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ABSTRACT

As voluntary carbon markets gain popularity, carbon farming emerges as a win-win strategy to mitigate climate change and improve farmers' income in developing countries. India, with over 50 active carbon farming projects and an impending domestic carbon market, forms an ideal case to explore the early-stage challenges of these initiatives. Using survey data from 841 farmers from seven carbon farming project villages in Haryana and Madhya Pradesh, this study focused on socio-economic inclusion and adherence to additionality and permanence principles, which are underexplored in the existing literature. We found that carbon farmers were predominantly large-holders and from non-marginalized castes, showing patterns of systematic exclusion. Only 4% of participants were women. Around 99% of farmers had not received any monetary benefit. While certain agricultural practices predated carbon projects, raising concerns about additionality, practices like no-tillage, alternate wetting and drying, intercropping, reduced chemical fertilizers, micro-irrigation, and tree planting aligned with additionality principles. Nonetheless, a high disadoption rate (28%) raises concerns about the permanence of emissions reduction. Our findings also indicated that companies that exclusively focus on carbon credits, termed 'Carbon Core' companies in this study, were more efficient in spreading regenerative agricultural practices than subsidiaries or offshoots of larger corporations whose primary businesses are unrelated to carbon credits.

Key policy insights

- Promote Inclusivity: Policies should use differential pricing to incentivize the inclusion of small farmers and marginalized caste groups in carbon farming projects. Projects that are socially more inclusive should receive higher prices.
- Enhance Communication and Training: Mandate effective communication and regular training from project developers to improve the adoption and continuity of regenerative farming practices.
- Address Financial Barriers: Develop mechanisms to ensure timely payments to farmers, thereby reducing disadoption due to economic constraints.
- Collaborate with Institutions: Encourage collaboration with national and international research centres to design projects that avoid yield penalties.
- Improve Monitoring: Implement robust frameworks to ensure projects adhere to additionality and permanence principles, enhancing their credibility and effectiveness.

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Introduction

Climate change intensifies the environmental impacts of agriculture by reducing productivity, increasing soil erosion, and exacerbating greenhouse gas (GHG) emissions, underscoring the urgent need for sustainable and climate-resilient agricultural practices (Yang et al., 2024). Carbon farming, as an innovative approach to scaling sustainable agriculture, has the potential to mitigate climate change while presenting farmers with additional income avenues through carbon credits (Lin et al., 2013). To reduce GHG emissions and increase carbon storage, the carbon farming projects encourage the adoption of regenerative farming practices like conservation tillage, crop stubble management, mulching, cover-cropping, integrated nutrient management, conversion from annual to perennial crops or pastures, and livestock management (Barbato & Strong, 2023; Khurana et al., 2024; Tang et al., 2018; Tang et al., 2019; Tang et al., 2016). The voluntary carbon market (VCM), where carbon credits are traded, is witnessing a surge in popularity, with an increasing number of carbon credit registries, projects, proponents, and related businesses such as insurance and ratings. Agriculture carbon credits have seen significant growth in transaction volume, increasing by 283% from 2021 to 2022, and now command some of the highest prices in the voluntary carbon market, driven by demand for sustainable land management practices that offer robust co-benefits (Forest Trends' Ecosystem Marketplace, 2023).

India is emerging as a leader in this realm, with more than 50 agricultural carbon credit projects targeting 16.5 million hectares (Verra, 2024). This growing interest is part of a global trend where governments invest in projects and/or establish their own carbon markets to meet the Nationally Determined Contributions (NDC). In India, the government is actively working to establish both compliance and voluntary carbon markets to help achieve its NDC targets (PIB, 2023, 2024). However, a policy challenge arises because carbon credits sold internationally cannot be counted toward India's NDCs, leading the country to consider using domestically generated carbon credits to fulfil its commitments and ensure the environmental benefits contribute directly to its national goals (PIB, 2022). Other examples include compliance markets like the European Union Emissions Trading Scheme, New Zealand's Emissions Trading Scheme, and Australia's Carbon Credit Units scheme (QCI, 2024). In addition, there are several voluntary offset programmes, such as Japan's Voluntary Emission Trading Scheme and Australia's Emission Reduction Fund (Tang et al., 2016). Private and non-governmental offset programmes also encourage GHG mitigation activities worldwide. Notable examples include the US's American Carbon Registry and Climate Action Reserve, which operate in both compliance and voluntary markets. Voluntary offset schemes like Verra (globally active), France's Label Bas Carbone, North America's Pure Sky registry, Brazil's Social Carbon Standard, Switzerland's globally active Gold Standard, Scotland's Plan Vivo, and the blockchain-based Regen Network also play a vital role. All these programmes have developed methodologies for estimating soil carbon sequestration (QCI, 2024). However, significant concerns exist regarding the reliability and consistency of these programmes' soil organic carbon (SOC) quantification methodologies. Dupla et al. (2024) highlight discrepancies in scientific rigour across carbon credit protocols, noting that some rely on regional averages instead of in-situ analyses, leading to potential inaccuracies. The lack of standardization and oversight of critical factors (e.g. land use, climate, and soil properties) further undermines the validity of SOC estimates. These variations risk generating non-equivalent credits, potentially eroding trust in the integrity of crediting programmes (Oldfield et al., 2022).

Despite their popularity, carbon farming projects face unique challenges on both the demand and supply sides. On the demand side, the challenges concern consumer trust and understanding. Firstly, the complexity and opacity in the carbon sequestration process undermine credit authenticity, resulting in uncertainty and mistrust among buyers. The studies on credit credibility have also raised concerns about additionality, permanence, transparency, and leakage in carbon projects (Balmford et al., 2023; Delacote et al., 2024; Filewod & McCarney, 2023; West et al., 2020, 2023). Secondly, the market is saturated with labels and standards like Verra, Gold Standard, American Carbon Registry, *etc*., leading to 'label proliferation.' These excess options overwhelm buyers, diminishing their willingness to purchase (Marette, 2014). Additionally, buyers may be skeptical about long-term commitments to reduce emissions, especially when companies set distant future goals (Wongpiyabovorn et al., 2023). These issues create uncertainty regarding the reliability and environmental effectiveness of the credits. On the supply side, the challenges involve technical difficulties in quantifying carbon reduction/removal, high costs of monitoring, and the need to create farmer awareness for effective implementation (Wongpiyabovorn et al., 2023).

