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Forest carbon program enrollment in Pennsylvania falls below survey predictions

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Several US programs provide smaller-scale forest landowners access to carbon markets where they can earn payments in exchange for stricter timber management. We study participation in one program—the Family Forest Carbon Program—and find that 1% of likely eligible owners in five high-enrollment counties in Pennsylvania enrolled in the first 3 years, less than what landowner surveys predict. Comparisons of enrolled parcels with those of the likely eligible population reveal a similar average extent of harvesting over the 35 years prior to enrollment. Under the current owner, however, enrolled parcels had 50% more harvesting than comparable parcels. We find that more harvesting in the past 20 years reduces harvesting in the present, suggesting that, absent the Program, enrolled parcels might have less future harvests. The findings indicate that expanding carbon market access is one challenge, enrolling landowners, especially those with high offset potential, is another.

Forests offer low-cost opportunities for sequestering carbon at scale[1,2]. Fully realizing these opportunities will require the participation of smaller-scale forest owners—in the US, nearly 40% of forests are owned by families, with most owning less than 40 ha[3]. The complexity of carbon contracts and the high cost of monitoring have historically impeded widespread participation, but several programs have emerged recently that use innovative approaches to expand access to landowners with modest area, allowing them to earn carbon payments in exchange for practicing stricter timber management. Examples include programs by Forest Carbon Works, LandYield, and the American Forest Foundation. We expect such programs to attract considerable resources in the coming years, with the market for voluntary carbon offsets expected to surge to $100 billion by 2030[4]. To aid market development, the 2022 Inflation Reduction Act appropriated nearly half a billion in public funding for projects that, absent changes by the current administration, would "support forest landowner participation in emerging private markets for climate mitigation"[5]. Our study looks at data from one program—the Family Forest Carbon Program of the American Forest Foundation and The Nature Conservancy—to estimate uptake from the likely eligible forest owner population and describe who selects into the Program and its implications for carbon sequestration potential.

Prior studies suggest that many forest landowners are willing to participate in hypothetical carbon programs. A meta-analysis of 13 stated preference studies provides a willingness-to-accept estimate for private landowners with 8–100 ha in the US and who lack a forest management plan, which overlaps well with our study population. It finds that owners would on average accept a payment of $32 per hectare ($13 per acre) per year to sign a 20-year or less carbon contract[6], similar to the cash payment offered by the Family Forest Carbon Program. Including the in-kind benefits the Program estimates that it gives enrollees would further encourage participation. However, a separate meta-analysis of US and European landowner participation in voluntary programs for forest ecosystem services finds that "participation rates tended to be overestimated when landowner participation was elicited in hypothetical choice situations"[7].

What type of landowners and parcels will enroll is also unclear. Selection into a forest carbon program could be as-good-as-random if decision-making is dominated by mundane considerations, such as unawareness of the program[8]. Alternatively, various patterns of non-random selection are also plausible. For example, the 24% of private forest owners in Pennsylvania who say they are unwilling to cut trees[9] might have the most interest in enrolling. Or, prior experience contracting with loggers could make it easier for a landowner to contract for carbon, while those without such experience would be screened out[10].

Our study pertains to selection broadly and is distinct from prior studies of adverse selection in a broad class of programs that pay for ecological services[11–13]. Adverse selection occurs when landowners enroll at different rates based on predictors of future carbon stocks unobserved by program administrators. It therefore affects administrators' ability to do accurate carbon accounting. For example, forest owners that enrolled to supply offsets to California's carbon market were credited based on regional average carbon stocks. The practice implicitly assumes that selection into the

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program occurs at random within each region. More detailed data have revealed that enrolled areas have forest types that resulted in lower common-practice (counterfactual) carbon stocks than suggested by regional averages, an illustration of adverse selection. The discrepancy caused systematic over-crediting to enrollees in California's program[14].

Given the interest in adverse selection in the academic literature, it is easy to overlook how patterns in selection can matter apart from concerns about adverse selection and proper carbon accounting. If enrolled owners and parcels have characteristics that increase their future counterfactual timber harvesting, the program will induce more additional carbon sequestration than if owners enrolled at random and much more than if low-future-harvesting owners and parcels enrolled. Thus, selection can have implications for the total carbon sequestered and program cost per ton.

Our first finding is that actual enrollment in the Program's initial years is less than what prospective studies of hypothetical programs predict. We study five counties in Pennsylvania that had the most landowner enrollment, combining program and satellite data with county tax records for the universe of forest landowners. Using Program criteria to identify the likely eligible population, we estimate that in study counties 1.0% of likely eligible landowners, accounting for 1.2% of eligible forest area, enrolled in the Program.

Our second finding concerns the type of parcels and landowners that selected into the Program. Over the 35 years prior to enrollment, enrolled parcels had a roughly similar extent of timber harvesting as the average parcel in the population of likely eligible parcels, especially when accounting for parcel characteristics such as size and distance to road. This suggests that enrolled parcels do not have time-invariant characteristics that make them more or less prone to harvesting than other parcels. In years under current ownership, however, enrolled parcels had 50% greater harvesting than other likely eligible parcels. With our 35 years of harvesting history, we also find that more harvesting in the past 20 years predicts less harvesting in the present. Projections of future harvesting suggest that enrolled area may have somewhat lower carbon sequestration potential than the average parcel from the broader population of likely eligible parcels, particularly in the early years of the contract.

The Family Forest Carbon Program

The Family Forest Carbon Program is emblematic of new efforts to expand access to carbon markets. Traditional forest carbon projects have such high contracting and monitoring costs that only landowners with very large tracts can afford to participate. For example, participants in California's carbon program have on average about 18,000 ha, and only 8% of participants are family owners[15].

