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Redesigning payments for ecosystem services to increase cost-effectiveness

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Payments for Ecosystem Services (PES) are a widely used approach to incentivize conservation efforts such as avoided deforestation. Although PES effectiveness has received significant scholarly attention, how PES design modifications can improve program outcomes is less explored. We present findings from a randomized trial in Mexico that tested whether a PES contract that requires enrollees to enroll all of their forest is more effective than the traditional PES contract that allows them to choose which forest parcels to enroll. The modification's aim is to prevent landowners from enrolling only parcels they planned to conserve anyway while leaving aside other parcels to deforest. We find that the full-enrollment treatment significantly reduces deforestation compared to the traditional contract (41% less deforestation; $p = 0.01$). As a result, cost-effectiveness of the PES program quadruples. This result highlights the potential to substantially improve the efficacy of conservation payments through simple contract modifications.

Human-driven tropical deforestation is a significant contributor to greenhouse gas emissions[1] and biodiversity loss[2–5]. Tropical deforestation often occurs in high-poverty areas with limited government capacity to enforce bans. Consequently, Payments for Ecosystem Services (PES) programs have emerged as a promising policy to achieve forest conservation without exacerbating poverty[6,7]. PES programs offer cash or in-kind incentives to participating landowners or communities, with payments conditional on specific natural resources management activities, such as forest protection[8,9]. A recent review recorded 550 active PES programs globally with around US$40 billion in annual transactions[10].

Whether and when PES programs are effective in achieving desired outcomes has received considerable scholarly attention. The consensus is that the essential preconditions are that participants face low opportunity and transaction costs to conserve, which makes it possible to increase their conservation activity using feasible payment amounts[11]. In addition, program performance is said to depend on contextual, implementation, and program design factors[6,12]. Regarding program design, the relationship between design features and program outcomes has been discussed conceptually[12–14] and empirically[6,15], and prior studies have used lab-in-the-field or framed field experiments to examine the effects of PES design on outcomes such as participation[16], equity perceptions[17], and collective action[18,19]. While randomized controlled trials (RCTs) that assess environmental outcomes of actual PES schemes have emerged in recent years, these have mostly evaluated program effects against a no-program scenario[20–26], as opposed to isolating the effects of design variations. One exception is a study of PES to reduce agricultural burning in India that experimentally varied payment levels, conditionality, and upfront versus ex-post payments[27].

We test a design variation aimed at reducing inframarginal payments in PES for forest protection. PES effectiveness depends crucially on the extent to which payments are inframarginal, or made for protecting forests that would have been protected even without the financial incentive[8]. Locating a program in a landscape with low deforestation risk can exacerbate inframarginality[6]. We focus on another source of inframarginality: participants' strategic selection of which land to enroll[28]. If eligible landowners systematically enroll the subset of their lands that they were unlikely to deforest, many of the payments will be for conservation that would have happened anyway.

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Reducing inframarginal payments is especially important because the policy objective for PES is not just effectiveness but cost-effectiveness, e.g., additional forest cover per dollar of program expenditures. Inframarginal payments add to program costs without generating benefits, so they depress cost-effectiveness. Improving cost-effectiveness is critical given under-funding of conservation initiatives[29] and a recent trend of PES program downsizing or discontinuation in some contexts[30–32], including Mexico, our study's setting.

In this article, we conduct the first randomized trial to test the impacts of requiring PES participants to enroll all of their eligible forest landholdings (full enrollment). The primary outcome is avoided deforestation, measured using satellite imagery. The study takes place in the Marqués de Comillas (MdC) municipality in Selva Lacandona, Chiapas state, Mexico.

We compare the full-enrollment treatment group to a control group that was offered a PES contract that gives participants the flexibility to enroll some lands for conservation while leaving other lands outside the program (standard PES or partial enrollment). Since payments are conditional on maintaining only the enrolled parcels, under standard PES, participants can be in compliance yet continue their business-as-usual deforestation by clearing non-enrolled lands. The partial enrollment provision is used in Mexico's national Pago Por Servicios Ambientales (PSA) program and other major PES programs worldwide such as the Conservation Reserve Program in the US[33]. Our standard contract closely follows PSA but with a one-year duration (June or July 2021 to June or July 2022) rather than a five-year duration. Note that there is no pure control group that was not offered PES; the study is designed to measure the relative performance of full enrollment, compared to standard PES.

The 64 study participants are landholders who had recently applied to PSA and met PSA's program requirements but who were rejected due to Conafor's limited budget. This sampling strategy zeroes in on a population interested in participating in PES. Moreover, because we have access to their PSA applications, we know which land parcels the full-enrollment treatment group would have chosen to enroll had they been allowed to partially enroll their land. We mapped all of the forests owned by each landholder, so we also know the parcels left out of the program by the standard-PES control group.

To expand on why full-enrollment might (or might not) be a valuable modification, suppose the owner of 20 forest hectares wants to clear 4 hectares during the contract period. With a standard PES scheme, she can enroll the other 16 hectares, keep them intact, deforest the left-out 4 hectares, and receive payment, despite not having reduced her deforestation at all. She is paid for 16 hectares of conservation, but the payments are entirely inframarginal. In contrast, a full-enrollment scheme offers her the choice of not participating or enrolling all 20 hectares she owns. Now she cannot receive payment without reducing her deforestation. If she complies, she will generate more additional forest cover under full-enrollment (4 hectares versus 0 hectares). However, another implication is that, due to the more demanding contract terms, full enrollment reduces the likelihood that she chooses to comply. Combining these two predicted effects, the net effect on forest cover is ambiguous, though full enrollment should outperform standard PES on forest cover per dollar spent, or cost-effectiveness. We test all of these predictions.

Our study is the first to empirically compare full-enrollment against standard, partial-enrollment PES. We build on a previous study that evaluated the impact of full-enrollment PES in Uganda relative to a no-PES control group[25]. That study found less inframarginality and more cost-effectiveness than is typical for PES. Based on that result, we hypothesized that requiring full enrollment among PES participants in Mexico would increase cost-effectiveness and likely the amount of forest preserved.