Although the existing literature explores the potential of carbon credits to facilitate the transition toward sustainable practices (Abdul-Salam et al., 2019; Badgery et al., 2021; Singerman et al., 2012), and the role of carbon pricing in reducing on-farm GHG emissions in a changing climate (Tang, 2024; Tang & Hailu, 2020), farmers' perspectives offer crucial insights into these initiatives' practical challenges and successes. Also, while many entities adopt nature-based solutions for sustainability and net-zero strategies, some nations and Indigenous groups reject this term due to uncertainties about its effectiveness and impacts (Seddon, 2022). Understanding these perspectives is essential for effective policy-making and successful implementation of carbon farming projects. For instance, farmers face barriers such as physical-environmental constraints, lack of information, complex project requirements, long-term commitments, uncertainties about financial returns, and unpredictability of carbon market processes (Barbato & Strong, 2023; Buck & Palumbo-Compton, 2022; Cook & Ma, 2014; Feliciano et al., 2014; Kragt et al., 2017; Mattila et al., 2022; Rochecouste et al., 2017; Siedenburg et al., 2016; Wang et al., 2021). Drivers of farmer participation include perceived co-benefits, such as biodiversity conservation, soil health improvements and environmental benefits, flexible programme designs, reliable information, effective communication, economic incentives, and educational approaches (Barbato & Strong, 2023; Buck & Palumbo-Compton, 2022; Cook & Ma, 2014; Feliciano et al., 2014; Gramig & Widmar, 2018; Kragt et al., 2017; Lee et al., 2016; Siedenburg et al., 2016; Torabi et al., 2016; Wang et al., 2021).

Despite this robust literature, there remains a need to understand the specific implications of these perspectives for the development trajectory of India's carbon market. However, few studies have fully explored the socio-economic inclusion of farmers in carbon farming projects. An examination of social inclusion gains increased importance for the caste system prevailing in India: a complex social hierarchy significantly influencing social and economic interactions. The major caste groups include Scheduled Castes (SC), Scheduled Tribes (ST), Other Socially Marginalized Classes (OSMC), and non-marginalized castes (NMC). The marginalized groups face social and economic disadvantages, which can impact their participation in rural development programmes (Birthal et al., 2015; Ramakrishnan, 2021; Thorat & Sabharwal, 2015). Additionally, the alignment of agricultural practices with additionality and permanence principles, and the unique challenges faced by smallholders and marginalized communities in India are underexplored. This paper addresses this gap by focusing on these critical aspects, providing actionable insights for policymakers and practitioners shaping the future of carbon markets in Indian agriculture.

Here, we investigate the following questions: How socio-economically inclusive are carbon farming projects in terms of including marginalized communities, such as SC and ST, women, and smallholder farmers in carbon projects? How well do carbon projects adhere to the principles of additionality and permanence? What are the barriers and enablers for adopting and discontinuing carbon farming practices? Lastly, is there a relationship between these and the type of project developer? Are specific projects more inclusive and better at adhering to additionality and permanence principles? The goal is to offer insights that are both academically significant and directly relevant to those involved in policy and project implementation.

The rest of this paper is structured as follows: The next section presents the data collection methods and the classification of carbon farming project developers. Following that, the empirical framework is outlined. The subsequent section presents and discusses the empirical results. Finally, the paper concludes with a discussion of the implications of these findings for practice and policy.

Methods

Data

The data for this study is obtained from a farmer survey conducted among participants and non-participants in carbon farming projects across the Indian states of Madhya Pradesh and Haryana. These states were chosen because they had a high concentration of carbon farming initiatives, providing a valuable context for understanding such projects' implementation design and impact. The survey questionnaire and sampling procedure were informed by literature, project documents in the Verra registry, and consultations with multiple project developers. These sources provided detailed information on project locations, the roles of project developers and implementation agencies, incentives offered, and the specific sustainable agricultural practices adopted. This information enabled us to design a questionnaire that accurately reflects the operational realities of the carbon farming projects and to select the sample states, projects, and villages.

From the Verra registry, seven carbon farming projects were identified, which were distributed across Haryana (North India) and Madhya Pradesh (Central India) at various stages of development – two were undergoing validation, three were under development, and two were pending registration and verification approval. Four villages were randomly selected per project, totalling 28 from the list in the project design documents or obtained from project developers upon request (Figure 1). In each village, three lead farmers were initially interviewed to compile lists of carbon farmers (those participating in carbon credit projects) and non-carbon farmers (those not participating). From these lists, 15 carbon and 15 non-carbon farmers were randomly selected per village, ensuring a balanced representation of perspectives. This approach resulted in a total sample of 841 farmers: 30 farmers per village and 120 farmers per project, split equally between carbon and non-carbon farmers.

Data was collected using the Computer-Assisted Personal Interviewing (CAPI) method during July and August 2023. It included programming the questionnaire in the Kobo Collect app and administering the survey using Android tablets. For the survey, carbon farming was defined to the farmers as 'practising sustainable agricultural practices like direct seeded rice (DSR), alternative wetting and drying (AWD), zero-tillage (ZT), crop residue management, reduced chemical fertilizer application, use of organic fertilizer, biochar, etc. These practices are carried out in collaboration with Agtech companies and NGOs to earn carbon credits. The companies typically sell these carbon credits and promise payments to the farmers. For this, GPS coordinates of plots are recorded, and data is collected on the practices followed and their start dates to measure and monitor GHG emissions reductions and carbon sequestration.'

The questionnaire included sections on general household information, carbon farming participation, adoption of regenerative agricultural practices, farmer household and plot characteristics, material inputs and outputs, and training and support provided by project developers (refer to the supplementary file for the full questionnaire). Each survey session lasted approximately 45 min. Respondents were asked about their participation in carbon farming, how they learned about it, their reasons for participating or not, the companies involved, their motivations, new sustainable practices adopted, training received, company interactions, payments, and contract details. They were also asked if they recommended other farmers for the project, whether they are continuing with carbon farming, and reasons for discontinuation if applicable.

This research protocol was approved by the CIMMYT Internal Research Ethics Committee (IREC) under the code 2023.021.

Classification of project developers

As discussed earlier, we selected seven projects at various stages of registration. Two projects were led by companies focused solely on carbon credits, three were subsidiaries or corporate social responsibility (CSR) wings of larger corporations primarily operating in other sectors, and two were established agribusinesses involved in organic farming or rice exports, which require adherence to Maximum Residue Limits (MRL) concerning application of plant protection chemicals.

To capture these distinctions and test their relation to the effectiveness of project implementation, we categorized the seven project developers into three groups:

1. Carbon Core: Companies that exclusively focus on carbon credits. These are typically startups whose sole operational objective is developing and managing carbon credit projects.
2. Carbon Branch: Subsidiaries or offshoots of larger corporations, often with core businesses unrelated to carbon credits. For example, a chemical company with a subsidiary dedicated to carbon credit projects. These subsidiaries leverage the resources and networks of their parent companies while focusing specifically on carbon credit initiatives.
3. Carbon Blend: These are not primarily carbon companies; instead, they might be involved in organic farming, exports, or other agricultural activities. They engage in carbon projects as an additional venture, potentially onboarding farmers they already work with for other business purposes.