In contrast, the Family Forest Carbon Program aims to enroll small family landowners in the United States unlikely to access carbon markets through conventional channels. The average landowner in our study counties enrolled about 60 forested hectares in the Program, which uses a grouped project model that lowers administrative costs. It works by monitoring a random sample of participants from the group and then applying estimates of carbon benefits to the whole group. To estimate the carbon benefit, the plots of sampled enrollees are matched to Forest Inventory and Analysis plots, which are continuously monitored by the US Forest Service. The plots are matched at the start of the contract, but the comparison is updated when new Inventory data becomes available, yielding dynamic estimates of carbon benefits[16]. Observing differences over time with a matched control group overcomes the known weakness of carbon-credit methods that use only ex-ante information to create counterfactual harvesting behavior[17].

The American Forest Foundation and The Nature Conservancy first offered the Program in 2020 in select Pennsylvania counties. The selection of counties was based on their assessment that improved forest management could yield carbon benefits relative to the common practice of high-grade cuts that remove only the most economically valuable trees. In 2021, the Program expanded eligibility to more counties in Pennsylvania and for the first time to West Virginia, Maryland, and Virginia. Only harvestable parcels are eligible for the Program: after an initial phone screening and landowner self-description of their forest, the American Forest Foundation sends a forester to confirm that the owner has sufficient area of commercially viable timber.

Landowners enroll in the Program by signing a 20-year, legally-binding contract that prohibits owners from harvesting more than the contract-specified percentage of the initial basal area, which is the cross-sectional area of all tree stems in the enrolled area. The percentage can range from 25% to 35% and is cumulative throughout the contract term. It also prohibits harvests that would decrease by 10% or more a common measure of the average diameter of standing trees. This effectively prohibites harvests that remove only the largest trees, which evidence suggests reduces forest health and carbon storage potential[18]. The Program expects the requirements to increase net tree growth and generate a net emissions reduction of about 3.5 tons of carbon dioxide equivalents per hectare per year relative to comparisons plots and accounting for factors such as leakage and storage in wood products[16].

The Program sends payments annually throughout the duration of the 20-year contract. For our study period and area, the average of the tiered payment rates is about $30 per ha per year, with exact payments depending on an initial assessment of the potential carbon benefit of enrolling the parcel, as well as projections of carbon credit price increases and inflation. In addition, Program administrators estimate that they provide technical assistance worth around $1100 per landowner and stewardship assistance (e.g., connections with other conservation programs) worth $300 per landowner per year. See Supplementary Note SI.1.1 for more Program details.

The Program continues to evolve, and our data reflect its workings in study counties in its initial years, not necessarily the Program as it has subsequently matured and expanded. The Program has recently made changes such as increasing its minimum board-foot requirement and giving landowners the option of using one of its foresters to complete the required forest management plan. As such, our findings might not apply to future iterations of the Program. We also note that our focus is not on the optimal design of carbon contracts or programs. Numerous studies raise important questions about the short and long-term tradeoffs between carbon sequestration and storage on the landscape compared to storage in wood products[19], though these questions are not the focus of our study.

Enrollment decisions

At its heart, the Program's contract imposes limits on the scale and type of timber harvesting that can occur over 20 years. Economic logic would predict that owners who find these limits least burdensome would be most inclined to enroll. The burden, here, is understood as an increasing function of the difference between the owner's harvesting with and without these contractual limits.

The owner's ideal unconstrained harvesting plan will likely depend on owner and parcel characteristics. In forest economics, the optimal stand age for harvesting is calculated as that which equates the marginal benefit and the marginal cost of delaying harvest, known as the Hartman-Faustmann rotation age. The benefits and costs of delay are typically modeled as functions of the growth rate of the volume of commercial timber, the discount rate, as well as amenity benefits the owner derives from the forest[20]. Although typically applied to a forest where all the trees are a similar age, the model provides a general framework for thinking about how harvest behavior will vary across a diversity of forest owners and parcels. It also specifies a mechanism of action for carbon payments–they increase the marginal benefit of delay, which increases the optimal stand age.

The framework suggests that a forest owner will be inclined to enroll if the carbon payment is sufficient to increase the optimal stand age on their parcel such that the contractual limits on harvesting do not bind. This is most easily accomplished for owners whose preferred harvest is within, or at least close to, what the contract allows, for example, owners whose forests have had more recent harvesting, or who derive particularly large amenity

values from older forests[6]. The benefit to enrolling is largest for these owners. Conversely, timber production-oriented owners with forests ripe for harvest are more likely to have harvest preferences that differ substantially from the contractual limits and would therefore be less inclined to enroll for any given carbon payment amount.

Use of the framework does not imply that all enrollment decisions can be distilled into a few financial or amenity factors. We recognize the potential for numerous factors to motivate enrollment, such as gaining access to a forest-owner network and trusted technical assistance. The framework nonetheless provides one lens to interpret the empirical patterns described in the next sections.

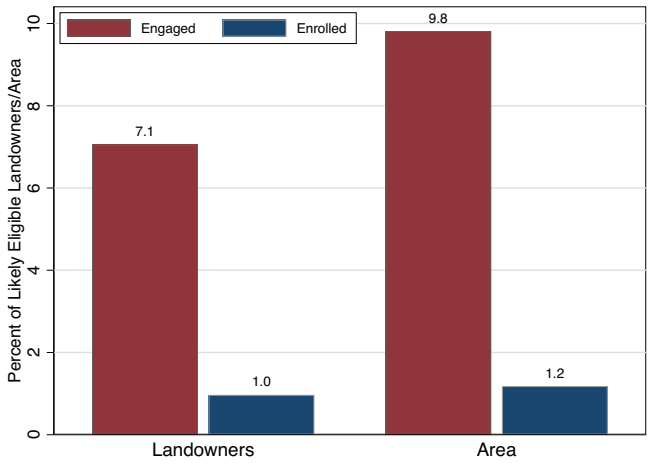

Fig. 1 | Program engagement and enrollment rates. *Notes:* Authors calculations based on program data from AFF, county tax records, LandTrendr vegetation data, and USGS National Land Cover Database. Engaged owners include those who enrolled in the Program, those who engaged but later declined enrollment, and those still engaged (in process). Area calculations are based on the likely eligible forested portions of parcels owned by likely eligible owners.

