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Research article

A terminated REDD+ project in Mozambique: Mitigation underperformance, lasting local benefits

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ABSTRACT

This study evaluates the long-term performance of the Sofala Carbon Community Project (SCCP) in Mozambique, a Payments for Ecosystem Services (PES) program combining asset-building, use-restriction strategies, and development interventions, partially financed through the voluntary carbon market. Using quasi-experimental analysis of remote sensing data, we find that the SCCP reduced tree cover loss by 2.2 percentage points during implementation (2005–2014) and by 2.1 percentage points in the five years after its conclusion (2015–2019), corresponding to 41% and 20% reductions in deforestation relative to control areas, with no evidence of spatial leakage. Yet, the attenuating forest cover impacts largely disappeared 5 years after the project ended. Household surveys suggest that 95% of agroforestry systems adopted during the project persisted seven years post-program, and participants report stronger conservation skills, higher perceived efficacy, and higher socio-economic status compared to non-participants. Former SCCP employees are about five times as likely as non-participants to hold long-term jobs in the neighboring national park, consistent with skill and network gains as plausible mechanisms. However, limited understanding of contractual terms and land tenure arrangements raise equity concerns. Our findings are consistent with literature on VCM-financed PES programs that are unlikely to meet mitigation claims without rigorous, empirically validated carbon accounting and resilient financing structures. With this single case study in mind, such projects may also be associated with lasting local environmental and socio-economic benefits.

1. Introduction

Nature-based climate solutions (NCS) are increasingly recognized as a vital component of global strategies to reduce greenhouse gas (GHG) emissions (Anderson et al., 2019; Griscom et al., 2017; Karki et al., 2023; Nolan et al., 2021; Seddon, 2022), particularly in tropical regions (Griscom et al., 2020). In addition to their mitigation potential, NCS can offer important co-benefits for biodiversity and a range of ecosystem services (Seddon et al., 2020). Among these strategies, the protection of existing forests has emerged as a top priority (Cook-Patton et al., 2021), given that deforestation contributes substantially to global GHG emissions (Baccini et al., 2017; van der Werf et al., 2009). Tree planting and ecosystem restoration efforts, whether in forests or agricultural landscapes, have been identified as another NCS with significant climate mitigation potential (Bastin et al., 2019; Lewis et al., 2019). In response, forest protection and landscape restoration have gained increasing international political support. Major initiatives include the Bonn Challenge, the “30 by 30” target under the Global Biodiversity Framework, and the COP26 pledge to halt and reverse deforestation by 2030.

Financing has consistently been identified as a major obstacle to scaling up global NCS efforts (Seddon, 2022). However, the private sector has shown growing interest in NCS to meet voluntary climate commitments (Seddon et al., 2020). The voluntary carbon market (VCM) plays a key role in this context and is rapidly growing (Romm et al., 2025), with forest and land-use being the largest sector by volume and with transactions of more than 342 mill. USD in 2024. Within this category, REDD + projects (Reducing emissions from deforestation and forest degradation) account for the largest share of credits, followed by improved forest management and afforestation/revegetation activities (Forest Trends’ Ecosystem Marketplace, 2025).[1] However, the

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[1] The underlying model of mobilizing funding from the Global North to support mitigation activities in the Global South, also forms the basis of bilateral REDD + initiatives (Angelsen, 2017).

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nature of carbon markets, marked by fluctuating demand and prices, makes such financial incentives inherently unstable. This instability not only challenges the long-term permanence of mitigation outcomes but may also has significant implications for local livelihoods. A substantial portion of the mitigation potential from NCS lies on smallholder or community-managed lands (Seddon et al., 2020, 2021; Shyamsundar et al., 2022), making the reliability of funding a critical issue for the social sustainability of these efforts.

In this paper, we examine the long-term impacts of a VCM project in Mozambique that combined avoided deforestation with restoration activities through agroforestry. In addition, alternative livelihood development activities were implemented, so that the overall combination of measures can be considered typical for many REDD + initiatives (Wunder et al., 2024). A cornerstone of the Sofala Community Carbon Project (SCCP) were direct Payments for Ecosystem Services (PES) (Engel, 2016; Wunder, 2015) to households for adopting agroforestry practices and to communities for forest conservation. In 2014, the project was forced to cease operations due to financial difficulties following declining global carbon credit prices. We evaluate the SCCP's performance from two complementary perspectives. First, from a global mitigation standpoint, we assess the extent to which the project's claimed carbon sequestration translated into actual net emission reductions. Mounting evidence suggests that VCM REDD + projects underperform. A key reason is the use of inflated baselines that overstate projected emissions in the absence of the project (West et al., 2024), routinely resulting in overestimations of climate impact by a factor of five to ten (Romm et al., 2025). When not accounting for credited emission reductions but focusing on the net impact of REDD + interventions on forest cover, a more positive picture emerges. Reviews by Wunder et al. (2024) and Duchelle et al. (2018) find small but statistically significant positive outcomes. Nonetheless, additional concerns, such as conflicts of interest, and the risk of leakage, further undermine the environmental integrity of many offset projects (Romm et al., 2025; Delacote et al., 2024, 2025; Filewod and McCarney, 2023; West et al., 2025). Reform efforts, notably the Integrity Council for the Voluntary Carbon Market (ICVCM) core carbon principles, aim to address these concerns, so our findings speak primarily to established practices rather than future potential of the VCM.

The issue of permanence may be particularly relevant for VCM funded projects that are exposed to market risk from the demand side. Nonetheless, empirical evidence on the permanence of emission reductions from terminated REDD + projects remains scarce (Wunder et al., 2024), as many available impact evaluations focus on uncertified projects, often in pilot phases (Malan et al., 2024). Carrilho et al. (2022) concluded that deforestation resumed once a REDD + project in Brazil was terminated, resulting in no net difference in forest cover after project completion. Demarchi et al. (2023), evaluating the same program using remote sensing rather than self-reported data, corroborated this finding. An evaluation of a PES program in Uganda found that land users reverted to pre-PES deforestation practices after payments ceased, although gains achieved during the program were maintained (Kemigisha et al., 2023; Jayachandran et al., 2018). Beyond REDD+, research on the permanence of PES schemes that incentivized the adoption of silvopastoral practices in Latin America found lasting adoption of these practices in Colombia and Nicaragua (Calle, 2020; Pagiola et al., 2016a, 2020) and Costa Rica (Rasch et al., 2021).

We complement this global mitigation perspective with an analysis of associations between project participation and local livelihood outcomes, both objective and perceived. Even if projects fail to deliver measurable, additional, and permanent mitigation, they may still negatively or positively affect local populations. In the best case, payments and development components can create new income and livelihood opportunities and enhance local environmental benefits (e.g., forest products or other ecosystem services). In the worst case, payments may fail to reach local communities or only benefit local elites, while projects increase restrictions on forest use (Duchelle et al., 2017), echoing broader concerns about REDD+ (Corbera, 2012). A recent meta-analysis finds positive but modest livelihood impacts, particularly for objective rather than subjective measures (Wunder et al., 2024), with considerable heterogeneity between projects (see also 1–5). Whether local populations gain or lose depends on how incentives and disincentives are combined (Duchelle et al., 2017).

Few studies have simultaneously evaluated environmental and socioeconomic outcomes of REDD + projects.[2] Malan et al. (2024) assessed the impact of a REDD + project in Sierra Leone, finding that while the project reduced deforestation by 30% (accounting for roughly 85% of awarded credits), it had no significant effect on economic well-being or conservation attitudes. Montoya-Zumaeta et al. (2022) report that a REDD + initiative in Peru had no significant effect on deforestation or forest degradation, while participants experienced significantly lower subjective well-being. Nantongo et al. (2024) find that a REDD + program in Tanzania improved forest conservation and increased livelihoods in one of the three pilot areas. However, all three studies focus on a rather short-term perspective, limited to the period when the projects were in operation. Most closely related to our study, Carrilho et al. (2022) evaluate a REDD + program in Brazil during and after its implementation. They find positive impacts on perceived well-being during the program period, but negative impacts following its conclusion. In terms of environmental outcomes, they find a positive effect on forest cover during the project that disappeared once the program ended.

This paper contributes to this line of research by providing a holistic post-termination assessment of a REDD + project along two dimensions that have rarely been examined in combination. First, we evaluate the permanence of a terminated program after its conclusion. Second, we do so across two distinct outcomes: forest cover and local livelihoods. With one notable exception (Carrilho et al., 2022), prior studies have addressed only one of these dimensions: either examining the environmental permanence of terminated programs through remote sensing (Jayachandran et al., 2018) or self-reported survey data (Kemigisha et al., 2023), or combining both dimensions but limiting analysis to periods during or immediately at the end of active projects (Malan et al., 2024; Montoya-Zumaeta et al., 2022; Nantongo et al., 2024). The abrupt discontinuation of this project due to unstable funding further illustrates a structural risk inherent to VCM-financed conservation initiatives.