Mexico has one of the oldest and largest government-funded PES programs worldwide, in terms of both area enrolled and public spending[34]. Since 2003, it has been implemented by the National Forest Commission (Conafor) and has focused on preventing land cover change, particularly deforestation, in critical ecosystems[35,36]. Mexico's PES (or PSA in Spanish) provided annual payments of MX $1,000 (approximately US$50) per hectare in the study area in 2021. The conditions for payment are maintaining forest cover and performing forest management activities on enrolled lands. Program compliance is monitored through periodic field visits and remote sensing. Most applications are made at the ejido (community) level, bundling individual and sometimes collectively-managed landholdings[15]. Local implementation is facilitated by Conafor-appointed intermediaries who help communities prepare applications and oversee program activities. Our implementing partner, the non-profit Natura Mexicana, is a Conafor intermediary.

Many but not all studies find that PSA has been effective at reducing deforestation[35,37–39]. However, PSA's funding has declined. From 2015-2019, Conafor's annual budget was cut by 70% in real terms[40]. Although demand for PSA has exceeded available funding since the program's outset[36], the shrinking budget has recently made access considerably harder for interested communities[15].

Previous research specifically in MdC finds that PSA has reduced deforestation on enrolled lands[38,39] and yielded socio-economic co-benefits[41,42]. However, prior research also finds that most landholders enroll only a fraction of their eligible property, and deforestation rates are high on non-enrolled lands, which participants consider more productive for ranching and agriculture[28].

As reported below, we find that the full-enrollment contract significantly reduces deforestation compared to the standard contract, and all of the extra conservation is on parcels that the landowners would have left out of the program had they been offered that flexibility. We estimate that the full-enrollment treatment more than quadrupled cost-effectiveness, which highlights the potential to substantially improve the efficacy of conservation payments through simple contract modifications.

Results

Treatment effect on deforestation

Table 1 reports the effects on deforestation of the full enrollment contract (treatment), relative to standard PES. Specifically, we examine how much of the forest that existed at baseline was deforested over the PES contract period. The outcome is a binary variable that equals 1 if the pixel is non-forested at the end of the study period. The baseline month is May 2021 (because the first contracts started in June 2021), and the endline month is August 2022 (because the last contracts ended in July 2022).

We first analyze deforestation within each participant's entire forest area, enrolled or not (column 1). In the standard contract arm, 14% of the forest area was deforested over the year. The treatment group deforests 5.7 percentage points (pp) less (p-value = 0.01), equivalent to 41% less deforestation. Supplementary Fig. 1 presents this treatment effect in the context of deforestation trends from 2017 to 2023. The treatment years of 2021 and 2022 are the only years when the deforestation rate is significantly lower in the treatment group than control group.

Column 2 restricts the sample to forest pixels the individuals were planning to enroll in Conafor's PSA (Conafor area). This area is covered by our PES contract for both treatment and control groups. The number of observations (pixels) in column 2 is 49% of the observations in column 1, which represents the proportion of their forest that landowners enrolled when given choice. For this land, the deforestation rate is relatively low (1.9%) in the control group and nearly identical in the treatment group.

We next examine the forest that the participant had not wanted to enroll in PSA (column 3). Five people included all of their forests in their 2021 PSA application so have no non-Conafor area. The control group was in compliance with their contract regardless of what they did on these parcels, while the treatment group had to conserve them to be in compliance. Deforestation is very high in the control group for these parcels, at 28.8%. In the treatment group, the deforestation rate is 13.5 pp lower (p-value = 0.000), equivalent to 47% less deforestation on these parcels.

As an alternative analysis, Table 2 presents the results at the individual level instead of pixel level. Odd columns present average treatment effects, while even columns study heterogeneity by the amount of forest at baseline. Column 1 shows that weighting each landowner equally, there is no significant difference in deforestation between the contracts. This pattern can be reconciled with the result in Table 1 if the treatment reduced deforestation more for owners of large amounts of forest. Column 2 shows that this heterogeneity indeed is present. The treatment reduces deforestation among those who own above-median forests (by 8.2pp on net, p-value = 0.005), but not among those with below-median forests. Columns 3–6 show results for the Conafor and non-Conafor parcels, and, as expected, the improved performance of the treatment contract is because of lower deforestation in the non-Conafor area.

Treatment effect on compliance

In the control group, 30 out of 33 individuals (91%) complied. In the treatment group, 22 out of 31 (71%) complied. One landowner in each arm chose not to enroll in the PES program. The other non-compliers enrolled but deforested some of their enrolled land. The lower compliance rate in the treatment group (p-value = 0.04) is consistent with the stricter requirements of the full-enrollment contract. Despite the lower compliance rate, the treatment reduced total deforestation because it led to much higher averted deforestation per person who complied.

Table 1 | Treatment effects on deforestation

	Deforestation May 2021–August 2022		
	Property area (1)	Conafor area (2)	Non-Conafor area (3)
Treat	− 0.057	− 0.004	− 0.135
	(0.021)***	(0.008)	(0.036)***
	[0.01]	[0.62]	[0.00]
Control mean	0.142	0.019	0.288
N	779451	382350	397101

Each observation is a 4.59 m by 4.56 m pixel within the landholding of a study participant, that was forest-covered at baseline. All regressions include ejido fixed effects. Robust standard errors are in parentheses and are based on a two-sided test. p-values in square brackets.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Cost-effectiveness

Our finding that the treatment reduced deforestation by 5.7% of total forest area relative to standard PES (Table 1, column 1), is one input into a cost-effectiveness calculation. We also need the absolute amount of avoided deforestation under each contract type. For this, we need to make an assumption about how much-averted deforestation was caused by standard PES relative to a scenario with no PES. Based on the previous literature, we assume standard PES led to 2.2% less deforestation per year on enrolled land, which implies 1.1% less deforestation on total land[38]. This assumes no impacts on non-enrolled land, which is a generous assumption for standard PES because deforestation might have shifted from enrolled to non-enrolled land. This assumption choice yields a conservative estimate of the gains in cost-effectiveness from our treatment.