Table 1 | Parcel and owner counts by engagement group

	Parcels	Owners
Unengaged	12023	7855
Declined	208	136
In process	497	378
Enrolled	127	82
Total	12855	8451

Declined, In Process, and Enrolled owners/parcels are based on AFF Program data. The Unengaged group reflections our application of Program rules to the result of the owners and parcels in our study counties and is based on county tax records, LandTrendr vegetation data, and the USGS National Land Cover Database.

Results

Engagement and enrollment

Our five-county study area in Pennsylvania had the highest number of enrolled owners as of October 2023, accounting for one-third of all enrollment in Pennsylvania and nearly one-fifth of enrollment across all states. Treated as a whole, forests account for 70% of the study area. Of this forested area, 71% is owned by what could be construed broadly as family landowners, or more specifically, private non-corporate and non-commercial owners (see Section "Identifying the likely eligible population"). Among those with 4 ha or more of forestland, these family owners have 29 ha of forest on average, similar to the national average of about 28 ha[3].

During the Program's first 3 years (Fall of 2020–Fall of 2023), 7.1% of likely eligible forest owners in the study area engaged with the Program. Among the same population, 1.0% enrolled by signing the Program's 20 year contract (Fig. 1 and Table 1). In terms of area, engaged and enrolled owners had 9.8 and 1.2% of likely eligible forested land. In time, the enrollment rate will likely increase as some in-process owners enroll.

Selection: unconditional mean comparisons

Figure 2 shows that over the 1985–1999 period, enrolled parcels had the same average annual percent area harvested as the general population of likely eligible parcels. From 2000 to 2014, however, enrolled parcels had 35% more harvesting (2.72%–2.01%). In the 5 years prior to any enrollment, the difference in harvesting was smaller, being only 13% higher for enrolled parcels. Looking at other characteristics in the likely eligible population, enrolled parcels are also larger, have a centroid further from the road, have been under current ownership for less time, and are less likely to have an owner located within 40 km of the parcel. In contrast, they are about as likely to be owned by a person rather than an entity. See Table 2 for mean values and Table 3 for normalized mean differences and p-values from a test for a difference in group population means.

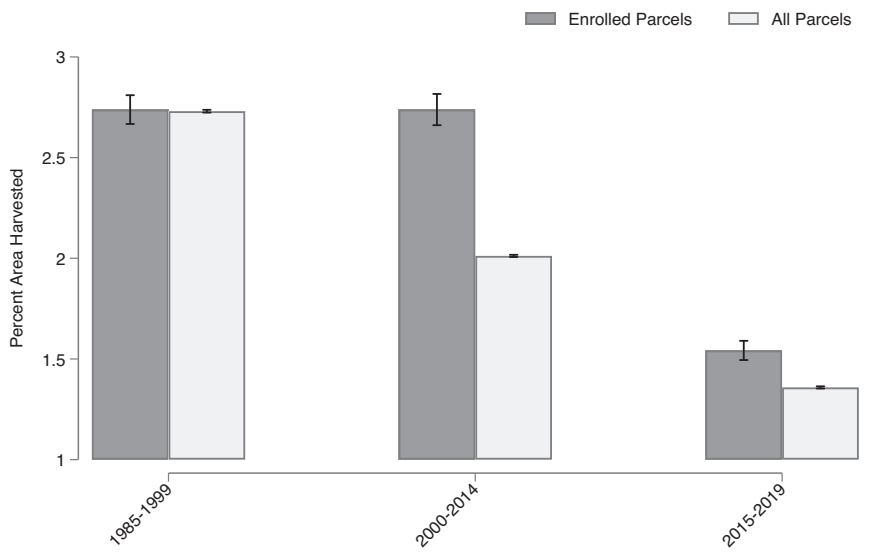

Fig. 2 | Average annual percent area harvested, enrolled, and all parcels. *Notes:* The parcel-level percent area harvested is based on satellite-based disturbances in vegetation at the 30 × 30 m pixel level. See Section "Data and methods". 95% confidence intervals are shown with the vertical bars. All periods shown are prior to actual parcel enrollment in the Program.

Table 2 | Mean values by engagement group

	FFCP engagement status of parcel				
	Unengaged	Declined	In process	Enrolled	All
Normalized vegetation index (NDVI), 1985	803.65	810.90	807.85	803.10	803.92
Change in NDVI, 1985–2019	31.96	27.98	36.17	26.85	32.01
Average annual percent forested area cut, 1985–2019	2.14	2.52	2.29	2.49	2.16
Average annual percent harvested, 1985–1999	2.72	3.11	2.87	2.74	2.73
Average annual percent harvested, 2000–2014	1.99	2.24	2.18	2.74	2.01
Average annual percent harvested cut, 2015–2019	1.35	1.93	1.41	1.54	1.36
Forest area (Ha)	65.87	114.54	128.46	96.04	68.92
Forest area: Less than 4 ha	0.26	0.08	0.07	0.09	0.25
Forest area: 4–20 ha	0.34	0.31	0.33	0.36	0.34
Forest area: 40–79 ha	0.36	0.47	0.48	0.48	0.37
Forest area: 80 or more ha	0.05	0.14	0.12	0.06	0.05
Distance to road, meters	319.48	462.26	361.60	446.53	323.99
Distance to road: Less than 100 m	0.24	0.10	0.14	0.06	0.24
Distance to road: 100–249 m	0.26	0.21	0.28	0.28	0.26
Distance to road: 250–500 m	0.30	0.36	0.35	0.37	0.30
Distance to road: 500 or more meters	0.20	0.34	0.23	0.30	0.20
Years owned	15.84	19.40	13.63	11.26	15.75
Years owned: Less than 5 years	0.21	0.21	0.29	0.34	0.21
Years owned: 5–9 years	0.10	0.09	0.11	0.13	0.10
Years owned: 10–14 years	0.08	0.08	0.12	0.06	0.08
Years owned: 15 or more years	0.61	0.63	0.48	0.47	0.60
Owner is a person, not entity	0.85	0.73	0.85	0.83	0.84
Owner address is within 40 km of parcel	0.47	0.43	0.40	0.39	0.47

Authors calculations based on program data from AFF, county tax records, LandTrendr vegetation and disturbance data, and USDA Cropscape data. The sample contains 12,855 parcels likely eligible for the Family Forest Carbon Program. Parcels whose owners never considered them for the Program are Unengaged (n = 12,023), those considered but whose owners declined to enroll are Declined (n = 208), those in process are In Process (n = 498), and those for which a contract has been signed are Enrolled (n = 127).