Our evaluation employs two complementary empirical strategies that differ in identification strength. First, we use high-resolution remote sensing data (Hansen et al., 2013) and matching techniques to identify a control group with pre-intervention deforestation trends and geographic characteristics comparable to those of SCCP areas. We then estimate the program's impact on tree cover loss using a difference-in-differences (DiD) specification, measuring outcomes during the implementation (2005–2014) and the post-project period (2015–2019). Second, a household survey conducted in 2022 enables us to compare household wealth, conservation motivations, and environmental agency between treated and control villages in the vicinity of the project area. This approach offers an assessment of both environmental and economic long-term PES outcomes, combining causal evidence on forest cover with correlational evidence on socioeconomic differences, including conservation benefits such as increased tree cover from reduced land clearing and improved soil health from agroforestry (Muchane et al., 2020). It also captures potential income and wealth gains from

[2] Beyond REDD + initiatives, there are also few integrated assessments of forest conservation or restoration programs. Alix-Garcia et al. (2015) find that while Mexico's national PES schemes generate modest poverty gains, they also reveal a trade-off: environmental impacts tend to be greater where poverty is lower, and vice versa, underscoring the difficulty of balancing these objectives. Coleman et al. (Bak-Coleman et al., 2021) assessed large-scale tree planting initiatives in Northern India and found limited environmental and livelihood impacts.

enhanced agricultural productivity and agroforestry earnings, as well as potential income losses from reduced deforestation, thereby providing a holistic perspective on the trade-offs and synergies between conservation and livelihoods.

Our analysis shows that the SCCP substantially reduced deforestation in participating areas during and after program implementation, with effects persisting, though attenuating, five years after payment cessation. From a global mitigation perspective, however, the carbon sequestration achieved represents only a small fraction of the credits sold, echoing broader concerns about the integrity and additionality of offsets in the VCM. At the same time, participants in treated communities report stronger environmental agency and continued adoption of agroforestry, consistent with persistent behavioral change rather than short-term compliance. Survey data further indicates that SCCP participation is associated with higher perceived socio-economic status and permanent employment. Taken together, these findings are consistent with locally grounded PES interventions generating durable social and ecological benefits, while also revealing the limitations of scaling such initiatives as reliable instruments for global climate mitigation.

2. Conceptualizing permanence of REDD + impacts

Payments for Environmental Services (PES) have become a widely promoted market-based approach for addressing global environmental challenges, from deforestation to biodiversity loss (Salzman et al., 2018). Their central idea is simple: those who benefit from ecosystem services (such as carbon storage, water regulation, or biodiversity protection) financially reward those whose land-use decisions help maintain these services (Chichilnisky and Heal, 1998; Ferraro and Pattanayak, 2006; Kinzig et al., 2011). PES are a cornerstone of many REDD + projects but often combine it with alternative livelihood development activities (Wunder et al., 2024). The decision of land users to participate and sustain new practices is influenced by the perceived profitability of conservation relative to conventional land uses, associated transaction costs, and individual motivations incentives (Jack and Jayachandran, 2019).

We conceptualize PES impacts and their *permanence* along three temporal dimensions. Short-term effectiveness refers to measurable outcomes during program implementation, when financial incentives directly shape land-use decisions. Medium-term permanence captures the preservation of these impacts after payments cease; our observation window of five to seven years after project termination covers this temporal dimension. We reserve the complementary term *persistence* for the continuation of specific practices, such as maintaining agroforestry systems, or attitudes. Long-term permanence is in turn determined by structural changes, such as fundamental shifts in land use, livelihoods, or institutions, that can sustain or disrupt impacts beyond what can be assessed with the data at hand. Our hypotheses map onto these dimensions as follows.

PES schemes fall into two broad categories (see Fig. 1). First, use-restricting PES pay land users to avoid harmful activities such as deforestation or overgrazing (Wunder, 2005, 2008). These schemes aim for immediate behavioral change and can produce clear environmental gains while payments are made (Börner et al., 2017; Wunder et al., 2020). We therefore hypothesize that **(H1)** project areas experienced lower deforestation rates than control areas before payments ceased (short-term effectiveness). This anticipated effect stems from the direct financial incentives and enhanced collective action, such as community fire patrols, designed to curb deforestation. However, the permanence of these gains is a significant concern: studies frequently document a high risk of reverting to pre-PES land-use practices once payments end, suggesting that behavioral change was primarily extrinsically motivated (Jayachandran et al., 2017; Etchart et al., 2020; Le Velly et al., 2017; Roopsind et al., 2019).

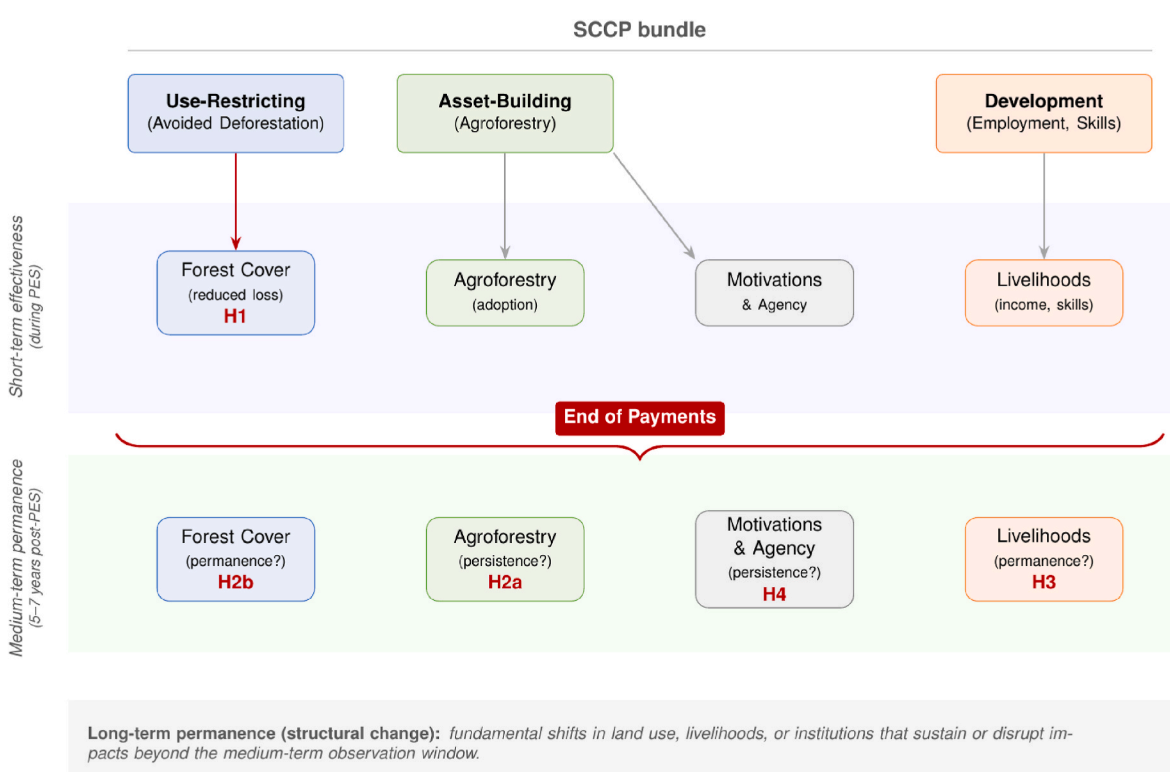

Fig. 1. Conceptual framework of the multi-component PES program and hypothesized causal pathways.
Notes: Conceptual framework of the SCCP and hypothesized pathways across three temporal dimensions. The framework distinguishes short-term effectiveness (during PES payments) and medium-term permanence (5–7 years post-PES). Solid arrows indicate direct effects during the project duration. See Table 1 for the mapping between SCCP components, hypotheses, mechanisms, and data sources.

A second type, asset-building PES, encourages the adoption of sustainable land-use practices, such as agroforestry, by subsidizing initial investments and providing technical support (Pagiola et al., 2016a). The underlying assumption is that, once established, these practices will become profitable and self-sustaining, generating long-term benefits even after payments cease. This logic leads to two interconnected hypotheses regarding the post-payment period. First, we test the core premise of the asset-building model, hypothesizing that **(H2a)** participants sustained higher rates of agroforestry adoption and maintenance than non-participants after payments ceased (persistence). We expect that benefits such as improved soil fertility, diversified income, and skills development provide sufficient incentives for continued adoption. Second, we test the environmental permanence of project's impacts, hypothesizing that **(H2b)** project areas experienced lower deforestation rates than control areas even after payments ceased. This sustained environmental impact is presumed to be mediated by the persistence of agroforestry practices (H2a), which can intensify production on existing plots and reduce pressure to clear new land. However, evidence for the long-term success of asset-building PES remains scarce, and a reversal is possible if the new systems fail to generate sufficient returns or if income gains relax capital constraints that enable further agricultural expansion.

Beyond agroforestry, we examine whether the SCCP produced lasting economic benefits through durable assets and transferable skills (Wunder et al., 2024; Alix-Garcia et al., 2015; Jayachandran, 2023; Pattanayak et al., 2010). We posit that the project's holistic approach, combining durable assets such as agroforestry systems with transferable skills, generated lasting economic benefits that persisted beyond the period of direct financial support. We therefore hypothesize that **(H3)** participants retained lasting socioeconomic benefits after direct payments ceased (medium-term permanence). A contrasting outcome would be expected if new practices proved insufficiently profitable or if acquired skills could not be transferred to other viable economic activities.

Finally, the project may have also led to persistent attitudinal and belief changes. Beyond financial incentives, factors such as intrinsic motivation, self-efficacy, and agency are critical for sustaining pro-environmental behaviors after external support is withdrawn (Winkler-Schor and Brauer, 2024). In the broader PES literature, concern has been raised that the monetization of conservation efforts may undermine participants' intrinsic conservation motivation – potentially reducing the effectiveness of PES in the long run, particularly when payments stop (Rode et al., 2015). However, more recent evidence suggests that PES can crowd-in intrinsic motivation (Rode et al., 2015), and the SCCP's design, which emphasized training, participation, and experiential learning, was intended not only to build physical assets but also to enhance participants' sense of capability and pro-environmental identity. This "crowding-in" of internal motivation is hypothesized to be a key driver of long-term success (Blanco et al., 2023; Grillos et al., 2019), and is especially relevant in contexts where a limited capacity to aspire or a sense of helplessness can constrain pro-environmental behaviors (Silva et al., 2018). We therefore hypothesize that the intervention's influence on long-term behavior operates through these psychological channels, leading to our final hypothesis: **(H4):** The project created a lasting increase in participants' environmental motivations and self-efficacy. This in turn can may contribute to the persistent adoption of sustainable practices after payments ended. Table 1 summarizes the mapping between SCCP components, hypotheses, underlying mechanisms, temporal dimensions, and data sources.