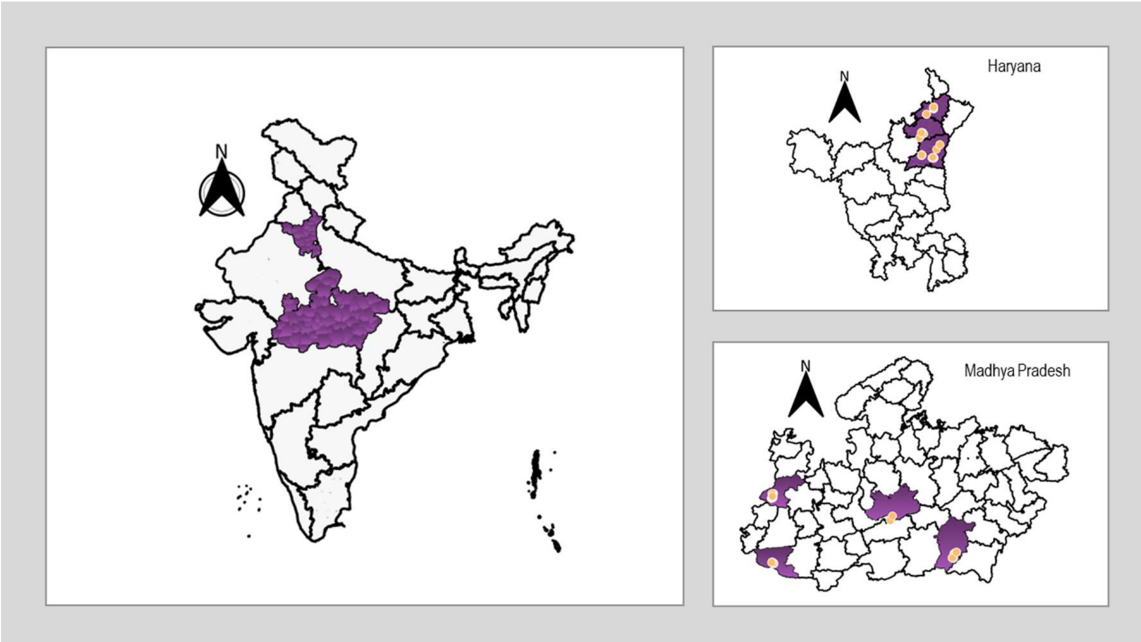

Figure 1. Map showing the study areas.
Note: The circles in the map indicate sample villages.

During our field visits and interactions, we observed notable differences in engagement and transparency among these three types of companies. New companies and startups were more actively involved on the ground, had more staff, were more approachable, and had partnerships with NGOs or other partners like machinery service providers. In contrast, established developers primarily engaged in organic farming or rice exports viewed carbon credits as a secondary venture and had minimal staff on the ground. For these reasons, we expect the performance to be highest in the Carbon Core, followed by the Carbon Branch, and then the Carbon Blend.

Analytical framework

This study employed the probit model with sample selection to analyze factors influencing farmers' participation in carbon farming projects and their continuation with these practices (Van de Ven & Van Praag, 1981). Farmers' decision-making involves two stages. The first concerns adopting regenerative farming practices as part of a carbon farming project. The second involves deciding whether to continue or discontinue these practices.

To analyze this, we use a two-stage estimation framework. This approach recognizes that farmers who did not initially adopt regenerative practices have no chance to continue them. The first-stage probit model identifies the factors influencing adopting regenerative practices within a carbon farming project. The second-stage probit model determines the factors affecting the continuation of these practices. The second-stage sample, consisting of those who continued with carbon farming practices, is a subset of the first stage. Since this subset is likely non-random and differs from those who chose not to participate, the sample selection bias must be controlled for. This is achieved by including the Inverse Mills Ratio (IMR) in the second-stage probit model, similar to the method proposed by Heckman (1979) for cases where the second stage has a continuous dependent variable (the 'heckprobit' model). The probit model with sample selection (heckprobit) is suitable for addressing sample selection bias and providing consistent, asymptotically efficient estimates for all parameters (StataCorp, 2023) and is widely used by researchers in similar settings (Keil et al., 2017, 2019).

The first-stage selection equation of the model examines the factors influencing farmers' decisions to adopt regenerative practices in a carbon farming project. The dependent variable is binary, indicating whether a farmer is practising carbon farming (= 1) or not (= 0). The independent variables used in this stage included caste groups (represented by a set of dummy variables for NMC, OSMC, SC, and ST), land size categories (with dummy variables for landholding categories: marginal (<1 ha), small (1-2 ha), semi-medium (2-4 ha), and medium & large (>4 ha)), standardized age, education level, household size, primary income from agriculture (binary), bank account ownership (binary), possession of a MGNREGA job card (binary), membership in farmer collectives (binary), access to information (binary), use of a soil health card (binary), crop insurance (binary), and district dummies to account for location-specific effects.

The second-stage outcome equation of the model investigates the determinants of farmers' continued compliance with regenerative farming practices into the second year. The dependent variable is binary, coded 1 if the farmer reported to continue with regenerative practices from the second year and 0 otherwise. The independent variables in this stage included a binary variable indicating whether the project developer maintained contact with the farmer after enrolment, a binary variable indicating whether the farmer received training related to carbon farming practices, and other variables such as caste, land size, age, education, membership in farmer collectives, access to information, crop insurance, project developer type (carbon core, branch, or blend), and district dummies.

Results

Are the existing carbon farming projects inclusive?