We further compare enrolled parcels to those whose owners considered the program but declined to enroll (declined). The two groups appear to be on different harvesting cycles, with enrolled parcels having less harvesting than declined parcels in the 1985–1999 period but considerably more during the 2000–2014 period (Tables 2 and 3). The two groups are generally more comparable when considering area or distance to road, but not for years owned, where 47% of enrolled parcels have been owned for 15 years or more compared to 62% for declined parcels.

The in-process group reflects a mix of owners and parcels who will inevitably enroll or decline to enroll. Although statistics for them have a less clear interpretation, we expect them to have mean values that generally fall within the range of the enrolled and declined means. This is generally what we observe in Tables 2 and 3. For some characteristics in-process parcels look more like declined parcels and in others more like enrolled parcels. For example, when looking at harvesting over 2000–2014, in-process parcels look like declined parcels; when looking at the percent of parcels owned for 15 years or more, they look like enrolled parcels.

Although not shown, we also compare average harvesting on enrolled and unenrolled parcels among the 10 enrolled owners who did not enroll all of their forested parcels. Compared to never-enrolled parcels of the ten owners, parcels they later enrolled had less harvesting during 1985–1999 (2.3 vs 2.9%) and more harvesting during 2000–2014 (4.3 vs 3.0%). This fits the pattern of the broader sample in which enrolled parcels had more harvesting during 2000–2014.

Selection: historical harvesting conditional on observable attributes

The greater harvesting of enrolled parcels might be statistically explained by the differences noted above. Or, it may reflect parcel or owner attributes unobserved by us but correlated with harvesting proclivity. To explore these possibilities, we compare across engagement groups the annual extent of harvesting during 1986–2019 while controlling for the parcel and owner attributes mentioned in the prior section. Our first comparison uses all years of data, regardless of who owned the parcel at the time, and controls for year and county fixed effects and the lagged vegetation index and its square. We then add indicator variables related to parcel size and distance from the parcel centroid to the nearest road. Lastly, we add owner characteristics and include only years since the current owner purchased the parcel. See Supplementary Note SI.1.4 for details.

The first conditional comparison of harvesting reveals that relative to unengaged parcels, the percent of area harvested was somewhat greater for enrolled parcels and declined parcels. Both point estimates shrink when adding the indicator variables related to parcel size and distance to road, with 0.26 and 0.20% points in greater harvesting for declined and enrolled parcels. For both regressions, in-process parcels had harvesting similar to unenrolled parcels (Table 4, columns 1 and 2).

When adding owner characteristics and including only years since the current owner purchased the parcel, a large harvesting difference emerges for enrolled parcels (Table 4, column 3). The difference indicates that enrolled owners are distinct in ways unobserved to us and that are correlated with harvesting extent. (See Supplementary Fig. SI.1 for this regression's coefficients on owner and parcel characteristics.) Specifically, current owners of enrolled parcels historically harvested nearly 1.1% points more of the area of enrolled parcels annually (95% CI 0.27–1.91). In percent terms, the greater harvesting is 50% above the full study period average of 2.16%. In contrast, looking at years under current owners, which focuses on more recent years, makes the harvesting difference between declined and unenrolled parcels fall to near zero. This is consistent with the unconditional

Table 3 | Differences in subgroup and population means

	Normalized mean difference			*P*-value for one-sample *t* test		
	Declined	In process	Enrolled	Declined	In process	Enrolled
Normalized vegetation index (NDVI), 1985	0.142	0.080	−0.017	0.000	0.000	0.249
Change in NDVI, 1985–2019	−0.096	0.098	−0.122	0.000	0.000	0.000
Average annual percent forested area cut, 1985–2019	0.074	0.028	0.067	0.000	0.000	0.000
Average annual percent forested area cut, 1985–1999	0.150	0.057	0.003	0.000	0.000	0.827
Average annual percent forested area cut, 2000–2014	0.111	0.083	0.358	0.000	0.000	0.000
Average annual percent forested area cut, 2015–2019	0.286	0.028	0.091	0.000	0.000	0.000
Forest area (Ha)	0.509	0.478	0.330	0.000	0.000	0.000
Forest area: Less than 4 ha	−0.383	−0.399	−0.350	0.000	0.000	0.000
Forest area: 4–20 ha	−0.060	−0.019	0.054	0.000	0.007	0.000
Forest area: 40–79 ha	0.219	0.240	0.232	0.000	0.000	0.000
Forest area: 80 or more ha	0.402	0.299	0.060	0.000	0.000	0.000
Distance to road, meters	0.440	0.195	0.425	0.000	0.000	0.000
Distance to road: Less than 100 m	−0.321	−0.232	−0.425	0.000	0.000	0.000
Distance to road: 100–249 m	−0.126	0.045	0.027	0.000	0.000	0.064
Distance to road: 250–500 m	0.117	0.108	0.149	0.000	0.000	0.000
Distance to road: 500 or more meters	0.344	0.073	0.251	0.000	0.000	0.000
Years owned	0.035	−0.226	−0.326	0.002	0.000	0.000
Years owned: Less than 5 years	−0.007	0.196	0.311	0.518	0.000	0.000
Years owned: 5–9 years	−0.047	0.009	0.070	0.000	0.238	0.000
Years owned: 10–14 years	−0.021	0.129	−0.068	0.057	0.000	0.000
Years owned: 15 or more years	0.048	−0.242	−0.265	0.000	0.000	0.000
Owner is a person, not entity	−0.314	0.015	−0.025	0.000	0.043	0.077
Owner's address is within 40 km of parcel	−0.087	−0.135	−0.169	0.000	0.000	0.000

The first three columns show the subsample mean values less the population mean value divided by the population standard deviation. Thus, it measures mean differences in standard deviation units. The *p*-values shown in the right three columns correspond to a one-sample *t* test for the hypothesis that the given subsample (e.g., enrolled parcels) was drawn at random from the population of likley eligible parcels.

comparisons showing that declined parcels had the greatest harvesting in the earlier 1985–1999 period.