3. Methods and material

3.1. The Sofala Carbon Community Project

The SCCP was located in the Sofala region of Mozambique, neighboring the Gorongosa National Park (GNP), see Fig. 2. The area features a woodland mosaic that includes miombo, savannah, and riverine woodlands, that is threatened by agricultural expansion due to population growth and in-migration, charcoal production, and uncontrolled fires from burning fields for new crops (Hegde and Bull, 2008). The project was launched in 2004, initially financed by the European Union. After the pilot period, the implementing NGO *Envirotrade* financed activities through the VCM and expanded the project area in 2007 (one south of the project area, and north-east of the GNP in the Zambezi region (Envirotrade, 2010)). In this study, we solely focus on the core area as most of the PES contracts were issued here. The SCCP faced financial challenges due to low carbon prices on the VCM, so that no new contracts were signed after 2010. The project officially ended in 2015, with the final payments for services provided in 2016 for the 2014 project year. The SCCP addressed deforestation through three integrated components.

1. Agroforestry (Asset-Building PES): Households voluntarily adopted new practices, such as planting fruit orchards or fast-growing trees, under 100-year contracts. Financial payments were provided over the initial seven years (averaging $560 per household), intended to incentivize adoption until the systems became self-sustaining and profitable.
2. REDD+ (Use-Restriction PES): Local communities received payments for protecting existing miombo woodlands, primarily enrolling communal forests. These payments funded community benefits through a trust fund (e.g., fire patrolling, infrastructure), effectively functioning as compensation for forest conservation over ten years. The carbon offsets were calculated using a baseline deforestation rate of 2.4% per year, assuming full forest loss within 42 years without intervention.
3. Development: The SCCP provided employment opportunities, offering alternative livelihoods through microenterprises (e.g., tree nurseries, carpentry). This component generated significant wage employment and skill transfers within the project villages.

Compliance was ensured via a monitoring and enforcement system that directly linked payments to performance. For the REDD + component, this included annual verification using satellite imagery and

Table 1
Linking SCCP components to hypothesized short- and medium-term outcomes.

SCCP Component	Hypothesis	Mechanism	Temporal Dimension	Data Source OR Identification strategy
Use-Restricting (REDD+)	H1: Reduced deforestation during payments	Financial incentives + community enforcement	Short-term	Remote sensing panel (DiD)
Asset-Building (Agroforestry)	H2a: Agroforestry maintained	Self-sustaining profitability of new practices	Medium-term	Household survey
Use-Restricting + Asset-Building	H2b: Lasting forest cover impacts	Agroforestry reduces pressure on forests	Medium-term	Remote sensing panel (DiD)
Development (Wealth, Employment, Skills)	H3: Lasting socioeconomic differences	Skills, networks, alternative livelihoods	Medium-term	Household survey
All components	H4: Strengthened motivations and agency	Training, participation, experiential learning	Medium-term	Household survey

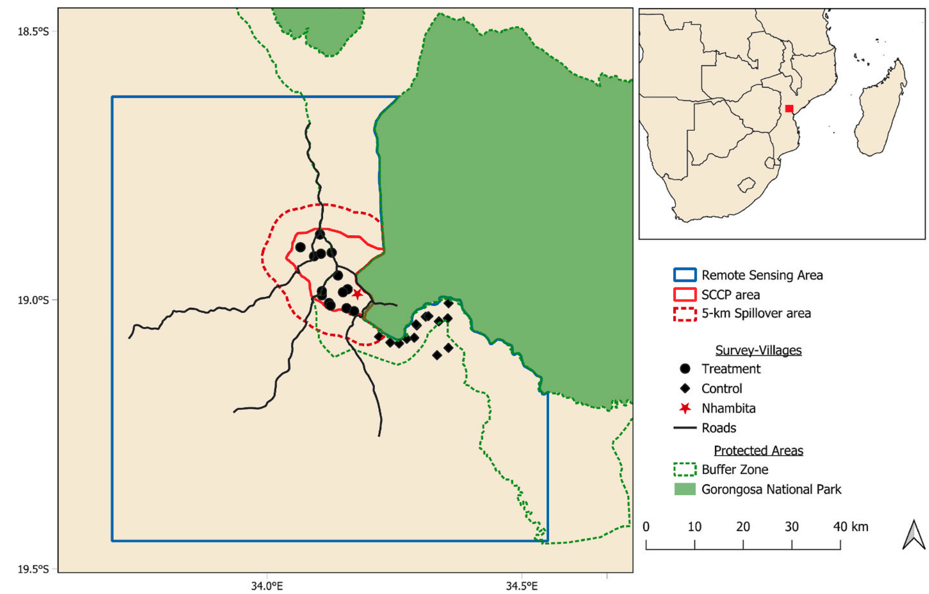

Fig. 2. Study site overview.
Notes: Created in QGIS 3.3 using freely available Natural Earth data for the background maps, SCCP boundaries provided by IIAM, and boundary data of the GNP and its buffer zone provided by the GNP.

ground inventories, while payments were reduced or suspended for falling below compliance thresholds. Between 2003 and 2013, the project sold 215,827 tCO2 from agroforestry and 159,817 tCO2 from REDD + on the VCM. Supplementary Section S1 provides more details on the project design and carbon accounting.

3.2. *Data & analyses*

Our empirical strategy combines two complementary approaches that differ in identification strength. For hypotheses H1 and H2b (forest cover outcomes), we use a 20-year panel of remotely sensed forest data (2000–2019) and apply propensity score matching combined with difference-in-differences estimation. This design leverages repeated observations of the same grid cells before, during, and after the SCCP, allowing us to control for time-invariant confounders and test for parallel pre-trends. For hypotheses H2a, H3, and H4 (agroforestry adoption, socioeconomic outcomes, and motivations/agency), we rely on a household survey conducted in 2022, seven years after the project ended. Because baseline data were unavailable for control villages, this component constitutes a post-treatment cross-sectional comparison with regression adjustment for observable characteristics. It provides correlational evidence on differences between SCCP and control households but cannot establish causality with the same confidence as the panel-based forest analysis.

We face several econometric identification challenges in estimating the SCCP's long-term causal impact that we address through multiple strategies. The program's non-random placement potentially creates endogeneity and introduces bias, as participating communities may differ systematically from non-participating communities (e.g., proximity to roads, deforestation risk, socio-economic status). Within communities, household-level selection adds further potential bias: larger households were more likely to join, while recent migrants were less likely (Jindal et al., 2012). However, by 2009, 80% of households held agroforestry contracts, with broad participation across socio-economic groups (Jindal et al., 2012), reducing concerns for self-selection biases at this level.

3.2.1. *Remote sensing: measuring the conservation impact*

To estimate the SCCP's causal impact on forest cover, we apply matching before difference-in-differences (DiD) estimations (Blackman, 2013), using Hansen et al. (2013) global forest dataset (30 m resolution, 2000–2019).

1. Forest classification: We define forest as pixels with ≥20% canopy cover in 2000, reflecting miombo woodland structure (Anchang et al., 2020) and report a 30% threshold as robustness check (Table S7).
2. Tracking forest loss (2000–2019): The Hansen dataset records the first year a forested pixel experienced tree cover loss (*lossyear*, ranging from 1 to 19). For each year t, we classify a pixel as forested if (i) it was forest in 2000, and (ii) it had not yet been deforested (i.e., $lossyear > t - 2000$ *or* $lossyear = 0$).
3. Grid-level aggregation: We aggregate binary pixel maps into 9-ha (300 m × 300 m) grid cells and calculate the annual share of forested pixels (0–1). Cells are assigned to treatment if ≥ 80% of their area falls within SCCP boundaries and do not overlap with the GNP.

For the matching at the grid cell level, we include potential control cells from surrounding areas (excluding the GNP), covering in total an area of 6.160 km^2 (blue boundary, Fig. 2). Comparing treated and untreated cells show that the SCCP was placed in an area with higher forest cover and slower deforestation rates prior to the project between 2000 and 2004 (Table S2). We apply nearest-neighbor matching (caliper = 0.05, no replacement) using covariates linked to deforestation. Matching variables are drawn from the established deforestation drivers literature (Börner et al., 2017) and include distance to roads, agricultural areas and settlements, elevation, slope, and pre-treatment forest cover and forest cover trends (2000–2004). These covariates capture the spatial and biophysical factors most strongly associated with deforestation risk in the region. We report robustness to alternative matching specifications, varying the caliper width (0.01, 0.05, 0.10) and sampling with versus without replacement (see Table S8). Matching substantially improves balance, reducing median standardized bias from 44.4% to 4.2%, with all treated cells on common support (Table S3).

