Title: Making a difference takes time: comparing the impacts of two direct conservation interventions on forest cover in a biodiversity hotspot

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Short running title: Forest impacts of two direct-incentive conservation interventions

Abstract:

Direct conservation incentive programs have attracted interest due to their potential to increase tropical forest benefits while avoiding harms associated with protected areas (PAs). Here we compare the cost-effectiveness of two direct incentive conservation programs—public land acquisitions (PLA) and payments for environmental services (PES)—on forest cover in a biodiversity hotspot. While PLA and PES both compensate landowners for their loss of land-use rights, their relative cost-effectiveness is uncertain because of differences in enforcement capacity, implementation capacity and permanence. Our study region, eastern Antioquia in the Colombian Andes, has dedicated public funding to both incentives for 10–30 years, enabling outcome and impact comparison. We find that PES were implemented over a larger area than PLA (67,000 vs. 9000 hectares) due to lower up-front costs, acceptance of less formal tenure, and broader political support. However, using causal impact estimation methods and novel forest cover change data, we estimate that PES had smaller percentage effects on net forest cover than PLA (+0.33% vs. +10.05%), and that PLA had larger overall impacts on forest area (+306.25 ha vs. +125.95 ha) when including forest gain. There were no detectable differences in cost-effectiveness. As the two interventions can achieve different outcomes, choices between the two interventions depend on the ecological aims, institutional constraints, and the land users' contexts, which require equity considerations. Our results highlight that impacts are dependent on implementation opportunities and capacity, can vary based on outcome measurement, and are affected by the study's time frame.

Major classification: Social Sciences
Minor classification: Environmental Sciences

Keywords:
Conservation and Development, Deforestation, Forest Conservation, Impact Evaluation, Investments in Watershed Services, Land Acquisitions, Latin America, Mixed Methods, Payments for Environmental Services, Payments for Ecosystem Services

Significance statement:

This empirical study compares two direct incentive programs, payments for environmental services (PES) and public land acquisitions (PLA) and estimate their causal impact on forest cover using state-of-the-art remote sensing data and statistical methods. Surveys and interviews provide insights into differential implementation and understanding of the equity implications of the programs. Findings reveal that PLA, despite being costlier and less widespread in the short term, outperforms PES by producing higher land cover impact percentages and overall area impacts, specifically in terms of forest gain. No significant differences in cost-effectiveness were observed. The study underscores the significance of implementation capacity for program success and highlights the complex tradeoffs involved in making evidence-informed decisions.

Introduction:

Tropical forest ecosystems, like those found in the Colombian Andes, continue to be degraded and destroyed (1). Every year, billions of dollars are devoted to interventions aiming to protect forest biodiversity and environmental services (ES) (2). The effectiveness of conservation interventions is of concern to conservation proponents and its financiers, who must justify their spending to donors and the taxpaying public. Scientists are still in the process of building a credible evidence base as to what extent different conservation policies, projects, or programs achieve environmental objectives in what context(s). Protected areas (PAs) are the traditional cornerstone of conservation and have been better studied than any other conservation intervention (3). However, PAs can be ineffective in some contexts (i.e., where they are under-funded and under-managed), and can cause human rights concerns, e.g., if they prohibit people from pursuing their livelihoods or displace them from their lands (4, 5).

Other common but less-studied conservation instruments are direct incentives, such as payments for environmental services (PES) and land acquisitions. These instruments attempt to compensate landowners or landholders (hereby known as land users) for ceding land-use rights in environmentally important areas. Payments for environmental services are arrangements between ES buyers and sellers whereby payments to an ES provider are made so long as the ES provisions are rendered (6). These agreements usually entail a *temporary* transfer of *partial* land-use rights, with the land user retaining a subset of rights (e.g., access, residence, or farming on previously cleared land). In contrast, land acquisitions involve a *permanent* transfer of *all* land-use rights following a lump-sum payment. Payments for environmental services are popular, but whether they are responsible for achieving intended environmental impacts, such as the avoidance of forest loss, is not yet well-evidenced through causal impact evaluation (7). Although frequently used in high-income countries (8), land acquisitions for forest conservation appear to be less common and less frequently studied in lower and middle-income countries, resulting in scarce evidence about their effectiveness in reducing deforestation in such contexts.

Academic theory and economic intuition lead to ambiguous conclusions about the expected relative effectiveness of PES and land acquisitions. Either instrument can fail to reduce deforestation if it tends to target areas that would have remained forested regardless of an intervention, such as areas with low deforestation pressure (9). However, there is little evidence on whether or not these two instruments differ with respect to how exposed participating parcels are to deforestation risk. Payments for environmental services are known to be prone to suffer from adverse selection of this kind because people are more likely to participate in a voluntary program if they do not have strong incentives to deforest (10), although areas may also be acquired based on low purchase price, which can be related to low conversion threats (11). However, if both interventions reduced deforestation at equal rates, then PES could have more overall impact by being relatively easier to implement over larger areas for a similar or lower budget, thus accumulating more impact across space. Alternatively, the temporary nature of PES could lead to less cumulative impacts than land acquisitions over time. Furthermore, PES could be more effective because land users would have incentives to protect their own forests from encroachment, whereas public land acquisitions can require government enforcement to avoid intrusions. Concrete empirical evidence is needed to clarify these theoretical ambiguities. Moreover, the conservation impact of land acquisitions and PES can be further complicated when used in combination with other interventions, such as PAs.

Colombia is unique among tropical countries for legally requiring subnational governments to dedicate a share of their income to direct incentives for conservation as Investments in Watershed Services (IWS), relying first on PLA, and later allowing the use of PES. *Corporación Autónoma Regional de las Cuencas de los Ríos Negro y Nare* (CORNARE), the environmental authority responsible for eastern Antioquia, was the first to re-allocate a large share of its conservation funding (from public and private sources) from PLA to PES. Run by the local non-profit Masbosques, its PES program "BancO2" has national and international ambitions and has, at the time of writing, expanded to sixteen additional Colombian departments.

Policymakers need to balance implementation difficulty with the expected environmental and socioeconomic effects of their policies, inevitably generating vigorous discussion about how to spend environmental funds. This is especially true for the Colombian Andes, where the choice between PES and PLA is situated in a complex political, social, and historical context. Our study region was greatly affected by the violent conflicts in Colombia that have spanned from the 1950's to the present, making the well-being of the families who have been returning from forced displacement a priority for local communities and governments. However, implementing land acquisitions is a challenge in Colombia: Common issues relating to land acquisitions, such as dependence on land users' willingness to sell and reliance on a limited budget (12), are complicated by high levels of land tenure informality (13, 14). Despite these challenges, interviews and surveys indicate that decision-makers opt for PLA because they prefer permanent and total protection for water supplies (13). These interviews and survey data also revealed skepticism about PES resulting in additional forest cover impacts (Ibid.). Nonetheless, our previous work finds that recent historical rural displacement and land dispossession due to violent conflict can lead to political preference for PES, which can allow people to stay on their lands rather than displacing more people and further depopulating rural lands (11, 14). Moreover, PES can be more politically viable because decisionmakers often have parallel social aims of alleviating poverty and increasing equity (15, 16). The PES literature identifies three main dimensions of equity: distributional (or the allocation of costs, benefits, and risks), procedural (participation in decision-making), and contextual (distribution of access, capabilities, and power) (17). The conservation community is increasingly concerned with the equity implications of interventions, and this work posits equity concerns as fundamental within conservation interventions (18).

