project were obtained through recall, which may not be completely accurate. We note the limited number (6) of projects in the registry that received credits in the forestry and land use category in India. Although these projects represent approximately 20 000 plots, it is not possible to have replicated analysis to assess outcomes in terms of projects characteristics, such as NGO vs private sector-led and distance to cities. An additional limitation is the reliance on recall data for the household surveys for income and assets. Income is a notoriously difficult variable to accurately capture in rural households with many sources of income. Assets can be a reliable indicator of economic well-being, although differences in access to assets can limit comparability among projects. A final limitation is the lack of farm-level information for the projects that are unsuccessful or on the verge of closure on the ground. Since we could only obtain participant information from the project proponents, we were only able to analyze the impact of VCM projects at the household level for the projects which are still operational. In light of the growing demand for NBS in the carbon market space, this study represents the insights to be gained from on-ground reality of VCM afforestation projects and comparison with robust counterfactuals.

## Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: Agarwal S 2024 Assessment of Voluntary Carbon Market in India. Online: osf.io/zgm8u.

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