PES programs risk leakage if participants shift deforestation outside project boundaries (Börner et al., 2017; Wunder and Angelsen, 2008), though positive information spillovers (e.g., adoption of agroforestry practices) may offset this (Lewis et al., 2011). Such spillovers threaten the Stable Unit Treatment Value Assumption (SUTVA) underlying the DiD approach. One common strategy is to create buffer zones around the intervention area, where spillovers are most likely. We implement this by excluding potential control cells within 5 km of the project area as our baseline specification. However, selecting the buffer width involves a trade-off: narrower buffers retain more potential control cells for matching, which are closer to the treated areas and thus typically more similar on both observables and unobservables, but increases the risk of contaminating the control group if spillovers extend beyond the buffer. We therefore present results across 2-km, 5-km, and 10-km buffers to assess robustness to this choice (Rubin, 1980). Additionally, we provide separate estimations of spillover effects within the 5-km buffer zone (2 km and 10 km as robustness check) around the SCCP project area (see Fig. S2). The same matching procedure is applied for the spillover areas, which significantly improves covariate balance. Detailed diagnostics, bias reduction plots, and common support figures for spillover zones are provided in Fig. S3.

Econometric strategy: We estimate a two-way fixed effects model with time-varying treatment effects for each matched sample:

$$Y_{it} = \alpha_i + \beta_1 Post_t + \beta_2 (SCCP_i * Post_t) + \varepsilon_{it} \tag{1}$$

where Y_{it} is the forest cover in cell i in year t. α_i are cell fixed effects that control for time-invariant unobserved characteristics. β_1 captures the effect of the categorical time variable $Post_t$, which divides our study period into three phases: pre-treatment (2000-2004), treatment (2005-2014), and post-treatment (2015-2019). β_2 is our coefficient of interest, capturing the differential impact of SCCP exposure on forest cover for each of the three time periods through the interaction term ($SCCP_i * Post_t$).

The critical assumption of the DiD approach is parallel pre-trends in forest cover of treatment and control. For the core SCCP areas, we observe no statistically significant pre-trend differences (all $p > 0.05$), with treatment effects ranging from −0.01 to 0.01 percentage points across 2001-2004 (see Fig. S4). For spillover areas results are mixed: The 10-km spillover area shows statistically significant pre-trend differences in 2003 and 2004 ($\beta = 0.07$, $p < 0.05$ and $\beta = 0.08$, $p < 0.05$ respectively), indicating that treated areas were already diverging from controls before the intervention. The 5-km spillover area shows a marginally significant difference in 2001 ($\beta = 0.04$, $p < 0.10$), while the 2-km spillover area shows no significant pre-trend violations. The combined treatment area (project area + 5 km spillover) shows no significant pre-trend differences. Overall, the parallel trends assumption appears satisfied for the core SCCP analysis, while estimates for larger spillover zones should be interpreted cautiously due to potential pre-existing differences in deforestation trajectories (see Table S4).

3.2.2. *Household surveys: socio-economic associations*

The household survey was conducted together with the Instituto de Investigação Agrária de Moçambique (IIAM) in July-August 2022 across two areas (Fig. 2): 15 villages within the SCCP and 15 control villages outside, but also within the GNP buffer zone. In each village, a household list was compiled, and 15–50 households were randomly selected depending on the village size. In total, 738 landowners were interviewed (351 SCCP, 387 control). As baseline data were unavailable for our control area, comparability relies on prior evaluations showing no pre-project socio-economic differences (income, assets, literacy, jobs) between SCCP and nearby non-SCCP villages[3] (Jindal et al., 2012).

Several biases could in principle affect our self-reported survey outcomes, covering both socio-economic measures (wealth, income, perceived SES) and psychological measures (intrinsic motivations, environmental agency). The main concerns are social desirability bias, experimenter demand effects, and pre-existing between-group differences that cross-sectional data cannot rule out. We cannot assess directly whether any of these channels is operating in our setting. Our controls for time-invariant characteristics (age, education, household size, rootedness) provide partial mitigation for compositional differences but not for response biases. We therefore interpret all survey-based findings as associations rather than causal effects throughout the paper.

Sample characteristics: Respondents average 44 years of age, have 4 years of schooling, 35% are women, and live in 8-person households; 35% have always lived in the same village (see Table S17). We find that respondents from SCCP villages are slightly more likely to have lived their entire life in the same village, but they do not differ in other time-invariant characteristics from respondents in control villages, giving us some reassurance that both groups also did not differ in terms of motivations and socio-economic status prior to the SCCP. We account for missing data by multiple imputation through chained equations (MICE) to improve precision of our model estimations (Azur et al., 2011). We compare effects from the imputed regression to full-case regressions and find no differences in effect signs, only precision of estimates (see Table S23–S27).

We estimate both the average effects of the SCCP as well as four group specific effects depending on the selection of participants into the SCCP: The first group consists of respondents from households that had no agroforestry contracts nor a job in the SCCP, but their community received REDD + benefits (38%, n = 135). To the second group belong households that had a job in the SCCP on top of the community REDD + benefits (8%, n = 27). The third group consists of households that had community benefits and agroforestry contract(s) (13%, n = 47). Lastly, there is a group of households with all benefits: agroforestry contracts, a job in the SCCP, on top of the of REDD + benefits (41%, n = 142).

Outcome measures: We compare household wealth, income, perceived economic standing and psychological outcomes (environmental motivations and agency) between SCCP and control villages. Wealth is a PCA-derived index from self-reported assets (radio, TV, sewing machine, bicycle, motorbike, car, mobile phone, solar home system, fishing gear), livestock (goats, chickens, ducks) and farm size. The first component (eigenvalue = 1.7) explains 56% of the variance and serves as the wealth proxy. Income is the respondent's self-reported monthly household earnings for an "average" month. Perceived socio-economic status is measured with Cantril's Self-Anchoring Scale (11-rung ladder) as in Kahneman and Deaton (2010). A higher rung indicates a better perceived economic situation (see Fig. S9).

Motivations to plant trees and environmental agencies were assessed with 5-point Likert items. A PCA on four intrinsic-motivation items yields a single component (≈49% variance explained) with positive loadings on all items. A PCA on three extrinsic-motivation items produces one component accounting for 58% of the variance. Environmental agency is estimated via factor analysis of ten items covering self- and outcome-efficacy, skills, opportunities and locus of control. Detailed eigenvalues and loadings are reported in Tables S18–S21.

Table 2 summarizes the outcome variables used in the analysis. For each variable we give a short definition, the data source, the level of measurement, and the hypothesis (H1–H4) to which it relates. Remote-sensing forest cover maps onto H1 and H2b; agroforestry maintenance onto H2a; household wealth, monthly income, and perceived socio-economic status onto H3; and intrinsic motivations and environmental agency onto H4. GNP employment is used in additional exploratory analysis to understand potential mechanisms underlying H3.

Statistical analysis: All outcome measures are standardized (z-scores) for ease of comparison. For each outcome Y_{ij} (wealth, income, perceived economic situation, motivations, agency) we fit an ordinary least-square regression:

$$Y_{ij} = \beta_0 + \beta_1 * SCCP_j + \beta_2 * X_{ij} + \varepsilon_{it} \tag{2}$$

where β_1 is our estimate of interest capturing the association between

[3] Earlier studies have used the area of Cudzu as control area, which is located close to the SCCP area, but not within the GNP buffer zone. Considering that the GNP increased its activities in the buffer zone post-project, we opted to select a control area within the buffer zone instead.

Table 2
Outcome variables, definitions, and data sources.

Variable	Definition	Data Source	Level	Hypothesis
Forest cover	Share of forested pixels (≥20% canopy) per 9-ha cell	Hansen et al. (2013)	Grid cell, annual	H1, H2b
Agroforestry maintenance	Self-reported maintenance of agroforestry contracts	Household survey 2022	Household	H2a
Wealth index	PCA of self-reported assets, livestock, farm size	Household survey 2022	Household	H3
Monthly income	Self-reported household earnings (average month)	Household survey 2022	Household	H3
Perceived SES	Cantril Self-Anchoring Scale (11 rungs)	Household survey 2022	Individual	H3
Intrinsic motivation	PCA of 4 Likert items on tree-planting motivation	Household survey 2022	Individual	H4
Extrinsic motivation	PCA of 3 Likert items on payment-driven motivation	Household survey 2022	Individual	H4
Environmental agency	Factor analysis of 10 items (self/outcome efficacy, skills)	Household survey 2022	Individual	H4
GNP employment	HH member permanently employed by GNP (binary)	Household survey 2022	Household	H3

exposure to the SCCP and the outcome of interest. The vector X_{ij} includes a series of stable individual characteristics: age, gender, education, rootedness in the village, and household size including household members below the age of 14 for individual *i* in village *j*. For motivation and agency outcomes we additionally control for wealth and monthly income. In separate models, we replace the SCCP dummy with a categorical treatment intensity indicator (as described above) to assess whether more intensive participation strengthens these associations. Unfortunately, we are unable to investigate gender-specific impacts for the household level outcomes such as wealth and income. For the individual level outcomes such as perceived economic situation, intrinsic motivations and environmental agency we investigate whether the associations with the SCCP differed between men and women using interactions models (see Fig. S11).

4. Results

4.1. Long-term conservation impacts

4.1.1. Impact on tree cover

We observe substantial deforestation in our study area between 2000 and 2019, see Fig. 3. Forest cover declined from an average of 95% in 2000 to 83% in 2019 across the matched SCCP and control areas. Our estimate of the baseline deforestation rate (0.7% annually between 2000 and 2004) is significantly lower than the baseline annual deforestation rate of 2.4% (between 1999 and 2007) that was used for calculating reduced carbon emissions under the SCCP (Envirotrade, 2010). In a next step, we estimate whether the SCCP was able to slow down this deforestation trend relative to matched areas which are comparable in terms of pre-deforestation trends and geographic characteristics.