Full-enrollment PES therefore prevented 6.8% of forest area from being lost relative to no PES (1.1% + 5.7 %). This implies 65.8 hectares of avoided deforestation with full-enrollment PES and 7.3 hectares with standard PES.

The treatment increased hectares of forest enrolled and payments. In the standard PES group, we paid in total MX$313,400, and in the treatment group, MX$591,000. This implies MX$42,932 (US$2143) per hectare of avoided deforestation for standard PES versus MX $8,982(US$448.29) for full-enrollment PES. (We use the mid-July 2021 exchange rate of MX$20.036 = US$1.) Administrative costs are low relative to payments; they reduce the relative cost-effectiveness of the treatment because they are also incurred for non-compliers. Thus, our treatment increased PES cost-effectiveness by a factor of 4.8.

To quantify the carbon benefits of full-enrollment PES, we use prior estimates that the Lacandona forest stores 550 metric tons of CO_2 per hectare[43]. The environmental benefits of a short-term PES program derive from delaying deforestation. We assume that after the contract period ends, landowners revert to their business-as-usual deforestation: they do not continue with their higher conservation rate, but they also do not deforest at a higher catch-up rate[25]. Using a 3% discount rate, we can express the delayed emissions in terms of the equivalent permanently avoided emissions. This calculation yields that

Table 2 | Treatment effects at the individual level, including heterogeneity by baseline forest area

	Deforestation May 2021–August 2022					
	Property area		Conafor area		Non-Conafor area	
	(1)	(2)	(3)	(4)	(5)	(6)
Treat	−0.039	0.011	−0.007	−0.009	−0.126	−0.091
	(0.025)	(0.039)	(0.018)	(0.026)	(0.041)***	(0.070)
	[0.13]	[0.78]	[0.71]	[0.78]	[0.004]	[0.20]
Treat × Above-median forest area at baseline		−0.093		0.013		−0.063
		(0.050)*		(0.029)		(0.081)
Above-median forest area at baseline		0.023		−0.030		−0.001
		(0.043)		(0.035)		(0.062)
Control means	0.138	0.138	0.031	0.031	0.311	0.311
p-value: Treat + Treat × Above-median forest area at baseline = 0		0.005		0.767		0.001
N	64	64	64	64	59	59

Each observation is a landowner. All regressions include ejido fixed effects. Robust standard errors are in parentheses and are based on a two-sided test. p-values in square brackets.
*$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

full-enrollment PES's cost is US$4.76 per metric ton of permanently averted CO_2.

Discussion

Because tropical deforestation rates are high—contributing to climate change and biodiversity loss—while conservation funding is limited, there is a pressing need for design improvements in conservation policies[6]. Our findings from a proof-of-concept PES experiment in Mexico suggest that simple contract design changes can enhance the cost-effectiveness of conservation payments.

We found that introducing a requirement for PES participants to enroll all their forest led to 5.7 percentage points less annual deforestation than what is achieved with a standard PES contract that allows for strategic land selection, or 41% less deforestation. As predicted, the extra conservation is on parcels that individuals were not planning to enroll if given the choice. Drawing on prior estimates of the effectiveness of standard PES in our study context[38], we calculate that our contract modification more than quadrupled the cost-effectiveness of PES. Our results confirm our hypothesis that infra marginality can be widespread when PES design allows for strategic land enrollment by participants. Many PES programs worldwide give participants this latitude, so the modification we introduce has wide applicability.

Importantly, the improvement in PES performance did not require a sophisticated market mechanism to elicit the landowner's private information about their opportunity costs and planned land decisions[44,45] or a prediction model to identify where additionality and ecological benefits would likely be high[46–48], as have been suggested to improve spatial targeting. Our improvement came from amending a clause in the contract and essentially closing a loophole that allowed landholders to continue business-as-usual deforestation but receive PES payments.

Moreover, we document a high rate of landowner satisfaction with the program: 100% of endline survey respondents in the full enrollment arm and 90% in the standard PES arm expressed satisfaction and interest in participating in a program like ours again. If we assume those who did not complete the endline survey were unsatisfied, the satisfaction rates were 84% for full-enrollment and 82% for standard PES—still quite high and, notably, as high among those offered the full-enrollment contract.

Yet our results also highlight the potential trade-offs when tweaking policy design. Adding a more stringent land enrollment requirement generated more additional forest cover among those who complied but also reduced the compliance rate. Theoretically, the net effect of our design change on total averted deforestation could have been positive or negative, depending on the magnitude of each effect. We attribute the observed net positive effect to how the design change interacted with contextual and implementation factors[12], namely (i) large land endowments, leading to widespread partial enrollment among participants; (ii) high deforestation rates driven by cattle expansion in the region, which created significant scope for reducing land conversion; (iii) a high degree of trust and local legitimacy towards our procedures, as reflected by participant satisfaction; and (iv) our ability to monitor and sanction non-compliance effectively.

We note that some of our study innovations relative to Conafor's PSA, such as mapping of total landholdings and more stringent enforcement, would be challenging to achieve at a large scale from technical and political standpoints. In addition, our contract duration was only one year, and with a longer contract period, landowners may be less willing to comply with the more demanding full-enrollment contract. One needs to be cautious in extrapolating our results to a more typical five-year contract duration. Two additional study limitations are that the results are based on a small sample, and we focused on effects on deforestation; our study does not analyze socioeconomic effects. Thus, we view our results as demonstrating the possibility of very large gains from using a full-enrollment contract design, with more evidence needed to understand the gains that would be achieved at larger scale and over a longer duration.

Future studies could also test our design modification in other contexts or test other PES innovations. We encourage more A/B testing like this, particularly using random assignment because of its ability to isolate and quantify the effect of specific design or implementation features[27]. There are disadvantages of not having a pure control group, but A/B testing has the advantage that everyone is offered the program, which diminishes concerns about some study participants being left out[49]. By identifying how key design innovations can make conservation payments more cost-effective, we could help build stronger support for PES at a time when some programs face defunding[30–32], as well as provide insight on how to increase the impact of nature-based carbon offsets, whose efficacy has been called into question[50].