Here we compare the impacts and cost-effectiveness of PES and public land acquisitions (PLA) in a tropical biodiversity hotspot. Our study area is eastern Antioquia, a subregion of a department (analogous to a state or province) in the Colombian Andes. This jurisdiction is unique in that it has received substantial and steady public funding for both direct incentive programs over many years (since 1993 for PLA, and 2013 for PES), providing a rich empirical context for our inquiry. Further, the question of relative cost-effectiveness in reducing forest loss in eastern Antioquia is not only an academic inquiry, but also has practical relevance for determining conservation resource allocation across the Colombian Andes, where most of the funding for PLA and PES is concentrated (13, 14). Our overarching inquiry concerned the comparative effects of PLA and PES on forest cover in eastern Antioquia and their equity implications. The quantitative aspects are divided into four parts: First, how do PLA and PES differ in the number and extent of their application, as well as in the amount of money spent (implementation) (Q1)? Second, how do the interventions differ in characteristics that affect the risk of forest loss prior to any intervention (Q2)? Third, using quasi-experimental methods (matching and difference-in-differences) with remotely sensed forest cover data, how do PLA and PES differ in their impacts on forest cover (Q3)? Finally, how do the interventions differ in their return-on-investment (ROI) (Q4)? Secondly, using thematic analysis of surveys and interviews, we ask what the equity concerns are for PLA and PES, as implemented. While we were not able to quantify equity outcomes, this work sought to identify equity concerns that academics and decision-makers should consider in PLA and PES. Although there were clear equity benefits to both interventions, our focus was on identifying areas for improvement in the ways that the interventions are operationalized.

Results:

Spatial analysis of program coverage and location shows that PES was not only implemented on a substantially larger areas than PLA (Q1a), but that PES parcels were also, on average, situated in more threatened locations than PLA (Q1b). Our lower-bound estimates suggest that PES enrolled ≥ 2,677 parcels covering ≥ 67,000 ha at an estimated cost of 5.5 million USD (all dollar amounts in 2020 USD). In contrast, the number of PLA were ≥ 728 parcels, covering ≥ 9,326 ha at a cost of between 32 and 48 million USD. Payments for Environmental Services were implemented over a larger area than PLA despite the shorter implementation timeframe (2013-2018 for PES vs 1993-2018 for PLA). Surveys and interviews with program officials and participants suggest that BancO2 was able to rapidly expand its PES programs within the study area due to favorable political will, relative ease of implementing PES in areas with informal land tenure, and lower up-front costs as compared to PLA. We find discrepancies in the characteristics associated with the baseline risk of forest loss between the locations where each intervention was implemented (**Figure 1**). Public land acquisitions were implemented in higher-elevation areas than PES (**Figure 1A** and **1B**) and had lower levels of deforestation risk than PES (**Figure 1B** and **1C**). Public land acquisitions generally covered more area in higher income subregions with concurrently higher land tenure formality and lower ecosystem endangeredness, while PES covered more area in lower-income subregions with less land tenure formality and higher ecosystem endangeredness (**Figure 2**). A substantial share of PES and PLA projects with spatial data (29% and 41%, respectively) were also implemented inside legally declared PAs (See **Figure 1**). Our surveys and interviews suggest that PLA and PES are sometimes used to provide compensation to land users who lost land use rights (full or partial) due to PA creation.

We used a combination of matching and difference-in-differences (DiD) methods to infer causal impacts of PLA and PES on forest cover (Q1c). Post-matching DiD regression compares differences before and after the intervention to before and after differences on the same dates in their corresponding controls, yielding the average treatment effect on the treated (ATT). As both PLA and PES were implemented over multiple years, we use DiD methods that allow for staggered treatment (multiple treatment periods) (19). We estimate the ATT at both the cohort level (parcels treated in the same year) and the exposure-time level (effects at each number of post-treatment years) separately for PES and PLA. Our measured outcome was the percentage forest cover found on each parcel, derived using pixel counts from a forest cover change dataset that was custom-made for the Colombian Andes using satellite remote sensing imagery and that accounts for both forest loss and gain (regeneration or reforestation) at an annual time interval between 1997 and 2021 (Bullock & Arévalo, in progress). Because the approach uses an ensemble of change detection algorithms, we refer to the resulting dataset as the "ensemble approach" dataset. We also employed other land cover datasets, as well as a loss-only "ensemble approach" dataset (with gain excluded) to determine differences in outputs both from different remote sensing algorithms and the relative importance in gain and loss in driving differences in forest cover (see S.I. for details).

Due to missing treatment dates and spatial data, and because of the temporal limitations of the remote sensing data, we were only able to measure forest cover impacts for 297 PLA parcels (41%) and 1,405 PES parcels (52%). (See S.I. for information on parcels with and without spatial data, **Figures S3**, **S4**, and **S5**). Our estimates suggest that PLA, on average, resulted in higher percentage impacts on forest cover than PES (**Figure 3** and **Figure S11**). Through a combination of reducing forest loss or increasing forest gain, PLA reduced net forest cover loss at a rate similar in magnitude to the background rate of forest loss (**Figure 3**). Treatment effects aggregated across all treatment years were, however, not statistically significant, possibly due to the influence of observations from later-treated cohorts, whose estimates were not significant at the cohort level (**Figure 3**). When including only significant cohort-level estimates, we estimate that PLA resulted in an increase of 10.05% forest cover in treated areas, corresponding to an overall increase of 306.25 ha relative to the counterfactual over the study period. In contrast, although some cohorts of PES also had significant positive impacts, these impacts were consistently smaller in magnitude than the overall background deforestation rate for the study area regardless of forest cover dataset used (**Figure S11**). They were also consistently smaller than those of PLAs. Using the same approach as for PLA, we estimate that, on average, PES resulted in a 0.33% increase in forest cover over our study period, corresponding in an overall increase of 125.95 ha relative to the counterfactual. Because aggregate impacts of both interventions increased over time, effects were not always immediately detectable in the early post-treatment years, but percent impact estimates were higher for PLA within the same post-treatment time window (**Figure 4** and **Figure S13**).