The results of our DiD estimations using the matched remote sensing data show that the SCCP slowed down decreases in forest cover in the SCCP area, see Panel A in Fig. 4. During the program period (2005-2014), forest cover in the SCCP area averaged 2.2 percentage points (pp) higher compared to the control group ($\beta = 2.19$, $p < 0.01$, 95CI = 1.74, 2.64). There was no immediate rebound effect, i.e. surging deforestation after payments stopped. In the post-program period (2015-2019), we find a sustained difference in forest cover of 2.1 pp ($\beta = 2.14$, $p < 0.01$, 95CI = 1.38, 2.91). These are economically sizable effects: deforestation in the SCCP area was 41% less during the program period (2005-2014) and still 20% less in the post-program period (2015-2019) compared to control areas.

Panel B shows predicted forest cover levels over time, revealing that while the program significantly reduced forest loss, it did not stop deforestation entirely. Forest loss accelerated dramatically after 2005 in both areas, but treatment effects peaked during the SCCP period (2005-2014) with maximum impacts of 3.3 percentage points in 2014 significant ($\beta = 3.34$, $p < 0.01$, 95CI = 2.64, 4.04), before gradually declining in the post-program period. By 2019, the treatment effect had diminished to 0.88 pp and was only marginally significant ($\beta = 0.88$, $p = 0.07$, 95CI = −0.06, 1.82; see Panel C of Fig. 4). In summary, we find in our data support **for both H1** (short-term effectiveness), but **only partial** support **for H2b** (medium-term permanence).

Results are robust to alternative forest definitions: using the common 30% canopy cover threshold instead of 20%, we find larger treatment effects of 3.1 percentage points during the SCCP period which increase to 4.0 pp in the post-program for core SCCP areas, with positive spillover effects across all buffer zones (see Fig. S5 and Table S7).

Our DiD estimates account for two sources of leakage. First, by comparing the entire project area against matched controls, any deforestation displaced from REDD + -protected forests — a subset of the project area — to unprotected forest within the SCCP boundary is netted out. Second, we exclude control cells within a 5-km buffer to guard against spillover effects from the outside of the project area. We quantify this external leakage by analyzing forest-cover change in the 5-km buffer. During the program period (2005-2014), forest cover was on average 0.4 pp higher compared to the control group ($\beta = 0.43$, $p < 0.01$, 95CI = 0.11, 0.75). In the post-program period (2015-2019), we find no significant difference in forest cover anymore ($\beta = 0.14$, $p = 0.62$, 95CI = −0.40, 0.67). These results suggest that there has been limited leakage. The findings are robust across alternative spillover zone definitions, with some persisting positive spillover effects in the 2-km area and negative spillovers in the 10-km area, which we treat as suggestive given the pre-trend violations noted above (see Table S4).

The main analysis excludes the GNP from the buffer zone for potential leakages but also from the pool of potential control units, as we consider the enforcement in the GNP as strict resulting in a minimal risk of deforestation. To assess whether proximity to the GNP moderates estimated deforestation reductions, we split the SCCP area at the median distance to the park, see Table S9. Treatment effects are somewhat larger in SCCP cells within 6 km of the GNP boundary (2.4 pp during SCCP, 3.3 pp post-SCCP) than farther away (2.0 pp during, 1.0 pp post-SCCP). This pattern is consistent with several potential mechanisms, including displacement of logging into the park, enforcement spillovers from GNP management, or unobserved heterogeneity along the park edge.

To check for illegal leakage into the GNP, we compare forest-cover trends in GNP cells close to versus far from the SCCP boundary (Table S10). We find no evidence of accelerated forest loss near the SCCP boundary. If anything, GNP cells within 2 km of the SCCP boundary retain slightly more forest after 2005 than cells farther away. GNP forest cover is nearly stationary throughout our observation window (approximately 70%, with a modest 1 pp decline by 2019 in far cells).

Lastly, to assess the potential bias from selection on unobservables, we apply the Rosenbaum procedure for bounding treatment effect estimates (Rosenbaum and Rosenbaum, 2002). This sensitivity analysis evaluates how strong an unobserved confounder would need to be to nullify the estimated treatment effects. We conduct this analysis using matched cell pairs (n = 2251) and estimate bounds for the SCCP

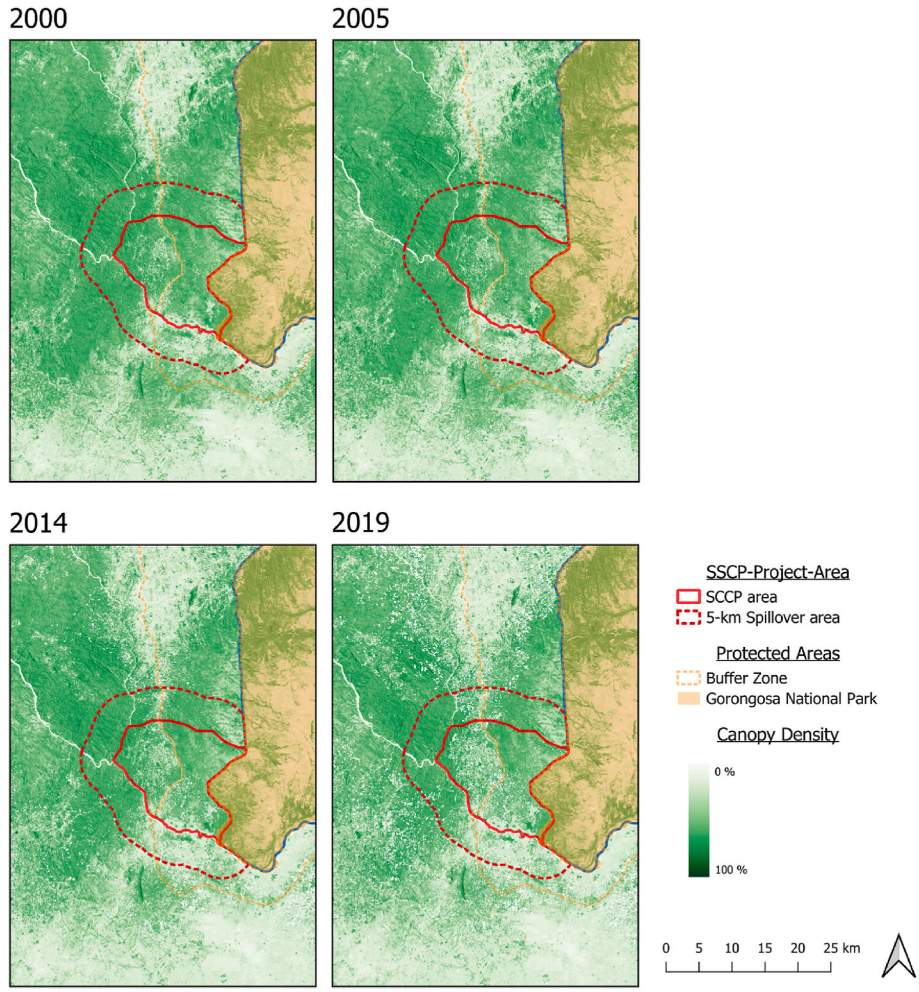

Fig. 3. Forest canopy density changes (2000-2019).
Notes: Forest canopy densities in the study area based on Hansen Global Forest Change v1.7 data. Baseline (2000) forest cover and cumulative loss for 2005, 2014, and 2019 are shown using 'lossyear' data. Maps were created in QGIS 3.3 with Natural Earth basemaps, SCCP boundaries (IIAM), and GNP and buffer zone data (GNP).

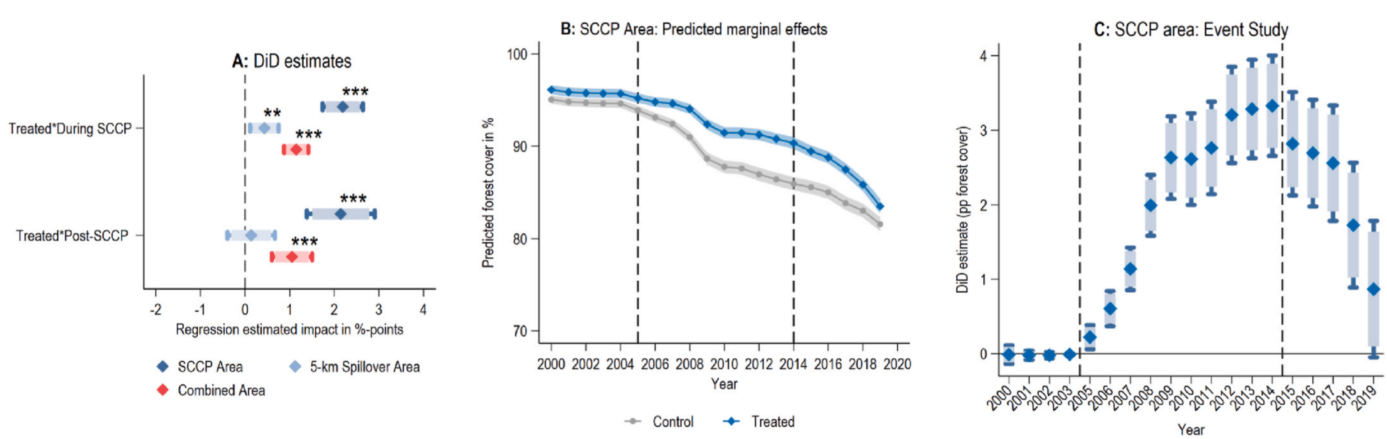

Fig. 4. Impact of the SCCP on forest covers.
Notes: All three panels use the pre-project average (2000–2004) as reference. Estimates are from panel regressions with cell fixed effects. Panel A shows DiD estimates for SCCP (2005–2014) and post-SCCP (2015–2019) with 90% and 95% confidence intervals. Panel B displays predicted marginal effects for treatment and matched control cells. Panel C reports year-by-year DiD coefficients (event study) for the SCCP area using Hansen annual data with 2004 as the reference year, showing flat pre-trends (2000–2003), peak effects in 2012–2014, and attenuation through 2019. Standard errors are clustered at the matched-pair level (*$p < 0.10$, **$p < 0.05$, ***$p < 0.01$). Full models and robustness checks in Table S5–11.

implementation period (2005–2014) and the post-SCCP period (2015–2019), comparing both to pre-program forest trends

(2000–2004). The estimate Γ indicates the extent of hidden bias needed to render the treatment effect statistically insignificant. During the SCCP, the treatment estimate remains robust up to $\Gamma = 1.6$ ($p = 0.02$), implying that an unmeasured confounder would need to increase the odds of SCCP participation by at least 60% to overturn the results. In contrast, the post-SCCP deforestation estimates are more sensitive to hidden bias, becoming statistically insignificant at $\Gamma = 1.4$ ($p = 0.17$) and reversing direction at $\Gamma = 1.6$. These results suggest that the observed reductions in deforestation during SCCP implementation are moderately robust to potential hidden bias, whereas post-SCCP outcomes are less stable and more likely to be confounded by unobserved factors. For full results, see Table S11.