Land ownership patterns

In Haryana and Madhya Pradesh, carbon farmers cultivated 51% and 32% more land than non-carbon farmers (***Panel A*** Figure 2). Generally, per capita landholding size was higher in Haryana than Madhya Pradesh. Further insights emerged when comparing landholdings among carbon farmers engaged with different types of project developers (***Panel B*** Figure 2). Haryana had Carbon Core and Carbon Branch projects, while Madhya Pradesh had all three types of projects, including Carbon Blend. In Haryana, Carbon Core companies

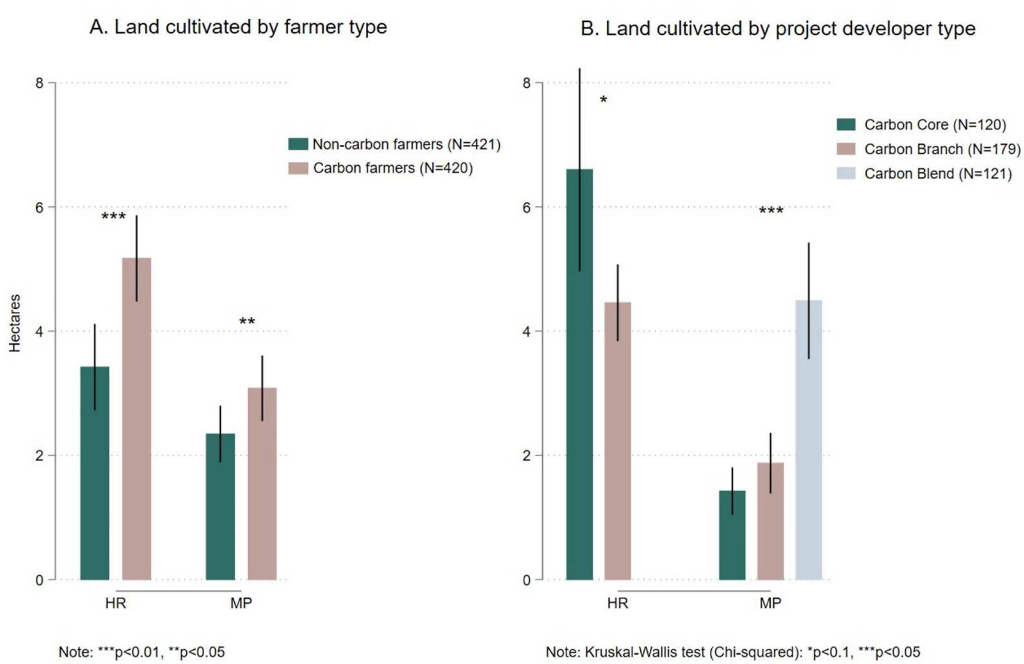

Figure 2. Mean differences in land cultivated by farmer and project developer type.

Note: Plot B is conditional on being carbon farmers. The bars represent the 95% confidence intervals of the mean values. HR – Haryana, MP – Madhya Pradesh.

predominantly onboarded larger farmers, as opposed to Carbon Branch. On the other hand, in Madhya Pradesh, it was the Carbon Blend companies that onboarded larger farmers, likely reflecting their existing business relationships in areas like rice or organic food exports. Interestingly, Carbon Core and Branch companies in Madhya Pradesh tended to onboard smaller farmers, with an average landholding of about 1–2 hectares.

Social inclusion

A crucial dimension of inclusivity extends beyond land ownership to social marginalization – specifically, the representation of various caste groups among the participants in these projects. To evaluate social inclusion, we compared the caste distribution of carbon farmers to non-carbon farmers. If the caste composition in both groups is similar, it indicates that the carbon farming initiatives are equitable and do not disproportionately favour or exclude any particular (especially marginalized) caste group.

When both state datasets were combined for analysis, we found that 46% of the land owned by non-carbon farmers was operated by non-marginalized castes (NMC) and 54% by marginalized castes (37% OSMC, 12% ST, and 5% SC) (***Panel A*** Figure 3). A stark contrast was observed among participants of carbon projects, especially in Carbon Core and Carbon Branch projects, where a significant majority of land (83% and 69%, respectively) was cultivated by NMC farmers. In carbon core projects, marginalized farmers (SC and ST households combined) have a meagre 5% share in cultivated land compared to 17% in non-carbon farmers. In contrast, Carbon Blend projects showed better social equity, with OSMCs and SC-ST combined farming about 47% and 16% of the land, respectively.

Having said that, when comparing the distribution by state, we found an overrepresentation of NMC groups in carbon farming projects in both Haryana and Madhya Pradesh (***Panel B*** Figure 3). In Haryana, NMCs cultivated 81% of the land among non-carbon farmers and 90% among carbon farmers. SCs had a 5% share of the land cultivated by non-carbon farmers, which dropped to almost 0% among carbon farmers. In Madhya Pradesh, NMCs' share of land cultivated among non-carbon farmers was 8%, while it rose to 29% among carbon farmers. Thus, from the descriptive analysis of the primary data collected, it can be inferred that marginalized caste groups were systematically excluded from carbon farming projects.

Also, only about 1% of non-carbon farming households were led by women, compared to 4% in carbon farming. Despite relatively higher female involvement in carbon farming, there is significant potential for improving gender equity in these projects.

Do the carbon farming projects align with fundamental carbon credit principles?

Evaluating carbon farming projects requires examining their compliance with additionality and permanence principles. Additionality means that the projects should lead to a greater reduction in GHG emissions than in their absence. On the other hand, Permanence implies that these changes are sustained over time, preventing the captured GHGs from returning to the atmosphere. We study whether the on-ground practices of various projects align with these principles.

Additionality in practice

To investigate additionality, we analyzed the range of practices adopted against their baseline adoption levels before the project initiation. Practices adopted in Haryana included DSR, AWD, ZT, minimum tillage (MT), cover crops, laser land levelling (LLL), intercropping, and reduced chemical fertilizers. In Madhya Pradesh, reduced pesticide and chemical fertilizer application, not burning residues, organic manure, planting trees, micro-irrigation, and MT were followed. Various registries mandate that projects adhere to strict guidelines for additionality. For example, Verra's agricultural methodology requires a weighted mean adoption rate of project activities to be below 20% before the project start date to demonstrate that the activities are not common practice and fulfil the additionality criterion. Furthermore, it mandates showcasing regulatory surplus and identifying barriers to adoption (Verra, 2023).

We find that several practices like LLL, cover cropping, and MT in Haryana and not burning crop residues, organic manure use, and MT in Madhya Pradesh were adopted by over 20% of the participants even before the project introduction, suggesting the failure to meet the additionality criterion for these practices