The estimates imply that over a decade the average landowner would have harvested about 21.6% of his or her forested area (10 years × 2.16% per year). By comparison, the average enrolled owner would have harvested about 32%, or about 7 additional hectares. The greater harvesting among enrolled parcels under current owners is robust to estimation that gives equal weight to parcels regardless of how many years they are under current ownership. It is also robust to including a county for which we do not have date of acquisition data (Supplementary Note SI.1.5).

Predicted future harvesting based on observed past harvesting

The greater extent of harvesting among enrolled parcels under current ownership could affect future harvesting. For example, greater past harvesting might lower the probability of future harvesting (relative to the average parcel) by leaving fewer valuable trees to harvest. Alternatively, harvests that remove lower-valued trees can improve the value of future harvesting by encouraging higher growth rates among the remaining high-value trees. Effects on the future probability of harvesting would, in turn, affect the parcel's ability to generate additional carbon sequestration.

We use our harvesting history data to estimate the relationship between past and current harvesting, which shows that harvesting in years t-2–t-19 predicts less harvesting in the present (Supplementary Fig. SI.2). Using the estimated relationships in a 25-year lag model, we predict harvesting over the 2020–2039 period as if the Program never occurred, and 2019 were the last year for which we had data. The 2020–2039 period corresponds to the contract period for a landowner enrolling in 2020, which is when the first landowners enrolled.

The harvesting history on enrolled parcels predicts considerably less harvesting in the early 2020s relative to the average parcel, a difference that is partially offset by more harvesting in the 2030s (Fig. 3). Over the full 20 years the model predicts that absent the contract enrolled parcels would have had about 2.3% points less harvesting on net relative to the average parcel in the likely eligible population.

To be clear, we are not assessing the adequacy of the Program's carbon accounting methodology, nor the ability of the contract terms to cause additional carbon storage. Rather, we are predicting future harvesting of enrolled parcels relative to that of the average parcel in the likely eligible population of parcels, with the predictions driven solely by differences in parcel fixed effects and harvesting history.

Discussion

One of our main findings concerns the lower-than-expected enrollment in the program, with 1% of likely eligible owners enrolling in the Program. The low enrollment rate does not primarily reflect competition from other carbon payment programs. During our study period, LandYield operated only in Southern states, and as of September 2023, Forest Carbon Works had enrolled four landowners across our five study counties (FCW, personal communication). The now-defunct Natural Capital Exchange program had enrolled some Pennsylvania landowners in its 1-year contract but ceased offering enrollment opportunities after the Spring of 2022. However, only 11 parcels in the study counties were

Table 4 | Annual percent area harvested, 1986–2019

	(1)	(2)	(3)
Declined	0.330***	0.257**	−0.030
	(0.116)	(0.115)	(0.197)
In process	0.045	0.015	−0.021
	(0.065)	(0.065)	(0.113)
Enrolled	0.232	0.199	1.087**
	(0.156)	(0.154)	(0.417)
Lag.NDVI	−6.476***	−8.707***	−9.536***
	(1.673)	(1.757)	(1.649)
Lag.NDVI^2	76.904***	68.899***	95.289**
	(19.990)	(19.619)	(39.997)
Mean of Dep	2.29	2.29	2.1
County-year FE	Yes	Yes	Yes
Parcel controls	No	Yes	Yes
Owner-specific controls	No	No	Yes
Ownership	All	All	Current
Adjusted *R*-squared	0.118	0.120	0.101
N	435,744	435,744	103,108

The dependent variable is the percent of the parcel's forested area harvested over the year. The coefficients on the key variables of interest (declined, in process, and enrolled) give the mean difference in dependent variable between each engagement category and the unengaged group, conditional on other model variables. The parcel controls included in the regressions in columns 2 and 3 are three binary variables reflecting the parcel's forest size and three binary variables reflecting its distance to the nearest road. The owner-specific controls are three binary variables indicating the years the owner has owned the parcel, a binary variable for owner type, and a binary variable for the owner having an address near the parcel. The results in column 3 exclude Bedford County, which lacks data on when the current owner acquired the parcel. ***denotes significance at 1% level, ** at 5% level, * at 10 % level.

deemed ineligible because of enrollment in other carbon programs, and landowners who had a Natural Capital Exchange contract were later eligible to join the Family Forest Carbon Program. The enrollment rate we observe therefore, provides a good estimate of the market-wide level of participation during our study period.

A natural next question is: what are the key obstacles to achieving higher enrollment? If we imagined enrolling 1% of all family forest lands in the US, it would amount to 1.1 million hectares[21]. This approximates the area potential of a program expanded to the entire US and that experiences the same enrollment rate as in our study counties. Further increases would require understanding and addressing key obstacles to raising the enrollment rate.

One potential obstacle to enrollment is that landowners may lack information or awareness of the Program. To assess this explanation, we note that 86% (6.1/7.1) of engaged owners declined to enroll or are still considering it. This suggests that, even in a population where everyone is aware of the Program, there might be an upper-bound on the population enrollment rate of around 14% (the shares are similar when computed in terms of area). This would represent a 14-fold increase in the current enrollment rate (14/1.0), and could be interpreted as what may be achievable through greater outreach alone.

A second potential obstacle to participation is contracting costs, which include the time to meet with Program representatives and review and understand the contract. To assess this explanation, we look at how enrollment rates differ between smaller and larger landowners. Because the cost of understanding the contract, for example, is similar for a small and large landowner, we expect landowners with the least land area to have the highest per hectare contracting costs. Consistent with this hypothesis, enrollment rates are 0.7–0.8% for the first three quartile of owners by eligible area and 1.6% for the fourth quartile of owners, who would have the lowest per hectare contracting costs. If such costs could be reduced to where they present no greater obstacle for smaller landowners than they do for larger landowners, we might expect enrollment to increase to 1.6% across the board. This would increase the enrollment rate by 60% (1.6/1), and is indicative of what might be achievable through reductions in contracting costs alone.