4.1.2. Carbon sequestration and credit issuance

To benchmark the SCCP's mitigation performance, we compare our DiD estimates of avoided deforestation against the project's claimed emission reductions and sold carbon credits, restricting the analysis to the REDD + component for which reliable carbon stock data are available. A detailed description of the approach is provided in SI, Section "Emission Reduction Benchmarking". The project's technical specification assumed that, absent intervention, the entire 9105 ha REDD + area would be deforested by 2047 at an annual rate of 2.4%, and that all remaining forest would persist indefinitely under the project in order to claim permanence. Applying forest-type-specific sequestration potentials and deducting a 30% buffer pool yielded claimed avoided emissions of 571,690 tCO2e. Accounting for a deficit between agroforestry credits sold and generated, we estimate that 273,871 credits were effectively drawn from the REDD + component.

To estimate actually avoided deforestation, we apply our maximum and minimum annual DiD estimates to the full project area of 21,725 ha. For 2014, we estimate a 3.3 percentage point increase in forest cover, corresponding to 717 ha of avoided deforestation. For 2019, the minimum impact estimate yields a 0.88 percentage point gain, translating to 191 ha of conserved forest. We then conservatively assume that all avoided deforestation occurred in the forest type with the highest sequestration potential (riverine forest at 47 tC/ha) and convert it to tCO2e. This yields an upper bound of 123,574 tCO2e and a lower bound of 32,919 tCO2e of avoided emissions. Benchmarked against claimed emission reductions, the project achieved roughly 6% to 22% of its stated mitigation target. Benchmarked against credits actually sold, performance improves modestly to roughly 12% to 45%, as not all marketable credits were sold.

Across all benchmarks, the SCCP delivered a small fraction of its claimed mitigation, consistent with broader concerns about additionality and permanence in VCM-financed REDD + projects. This comparison is an approximation rather than a precise reconciliation. The ex-ante project estimates cover designated REDD + zones under an assumed high-deforestation counterfactual, whereas our ex-post estimates cover the entire project area using observed forest cover changes. Because the two approaches differ in spatial scope, temporal coverage, and accounting methodology, the resulting percentages should be read as indicative of the order of magnitude rather than exact figures; we return to these differences in the Discussion.

4.1.3. Maintenance of agroforestry systems

We next focus on survey data to investigate agroforestry adoption and permanence.[4] Respondents with agroforestry contracts ($n = 188$) had on average 1.7 contracts each, totaling 320 contracts covered with our sample. The most common agroforestry contracts were for boundary planting and dispersed interplanting, followed fruit orchards (mango/cashew) and woodlots (see Panel A in Fig. 5).

One major threat to the permanence of asset-building PES is a rebound effect once payments stop, i.e. participants cut down the trees planted during the project. Seven years after the project, only 15 out of 320 (5%) agroforestry systems were not maintained (panel B), providing support **for H2a** (medium-term persistence of agroforestry) Recipients reported improved microclimate (38%) due to shade and moisture retention by the trees, and enhanced soil quality on their farming plots (34%) as the primary reason for upkeep. Additionally, many respondents reported benefits from regular fruit harvests from their orchards (39%). A minority (3%) mentioned using their trees for timber or firewood. Furthermore, many respondents (28%) were motivated to maintain their systems in the expectation of future payments. Another prominent issue is confusion over ownership; more than half (55%) of respondents who signed agroforestry contracts believe the trees are owned by the implementing NGO *Envirotrade* rather than by themselves.

Of those respondents who abandoned an agroforestry system ($n = 14$), about 50% reported that they didn't know why they did so (see panel D) – potentially indicating a preference not to share what they did with the trees planted under the SCCP. Those who gave a reason reported they cleared the trees for farmland (36%), lack of benefits (7%), or used their trees for firewood (7%).

4.1.4. Intrinsic motivations & environmental agency

We test how participation in the SCCP correlates with intrinsic motivations to plant trees, as well as general environmental agency – i.e., whether people believe they have the power to change environmental outcomes with their actions. REF _Ref168668489 \r \h On average, participants exposed to the SCCP score slightly higher in terms of intrinsic motivations to plant trees than respondents from control villages; however, this difference is not statistically significant ($\beta = 0.12$, $p = 0.30$, 95CI = −0.11, 0.36). Subgroup patterns are reported in Fig. 6, Panel A.

In contrast, we find that perceived environmental agency is positively associated with SCCP participation (Panel B, Fig. 6). Participants exposed to the SCCP have 0.4 standard deviations higher agency than the control group ($\beta = 0.42$, $p < 0.01$, 95CI = 0.23, 0.61), with no significant differences observed across subgroups. In terms of gender, we find no significant differences in motivations and agency (for details see Fig. S11). Overall, SCCP participation is positively associated environmental agency and not negatively association with intrinsic motivations, thus supporting **H4**.

4.2. Household wealth, income, and perceived socio-economic status

Using our household survey data, we further examine long-term associations between SCCP participation and wealth, monthly household incomes, and perceived SES. Respondents from SCCP villages do not differ significantly in wealth from those in control villages ($\beta = 0.15$, $p = 0.13$, 95CI = −0.04, 0.34, see Fig. 7, Panel A). However, differences vary markedly with the intensity of SCCP involvement. Participants who received only community REDD + payments or agroforestry benefits show no positive wealth differences relative to controls. In contrast, individuals who held a job in the SCCP in addition to receiving REDD + payments score 0.30 SD higher on the wealth index ($\beta = 0.30$, $p = 0.04$, 95CI = 0.02, 0.59). and those who participated in all SCCP components exhibit an even larger wealth of 0.37 SD ($\beta = 0.37$, $p < 0.01$, 95CI = 0.11, 0.63). This gradient is consistent with the expectation that the most intensively involved households realize the greatest long-term benefits.

Self-reported household income is significantly higher in SCCP villages, with respondents averaging 0.21 SD above controls ($\beta = 0.21$, $p < 0.01$, 95CI = 0.07, 0.35). This gain is concentrated among full-benefit participants (Panel B). Perceived SES is on average also higher compared to control ($\beta = 0.22$, $p < 0.01$, 95CI = 0.11, 0.33, Panel C), a pattern observed across all treatment subgroups except those with only agroforestry contracts. In terms of gender differences in perceived SES, we find that women in general perceive their economic situation as

[4] See Table S22 for ex-post analyses of selective participation in the agroforestry component.