To understand how the choice of land cover data and estimates of forest cover gain influenced our results, we repeated our analysis with three alternative forest cover change data products, none of which provided estimates of forest gain. These data sets included maps made for the Colombian Andes using a different approach to the satellite imagery (see Methods), the Hansen (2013) forest loss maps, and the "ensemble approach" maps, excluding gain. Excluding forest gain from the analysis, PES generated higher overall area impacts (among significant cohort-level effect estimates), though the percentage impacts were still lower (**Figure S12**). This result suggests that most of the impact that observed from

PLA was due to forest gain and not avoided forest loss, though we urge caution when interpreting area impacts, as formal confidence intervals for the land cover area estimates based on pixel counts were not available due to time constraints (20).

We also examined whether forest cover impacts varied as a function of parcel location and characteristics by estimating impacts for subgroups of PLA and PES (**Figure S14** and **S15**). We compared average overall percentage- and area impacts between paired subgroups through the matching same method as above and examined the trends in the cohort-level estimates (using only cohorts where ATT was significant). We found weak evidence (due to small sample sizes) that PES and PLA had greater impacts when implemented outside of PAs, and (in line with expectations) that both interventions had greater impacts when implemented at low elevations. PES parcels with high deforestation pressure had larger impact than those with lower deforestation pressure. When including forest gain, PLA had larger impact on parcels in areas with low deforestation pressure. Accounting only for forest loss, in contrast, PLA showed larger impact in areas of high deforestation pressure. Parcel funding (public or private), size, and travel time to cities were not associated with differences in treatment impacts. Subgroup results should be treated with caution because of small sample sizes, particularly for PLAs.

Surveys and interviews suggested that a key reason for the PES program's limited impact could be insufficient targeting for forest cover outcomes. This insufficiency was partly due to BancO2 managers' strong incentive to meet ambitious targets for both forest area protection and number of families enrolled. One wealthy landowner we surveyed stated that he had already established a substantial forest reserve before being approached by BancO2. The landowner attempted to dissuade BancO2 from including their property in the program because they did not need the income. According to the landowner, BancO2 managers insisted on their participation so that BancO2 could achieve an enrollment area large enough to claim certain carbon sequestration outcomes. The landowner explained that the payment was insufficient to hire a forest guard, implying little effective incentive offered by the PES program in such a context.

More generally, many PES participants indicated that they would not likely clear forest even without payments, either due to limited labor capacity or because they already valued their forests. Some communities had previously organized to manage local aqueducts and protect water sources, and many land users were aware of their land-use impacts on the water supply. Additionally, in the publicly funded BancO2 program, all participants received the same payment regardless of the size of the forested area. This policy likely resulted in underpayment for those with greater opportunity costs when contemplating clearing lands for agriculture or forestry, or for those with larger parcels. This policy choice could discourage participation and increase adverse selection, particularly for those outside PAs whose forests are not regulated. Our field research provided evidence that active tree planting and passive regeneration likely played a role in the overall impact of PLA on forest cover. Interviews and investment spreadsheets showed that funds were frequently used to reforest acquired parcels and erect fences to protect young trees from cattle. While BancO2 did promote tree planting to PES participants, many interviewees did not engage in reforestation due to limited space and resources or because they preferred natural forest regeneration. As an additional check, we surveyed respondents about changes in land use on their properties, including those not in the PES program, finding no evidence of spillover effects (that participants had increased deforestation on other properties).

We conducted a return-on-investment analysis (ROI) to examine whether the observed difference in impact in PLA and PES translated into a difference in cost-effectiveness (hectares of forest saved or added per dollar spent) (Q1d). Overall, this ROI analyses found no evidence for a difference in cost-effectiveness between the two instruments (see S.I. and **Figure S19** for details). Potential differences were largely up to the choice of discount rate, with higher discount rates for the annualized value of PLAs resulting in lowered cost-effectiveness relative to PES. We emphasize that this analysis should be considered indicative as it required two strong assumptions: 1) To compare annual PES payments with PLA purchase prices, we translated PLA purchase prices into equivalent annual rent— a conversion that is sensitive to the choice of discount rate (see S.I. for details); 2) because data were only available on direct intervention costs (PLA purchase prices and PES payments), we assumed these costs were proportional to total program costs (in other words, that other annualized program costs were proportional to annualized direct costs). We also did not have data on the amounts PES payments funded by BanCO2 through private programs, and assumed that all PES recipients were receiving the standard public rate.

Interviews with land and program managers suggested that both PES and PLA have been used to address burdens and injustices imposed by the creation of PAs, or to act as alternatives or complements to PAs. Our results suggest that there are remaining equity issues concerning the implementation of both PES and PLAs both inside and outside of PAs. Although BancO2's PES program primarily targets low-income households, there are remaining issues related to procedural and distributional equity, especially for people living in PAs. An illustrative case concerns a community in the high plain of eastern Antioquia that faced significant challenges due to past violent conflicts. The community suffered from acts of violence, displacement, and loss of their homes. After fourteen years of forced displacement, some families were able to resettle with government assistance, which included the provision of housing and chain saws to resume forestry work. However, once repossessed of their land some areas were later designated as a forest reserve PA by CORNARE, jeopardizing their livelihoods and threatening a second forced displacement. BancO2 allowed property holders to remain in the PA despite the prohibition on forestry activities, but those without some tenure documentation were ineligible to receive payments. This situation created hardships, with one family having to make the difficult decision of having their child leave school to work and support the family. Procedural equity issues arose from the creation of the PA by CORNARE without community consultation in formulating the conservation rules. Further, the BancO2 program could not provide distributional equity because it could not compensate all families within PAs due to barriers related to the highly informal and precarious land tenure of the area. In the same PA, some families lost their payments because they cleared regrowth in areas that had previously been used for agriculture before their forced displacement. Many community members harbored a defiant attitude toward CORNARE, feeling that the restrictions imposed on them were unfair and claiming that CORNARE had not collaborated with them to find a solution that would balance conservation and their survival. These dynamics underscore ongoing procedural and contextual inequities, where PES participants lacked the ability to challenge decisions made by more powerful parties, such as the BancO2 program and CORNARE, and could not participate in defining what constituted a protected forest. The absence of procedural and contextual equity meant that participating in BancO2 programs became a matter of survival for people residing within PAs, rather than a voluntary agreement.

Administrative shortcomings also likely contributed to some adverse outcomes. Because of funding shortfalls, BancO2 missed several payments that were never compensated (according to several of our survey respondents), highlighting further procedural and contextual inequities within program operations. Interviews with managers revealed one explanation for the missed payments, which was the lengthy negotiation process for renewed funding during administration changes in municipal governments. Several PES participants reported abrupt, permanent termination of their payments without any prior notice. The imbalance of power between BancO2 and the PES participants meant that, although BancO2 could easily withdraw payments when participants did not comply, that PES participants had little recourse when BancO2 did not hold up their end of the agreement. There are clear wider concerns for distributional equity posed by the BancO2 program. Our surveys found that PES participants who gave up forestry activities were not compensated up to the amount that they would have normally earned, and they received the same amount as others who were not making a change in their livelihood strategies.