Methods

Sample selection

We study five ejidos in Marqués de Comillas (MdC) municipality in Chiapas state (see Fig. 1). MdC is an agricultural frontier region within Selva Lacandona, which is the largest high-canopy tropical rainforest remnant in Mexico and a biodiversity hotspot[51], but also a region of high deforestation for cattle ranching and agricultural production[52]. Landholders in MdC manage individual endowments of 30-50 hectares, which they allocate to a combination of pastures, agricultural fields, and forest reserves. Many households face economic poverty[41]. The five communities have previously participated in several PSA contracts since the late 2000s.

We recruited 64 landholders from five ejidos who applied to Conafor's PSA (January 2021) with individual landholdings but were rejected (April 2021) due to insufficient funding. We started with the 118 rejected applications to PSA in 2021 from these ejidos. Although Conafor does not disclose the ranking evaluations, Natura Mexicana staff attribute the rejections to the lands not being within a federal natural protected area and the communities having participated in PSA during the five preceding years and lacking forestry certification, all of which lower priority.

We attempted to enroll 96 rejected applicants, excluding those who had requested to enroll more than 90 hectares (for project budget reasons). Of these, 13 were unreachable during baseline data collection and 19 declined to participate in the study (reasons included having alternative land use plans and not wanting to have landholdings measured or answer survey questions). Study participants completed a baseline survey in April-May 2021 and had their entire individual landholding mapped. In June-July 2021, Natura Mexicana held meetings in each community and offered each study participant one of two PES contracts: (a) a contract to enroll the same forested lands that she had previously submitted to PSA in 2021 (standard PES, or control group) or (b) a contract that required her to enroll all of her forested lands (full enrollment, or treatment group). We determined participants' contract type based on a random number generator in Stata, with the randomization stratified by ejido.

To determine the enrolled area for the control group, we use the shapefiles that ejidos submitted with their 2021 PSA application indicating the forest parcels they wanted to enroll. We also have this information for the treatment group, so we know the parcels they would have enrolled had they been offered standard PES. Similarly, because we mapped all of the forest owned by each landholder, we have the polygons for forest area left out of the PES contract for the control group. Thus, we can compare the treatment and control groups' deforestation rate overall for their forest and also separately for the parcels they would have included versus excluded if given the partial-enrollment option. On average, landowners left out 49% of their forest area from their PSA application.

At the community meeting, participants chose whether to enroll (sign the contract); the contract took effect immediately. The control

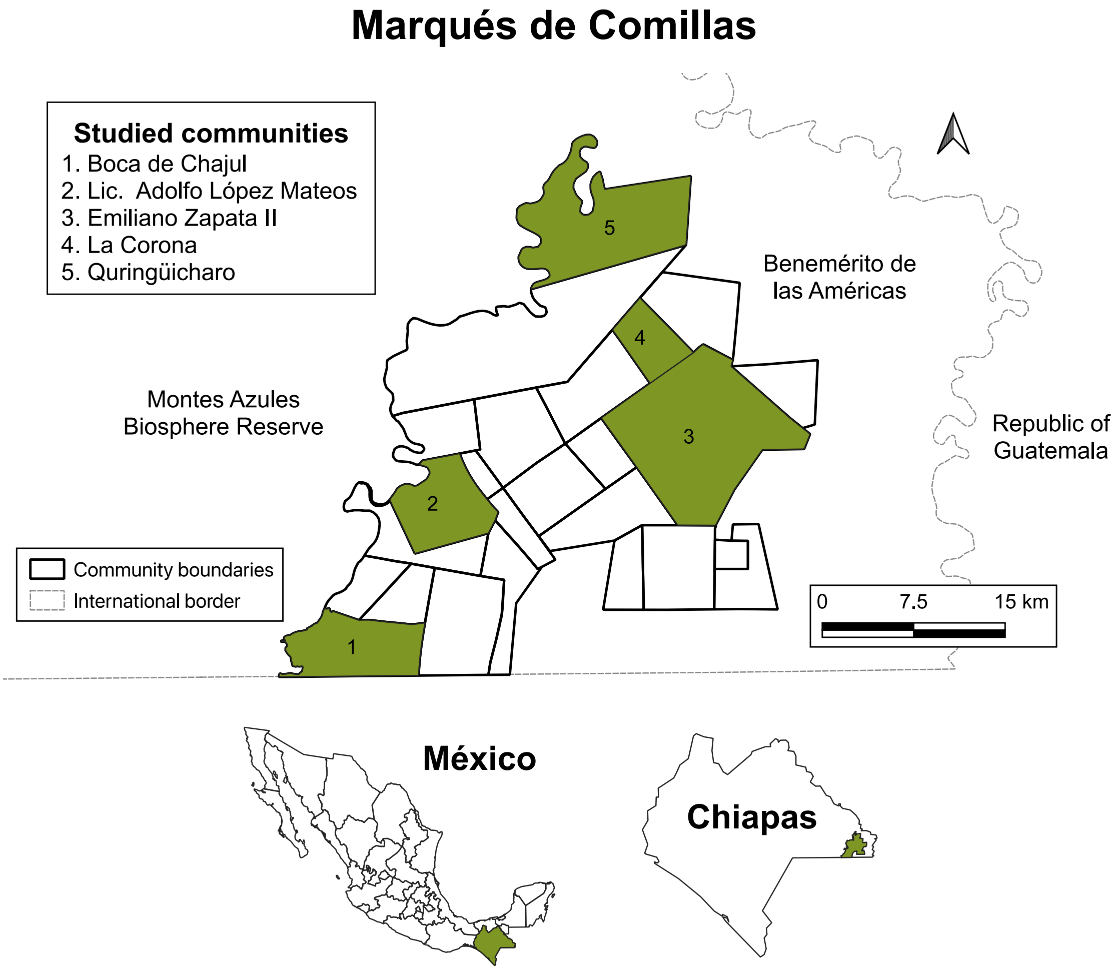

Fig. 1 | Map of study location. The top panel depicts the municipality of Marques de Comillas (MdC), with the five ejidos in the study shaded in green. The shading in the bottom panel indicates the location of MdC within Chiapas and the location of Chiapas within Mexico.