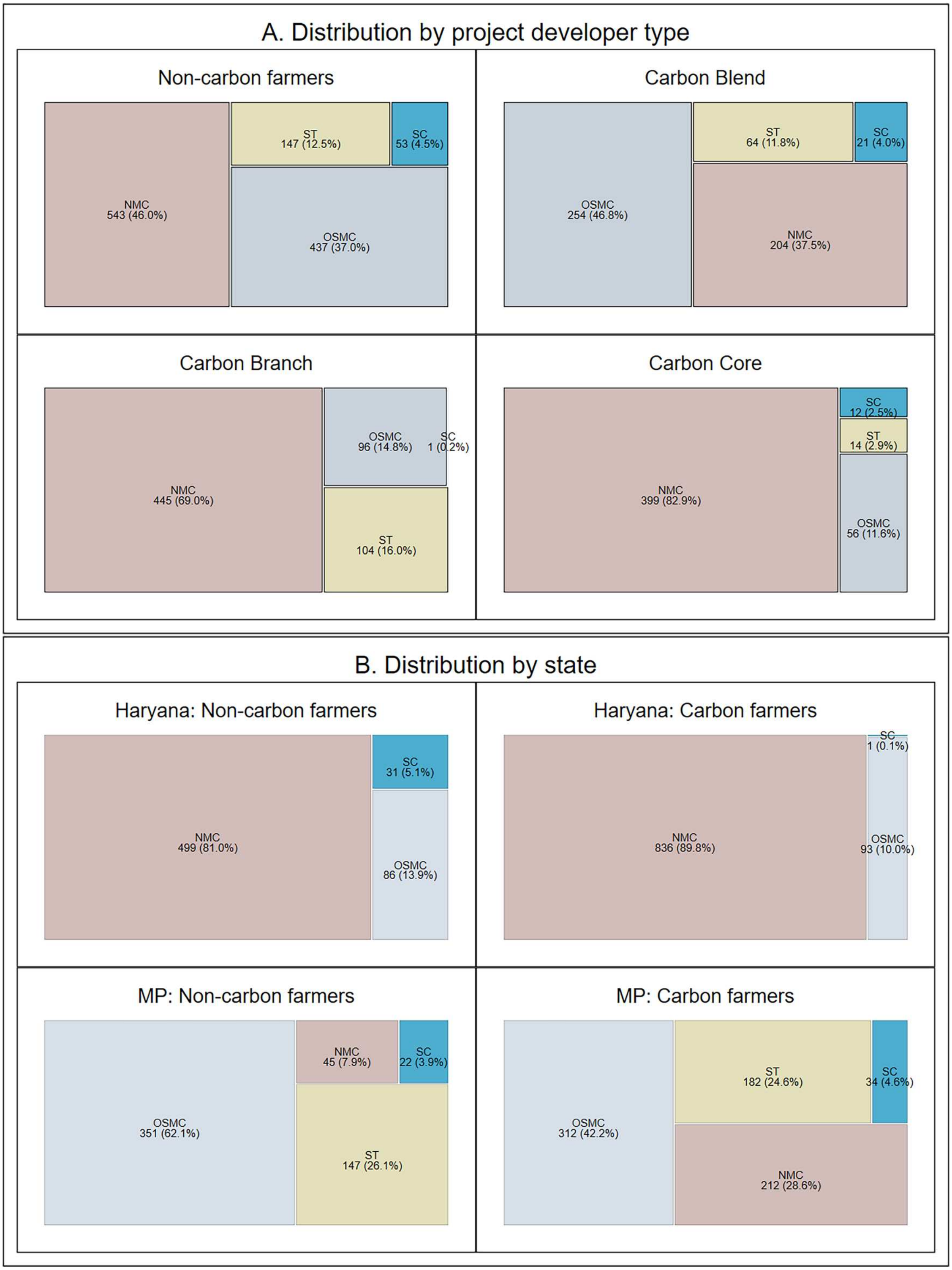

Figure 3. Distribution of cultivated land across different caste groups.

Note: Land cultivated by farmers from each category is indicated below the caste groups and figures in parenthesis are percentage share. NMC – Non marginalized castes, OSMC – other socially marginalized castes, SC – scheduled castes, and ST – is scheduled tribes.

individually (Figure 4). This pattern of pre-existing adoption extends beyond mere percentages. The practices, for which the baseline adoption rate was >20%, had been prevalent for around 6 years in Haryana and 12 years in Madhya Pradesh. In Haryana, cover cropping has been practised by farmers for the past 9 years, LLL for 6 years, and MT for 4 years. Similarly, in Madhya Pradesh, not burning crop residues has been followed for the past 15 years, with organic manure application for 11 years and MT for 8 years. Among adopters in Carbon Core, Branch, and Blend projects, the durations are 6, 8, and 9 years, respectively. The readers may note that these three types of projects started 2.5, 3, and 4.5 years before the survey (in 2023). Therefore, Carbon Core projects included project activities that are relatively newer in the project area.

Despite some practices pre-dating carbon projects, certain practices demonstrated clear additionality, indicated by their lower baseline adoption rates before project implementation. These practices include AWD, DSR, ZT, intercropping and reduced chemical fertilizer use in Haryana; and reduced pesticide and fertilizer use, tree planting, and micro-irrigation in Madhya Pradesh. Their relatively low initial adoption suggests they were some