Our surveys revealed that PLA, while compensating landowners for their complete loss of land use rights, could be involuntary, might not have always provided adequate compensation, and could take a long time to implement. The law allows for land expropriation when the protection of a parcel for its watershed services is deemed in the public interest. Our first PLA survey participant claimed they faced threats of expropriation when attempting to negotiate a higher land price. This example emphasizes ongoing procedural inequities, where land users are at a disadvantage in their interactions with government officials. Additionally, those who owned lands within PAs before their creation could be inadvertently coerced into selling to the government due to land use limitations, which prevented sales to other land users. Other survey respondents noted that these constraints on land user choices were often inadequately compensated by PLA, as they were generally not paid what they believed their property was worth. Selling land to the government was economically disadvantageous for some compared to selling to a private individual due to the bureaucratic hurdles involved, including extensive documentation requirements which resulted in the seller bearing the cost of essential land studies. To illustrate an extreme example of these burdens, one survey participant who owned a parcel within a PA prior to its declaration had been trying to sell their parcel (which they claimed protected substantial water resources) to the municipality since 1993. Since they could not work their lands, they had to perform day labor on others' properties while managing a physical disability. The delay in purchasing their land, which was generated by the passing of the case through several municipal administrations and the subsequent repeated bureaucratic hurdles, had substantial consequences on their family's financial wellbeing. The survey respondent, who was also in the PES program while attempting to sell their parcel, said that the payments they were receiving were too low to make up for this loss of income. Thus, although PLA can aim to compensate land users on environmentally sensitive lands for their loss of land-use rights, it is not always a nimble or fair instrument.

Discussion:

The legal mandate permitting a choice between investments in PLA or PLA within the framework of IWS created an opportunity to empirically observe the evolution and impacts of both policies in Antioquia. We observed a distribution and clustering of intervention execution that reflects implementation capacity and preferences. Since 2013 BancO2 was able to expand the implementation of PES across a much larger area compared to PLA. We can attribute this expansion to lower upfront costs, less stringent land tenure requirements, political favorability, and potentially the substantially lower commitment levels required for participation compared to PLA. However, despite its greater extent and relatively greater presence in areas associated with higher threat of forest loss, our analysis shows that PES avoided forest loss or increased forest gain at lower rates compared to PLA. Payments for environmental services yielded lower percentage impacts than the background rates of forest loss while PLAs, through a combination of avoided deforestation and forest gain, had rates of impacts equal to the background rates of forest loss.

Regarding the overall impact area, PLA had a higher impact on forest area only when including impacts from forest gain. When using datasets that do not include gain, we find that PES had a greater impact on forest area (**Figure S12**). Although regrowth timing is difficult to report with high accuracy (21), PLA are realistically more likely to support greater forest regrowth as all unforested areas of the parcel were left to naturally regenerate or were actively reforested. It is also logical that regrowth would have higher success in areas with low deforestation pressure, as was observed in our subgroup comparisons. Reforestation activities were by comparison not an emphasis or a requirement of the PES project at the time of analysis. It is important to consider that forest gain outcomes achieved by PLA may not hold the same ecological value as the avoided forest loss achieved through PES in terms of species richness or providing habitat for threatened species.

Policymakers need to balance implementation difficulty, including cost, with the expected environmental and socioeconomic effects of their policies. Our results suggest that the two instruments are not distinctly different in their cost-effectiveness (dollars per area of impact) over the study period. Payments for environmental services appear to generate lower impacts at a lower cost, while PLA generated higher impacts at a higher cost. The relative cost-effectiveness was sensitive to reasonable variation in the discount rate. Previous theoretical research posits that PES can be more affordable up-front and that PLA are cheaper in the long run (22, 23), but budget efficiency can depend on interest rates and the initial budget (24).

In our study, PES were estimated to mostly avoid forest loss, while the estimated effects of PLA were mostly driven by apparent reforestation or forest regeneration. The instruments were also applicable in different contexts. Therefore, we might consider that PES and PLA are not substitutable, but rather are tools that can be used for distinct purposes depending on the type, level, and urgency of action needed, as well as the constraints of the implementing bodies and the land user's context, where equity and fairness are concerns.

The choice between PES and PLA, as IWS with intended biodiversity co-benefits, is dependent on the environmental priorities in each geographical area. Public land acquisitions could be more suitable for the long-term protection of areas that require restoration, while PES could be targeted towards forests that are under urgent deforestation threats that are temporary in nature. While our assessment did not extend to other environmental outcomes, considering water benefits, we surmise that PLA likely yielded more favorable results for water quality. Public land acquisitions discourage land uses that harm water quality, such as fecal runoff from grazing animals and runoff of pesticides and herbicides from pastures and crops. In contrast, the PES program did not mandate participants to reduce pesticide use or relocate their livestock, although some survey respondents did so voluntarily. Further research is necessary to determine whether PLA or PES are more effective in achieving improved water quality and quantity and other intended environmental goals, such as PA connectivity.

Secondly, the choice of instrument depends on the capacity of the implementing bodies. Obstacles such as land tenure informality, funding availability, and institutional capacity can pose significant challenges to PLA implementation (13, 14). These constraints naturally limit the number of PLA that can be implemented at a time, underscoring the need to think strategically about their use. Where the need for action is urgent, PES is likely to be the more expedient choice.

The choice of instrument also depends on the land user's context. Not every landowner is willing to sell. However, for those who live in PAs, there is an element of coercion in their choice to sell, being that they cannot make much income off their lands and that they cannot sell to other farmers. In these cases, PES could be the preferred instrument choice. In either case, both instruments could be regarded as patches to existing PA policies instead of instruments that are meant to produce additional impacts. Increased involvement of local communities and municipal governments in environmental decision-making could mitigate many of the PA-associated procedural and contextual equity concerns of PLAs and PES.

Participants in BanCO2 were selected into the program with the aim of maximizing the area of forest and the number of families enrolled, with little optimization for maximal environmental impact beyond targeting environmentally prioritized zones. Public land acquisitions also likely did not necessarily optimize for projected costs or benefits. With both interventions, managers could understand their constraints and opportunities more clearly if they engaged in targeting exercises that considered predicted costs, projected benefits, and probability of future land conversion to optimize instrument targeting while not exceeding their given budget (25). These exercises can be implemented quantitatively using spatial cost datasets like the ones generated by Nolte et al. (2023), and freely available machine learning software to predict future land-use changes (26).

The distributional equity concerns that we identified in this research could be addressed by shifting some funding priorities. Starting with PLA, where threats of expropriation and high transaction costs are a concern, we propose the following: 1) The threat of expropriation should be used as a last possible resort for those who are engaging in egregious environmental degradation or destruction, and not for those who are asking for a higher purchase price. 2) Managers should allocate a segment of the PLA budget to cover the transaction costs. 3) Each PLA should be accomplished within one administrative term. In cases where this is impractical, and the parcel is within a PA that was established after land ownership, landowners should be compensated at their full opportunity cost until the sale can be realized or another agreement can be reached.