and treatment contracts were identical except for the land enrollment requirement. The payment rate was set at the level used by PSA, MX $1000 per year per hectare of forest. Payment disbursal at the end of the one-year contract was conditional on maintaining forest cover on all of the enrolled land, which was determined based on satellite imagery and, if needed, in-person verification. Our monitoring and sanctioning of non-compliance differs from Conafor's methods in PSA in two key ways: (i) our contracts are signed at the individual as opposed to the community level, which facilitates enforcement; (ii) participants on whose land non-compliance was detected receive zero payment, as opposed to Conafor's more lenient approaches where non-compliant participants can still receive partial payments[28]. For the satellite verification, we developed a random-forest model to analyze high-resolution Planet imagery, classifying pixels as forested or not. We use the same model to estimate the treatment impacts reported in the next section. Our implementing partners, Natura Mexicana and Innovations for Poverty Action disbursed payment to those who complied. We then administered an endline survey to study participants in August 2022.

Survey data collection

Innovations for Poverty Action collected baseline data in May-June 2021 and endline data in August 2022. To mitigate potential conflicts of interest in data collection, the enumerators were not from the study region and had no information on the treatment status of the surveyed individuals. At baseline, enumerators walked around the participants' plots to record the exact polygons for the deforestation analysis using GPS software on smartphones. At endline, we successfully resurveyed 58 of the 64 study participants, though the response rate was lower on several questions, such as income. We use the baseline data to ensure the study arms are balanced and the endline survey for supplementary analysis of impacts on satisfaction with the modified PES program. Because attrition from the endline survey could create selection bias when we analyze program satisfaction, we also provide a bound on the estimate that adjusts for this attrition.

Baseline balance between study arms

Table 3 presents summary statistics for the study sample. Each row presents the mean and then the standard deviation in parentheses. Column 1 presents statistics for the whole sample, column 2 for the treatment group (full enrollment) and column 3 for the control group (partial enrollment). Column 4 reports the standardized difference between the two groups (difference divided by the pooled standard deviation). 62% of study participants are male, average education is 7 years, and average household expenditures was MX$3500 in the previous month (around US$175). 60% had been enrolled in Conafor's PSA in the past. Study participants, on average, own 42 hectares of land, of which 19 are forest.

The only statistically significant difference between study arms is for previous-year deforestation in the forest land that participants had not chosen for enrollment in their 2021 PSA application (i.e., non-Conafor areas). Our main results are robust to controlling for this

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Table 3 | Balance in Baseline

Variable	Total	Treatment	Control	Standardized diff
	(1)	(2)	(3)	(4)
Male	0.625	0.645	0.606	
	(0.488)	(0.486)	(0.496)	0.080
Years of school completed	7.127	6.710	7.531	
	(4.054)	(4.391)	(3.724)	−0.203
Household expenditure in last month (Ln)	8.157	8.097	8.210	
	(0.751)	(0.797)	(0.715)	−0.150
Has been or is enrolled in a PSA program	0.603	0.645	0.562	
	(0.493)	(0.486)	(0.504)	0.168
Land area across all plots (hectares)	42.019	46.932	37.404	
	(20.976)	(21.056)	(20.129)	0.454
Distance to road (minutes)	15.581	16.245	14.957	
	(14.559)	(15.499)	(13.830)	0.088
Previous def. % Conafor area	0.007	0.009	0.006	
	(0.019)	(0.022)	(0.016)	0.158
Previous def. % Non- Conafor area	0.232	0.186	0.279	
	(0.194)	(0.186)	(0.193)	− 0.479
Primary forest area total across all plots (hectares)	18.812	22.790	15.076	
	(14.093)	(15.658)	(11.464)	0.547
Number of observations	64	31	33	

For each variable, each row presents the mean and below the standard deviation in parenthesis. Column 1 for the whole sample, column 2 for the treatment group and column 3 for the control group. Column 4 presents the standardized difference.

variable, as shown in Supplementary Table 1. An ex-post power calculation gives a minimum detectable effect (with 80% power and 5% significance) of 0.059 for deforestation in all the property areas.

Remote sensing measure of deforestation

We trained a random forest algorithm to automatically classify each pixel in satellite imagery of our study area as forest or not. We used the algorithm, applied to imagery from the end of the PES contract period, to determine if individuals complied with the contract. We also use the model output to construct the study's main outcome variable: deforestation. We use the sample of pixels with forest at baseline, according to the model, and the outcome variable is an indicator that equals 1 if the pixel was no longer forest cover at endline, according to the model.

We use satellite imagery from Planet-NICFI (Norway's International Climate and Forest Initiative). These images provide a monthly cloud-free image with a resolution of pixels 4.59 m × 4.56 m (the date(s) within the month for the specific images is not provided). We then created the smallest rectangle that contains all the polygons of individuals participating in the study. We divided the rectangle into regions of 100 × 100 pixels. Each region is divided randomly into training (56.25%), validation (18.75%), and testing data (25%). Where the yellow, pink, and purple squares in Fig. 2 represent the training, validation and testing data, respectively.

For the training data, we used hand-classified data from baseline that labeled whether each pixel in study participants' land was forest or not. Specifically, we use the polygons collected in the baseline survey, extract the imagery, and visually inspect each pixel, classifying it as forest or no forest. This manual labeling is what we used to determine the forest land to enroll in the PES contracts for both treatment and control groups.

For each pixel, there are four variables that are used as predictors: the red band, the green band, the blue band, and the infrared band. We tried several models and parameters and the best-performing was a random forest using 100 trees, a maximum depth of each tree of 50 (i.e., maximum 50 binary splits of the data in each decision tree), and two variables at each node (mtry parameter). The receiver operating characteristic (ROC) curve of the model with the performance of the model is shown in Fig. 3.