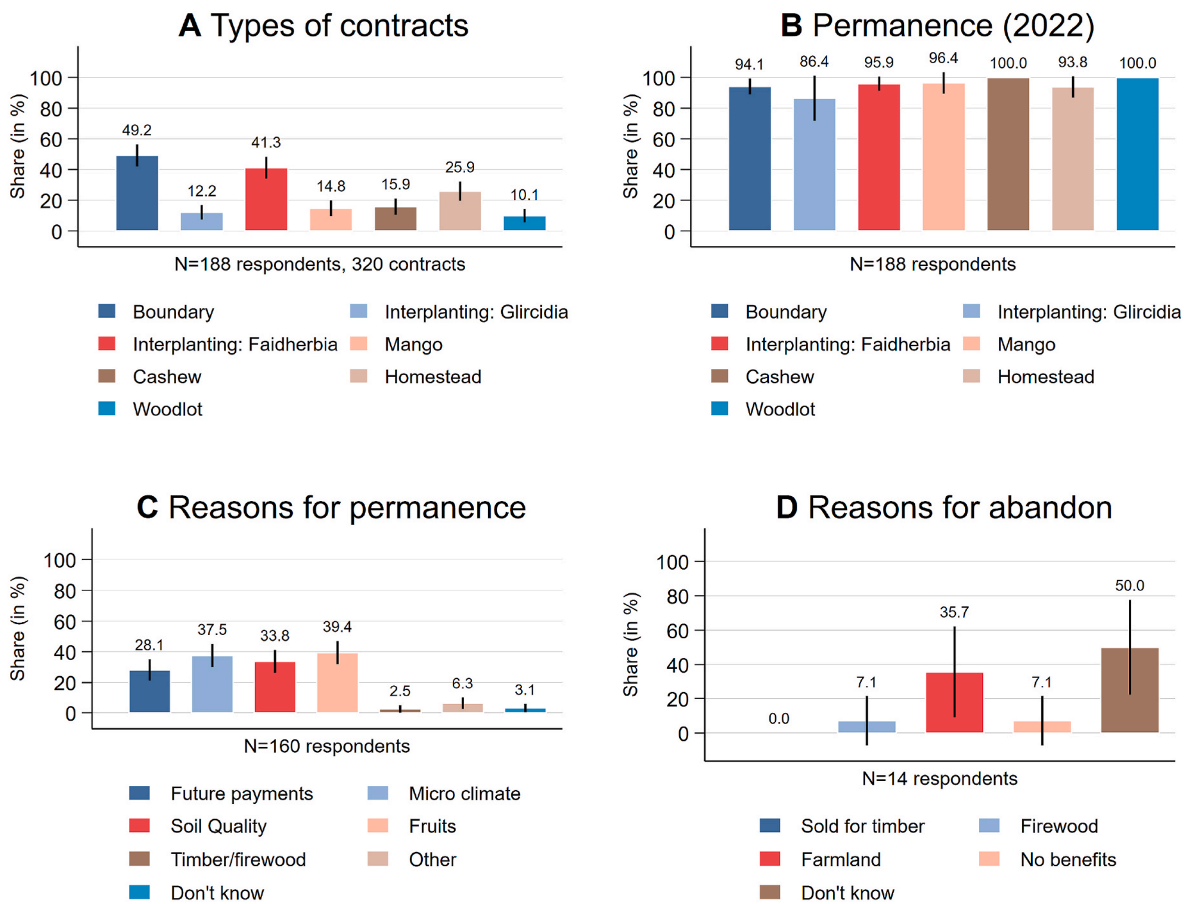

Fig. 5. Agroforestry permanence in SCCP sites.
Notes: This figure illustrates agroforestry contracts and their permanence among SCCP respondents. Panel A shows contract types and prevalence; Panel B, permanence rates in 2022; Panel C, reasons for maintaining systems; and Panel D, reasons for abandonment (n = 14). Respondents could select multiple reasons. Values are means with 95% confidence intervals.

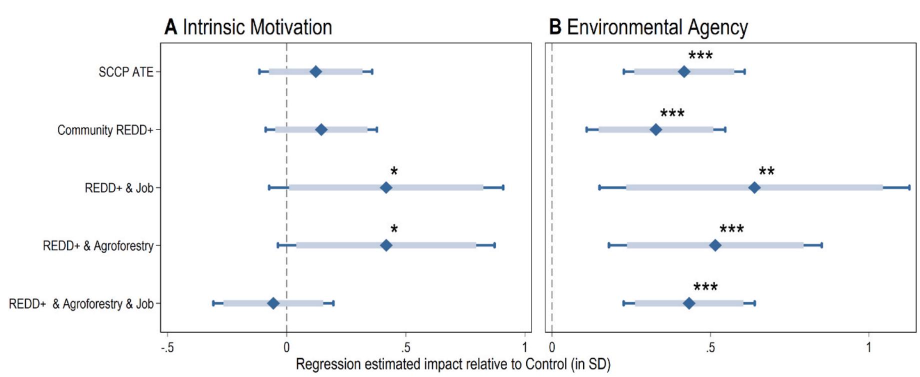

Fig. 6. Intrinsic motivation and environmental agency.
Notes: Buffer zone villages serve as the reference group. Estimates use Stata's 'mi estimate' with controls for age, education, household size, and rootedness. Standard errors are clustered at the village level (*p < 0.10, **p < 0.05, ***p < 0.01). Full results appear in Table S26 and Table S27.

better than men but the association with the SCCP does not differ between gender (see Fig. S11). Overall, SCCP participation is associated with higher perceived SES and modestly higher monthly incomes, thus supporting **H3.**

Overall, households that held employment in the SCCP appear to have sustained their economic gains after the project ended. This comparison is made within the SCCP treatment area: all households in the sample were exposed to the project, but only a subset held a job in it. Our data indicate that job-holding is positively associated to later permanent employment with the GNP, which may explain these persistent wealth differences. Fig. 8 shows that respondents with SCCP job experience are more than five times as likely to have at least one household member permanently employed by the GNP (e.g., as rangers or in tourism) compared to those who did not have this opportunity ($\beta = 19.25$, $p < 0.01$ 95CI = 7.28, 31.22). By contrast, there are no significant differences in non-permanent employment between the two groups.

Fig. 7. SCCP correlation with wealth, incomes, and perceived economic situation.
Notes: Buffer zone villages serve as the reference group. Estimates use Stata's 'mi estimate' with controls for age, education, household size, and rootedness. Standard errors are clustered at the village level (*p < 0.10, **p < 0.05, ***p < 0.01). Full models are in Table S23–25.

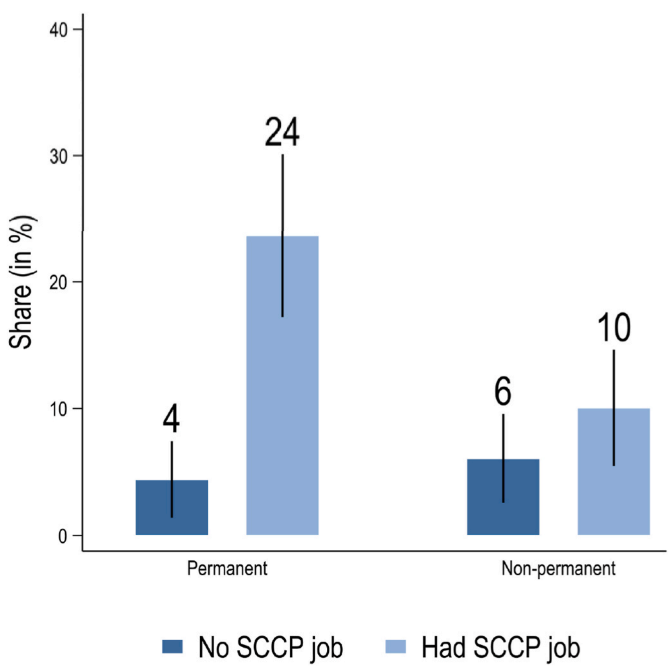

Fig. 8. SCCP area: Permanent and non-permanent employment in GNP.
Notes: Share of SCCP respondents (n = 351) with at least one household member permanently (left) or temporarily (right) employed by the GNP. Values are means with 95% confidence intervals.

5. Discussion

One of the key challenges of NCS initiatives concerns financing, which have led to an increased emphasis on private funding sources such as the VCM. Being a market-based instrument, such financing is inherently associated with uncertainty, which can lead to the unplanned discontinuation of schemes. This study presents a long-term evaluation of the Sofala Carbon Community Project (SCCP), an VCM-financed intervention that had to cease operations after running costs could not be covered by carbon credits sales. The scheme combined use-restriction with asset-building PES and development components, to decrease deforestation and support agroforestry adoption on smallholder farmland. By assessing environmental, socio-economic, and behavioral outcomes five to seven years post-project, this research provides evidence on the permanence of VCM project outcomes at the local level and from a global mitigation perspective. We distinguish between short-term effectiveness during implementation and medium-term permanence after payments ceased.

Our findings show that the SCCP had a measurable, though largely temporary, effect on forest conservation, and is associated with positive differences in rural livelihoods. During the program period, forest cover in SCCP areas was 2.2 pp higher than in matched controls, equivalent to a 40% reduction in deforestation. This effect persisted to a lesser extent post-intervention, with tree cover remaining 2.1 pp (a 20% reduction) five years after the program ended. However, by 2019, statistically significant differences were only observable using the 30% canopy cover threshold, suggesting a gradual rebound in deforestation to levels approaching those in control areas. We also detect short-lived positive spillovers to adjacent areas, further indicating that the program delayed rather than permanently reversed deforestation trends. These raise concerns about the long-term permanence of environmental gains, especially if deforestation accelerates beyond 2019. This attenuation pattern is more consistent with delayed rather than avoided carbon emissions, which reduces the mitigation value of the project below what a static end-of-period snapshot would imply. In line with recent critiques (Romm et al., 2025; West et al., 2025), our analysis reveals that the actual baseline deforestation rate (0.7% annually between 2000 and 2004) was substantially lower than the 2.4% rate used by SCCP implementers to estimate carbon benefits, suggesting that the program's claimed additionality and emissions reductions have been overstated.

From a global climate change mitigation perspective, the foremost question is whether the carbon credits sold in the VCM are reflected in sequestration achieved. Because the ex-ante claims and our ex-post estimates are not fully comparable in spatial scope and accounting, these figures are approximate. On conservative assumptions, the actually avoided deforestation represents roughly 6% to 22% of the targeted net sequestration, using respectively the 2019 estimate of 0.88 pp and the 2014 peak of 3.3 pp. Benchmarked against credits actually drawn from the REDD + component (including coverage of the agroforestry deficit), performance ranges from roughly 12% to 45%. These figures are largely in line with other rigorous impact evaluations of REDD+ and VCM projects who also apply quasi-experimental methods to remote sensing data (Demarchi et al., 2023; West et al., 2020; Probst et al., 2024), casting further doubt on the effectiveness of avoided deforestation projects under historical VCM practices. Ongoing reform efforts, such as the Integrity Council for the VCM core carbon principles, aim to address these shortcomings, but our findings corroborate the critique of past practices rather than of the VCM in principle. A recent review of 26 voluntary REDD + projects in six tropical countries found that 18 projects were not additional and the eight that did reduce deforestation delivered smaller results than claimed (West et al., 2023). This is not surprising, as project implementers, motivated to sell more offsets, have incentives to inflate baseline deforestation rates (Romm et al., 2025; West et al., 2024, 2025), aligning with our findings of an inflated baseline in the SCCP. Besides the inflated baseline scenario, SCCP project assumed that despite 7 years of REDD + payments these forests would be permanently conserved. Our event study, however, reveals a marginally significant treatment effect in 2019 (0.88 pp, $p = 0.07$), so the assumption that conservation gains persist over decades is inconsistent with the observed trajectory.