In the context of PES, addressing equity concerns can yield instrumental benefits for environmental outcomes. While it may not be feasible for a PES program to fully compensate all individuals safeguarding forests based on their needs, a successful PES arrangement bears the responsibility of meeting the opportunity costs of participants while ensuring the financial stability of the program. Long term solvency in a PES program is also critical, and yet other PES programs in Mexico and Ecuador also missed payments due to funding shortfalls (27). We agree with Etchart et al. (2020) that

PES programs should be designed to be financially sustainable over the longer term and argue that more careful targeting and implementation could help further this aim.

Theory suggests that the minimum payment through PES should be the cost of provisioning the environmental service (28), but BancO2's PES program often fails to pay the full opportunity cost of forgoing forestry activities. We argue that BancO2 should consider differentiating payments based on the socio-ecological characteristics of their intervention sites as well as the level of ES provision (15). This discernment could reduce adverse selection problems, where people who are more likely to deforest are less incentivized to participate. The effect size of BanCO2's PES program was similar to those measured by studies of other programs (SMD = 0.32, 95% CI [0.10, 0.55]) (7), but the short one-year time frame for BancO2 payment contracts deviates from general recommendations for program commitment, which indicate that mid- to long-term planning is preferable for transformational change (at least 10 years) (29). Requirements for longer-term commitments could provide stability for participants while also excluding those who planned on changing their activities once participation was no longer convenient.

While we believe that these findings are relatively robust due to the availability of adequate spatial data, appropriate counterfactual matches, and a long time series of forest cover change data in our subregion, there are some concerns for internal and external validity. One potential concern for internal validity is the representativeness of our geographic coverage due to missing data. We note that we were able to estimate impacts for only 41% of PLA and 52% of PES, and checks indicate that these data gaps did not greatly bias our results in time (**Figure S5**), however, a disproportionate amount of spatial data was missing for the *Bosques* subregion for PLA, which had high levels of forest cover and ecosystem endangeredness (**Figure S3**). This data gap may have reduced our ability to observe avoided forest loss in PLA. Potential for bias in our analysis may also arise from time-varying but unobserved characteristics that could act as confounders or effect modifiers. For example, family size, age, available labor resources, the number of financial dependents, and changes in household economic conditions could impact the evolution of deforestation risk. Additionally, the strength of local organizations focused on protecting their watersheds could act as a moderator. Our results would be influenced by these potential confounders if there was bias in participation favoring one group, an outstanding question that could be a topic for future research.

Because the apparent impact of both interventions increased over time, and effects were not always immediately evident in the early post-treatment years (especially in datasets with a shorter timeframe), valuable insights would be gained by tracking the longer-term performance of BancO2. While CORNARE initiated BancO2 in 2013, substantial public involvement did not occur until 2017. It may still be too early to discern the complete impacts of the more recent PES implementation, especially regarding regrowth trends that might not be evident with seven years of post-treatment observations. Conversely, PES might show decreasing impact due to payments ending or people leaving the program. More post-treatment observations are necessary for parcels that stopped receiving payments to understand impact permanence. Although some research in Colombia and beyond suggest that the effects of PES can persist after payments end (30), a significant concern about the long-term impacts of BancO2 is that the contracts are short-term (one year), and may not change behavior.

The PLA and PES implemented in CORNARE's jurisdiction represent 10% of all PLA in the Andes (13), and approximately 25% of all PES implemented by BancO2 (31). BancO2 has expanded to sixteen other departments. Results could differ in other regions. However, because there is more funding for these interventions in CORNARE's jurisdiction in eastern Antioquia, we speculate that greater area of PES and PLA implementation will occur here than in most other places, with consequently larger overall impact, unless targeting is much more efficient elsewhere.

Conclusions:

Investments in watershed services have generated significant conservation funding for direct conservation interventions, namely PES and PLA in Colombia, yielding an important opportunity for understanding their relative impacts. We observe disparities in implementation activity, resulting in PES being implemented over a considerably larger area compared to PLA. This expansion occurred in locations with higher deforestation threats, within a shorter timeframe, and at a substantially lower cost. However, PLA achieved higher rates of avoided deforestation and much higher rates of forest gain than PES. Nevertheless, the overall area impacts were higher for PLA only when including forest gain, and not when focusing on avoided forest loss. Furthermore, there were no detectable differences in cost-effectiveness between the two interventions. We conclude that the instruments can serve different functions in distinct contexts, depending on a variety of factors, including ecological needs, the constraints of implementing organizations, and land users' social and economic situation, which require careful equity considerations.

Because the impacts of interventions change over time, evaluators should consider budgeting time and funding for evaluations many years post-treatment (especially if deforestation rates are low) to avoid overlooking effects from insufficient post-treatment observations. We encourage researchers to examine how treatments evolve over time so that planners can understand projected mid- and long-term outcomes. Furthermore, observed results can vary based on land cover change datasets and measured outcomes (e.g. forest loss vs net forest loss). We urge evaluators to use caution in their choice of remote sensing data and encourage more research into the impacts of mapping errors on evaluations of forest cover impacts.

Methods:

Colombia has a unique legal framework mandating IWS, providing a rich empirical context for measuring the relative impacts of PES and PLA. In 1993, the Colombian government mandated all departments and municipalities spend 1% of their income on buying land for water conservation (32, 33). These lands are publicly held for environmental management. In 2013, the Colombian government also allowed IWS funds to be spent on PES (Decree 953) (34), giving practitioners the option between the two.

The regional environmental agency with jurisdiction in eastern Antioquia, CORNARE, was the earliest regional environmental agency to implement PES. In response to the perception that environmental laws were overly punitive and disproportionally affected lower-income households, in 2013 CORNARE's leaders created BancO2, a PES program providing payments to land users for conserving forests. BancO2 grew rapidly with the passing of decree 870 of 2017, which provided guidance for PES implementation (35). While Colombia had fifteen active decentralized PES programs by 2020 (36), BanCO2 was the only program with ambitions for national-scale activity; though the government has issued awards to the program, some accuse it of greenwashing and giving mining and oil companies social license to continue polluting the environment (37).

BancO2 provides monthly payments of 334,000 COP (about 90 USD, translating to roughly 40% of the national monthly minimum wage) to publicly funded participants who have at least one hectare enrolled in the PES program, with no pay differential based on forest area. Agreements are made for one year and can be renewed conditional on continued compliance and funding if participants continue to meet selection criteria (see S.I. for details). Public funding must be approved by a mix of actors, including the departmental government, municipal governments, and CORNARE. There are also private sources of funding for BancO2, such as companies using watershed services (e.g., hydroelectric companies) and which are mandated to spend 1% of their project budget on IWS by decree 1900 of 2006 (38). BancO2 uses funds from these compulsory contributions as well as from carbon offsets and voluntary contributions. Payments vary for privately funded BancO2 participants, who may receive up to a minimum salary. Technicians regularly monitor forests in participating parcels.