Figure 4 presents two examples of the satellite imagery and the predictions of the model.

In the regression analysis, we define a pixel as deforested if the model predicts it to be deforested in that month and the subsequent month (to reduce the rate of false positives).

Regression model

As treatment was randomized, we can estimate the effect of the program by comparing outcomes in the treatment and control groups. We do this by estimating the regression model shown in equation (1):

$$y_{pie} = \beta Treatment_i + \alpha_e + \varepsilon_{pie} \tag{1}$$

where y_{pie} is the outcome (deforested) for a pixel p owned by individual i, residing in ejido e. $Treatment_i$ is a binary variable that equals 1 if individual i was offered the full-enrollment contract. Finally, α_e are ejido fixed effects, the stratification unit for the treatment. When each observation is a pixel, we cluster standard errors at the individual level, allowing for arbitrary non-independence of the error term ε_{pie}, within an individual's pixels.

We can also conduct the deforestation analysis at the individual level and study heterogeneity by forest at baseline.

$$y_{ie} = \beta_1 Treatment_i + \beta_2 Treatment_i \times Z_i + \beta_3 Z_i + \alpha_e + \varepsilon_{ie} \tag{2}$$

where y_{ie} is deforestation of individual i, belonging to ejido e, and Z_i is a characteristic of individual i, for example, whether the individual had a large area of forest at baseline (above the median). ε_{ie} is the error term. We allow for heteroskedasticity-robust standard errors.

Cost-effectiveness calculation

Prior research estimates that Conafor's PES schemes reduce deforestation, relative to areas with no payment, by between 12 and 14.7% over a 6-year period[38]. Using the midpoint of the annualized estimates, we assume that standard PES led to 2.2% less enrolled land being deforested in a year. To convert this effect on enrolled forest to the effect on total forest, we use the fact that 49% of forest was enrolled in our sample, yielding an effect size of 1.1%.

To convert reductions in deforestation rates to hectares of averted deforestation, note that study participants in the control group had 663 hectares of forest at baseline, and the treatment group had 968 hectares. This implies that full-enrollment PES averted 65.8 hectares of deforestation, and standard PES averted 7.3 hectares.

The payments to enrollees in standard PES totaled MX$313,400, and the payments in full-enrollment PES were MX591,000. Using an exchange rate of US$1 = MX$20.036, this implies that the cost to avert a hectare of deforestation with full-enrollment PES was US$448.29, and the cost for standard PES was US$2143. Taking the ratio of these numbers, full-enrollment PES was 4.8 times as cost-effective.

To calculate the cost per averted metric ton of CO_2 emissions, we incorporate the estimate that each hectare of forest in our study area stores the equivalent of 550 metric tons of CO_2[43]. Thus, for full-

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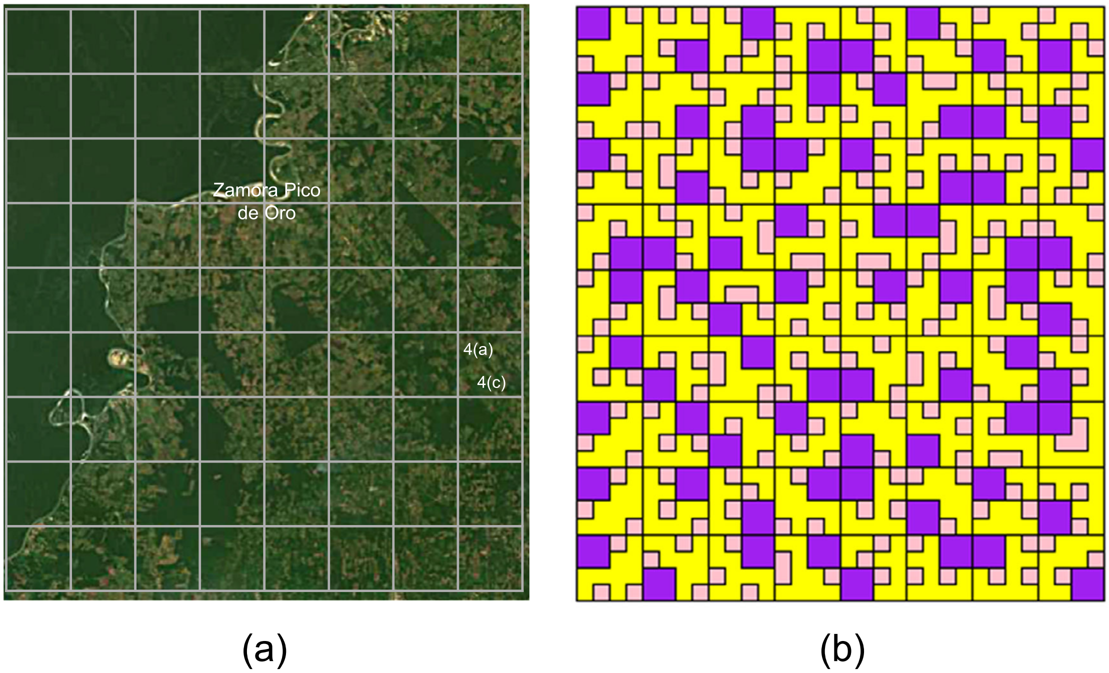

Fig. 2 | Division of study area for training, validation and testing. The study area on the left (**a**) is divided into 4.59 km × 4.56 km regions. Then each region is randomly divided into yellow, pink, and purple squares representing the training, validation, and testing data respectively, as shown on the right (**b**).