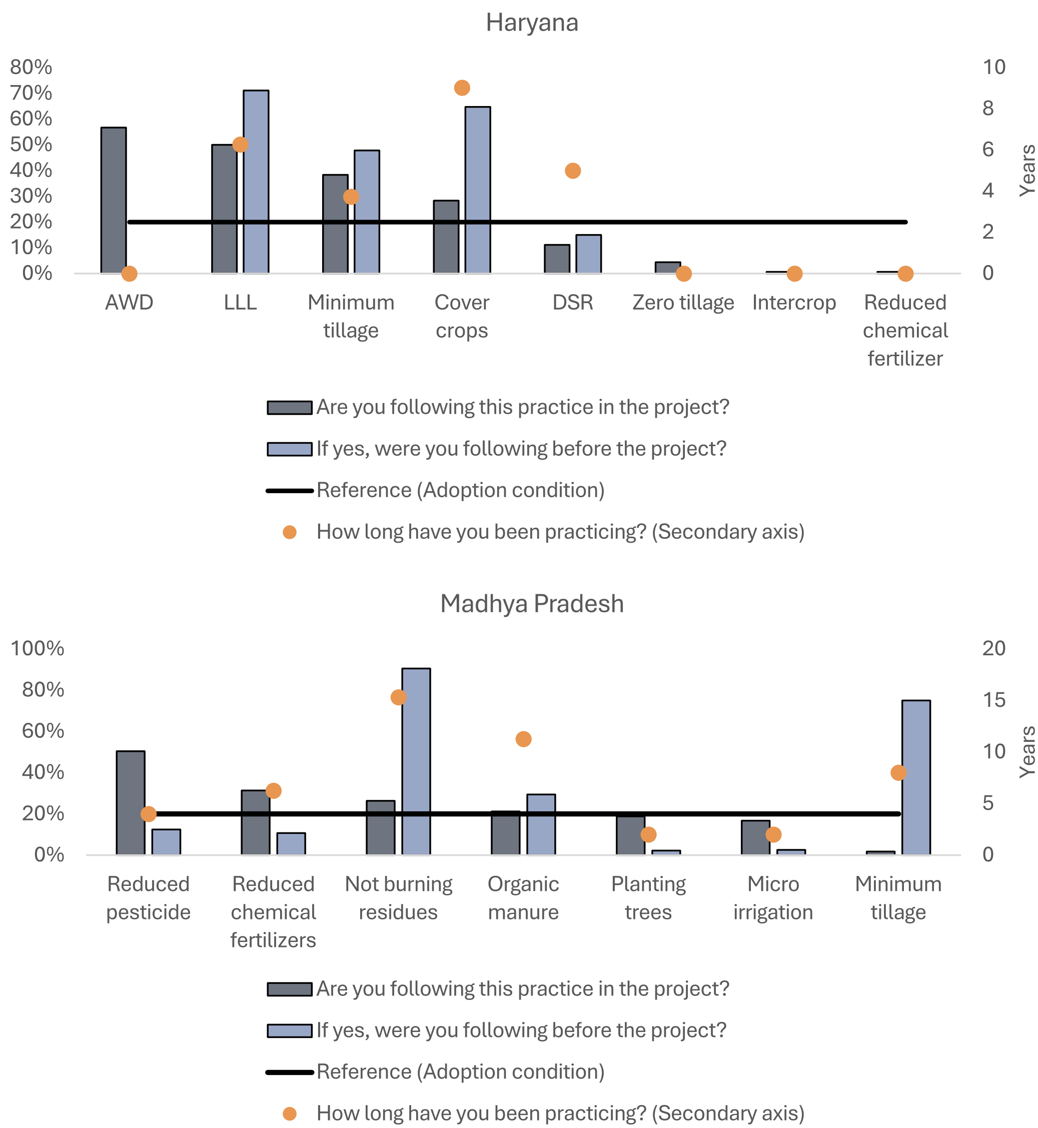

Figure 4. Additionality: Sustainable agricultural practices followed in the project and its history of adoption.

Note: These are farmers' self-reported adoption of project activities, choosing from 14 predetermined options plus an 'others' category for additional practices. 'Reduced chemical fertilizers' refers to the decreased use of synthetic fertilizers, while 'reduced pesticide' means a reduction in the application of pesticides.

of the new interventions introduced by the carbon farming projects, aligning with Verra's qualifying principle of additionality.

Permanence

To assess the adherence of carbon farming projects to the permanence principle, we investigated the continuity of adopted practices into the second year of project implementation (Figure 5). A higher rate of continuance (i.e. minimal disadoption) is critical for the carbon farming projects to achieve meaningful gains in terms of carbon credits and to contribute genuinely toward climate change mitigation.

We find that 93% of farmers involved in Carbon Core projects continued with the adopted practices in the second year, a notably high rate considering the complexity of these projects and the fact that 99% of the farmers have not yet received any monetary benefits from carbon credits. In contrast, the Carbon Branch and Carbon Blend projects demonstrated lower rates of practice continuance, at 66% and 71%, respectively. This reduced adherence to the practices raises concerns about these projects' long-term viability and permanence of emissions reductions.

A further examination of individual practices highlighted significant variations in their continuation. Practices such as intercropping, AWD, LLL, and ZT in Haryana; and organic manure use, reduced pesticide use, and MT in Madhya Pradesh witnessed 75% or lower continuation rates in the second year. This discontinuation of adoption underscores the need for enhanced support and incentives to motivate farmers to continue these practices.

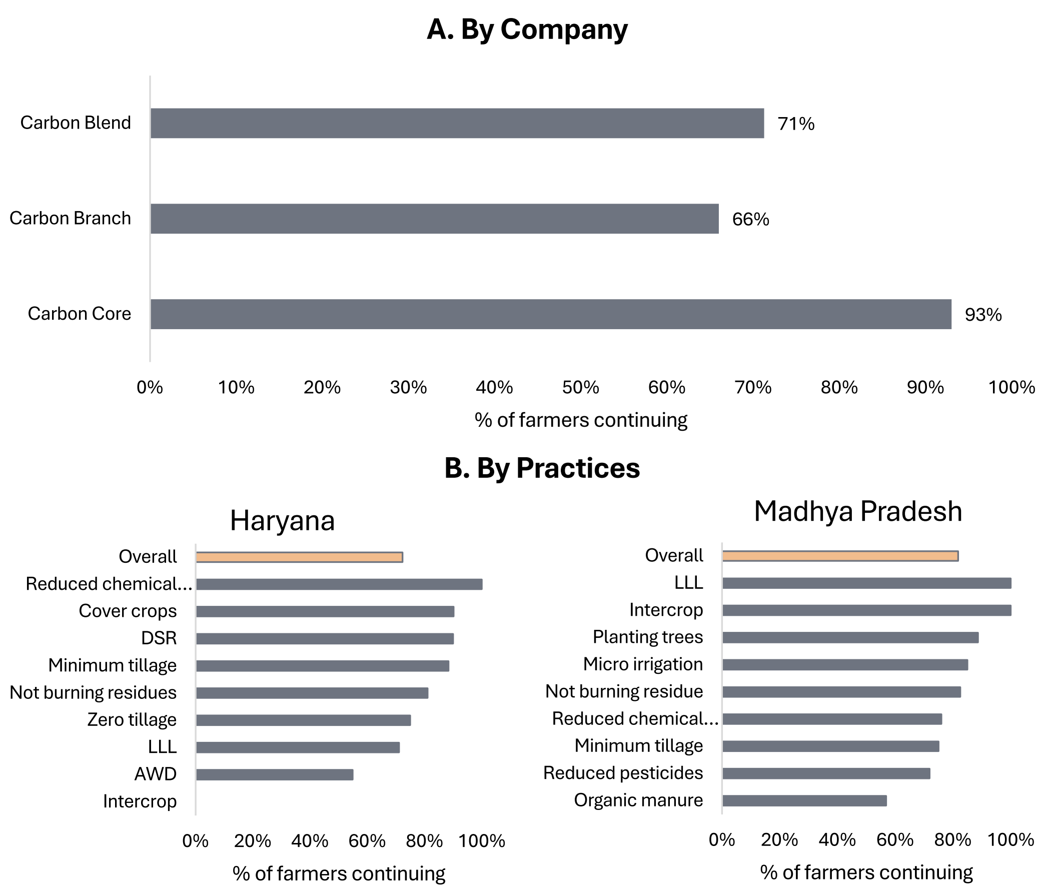

Figure 5. Permanence: Share of farmers continuing carbon farming from the second year by company type and practices.

Note: These are farmers' self-reported adoption of project activities, choosing from 14 predetermined options plus an 'others' category for additional practices.