Our study area (**Figure 1**) is composed of 26 municipalities with high geological, ecological, and socioeconomic diversity. The total area is approximately 827,600 ha, (13% of Antioquia and 0.7% of Colombia's territory), and encompasses a wide altitudinal range (200–3400 msl). The predominant natural ecosystems are Andean moist forest, sub-Andean moist forests, basal moist forests, and páramos (tropical alpine grasslands) (39). Antioquia is the Colombian department with the highest number of threatened species, with land-use change being a main factor in population declines (40). Forty-one PAs were declared in the region by 2020, covering 203,674 ha of territory (41).

Over half of CORARE's jurisdiction has already been converted to agricultural or urban land uses (**Figure S1**). Background deforestation rates range from 0 to 1.5% between 2000 and 2021, depending on the data source (**Figure S7**). In 2005, the region's population was 586,167 people (42). From 2000 to 2005, nearly 100,000 people were forcibly displaced from the region (43). The economy is characterized by agricultural activities, industry, mining, commerce, recreation, energy production, and tourism. Notably, the region's hydroelectric dams generate 26% of Colombia's electricity, contributing to the importance of water flow volume for the region as well as relatively higher resources for its management (44). CORNARE's jurisdiction is further subdivided into six subregions, each having their own ecological, geographical, and socioeconomic characteristics (**Figure 1 and Figure 2**).

Public land acquisitions data was collected by contacting government officials in charge of acquiring parcels via phone call, letter, or in person (see Reboredo Segovia et al., 2022). Data was received from both CORNARE and the Gobernación (department-level government), and included the number of parcels, the cost of purchase, date of purchase, and spatial location and extent from 19 of 26 municipalities in CORNARE's jurisdiction (see **Figure 1**) as well as spatial data on PES in their jurisdiction. Information about the dates and duration of the contracts on each parcel was provided by BancO2 (See S.I. for details).

Annual land cover maps for the period 1997-2022 were generated using two different approaches: The first (referred to as the "LC map" approach) used the continuous change detection and classification (CCDC) time series algorithm (45) applied to Landsat imagery using all spectral bands and several vegetation indices. The coefficients from the resulting time segments were used as predictors, along with ancillary topographic and climate data, to assign annual land cover labels using a random forest classifier. We applied tests for spectral stability and presence of transitional classes (e.g., regrowing vegetation) to improve the quality of the annual labels, following an approach similar to that used to generate the USGS-LCMAP product (46). The second approach (referred to as the "ensemble approach") applied a stacking generalization protocol (47) combining the outputs of two different change detection algorithms and one forest change product (45, 48, 49) aimed at reducing the errors in the detection of land cover change. This approach allows for forest gain detection as well as forest loss. We also compared impact estimates using yearly deforestation maps (2001-2021) produced by Hansen et al. (2013).

Our unit of analysis was area of forest cover at the parcel level. We drew both treated (i.e. enrolled or purchased) and untreated parcels from the rural cadaster map provided by Antioquia's geodatabase (50). We used spatial analysis to determine the location, area (ha), protected status, forest cover and forest cover change, and socio-economic characteristics of all relevant parcels (Q1a & Q1b). We developed a parcel-level dataset containing information on treatment, outcome, and key confounders (see S.I. for details).

We combined matching and differences in differences (DiD) with multiple time periods to estimate the causal impacts of PLA and PES on forest cover (Q1c). Matching identifies untreated (control) parcels which are as similar as possible to treated (intervened on) parcels in terms of observable confounding variables, and whose forest cover trends can indicate counterfactual outcomes on treated parcels (i.e., outcomes that would have been observed on treated parcels in the absence of treatment). Matching variables (**Table 1**) were selected based on our knowledge of the selection process, study area, literature review, and on Gradient Boosting Regression (GBR) that identified the main predictors of deforestation (**Figure S6**). Confounders that affected both the outcome and the probability of treatment were selected. We matched treated parcels with either never-treated parcels or not-yet-treated parcels (parcels that eventually received treatment) without replacement (without reintegration of selected parcels into the control pool). A novel protocol was used to implement this process, since it was necessary to 1) dynamically select control parcels that were untreated in the year that the comparison treated parcel was first treated (the reference year), 2) select data from the control parcels for the years prior to the reference year, as was already implemented in a previous study (51), 3) and ensure that some treatment year parcel cohorts would not be better-matched than others by virtue of being matched first (see S.I.). One treated parcel was drawn randomly at a time and matched to a dynamically created pool of control parcels based on the treatment year, which was then updated for the next randomly drawn parcel as control parcels were selected. Post-matching standardized mean differences (SMD) were small between treated and control groups (< 0.15 SMD for all variables) (**Figure S9**). Each intervention (PES and PLA) was matched to its own pool of controls because differences in implementation locations led to small samples of directly comparable parcels, particularly because of differences in elevation.

Ordinary two-way fixed effects DiD design can yield biased estimates for staggered implementation designs, meaning interventions that are implemented over multiple years (52). Because of the staggered implementation of both PES and PLA, we ran DiD with multiple time periods using the R package *DiD* and as described in Callaway & Sant'Anna (53), which yields average treatment effects on the treated (ATTs) in multiple data aggregations. We considered outcomes for scenarios in which either 1) parcels received treatment for any amount of time (presented in main text) or 2) parcel were excluded if they were dropped from the program at any point from the analysis. (See S.I. for deforestation time series for parcels that dropped out of the PES program.) We ran several robustness checks on the statistical methods (Table S2) and ran subgroup analyses on both PES and PLA by comparing results between 1) parcels treated inside- and outside of PAs, 2) parcels with high- and low deforestation pressure, 3) parcels at high- and low elevation, 4) parcels with high- or low travel time to the nearest city, and 5) parcels of large- or small total area. For PES, we also ran subgroup analyses on publicly vs privately funded PES. For PLA, we compared relatively high-cost parcels to low-cost parcels (see S.I. for details). We then compared the return on investment (ROI) of these two policies by first converting the purchase price of parcels to their equivalent yearly rents, then determining the overall area impacts of the two interventions and calculating the cost to impact ratio for each (see S.I. for details).

In addition to the econometric analysis, we conducted in-person surveys with PES participants and people who sold their lands (and relevant controls) and interviews with relevant stakeholders. The first and second authors spent nearly three months (between June and August, 2019) surveying 52 BancO2 participants, eight individuals who sold their lands, and fifteen control subjects who had not participated in either conservation program. The first and second authors also conducted twenty-six unstructured interviews with environmental activists, community members, municipal-level environmental managers, department-level environmental managers, university professors, BancO2 managers, Masbosques officials, and CORNARE officials. The surveys had eighteen sections detailing household data, land management, and conservation attitudes (full details in S.I.). These interviews served to triangulate information on selection method criteria for PLA and PES, inform the variables used for matching variables, understand the potential for leakage, and infer mechanisms for how interventions can contribute to additional impacts (or not). Themes and examples from the surveys and interviews helped to inform the equity implications of the interventions.