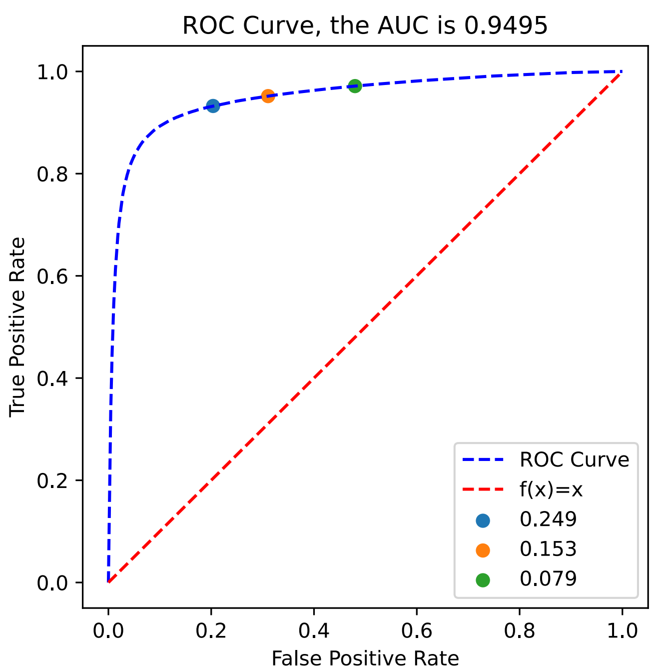

Fig. 3 | Receiver operating characteristic curve for the forest detection model. The receiver operating characteristic (ROC) curve of the model plots the true positive rate (TPR) against the false positive rate for different cutoffs. The TPR is the proportion of forest pixels accurately classified as forest. The FPR is the fraction of non-forest pixels incorrectly classified as forest. As we lower the cutoff, we increase the TPR and the FPR.

enrollment PES, the cost to avert (delay) a metric ton of CO_2 emissions is US$0.81

To benchmark the PES program against other ways of mitigating climate change, it is useful to convert the delayed deforestation to the equivalent permanent avoidance of emissions. We assume that after the program ends, landowners revert to their business-as-usual deforestation without PES. This maps to 15.3% of the baseline forest area being cleared each year – the standard PES mean deforestation rate in our sample is 14% (see Table 1, column 1), and above we laid out our assumption that this represents a reduction of 1.1% compared to the no-PES scenario. Without PES, if landowners deforest 15.3% of the baseline area each year, their remaining forest would be depleted 6.5 years after the baseline period of our study (1/0.153). At that point, both PES groups have additional forest left that they would then clear, we assume. Thus, the forest area that was conserved because of the program remains intact for an extra 6.5 years.

To value this delay in deforestation, we assume a discount rate of 3%. With discounting, damage (i.e., deforestation) that occurs in 6.5 years is $1/(1+0.03)^{6.5}$, or 83%, as costly as damage incurred today. Thus, the delay has a value equal to 17% of the damage $(1-1/(1+0.03)0.65 = 0.17)$. In other words, delaying a metric ton of emissions by 6.5 years is 17% as valuable as permanently averting it. Thus, the full-enrollment PES program's cost of US$0.81 to delay a metric ton of CO_2 emissions is equivalent to a US$4.76 cost per metric ton of permanently averted CO_2 (0.81/0.17 = 4.76).

Theoretical framework

The predictions about the effects of full-enrollment can be seen more formally through a stylized model. Consider a landowner i that owns a one-dimensional continuum of forest parcels, (OL) in Fig. 5. The parcels are ordered along the horizontal axis based on the net benefits of deforesting them, with higher net benefits on the right. Each parcel j would produce a private benefit b_j if deforested, the red line passing through A, B, and C. For simplicity, we assume the cost of deforesting each parcel is identical and equal to d. The blue line passing through F, A, and E is the cost to deforest each parcel.

Scenario without PES. Without a PES program, the landowner would deforest all grids with $b_j > d$. That is, the landowner would deforest the parcels in the line segment NL in Fig. 5. The net benefits to her from this deforestation are represented by the triangle ACE. For the segment ON, it is in her private interests to conserve this land, even without PES.