Reasons for lower continued compliance with carbon farming

When asked about the reasons for discontinuing project activities, a large share of disadopters (53%) cited the lack of monetary benefits as the primary reason for disadoption. We found that 99% of the farmers in our sample had not received any money from carbon credits. Further, 27% and 16% of disadopters reported yield penalties and lack of adequate information about carbon farming as the reasons for disadoption (***Figure S1***). In the Carbon Core projects, 75% cited insufficient information, while 25% saw no financial gain as the reason for their disadoption. The Carbon Branch farmers reflected these concerns, with 67% reporting no monetary benefits and 20% lacking information, alongside 8% experiencing yield loss. The Carbon Blend farmers highlighted yield loss (63%) as a significant issue, followed by 31% citing no monetary benefits. Other reasons included increased costs and projects not starting yet, although these were less common. These findings highlight the need for better information dissemination, timely financial incentives, and support to mitigate yield loss and cost increases in carbon farming projects.

We analyzed the relationship between farmer training/communication post-project enrolment and the sustained adoption of regenerative agriculture practices. This is crucial for farmers as carbon farming practices necessitate additional knowledge and skills. For instance, in projects promoting DSR or ZT, information and training on weed management are crucial to realizing the expected yield benefits (Ishtiaque et al., 2024). We find a clear correlation between training and communication with continued adoption. In the Carbon Core, Branch, and Blend projects, 68%, 49%, and 53% of farmers reported consistent contact with companies, and 43%, 28%, and 50% received training, respectively (***Figure S2***). This is positively associated with 93%, 68%, and 71% compliance rates in the Carbon Core, Branch, and Blend projects, respectively (***Panel A*** Figure 5). This underscores the importance of effective communication and training to continue adopting carbon farming practices.

Using a probit model with sample selection, we examined factors influencing the initial and continued adoption of carbon farming practices (Figure 6). We found that caste, indicative of social inclusion, plays a crucial role; notably, OSMCs are significantly less likely to participate than NMCs. Education level also significantly affects adoption positively. Primary income source was another key factor; households primarily reliant on agriculture were more inclined towards adopting carbon farming, likely due to their familiarity with agricultural innovations. Further, active social participation in community groups (like farmer collectives) enhances adoption, underscoring the role of social networks in spreading practices. Financial readiness, indicated by bank account ownership, necessary for handling carbon credit transactions, also showed a positive correlation. Involvement in government schemes, such as crop insurance and soil health cards, further influenced the likelihood of adoption. Crop insurance reflects a propensity for adopting risk-mitigating measures. At the same time, farmers with soil health cards are likely better informed about nutrient status, enabling them to apply fertilizers and soil amendments more precisely. Furthermore, we found that farmers with an MGNREGA job card, an indicator of poverty, were less likely to adopt regenerative practices in carbon farming projects, as expected. However, surprisingly, farmers with access to information were also less likely to adopt these practices, contrary to our expectations.

Turning to the factors influencing continued compliance, we found that regular communication by project developers was positively associated with sustained compliance. Despite small and OSMC farmers being less likely to be included in carbon farming projects, upon inclusion, they were more likely to continue regenerative agricultural practices, ensuring the permanence of emissions reduction. Enrolment in Carbon Branch and Carbon Blend projects showed a negative association with continued compliance, indicating that Carbon Core projects experience lower disadoption of project activities. This means they retain more farmers and are more likely to benefit over time.

Discussion

Our investigation has revealed a troubling fact that 99% of farmers have not received monetary benefits from carbon credits. Also, small farmers and marginalized communities (SCs, STs, and sometimes OSMCs) are excluded from participating in carbon farming projects. This indicates a potential bias in carbon farming

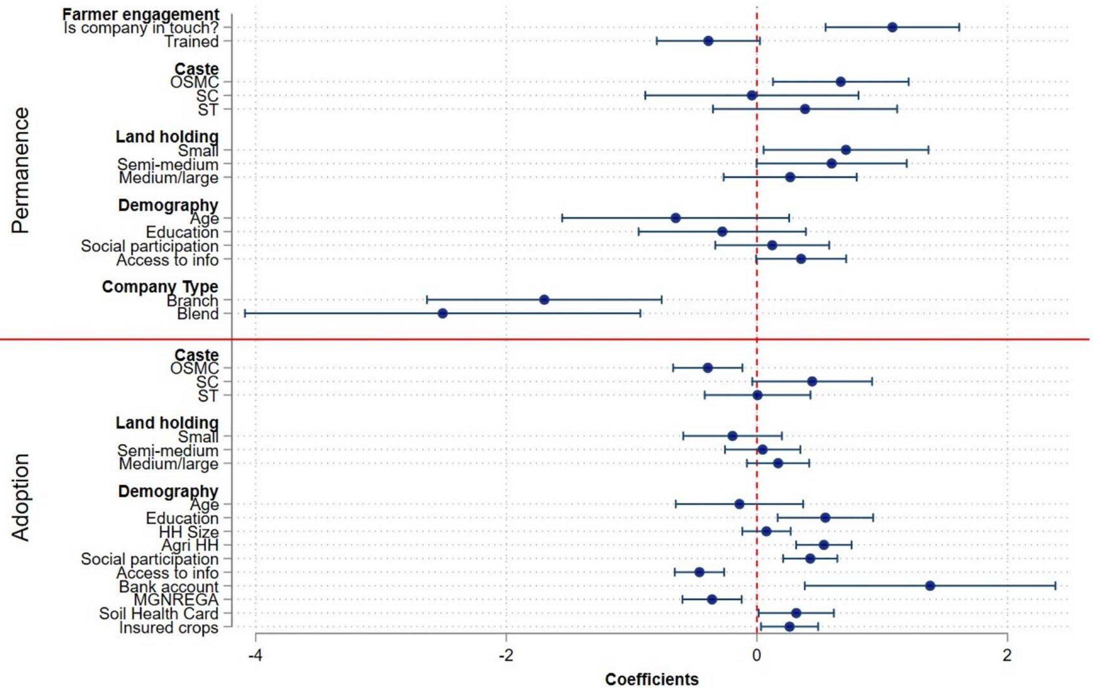

Figure 6. Probit model with sample selection (heckprobit) estimates of determinants of adoption of and continued compliance (permanence) with carbon farming.

projects towards non-marginalized large landholders, who might be more capable or willing to participate due to resource access or higher risk-bearing ability. From the perspective of project developers, the enrolment of large farmers could be a strategic choice to cover large areas with fewer participants, inadvertently excluding smaller farmers. This dominance of the NMCs and the underrepresentation of marginalized castes (especially SC and ST) and women raise concerns about the role of carbon markets in achieving inclusive developmental goals. A significant concern highlighted in the literature is that nature-based solutions often overlook local rights and knowledge, leading to the marginalization of Indigenous peoples. Recognizing and integrating local voices is crucial, as these communities possess invaluable ecological knowledge essential for sustainable climate and biodiversity solutions (Seddon, 2022). Project developers may actively engage with local communities and leaders to understand the barriers marginalized groups face and develop culturally appropriate and inclusive extension approaches.