Acknowledgements and Data:

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Tables and Figures:

***Table 1**: Selected variables for matching*

Variable	Source	Source Year	Year Used	Resolution/Units	Scaled to	Justification
% Forest cover on the year prior to treatment	Bullock and Arévalo (in progress)	2022	2006-2018	30 m	Parcel	Percent forest cover affects the potential measured change, and its selection for treatment.
% Forest loss in the past three years in a 60-pixel radius	Bullock and Arévalo (in progress)	2022	2006-2018	30 m	Parcel	Deforestation pressure is an important predictor in forest loss – any selection bias in the variable would affect the effect estimate.
Slope	Takaku, Tadono, Tsutsui, & Ichikawa (2018)	2019	NA	30 m	Parcel	Areas with higher slope are less arable and therefore are at lower risk of deforestation. Any selection bias in the variable would affect the effect estimate.
Elevation	GIS calculation	2019	NA	30 m	Parcel	Elevation can influence deforestation pressure. Selection bias in the variable could affect the effect estimate.
Access (travel time to markets)	Nelson, (2008)	2008	2008	30 arc seconds	Parcel	There are greater motives to deforest if the cost of getting a product generated by land use change to market is lower.
PA Category	RUNAP	2020		Vector	At least 20% of parcel	Different PA categories have different restrictions, which should be controlled for when selecting a counterfactual.
Whether PA was established at t-1	RUNAP	2020		Vector	At least 20% of parcel	Timing of PA creation during our study period required us to match based on pre-treatment conditions.
Subregion	CORNARE			Vector	Parcel	Different subregions have different socioeconomic characteristics driving deforestation and implementation.
Parcel area	GIS calculation			Vector	Parcel	Parcel area determines the yearly level of deforestation that can be observed due to the 30 m resolution of the land cover dataset.

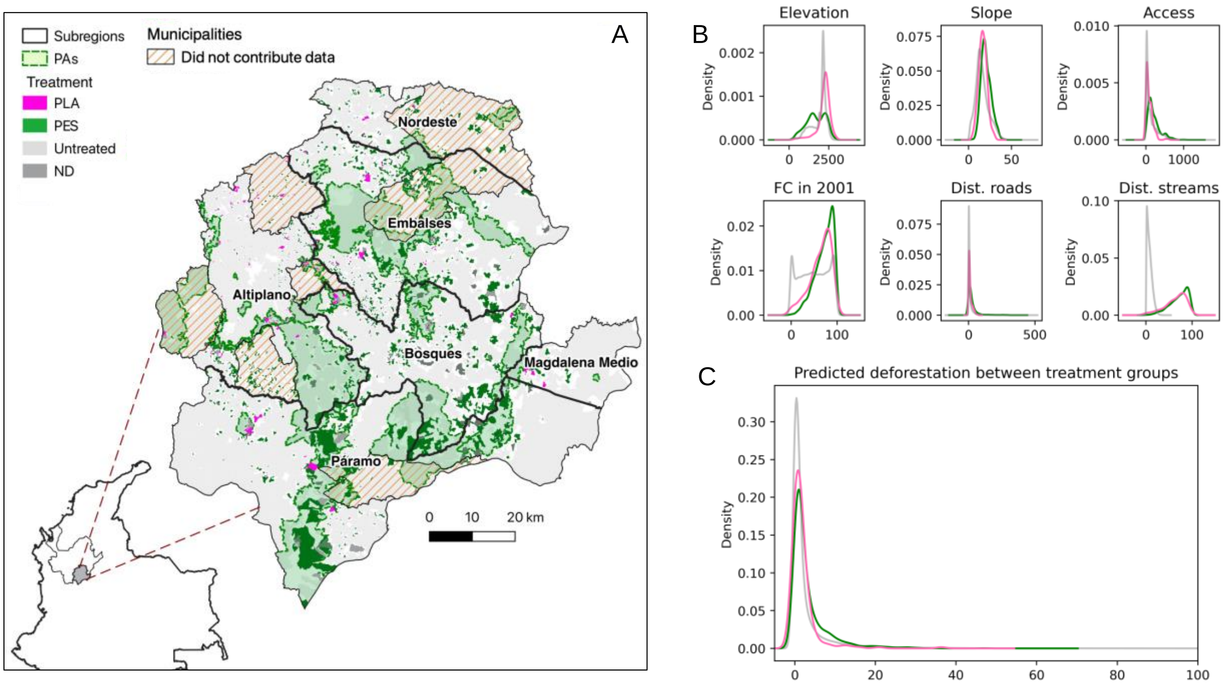

Figure 1: A) The distribution of PLA and PES inside the jurisdictional area of CORNARE. Both instruments are implemented inside and outside of PAs. Parcels with a ND label either did not have a date for implementation start or were not treated within the study's cutoff period for treatment (2006–2019). B) The distribution of covariates that are important for predicting deforestation throughout the land-use change time series. C) The distribution of predicted deforestation between the control, PLA, and PES parcels.