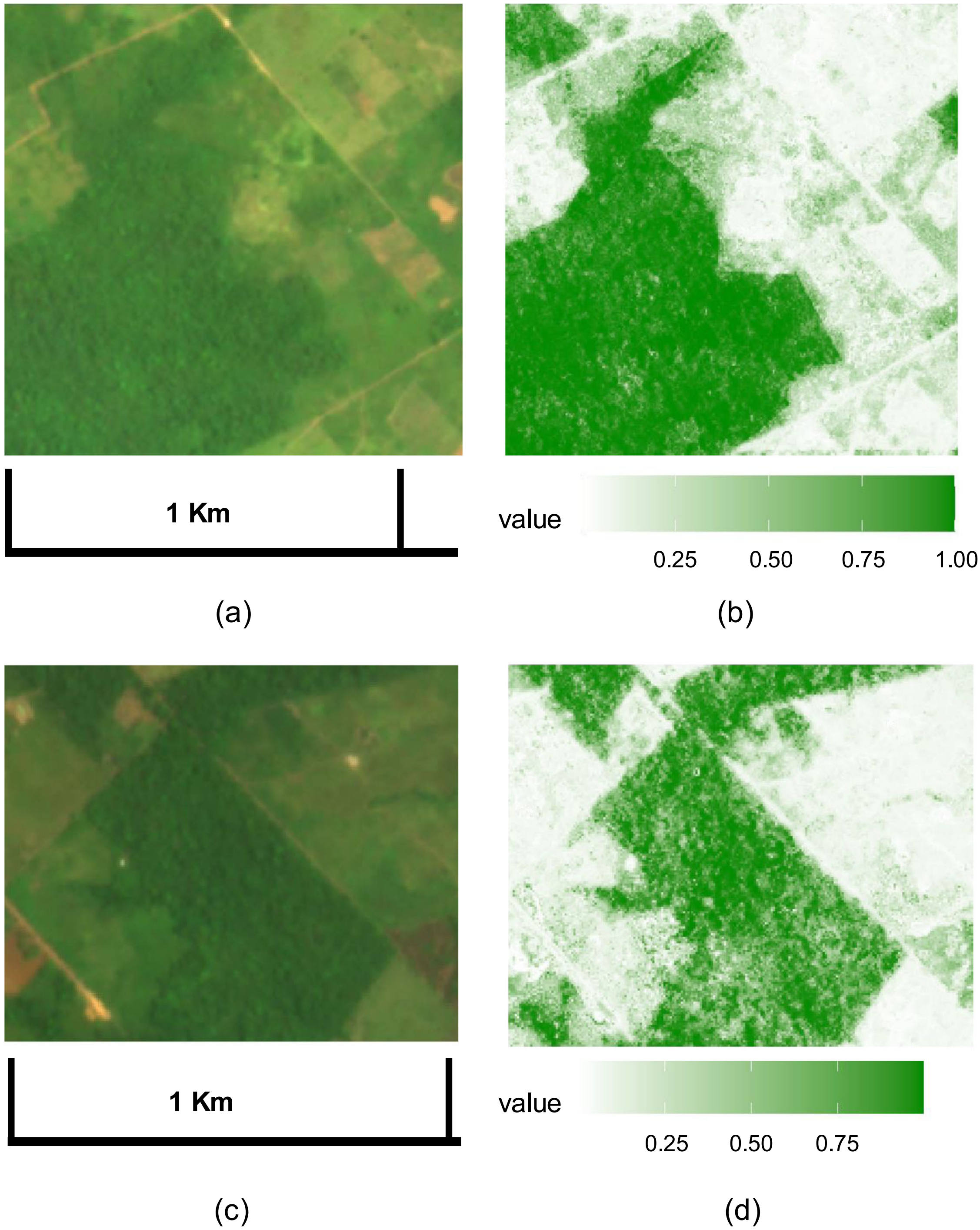

Fig. 4 | Examples of satellite imagery and forest detection. a, **c** Show raw satellite imagery of examples of land owned by study participants. **b**, **d** Show the corresponding remote sensing model output classifying each pixel's likelihood of being forest, on a scale from 0 to 1. Figure 2 shows the location of these example parcels within the study area.

Standard PES scenario. Assume now there is a PES program that pays p per enrolled grid. With a traditional PES program that allows the landowner to choose which grids to enroll, the farmer would enroll all grids with $b_i < p + d$. These are the parcels on the segment *OM*. The avoided deforestation is (*NM*), and she is also receiving inframarginal payments for parcels (*ON*) she would not have deforested anyway.

As long as there is some parcel where $b_j < d + p$ and a landowner can partially enroll land, in this simple model, she will choose to enroll and comply with PES. There will be additionality as long as there exist some parcels where $d < b_j < d + p$, which in our example, is the segment *NM*.

Full-enrollment PES scenario. Consider now the modified program where the farmer has to enroll all her forest land (*OL*). That would require the farmer not deforesting the grids *ML* that she would not have chosen to enroll under the standard contract. The avoided deforestation is (*NL*). She is also receiving inframarginal payments for the land she would not have deforested anyway (*ON*). A first prediction is that avoided deforestation is higher for someone who complies with

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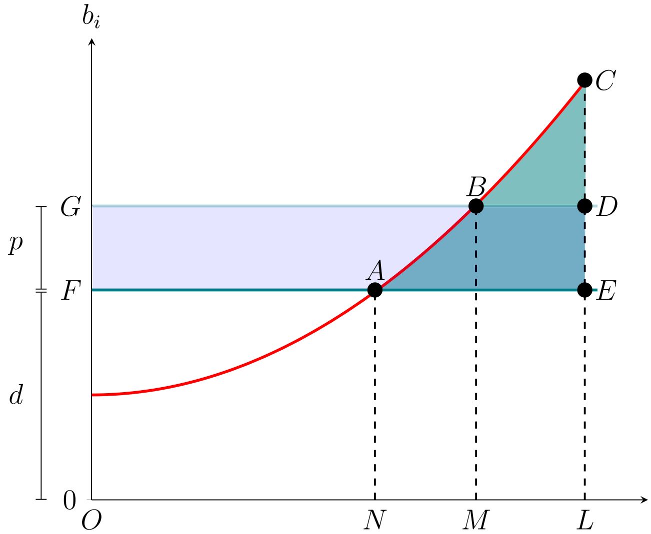

Fig. 5 | Theoretical representation of the standard PES program and the modified full-enrollment PES assessed in this study. The red line passing through A, B, and C represents the benefits of deforesting each parcel. The blue line passing through F, A, and E represents the private costs of deforesting the parcel. Consequently, without PES the farmer would deforest *NL*. With standard PES that pays *p*, the landowner enrolls *OM* and deforests the segment *ML*. With the modified PES, she will need to enroll and preserve *ML* to be in compliance. She will choose to comply if the rectangle of total PES payments (*DEFG*) is larger than the area of net benefits of deforestation (*ACE*) she would enjoy without PES.

full-enrollment PES than with standard PES. A second prediction is that this extra avoided deforestation is on the parcels that the landowner would exclude from the PES program if given the choice.

A third prediction is that the likelihood of taking up and complying with the PES program is weakly lower under full enrollment. As explained above, with our assumptions, everyone complies with standard PES. With full-enrollment PES, the landowner will comply if the rectangle of total PES payments (*DEFG*) is larger than the area of net benefits of deforestation (*ACE*) without PES. This condition may or may not hold. To see this, note that as $p \to 0$, the area of *DEFG* becomes 0, and when p is high enough that the line *GBD* intersects or is above the point *C* then the triangle *ACE* that represents the net benefits of deforesting is a strict subset of the payments rectangle *DEFG*.

Reporting summary
Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability
Due to the sensitive and identifiable nature of the data per the ethics approvals, the raw data is unable to be publicly shared. Please contact the corresponding authors for further details.

Code availability
Code is available in this link https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/KYE3VT.

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Author contributions
S.I.T., S.J., and S.S. designed the study. S.J. and S.S. processed the data and performed analyses. S.I.T., S.J., and S.S. interpreted results and prepared the draft manuscript. All authors were involved in revising the manuscript and approved the final version.

Competing interests
The authors declare no competing interests.

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