As a further thought experiment, combining maximum outreach with aggressive reductions in contracting costs might achieve as much as a 30-fold increase in the enrollment rate (1.6/1.0 × 14/1.0), which corresponds to an enrollment rate of 22%.

Thus, our analysis suggests that the low enrollment rate we observe in the study area cannot be explained by competition from other programs, and only to a limited degree by lack of information or high contracting costs. What, then, are the main barriers?

Engaged owners who ultimately decline to enroll have an opportunity to provide Program administrators the reasons for declining. For owners in study counties, the most common response, accounting for 28% of responses, was "contract term too long." This suggests that declining owners found that 20 years under contract limits would push their harvest behavior too far from their unconstrained ideal harvest. Although shortening the contract length may attract more owners, it may be unattractive to carbon market buyers, as it may lower the real or perceived quality of the produced carbon credits. The Program's silvicultural prescription depends on the twenty-year contract term to help transition forests to longer rotation lengths and "thinning from below" rather than high-grading, leaving more carbon standing on the land at any time[18]. Carbon credit buyers also prefer offsets that have longer-term storage potential (high "permanence" or "durability"), and may feel that shorter contract lengths are less certain to correspond to long-term storage, lessening the price at which these credits can be sold[22].

The second most common reason for declining, accounting for 24% of responses, was "compensation too low." Similar to the contract length reason, the compensation reason suggests that declining owners find the contract terms very binding, otherwise, they would not find the compensation too low. Both reasons fit research showing that revenue and economic factors are important considerations for forest landowners as they consider carbon programs[23–25]. Because the funds to pay landowners ultimately come from the sale of carbon credits, anticipated market prices constrain payment rates for voluntary forest-based carbon credits. It is also unclear how much enrollment would respond to higher payments. The contract payments and in-kind benefits constitute the price offered for committing to stricter forestry management. Enrollment decisions reveal information about the supply curve for stricter forestry management, with low enrollment akin to low supply at the given price. If the supply curve is fairly flat around the current price, a small increase in payments or in-kind benefits could substantially increase enrollment rates. If it is sharply upward sloping, the opposite will be true. Analysis of survey responses from Massachusetts family forest owners suggests that in that context the supply curve slopes upward sharply: increasing the payment rate by a factor of ten, from $25 per hectare per year to $250, increases the predicted enrollment rate from roughly 3% to 7%[23].

Other, hard-to-quantify aspects of a carbon program can also matter for enrollment. For example,[26] find that the complexity of the contracting process matters, and[25] find that landowners prefer working with non-profit organizations. Landowners may also greatly value in-kind program benefits, such as access to a network of like-minded owners, or flexibility in contract terms, such as those governing firewood collection. Changes to these program or contract details could therefore affect enrollment rates apart from major changes to contract length and payment.

Regarding the selection of parcels and owners into the Program, enrolled parcels have clearly had more harvesting (prior to enrollment) under current ownership. This is consistent with our conceptual framework, as is the finding that declined owners had more harvesting in the earliest period and would therefore be more likely to find the contract limits burdensome. The finding indicates that enrolled parcels are harvestable, and enrolled owners are willing to harvest them, both of which are consistent