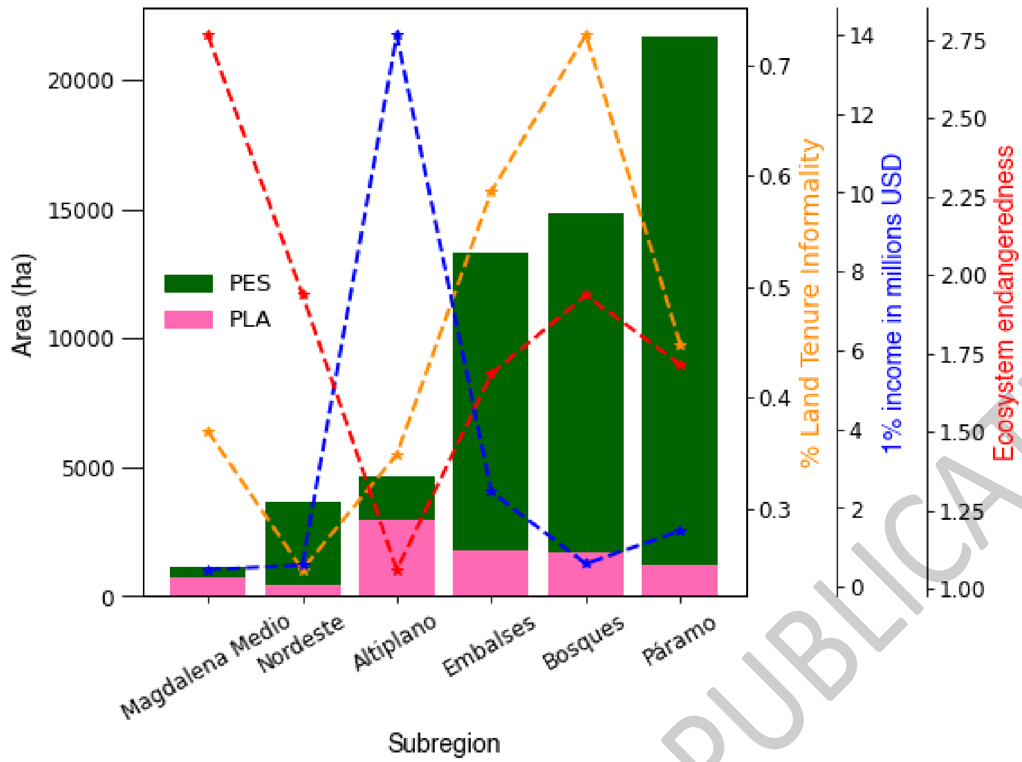

Figure 2: The distribution of implementation area among treatment type, regions, and relevant variables. Percent land tenure informality is derived from Tech ARD – USAID data (pers.comm.) One percent (the dictated investment by law) income to the municipality is calculated from 1993–2017 from DNP (2018) data (56) and reported in 2020 USD (values were adjusted using the annual Consumer Price Index (CPI) from the World Bank (57). The conversion of COL to USD in 2020 was 3694.8 COP to 1 USD (58). 869 PES and 18 PLA do not have spatial extent data. Ecosystem endangeredness was derived from the red list of ecosystems for Colombia (59).

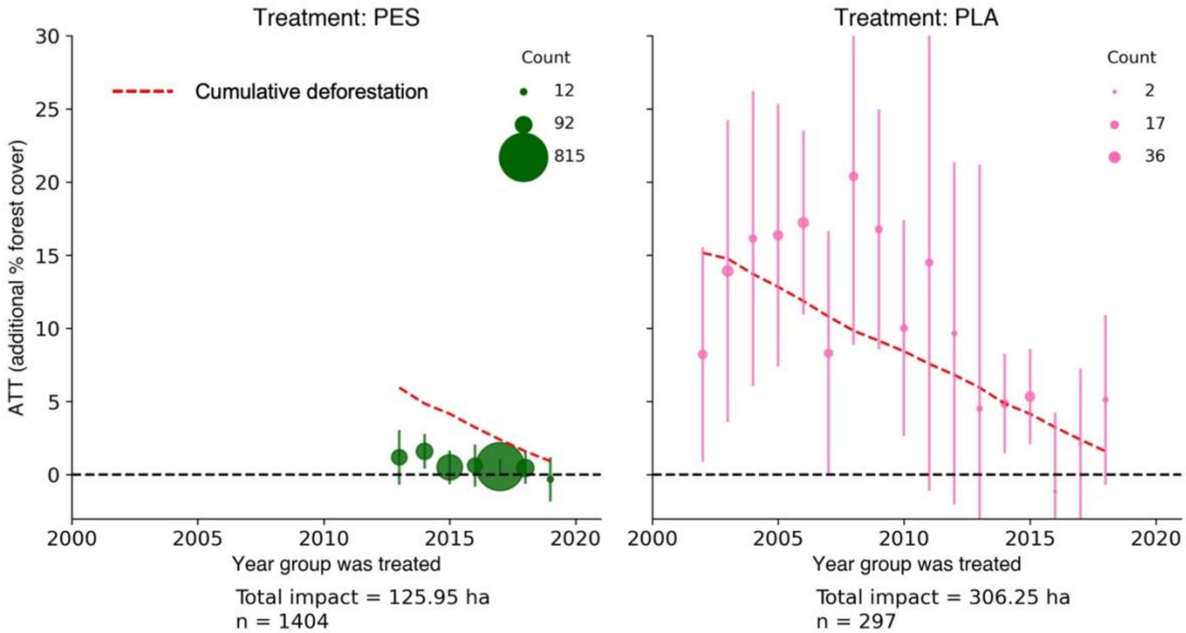

Figure 3: Treatment cohort level average treatment effect on the treated (ATT) for PES (left) and PLA (right). Land cover data: Ensemble approach (Arévalo & Bullock, in progress). Error bars show the 95% confidence interval for the impact estimate. The cumulative deforestation line shows the cumulative deforestation rates for all of eastern Antioquia, our study subregion, across the duration of each cohort's treatment period.

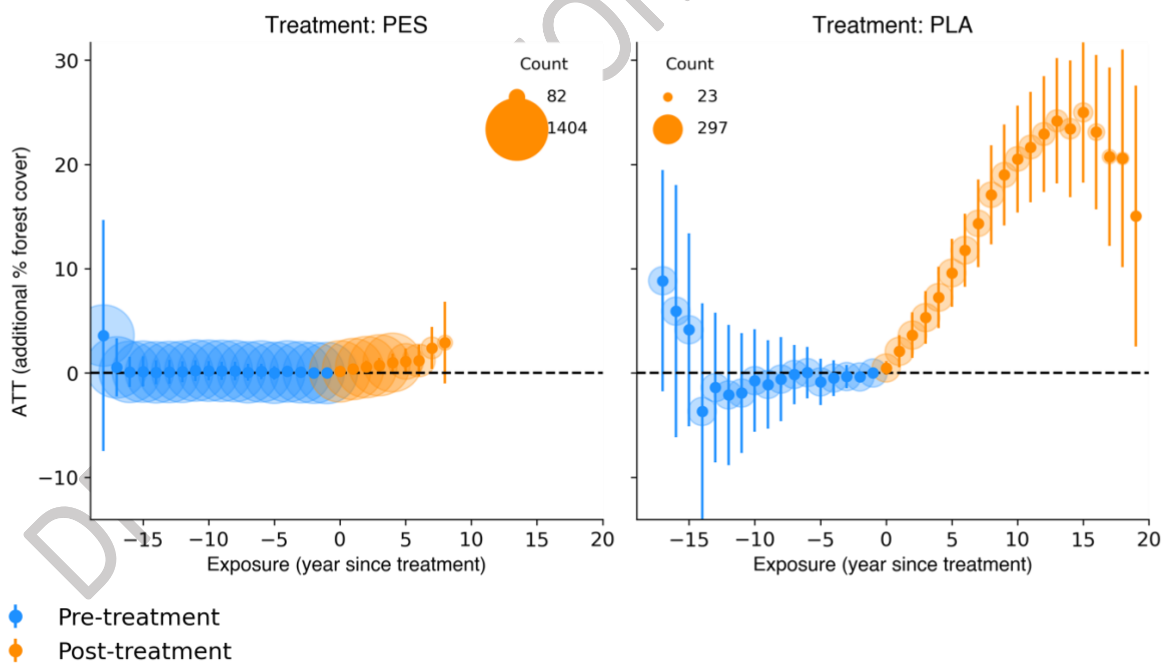

Figure 4: ATTs averaged by exposure length (the number of years) pre and post treatment for PES (left) and PLA (right). Forest cover data: Ensemble approach (Arévalo & Bullock, in progress). For PES, n = 1404. For PLA, n = 297. Error bars show the 95% confidence interval for the impact estimate.