The SCCP bundled forest protection with agroforestry assets and employment, so its environmental and socio-economic outcomes stem from the same components rather than from separate channels. A key difference from these prior studies is that we also investigated local impacts in terms of household wealth and income, perceptions of the program, and psychological effects. This approach allows us to contrast the program's performance in terms of climate change mitigation with suggestive evidence on the local socio-economic impact. Our findings, interpreted cautiously because of the correlational nature, suggest that SCCP participation is associated with higher household wealth and perceived economic status. Households in SCCP villages reported higher monthly incomes and a stronger sense of economic well-being than those in control villages, although these gains were not evenly distributed. Consistent with evidence from an earlier assessment of the SCCP (Jindal et al., 2012) and other asset-building PES programs (Pagiola et al., 2020), the most pronounced positive differences were concentrated among participants who had been employed by the project. Employment is most strongly associated with socio-economic advancement, consistent with short-term income during the program and potential longer-term gains in skills and networks. Consistent with this interpretation we find that former SCCP employees being more likely to obtain permanent wage employment in the neighboring Gorongosa National Park.

The asset-building component of the SCCP is also associated with lasting differences in land use. Seven years after the program ended, 95% of the agroforestry systems established during SCCP remained in place, suggesting a potential shift away from deforestation-dependent livelihoods. Information spillovers may have further supported adoption, as 64% of all surveyed households reported practicing agroforestry post-program, with no significant difference between treatment and control villages (Lewis et al., 2011).[5] These findings are in line with studies in Latin America focusing on the long-term impact of asset-building PES (Calle, 2020; Pagiola et al., 2016b, 2020; Rasch et al., 2021). Participants in our study cited improved soil quality, enhanced microclimates, and steady fruit harvests as major benefits, providing sufficient incentives to maintain agroforestry systems. However, limited market access has restricted the commercial viability of these systems (corroborated by anecdotal evidence during our field visits), with most production used for subsistence. This may explain why income gains from agroforestry were modest and largely limited to those with additional access to wage employment through the project.

Despite the SCCP's positive environmental and economic outcomes, our findings highlight a common challenge in PES implementation: balancing conservation goals with equitable development outcomes (Romm et al., 2025; Jayachandran, 2023). The concentration of economic benefits among employed participants underscores the risk of uneven distribution, particularly in low-income settings. This reflects broader concerns in the PES literature, where programs often struggle to align poverty alleviation with environmental objectives (Alix-Garcia et al., 2015). To ensure more inclusive outcomes, future interventions should adopt targeted strategies to expand access to employment and decision-making. In addition, we find troubling evidence of limited understanding of agroforestry contracts among respondents. About 25% of respondents who signed contracts believe there is a possibility of receiving future payments, even though the project was terminated and PES contracts only specify payments for the first seven years. Additionally, roughly half of these respondents think that planted trees are owned by *Envirotrade*, raising concerns that private PES schemes may be altering perceptions of property rights. This case illustrates the broader challenges in VCM where relationships between project developers and local communities is characterized by power and information asymmetries (Pan et al., 2022; van Kooten, 2017).

Regarding concerns about motivational crowding-out often associated with financial incentives in conservation programs (Rode et al., 2015; Akers and Yasué, 2019), our survey results suggest that the SCCP did not undermine participants' intrinsic conservation motivations. In fact, those who participated in agroforestry and REDD + activities show stronger environmental agency. Participants with SCCP exposure report stronger belief in their ability to influence conservation outcomes, which may be associated with the project's training in agroforestry, microenterprises, and employment opportunities. These findings align with evidence from other terminated PES projects indicating that environmental motivations are not crowded-out (Vorlaufer et al., 2023), when in-kind payments are used (Grillos et al., 2019) or when combined with skill development through trainings (Blanco et al., 2023). These findings suggest that PES programs, when designed with community involvement and long-term sustainability in mind, are consistent with reinforcing rather than undermining conservation motivations.

Taken together, our two empirical approaches yield a mixed picture of a single program that bundled household asset-building and employment with forest protection. The remote sensing analysis provides credible causal evidence that the SCCP reduced deforestation during implementation, with the gains persisting but attenuating five years after payments ended. The household survey, limited to correlational comparisons, points to lasting socio-economic gains, namely agroforestry assets, conservation skills, environmental agency, and employment, particularly among participants employed by the program. Agroforestry adoption persisted among 95% of contract holders, indicating that the asset-building rationale largely succeeded and may generate local environmental benefits on participating farms. These durable household-level outcomes did not, however, translate into sustained avoided deforestation; the attenuating forest-cover impact shows that on-farm adoption did not relieve pressure on the surrounding forests once payments and enforcement ceased. Positive associations between participation and environmental agency are consistent with the program having strengthened internalized conservation motivations, which may help sustain on-farm practices such as agroforestry. Even so, these behavioral drivers were not sufficient to maintain the forest-cover gains achieved during the project into the medium to long term.

A key limitation of this study is the non-random assignment of the SCCP, which could introduce selection bias and affect the causal inference of its impacts (Imbens and Rubin, 2015). Although matching techniques were applied to mitigate differences between treatment and control groups, unobserved factors may still have influenced participation. While Rosenbaum bounds suggest robustness against unobserved confounders, future research could strengthen causal inference by employing more sophisticated methods, ideally by randomizing access to the program. For the socio-economic impact assessment, we compared the project area to another area with similar characteristics; however, the absence of baseline data prior to project implementation precluded a Before–After–Control–Intervention design, as employed in prior studies (Malan et al., 2024; Carrilho et al., 2022; Montoya-Zumaeta et al., 2022; Nantongo et al., 2024). To our knowledge, most of these studies have been implemented in government-financed pilot projects rather than by VCM actors (except

[5] See Fig. S10 for additional information on agroforestry adoption in the control area using our survey data.

(Malan et al., 2024)). It is important to note that the nature of VCM projects often does not involve collecting pre-project data, which creates a strong risk of selection bias when solely focusing on projects meeting such pre-conditions. The same limitation applies to randomized programme access, which may provide more robust causal inference but cases where such interventions are implemented are hardly representative for the larger share of VCM projects. There consequently seems a trade-off between internal validity and generalizability. While remote sensing data can circumvent this challenge to some extent by applying quasi-experimental methods, it remains a key trade-off for socio-economic impact assessments.

Moreover, studies evaluating the permanence of REDD+ and PES projects more broadly face the question of what an appropriate time scale for assessment is. VCM projects often assume very long or even permanent environmental impacts - in our case, 100 years for agroforestry and indefinitely for the REDD + component - yet causal attribution of impacts becomes increasingly difficult over longer time horizons. Our findings are therefore notable: even within a relatively short post-project window of 5 years, the forest cover gains achieved during implementation had largely disappeared. Nonetheless, future studies ideally complement our and other studies on medium-term outcomes, with more long-term perspectives.

Finally, the SCCP was located adjacent to a national park that has, at least in recent years, received considerable donor funding. The employment pathway outlined as a post-hoc explanation for our findings is therefore specific to settings where PES projects operate near protected areas with active management and tourism infrastructure. Gorongosa National Park offered permanent ranger and tourism positions, which limits the direct transferability of our findings to other contexts. Many REDD+ and PES projects are, however, intentionally located close to protected areas, so the SCCP setting is not entirely idiosyncratic: existing conservation organizations active near or within protected areas frequently tap into the VCM, and implementing organizations strategically target areas with high biodiversity and iconic species; a pattern that appears to be corroborated by several prior impact evaluation studies (e.g. 27, 40).

6. Conclusion

Our study offers lessons for future PES design and for ongoing debates about the VCM as a global market-based climate change mitigation instrument. In line with emerging evidence from other REDD + projects, we find that the SCCP falls short of its claimed emission reductions, adding to concerns about the reliability of VCM-financed REDD + for global mitigation. Initial forest conservation gains achieved during the project were attenuating after its termination and largely disappeared after 5 years. Overstated deforestation baselines further underscore the need for conservative, empirically grounded carbon accounting, for example through ex-post evaluations (Delacote et al., 2025). In addition, blended public–private finance models may offer greater funding stability compared to relying solely on the VCM (Le et al., 2024).

Even if projects fall short from a global mitigation perspective, they can be associated with positive long-term outcomes at the local level, even when terminated prematurely. While our remote sensing analysis provides more robust causal evidence, the socioeconomic findings rest on a post-treatment cross-sectional comparison and should be interpreted cautiously. With this caveat in mind, the SCCP suggests that integrated approaches combining use-restriction payments with asset-building activities, such as agroforestry and skill-building, can yield environmental co-benefits and are associated with socio-economic gains at the local level. Development components that provide employment opportunities may be a particularly valuable element, given their association with more durable rural livelihoods. In our case, access to permanent employment in the national park is likely a precondition for such enduring benefits. To ensure these positive outcomes are broadly shared, future programs should prioritize access for marginalized groups, such as land-poor households, and promote inclusive governance of community-level PES revenues. Clear communication about contract terms and tenure rights is also essential to prevent long-term misperceptions. Overall, our results highlight the need for a differentiated perspective when evaluating projects under global instruments such as the VCM, complementing carbon mitigation assessments with a focus on local environmental and socio-economic outcomes.

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CRediT authorship contribution statement

Ivo Steimanis: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Tobias Vorlaufer:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Björn Vollan:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2026.130542.

Data availability

The replication package including the analysis scripts for STATA and datasets are publicly available on GitHub (link).

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