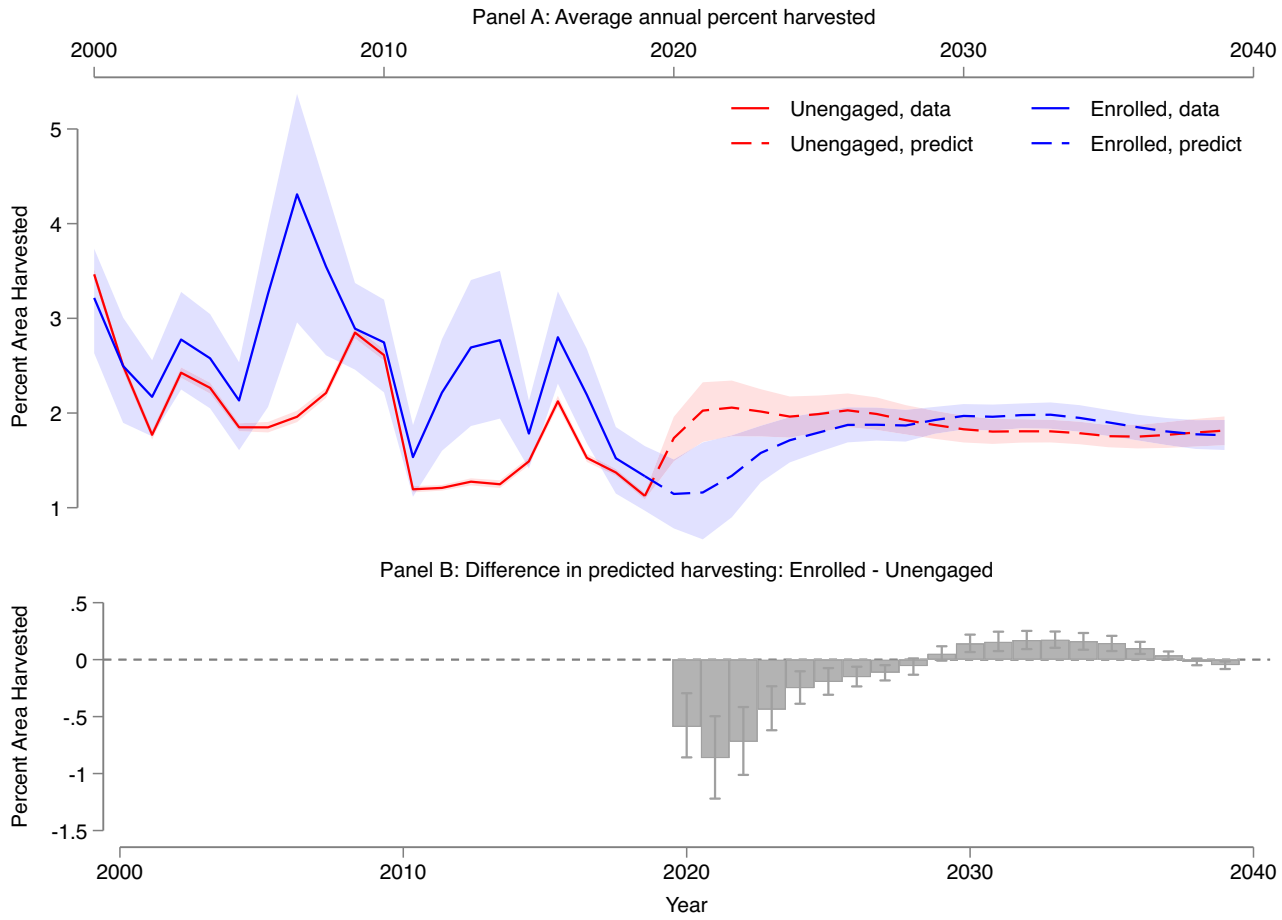

Fig. 3 | Observed and predicted percent area harvested. *Notes:* Solid lines are observed harvests; the dashed lines are the out-of-the-sample predicted harvests. The shaded area 95% confidence interval estimated using the bootstrap method with 250 bootstrap draws (blue for the unengaged group and red for the enrolled group).

with Program goals. Patterns in historical harvesting, however, suggest that the greater recent harvesting could lead to less future harvesting in a counterfactual scenario without program enrollment, particularly in the early years of the contract. This would, in turn, affect a parcel's potential for additional carbon sequestration. Apart from adverse selection, which concerns accurate carbon accounting, a program that attracts parcels and owners with higher sequestration potential will be more cost-effective than a program attracting those with lower potential.

Overall, our findings imply that bringing carbon market opportunities to family forest owners is one challenge; enrolling them is another. Moreover, this conclusion is based on a program designed and implemented by organizations with a history and expertise working in forestry and with private landowners. Carbon accounting challenges aside, it remains unclear if long-term carbon contracts can attract family forest owners to enroll considerable forested area–and the right type of forests–at payment rates that buyers of voluntary offsets will support.

Data and methods

Data and study area

We draw from three main sources of data: program data shared by the American Forest Foundation (AFF), satellite-based forest measurements (LandTrendr) from the Kennedy Geospatial Lab at Oregon State, and property tax records requested from county governments. AFF provided data on parcels and owners who have engaged with its Family Forest Carbon Program since its inception. The data also include each parcel's identification number for local property tax purposes, which we use to link it with tax assessment records and parcel shapefiles.

We generated normalized difference vegetation index (NDVI) estimates by accessing the Landsat satellite archive (US Geological Survey Surface Reflectance Tier 1 data) via Google Earth Engine[27,28]. Using the Landtrendr algorithm version 2.4 from the Kennedy Geospatial Lab and the Google Earth Engine Platform, we then generated maps of forest disturbances for Pennsylvania from 1985 to 2019, which indicate whether a harvest event occurred in a given year on a 30 × 30 m pixel. We calculate the annual percent area harvested as the percentage of pixels cut within the forested portion of the parcel that were disturbed. See Supplementary Note SI.1.2 for more details and all data sources.

Our study area covers the five Pennsylvania counties with the highest number of enrolled owners in the state as of October of 2023. These include Bedford and Somerset Counties in the South Central part of the state, Centre and Huntingdon Counties in the Central part of the state, and Potter County in the North. We chose these top five counties as they would give the largest samples of enrolled owners with the lowest data collection costs. At the time, the counties accounted for 18% of all Program enrollment and 32% of all enrollment in Pennsylvania. Three of the five counties were included in the first phase of the Program's rollout.

The five counties are some of the most forested counties in the state. Data from ref. 29 show the five study counties in the top 13 of the state's 67 counties in terms of total carbon stored in forests. In carbon density, the five have an average carbon stock per forested hectare about 11% higher than the average across all counties. The counties represent the state's forest diversity well. Three counties are in the South Central ecoregion, which has the largest share of Oak/Hickory forests in the state; one county is in the Southwest region, which has a more balanced mix of Oak/Hickory and Maple/Beech/

Birch forests; and one county is in the North Central region, which has the largest portion of Maple/Beech/Birch forests in the state[30].

Identifying the likely eligible population

We attempt to identify the population of likely eligible land and landowners by applying several of the Program's eligibility rules to our data. Program staff or contractors assess the eligibility of landowners who engage with it, which includes professional foresters determining the commercial viability of the land's timber. We exclude from our analysis and statistics any owners deemed ineligible by the Program according to its records. Although such owners and parcels engaged with the Program, our focus on the eligible or likely eligible population of parcels and landowners.

To identify this population, we apply most of the Program's eligibility rules to all unengaged owners and parcels: a minimum timber volume rule, a minimum area rule, and an owner-type rule. The Program requires a minimum volume of commercial timber, which during our study period was close to 12 m^3/ha (2000 board feet per acre). We lack volume estimates but observe the normalized vegetation density index (NDVI) of all forested areas, including those enrolled in the Program. NDVI is a very rough proxy for board-feet volumes but should nonetheless have some correlation with it because of the correlation between NDVI and aboveground biomass (see Supplementary Note SI.1.7). We therefore calculate the vegetation index for the forested portion of each parcel. To implement the board-foot rule, we exclude any parcel whose NDVI is below the 10th percentile of the NDVI for the forested portion of enrolled parcels. The Program also requires a minimum of about 12 forested hectares (30 acres), so we exclude any owner whose total forested area across all parcels in the county meeting the NDVI threshold is less than the minimum area. Because the Program works with only private, non-corporate owners, we also filter out entities whose name suggests ineligibility (e.g., "Inc." or "Township"). Applying the criteria yields 12,855 likely eligible parcels owned by 8451 owners (Table 1). See Supplementary Note SI.1.3 for more details, including estimates of error rates in eligibility status.