Theoretically, competitive markets, through efficiency and the trickle-down effect, should effectively distribute benefits to the last mile, which are often beyond the direct reach of government interventions. However, our observations suggest a divergence from this ideal in carbon farming projects. The prevalent market imperfections, as evidenced by the skewed participation favouring economically and socially more advantaged groups (large farmers, non-marginalized communities, and men) and information asymmetry, indicate that the intended equitable distribution of benefits is not realized. This deviation calls for a critical reassessment of market mechanisms and policies guiding carbon farming projects to ensure that they genuinely serve their purpose of equitable environmental benefit distribution. The Indian carbon market can incentivize carbon projects that prioritize social equity and inclusion. The incentives may include (but are not limited to) financial rewards, public recognition, or additional support for projects that successfully integrate marginalized groups. Carbon credits, with additional environmental and social co-benefits beyond carbon, have commanded a notable price premium in the VCM (Forest Trends' Ecosystem Marketplace, 2023).

VCMs have recently faced criticism for projects overestimating carbon credits generated, lack of transparency, as well as for project activities not adhering to guidelines on additionality, permanence and leakage

(Balmford et al., 2023; Delacote et al., 2024; Filewod & McCarney, 2023; West et al., 2020, 2023). In our study, while certain practices predate carbon projects, raising concerns about meeting the additionality criterion, other practices with high emissions reduction potential like ZT, AWD, DSR, intercropping, reduced chemical fertilizers, micro-irrigation, and tree planting (Cariappa et al., 2024; Sapkota et al., 2019), align with additionality principles. The longevity of practice suggests that these methods were integrated into the farming systems well before the initiation of these carbon projects, thereby challenging the notion that their adoption is solely attributable to the project. However, when combining practices, there is a strong likelihood that the weighted average adoption rate will fall below the 20% threshold required to prove additionality. For instance, in Haryana, farmers adopting MT and reducing chemical fertilizer use, or a combination of MT, micro-irrigation, reducing chemical fertilizer use, and tree planting, are likely to achieve this low adoption rate. This implies that carbon farming projects generally hold GHG reduction potential.

Projects in Haryana perform better in additionality while in Madhya Pradesh ensure better adherence to permanence. Caste, education, financial inclusion, and social participation are important factors influencing the adoption of carbon farming practices, while communication, social participation, and the nature of the project developer affect the continued adoption of practices. On average, 28% of farmers discontinued practices from the second year, and disadoption rates in Carbon Branch (34%) and Carbon Blend (29%) projects highlight the need for more effective strategies to ensure continued adoption by farmers. This finding implies that Carbon Core companies might be more effective in retaining farmers within their projects, likely due to better communication and engagement strategies. Farmers reported that lack of monetary benefits, information, and yield penalties are major reasons for the disadoption of carbon farming practices. Similar barriers were identified in carbon projects in the USA, Scotland, Madagascar, Mali, China, Australia, and Finland (Cook & Ma, 2014; Feliciano et al., 2014; Mattila et al., 2022; Rochecouste et al., 2017; Siedenburg et al., 2016; Wang et al., 2021). A concerning finding is that 27% of farmers reported that yield penalty is the reason for the disadoption of carbon farming practices. It is especially high in Carbon Blend projects, where 63% of the farmers report yield penalties as a reason. This has huge implications for the project as a whole. Project developers must recognize that the proper implementation of specific practices tailored to the crops and climate of a particular region is necessary to avoid negative impacts on crop yields (Brummitt et al., 2024). According to Verra's agricultural land management methodology, projects with a yield penalty exceeding 5% are not eligible for registration or carbon credit issuance (Cariappa et al., 2024). As of 08.07.2024, the Carbon Blend projects studied have been denied registration by Verra and are either on hold or inactive. This underscores the legitimacy of the farmers' concerns and the need for project developers to address these issues. If projects are not registered and farmers do not receive revenue from carbon credits, they face a double blow of yield loss and lost carbon credit revenue. This situation poses a significant threat to the adoption of carbon farming practices. Therefore, addressing these issues is crucial to avoid adverse impacts on the Indian VCM.

The successful implementation of carbon farming by Indigo Ag from 2018 to 2022 on 500,000 hectares of cropland in the US, which resulted in the issuance of around 300,000 tCO_2e of credits, demonstrates that going beyond addressing technical challenges – such as creating more accurate inventories of agricultural emissions, quantifying temporal changes in carbon stocks, and developing algorithms using remote sensing data for farm management practices or improving user interfaces – the broader adoption is facilitated by factors like appropriate pricing, tailored technical assistance, and a supportive policy environment (Brummitt et al., 2024). Furthermore, projects that command prices at or above the social cost of carbon, supported by strong local champions (e.g. a successful farmer or trusted extension agent working within farmer peer-led networks) alongside robust MRV systems, are more likely to harness higher environmental benefits.

Conclusions

India is developing guidelines for its VCM and has recently launched a framework for VCM in agriculture. To maximize the benefits of VCMs, learning from existing projects and addressing their shortcomings is crucial. Our study collected data from participating and non-participating farmers across seven carbon farming projects in Haryana and Madhya Pradesh, revealing several key issues. These include the exclusion of small farmers and marginalized communities (SCs and STs), disadoption of practices due to lack of monetary benefits and information, and poor communication and training from project developers, particularly in Carbon Branch and Blend projects.

To improve socio-economic inclusion, the Indian VCM should establish metrics that reward projects based on their inclusivity, with higher inclusion leading to higher prices. Additionally, to enhance additionality and permanence, project developers should collaborate with institutions like the Indian Council of Agricultural Research (ICAR) research institutes, Krishi Vigyan Kendra (KVKs), state agricultural universities (SAUs), non-governmental organizations (NGOs), and international research centres. This collaboration should focus on designing projects that avoid yield penalties and foster better engagement with farmers, involving them from the project design phase.

Addressing these issues is essential for the success of the Indian VCM. By fostering inclusivity, ensuring the additionality and permanence of carbon farming practices, and engaging farmers effectively, India can build a robust and equitable carbon market that truly benefits all stakeholders. We advocate for a paradigm shift towards carbon farming approaches that are inclusive, communicative, and grounded in principles of equity and sustainability. Such models enhance the effectiveness of carbon farming projects and contribute significantly to climate change mitigation efforts. As India is developing guidelines for its voluntary carbon market, the lessons drawn from this analysis provide valuable guidance for shaping the future of carbon markets in agriculture.

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