Engagement and enrollment rates

For both the engagement and enrollment rates, the denominator is the number of likely eligible owners. For the engagement rate, the numerator is a count of landowners who engaged with the Program, which includes those who enrolled, those who engaged but later declined to enroll, and those still engaged (in process). A landowner counts as having engaged as long as they provided basic information to the Program through its website and are deemed eligible. For the enrollment rate, the numerator is a count of landowners who signed the 20-year contract. Both rates can also be calculated based on area. The area-based engagement rate, for example, is then the total area owned by engaged owners divided by the total area of all likely eligible owners. Only the forested portion of the parcel is included in these totals and only if it passes the NDVI threshold.

Measuring selection into engagement groups

We first measure selection into the Program by comparing unconditional mean values of parcel characteristics by parcel engagement status: unengaged, engaged but declined, in process, and enrolled. We also report means for the full population of likely eligible parcels. The comparisons reveal if engaged or enrolled parcels, for example, are larger on average than those unengaged or whose owner was considering enrolling them but declined to do so. Engagement group status is at the parcel level because an owner can enroll–or consider enrolling–only some of their parcels. In practice, enrolled owners as a group enrolled 87% of their eligible parcels. To aid in comparing unconditional mean differences, we report differences between each engaged subgroup mean (declined, in process, enrolled) and the population mean divided by the variable's standard deviation. We also show p-values corresponding to a two-sided, one-sample t test for the hypothesis that the given subsample (e.g., enrolled parcels) was drawn at random from the population of likley eligible parcels, in which case any difference in means would reflect sampling error.

Another type of selection concerns variation in historical harvesting not correlated with characteristics we observe directly but are collectively captured by engagement group dummy variables. We quantify this type of selection by comparing across engagement groups the annual percent of forested area harvested conditional on various characteristics. We first look at the percent of each parcel's forested area that was harvested in year t regardless of who owned it while controlling for county-year fixed effects, our lagged vegetation index and its square, and binary variables indicating the parcel's engagement group. The lagged vegetation index and its square are meant to capture any non-linear relationship between available biomass and the likelihood and extent of a timber harvest[31] (see Supplementary Note SI.1.4 for further discussion). Specifically, we estimate

$$PH_{it} = \alpha_{ct} + f(NDVI_{it-1}) + \mathbf{X_i}\beta + \varepsilon_{it} \quad (1)$$

where PH_{it} is the percent of the forest portion of parcel i that is harvested in year t, α_{ct} is a county-year fixed effect, $f(NDVI_{it-1})$ is a flexible function of the parcel's lagged vegetation index (NDVI), which we have specified as a quadratic function.

The vector X_i includes time-invariant characteristics, which initially includes only binary variables for a parcel's engagement group. The coefficients on the group binary variables measure differences in the average value of the residual ε_{it} across groups. If the coefficient on the enrolled variable is near zero, for example, it indicates that characteristics not observed by us are either uncorrelated with enrollment status or are collectively uncorrelated with harvesting.

We then add to X_i binary variables for a parcel's forested area and its distance to the nearest road. Adding them removes their effect from the error term and may therefore change the coefficients on the engagement group binary variables, to the extent that they are correlated with those variables. Lastly, we add owner characteristics and include only years since the current owner purchased the parcel, which may likewise change the coefficients on the group variables if current enrolled owners, for example, have unobserved characteristics correlated with harvesting.

Predicting future harvesting

We predict the extent of harvesting in the absence of FFCP enrollment for enrolled and unenrolled parcels for the years 2020–2039, the period for which the contract would apply for those who enrolled in 2020. For the prediction, we use our 35 years of harvesting history to estimate the following autoregressive model relating the current percent harvested to the percent harvested in prior years:

$$PH_{it} = \eta_i + \sum_{\tau=1}^{\tau=T} \gamma_\tau PH_{i,t-\tau} + \delta \ln(price_{r(i),t}) + \varepsilon_{it} \quad (2)$$

where the main regressors $PH_{i,t-\tau}$ for $\tau = 1, \ldots T$ are lagged measurements of the percent of parcel i harvested up to T years in the past. η_i is a parcel fixed effect, which captures the mean value of PH for the given parcel and therefore any unique features that have a persistent effect on harvesting. The fixed effect permits estimation of the relationship between past and current harvesting apart from unobserved parcel and owner characteristics that are time invariant. We also add the demeaned natural log of an annual regional timber price variable. With the estimated parameters $\hat{\gamma}_\tau$, shown in Supplementary Fig. SI.2, we predict future harvests for 2020–2039 and compare the mean predictions across enrolled and unenrolled parcels. The demeaning of the price variable means that ignoring it in our predictions implicitly assumes that future prices will match past prices. See Supplementary Note SI.1.6 for details.

Reporting summary

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

Data availability

Much of the raw data incorporated into the analysis are publicly accessible in the sources described in the Supplementary Information data section, including satellite-based data and road data. County tax data and parcel boundaries can be accessed through data sharing agreements with the respective county government GIS or tax data office. Program data from the American Forest Foundation was obtained through a data use agreement that labels the data as confidential and prohibits its publishing on any public website, and requires that any statistics published must be such that no personal identifying information is revealed directly or indirectly. Accessing Program data would require, at a minimum, contacting the American Forest Foundation Family Forest Carbon Program (info@familyforestimpact.org) for access.

Code availability

All code used to generate the final figures, tables, and statistics in the manuscript and supplemental information are publicly available[32].

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Author contributions

Weber oversaw all aspects of the research and did the majority of writing. Wang contributed primarily to method development and performed the majority of the data analysis and generation of figures and tables. Mushegian assisted with writing, especially regarding institutional details and literature, and critically reviewed the entire manuscript. Calel assisted with conceptual framing, methods, and writing. Usmanov research, acquired, and processed satellite data and reviewed the manuscript.

Competing interests
The authors declare no competing interests.

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